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The Water-Energy-Food Nexus in the Eastern Nile Basin

Transboundary Interlinkages, Climate Change and Scope for Cooperation

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Abstract

With worldwide mounting pressure in the three highly interrelated resources of water, energy, and food (WEF) the 'nexus' concept has emerged as the best approach to address the complex and dynamic problem facing the three sectors. Though the challenge of balancing needs across competing uses and users is global, it is more intense in developing regions like the Eastern Nile basin as most of the riparian countries are faced with high poverty and a serious ongoing security problem with the three resources. In the basin, empirical evidence on the WEF nexus is needed to improve resource use efficiency and avoid adverse impacts of single-sector and unilateral development strategies and actions. Accordingly, this study applies the WEF nexus concept in the Eastern Nile basin to assess and quantify tradeoffs and synergies in the basin across sectors and between riparian countries. To address these objectives, combinations of qualitative (e-surveys and interviews) and quantitative (an integrated hydro-economic model) approaches are used.

Results suggested that cooperation across sectors and riparian countries is crucial for the basin because sectoral and transboundary interlinkages are tight, complex and dynamic. Findings from the qualitative assessments advocated that collaboration across WEF sectors is essential at a national and regional level to improve the efficiency of resource use and management in the basin. The same need for cooperation is suggested by the results of the hydro-economic model where the cooperative (system optimization) scenarios yield the highest economic benefits compared to the non-cooperative (tradeoff) scenarios under various levels of hydropower and irrigation developments in the basin. Results from the non-cooperative scenarios indicated the potential for large sectoral and transboundary tradeoffs in the basin if one sector or country is prioritized over the other. Assuming full cooperation, upstream hydropower developments are found to be beneficial to all riparian countries and could have a synergetic impact by ensuring more regulated year-round river flows, increasing irrigation benefits in downstream countries, reducing evaporation losses, and providing access to a large amount of clean and affordable energy in the region. However, new upstream irrigation developments could compete with existing water uses and potentially inflict costs on downstream riparians, unless measures are taken to improve irrigation efficiency in existing and proposed irrigation schemes.

Climate change will add further challenge and complexity to WEF nexus in the basin. It is highly uncertain how climate change is going to affect the supply of and demand for WEF resources in the basin. Predicted changes of river flow in the basin greatly vary across the ten climate change scenarios considered in this study where some (majority) scenarios forecasted increased flow, while others project a reduction in 2050. Also, most climate change scenarios forecasted higher irrigation water demand in the basin either due to reduced crop yield or increased evapotranspiration rate (both). The increase in irrigation water demand resulted in reduced total basin-wide economic benefits (from hydropower and irrigation) despite the predicted increase in total basin-wide inflow by the majority of the climate change scenarios. As climate change (coupled with population and economic growth) poses high uncertainty to the basin's future, dynamic collaborative efforts are needed among sectors and basin countries. There are various areas where riparian countries can cooperate on to enhance the benefit of future WEF developments in the basin. These include undertaking joint transboundary developments and promoting 'beyond the river' links in the region by strengthening existing technical, economic and institutional ties, and creating new ones.

Der Nexus Wasser-Energie-Nahrung im östlichen Nilbecken: Grenzüberschreitende Verflechtungen, Klimawandel und Kooperationsmöglichkeiten.

Zusammenfassung

Angesichts des weltweit zunehmenden Drucks auf die drei eng miteinander verknüpften Ressourcen Wasser, Energie und Nahrung (WEF) hat sich das "Nexus" -Konzept als der beste Ansatz herausgestellt, um das komplexe, dynamische Problem dieser drei Sektoren anzugehen. Die Herausforderung, den Bedarf an konkurrierenden Nutzungen und Nutzern zu decken, ist global. Dennoch ist diese in Entwicklungsregionen, wie dem östlichen Nilgebiet, intensiver, da die meisten Anrainerstaaten mit hohen Armutsquoten und anhaltenden Sicherheitsproblemen konfrontiert sind. Das Nil-Becken benötigt empirische Belege für den WEF-Nexus, um die Ressourceneffizienz zu verbessern und nachteilige Auswirkungen von einseitigen Entwicklungsstrategien und -maßnahmen zu vermeiden. Diese Studie nutzt das WEF-Nexus-Konzept im östlichen Nil-Becken, um *trade offs* und Synergien zwischen den Sektoren und Anrainerstaaten zu quantifizieren. Dies geschieht anhand einer Kombinationen von qualitativen (E-Surveys und Interviews) und quantitativen integriertes hydroökonomisches Modell) Ansätzen.

Die Ergebnisse zeigen, dass die Zusammenarbeit zwischen Sektoren und Anrainerstaaten für das Einzugsgebiet von entscheidender Bedeutung ist, da sektorale und grenzüberschreitende Verknüpfungen eng, komplex und dynamisch sind. Die Ergebnisse der qualitativen Bewertungen belegen ebenso, dass die Zusammenarbeit auf nationaler und regionaler Ebene von wesentlicher Bedeutung ist, um die Ressourcennutzung und -bewirtschaftung zu verbessern. Den gleichen Kooperationsbedarf zeigen die Ergebnisse des hydroökonomischen Modells: kooperative (Systemoptimierungs-) -Szenarien erbringen den höchsten wirtschaftlichen Nutzen im Vergleich zu nicht kooperativen (Kompromiss-) Szenarien bei verschiedenen Wasserkraft- und Bewässerungsentwicklungen. Die Ergebnisse der nicht kooperativen Szenarien zeigen das Potenzial für große, sektorale und grenzüberschreitende *trade offs*, falls ein Sektor oder ein Land Vorrang vor dem anderen hat. Unter der Annahme uneingeschränkter Zusammenarbeit erweisen sich vorgelagerte Wasserkraftwerke als förderlich für alle Anrainerstaaten und könnten synergetische Auswirkungen haben, da sie einen ganzjährigen Fluss sicherstellen, den Bewässerungsnutzen in den nachgelagerten Ländern erhöhen, die Verdunstungsverluste verringern. eine große Menge an Erdgas bereitstellen sowie saubere und bezahlbare Energie. Jedoch könnten neue, vorgelagerte Bewässerungsvorhaben mit bestehender Wassernutzung konkurrieren und Kosten für die nachgelagerten Anrainer verursachen, falls sich die Bewässerungseffizienz in bestehenden und geplanten Bewässerungssystemen nicht verbessert.

Der Klimawandel wird im Nil-Becken zu weitere Herausforderungen führen, da der Einfluss auf Angebot und Nachfrage nach WEF-Ressourcen ungewiss ist. Die erwarteten Veränderungen des Flusses variieren stark zwischen den zehn Klimawandelszenarien, die hier berücksichtigt wurden. Einige (Mehrheits-) Szenarien prognostizierten einen erhöhten Fluss, während andere eine Reduktion bis 2050 erwarten. Die meisten Szenarien prognostizieren außerdem einen höheren Bewässerungsbedarf im Becken, was zu einer Verringerung des gesamtwirtschaftlichen Nutzens führen würde. Der Klimawandel stellt eine große Unsicherheit für die Zukunft des Beckens dar, weswegen gemeinsame Maßnahmen zwischen Sektoren und Gebieten erforderlich sind. Dazu gehören die Förderung von Verbindungen jenseits des Flusses in der Region, durch die Stärkung bestehender technischer, wirtschaftlicher und institutioneller Bindungen, und das Schaffen neuer Verbindungen.

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List of Acronyms

AfDB	African Development Bank
BASW	Baro-Akobo-Sobat and White Nile
BCM	Billion Cubic Meter
BN	Blue Nile
CFA	Cooperative Framework Agreement
COMESA	Common Market for Eastern and Southern Africa
CPMAS	Central Agency for Public Mobilization
CSA	Central Statistical Agency
DSS	Decision Support System
EAC	East African Community
EAPP	Eastern Africa Power Pool
EEHC	Electricity Holding Company
EIU	Economic Intelligence Unit
ENMOS	Eastern Nile Multipurpose Option Scoping
ENPT	Eastern Nile Power Trade
ENSAP	Eastern Nile Subsidiary Action Program
ENTRO	Eastern Nile Technical Regional Office
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Models
GAMS	General Algebraic Modeling System
GHG	Greenhouse Gases
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
ha	Hectare
HAD	High Aswan Dam
HDI	Human Development Index
ICARDA	International Centre for Agricultural Research in the Dry Areas
IFPRI	International Food Policy Research Institute

IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IMPEND	Investment Model for Planning Ethiopian Nile Development
IPoE	International Panel of Experts
IRENA	International Renewable Energy Agency
IWRM	Integrated Water Resource Management
KII	Key Informant Interview
LEAP	Long-range Energy Alternative Planning
LUC	Land Use Change
M&I	Municipal and Industrial
MCM	Million Cubic Meter
MENA	Middle East and North Africa
MN	Main Nile
MoALR	Ministry of Agriculture and Land Reclamation
MoEE	Ministry of Electricity and Energy
MSIOA	Eastern Nile Multi-Sector Investment Opportunity Analysis
MWIE	Ministry of Water, Irrigation and Electricity
MWRI	Ministry of Water Resources and Irrigation
NARC	National Association of Regulatory Commission
NBI	Nile Basin Initiative
NEEOM	Nile Environmental and Economic Optimization Model
NELSAP	Nile Equatorial Lakes Subsidiary Action Program
NELSAP-CU	Nile Equatorial Lakes Subsidiary Action Program Coordinating Unit
NEOM	Nile Economic Optimization Model
Nile-COM	Council of Ministers of Water Affairs of the Nile Basin States
Nile-SEC	Nile Secretariat
Nile-TAC	Nile Technical Advisory Committee
NRBC	Nile River Basin Commission
NUNIS	Northern Upper Nile Irrigation Schemes

OECD	Organization for Economic Cooperation and Development
RCP	Representative Concentration Pathways
SDGs	Sustainable Development Goals
SHOM	Sudan Hydro-economic Optimization Model
SVP	Shared Vision Program
TECCONILE	Technical Cooperation Committee for the Promotion of Development and Environmental Protection of the Nile Basin
TLU	Tropical Livestock Unit
TSA	Tekeze-Setit-Atbara
UN	United Nations
UNEP	United Nations Environment Program
USA	United States of America
USBR	U.S. Bureau of Reclamation
USD	United States Dollar
WB	World Bank
WDC	World Dam Commission
WEAP	Water Evaluation and Planning
WEF	Water, Energy and Food

1. Introduction

1.1. Background on the Concept of Water-Energy-Food Nexus

Ensuring the adequate supply and sustainable use of water, energy, and food (WEF) is a major concern for the entire world as the three resources are vital for human wellbeing and economic development (Rasul, 2014). However, the scope and intensity of the concern vary across places depending on several aspects such as the existing resource base, the already available supply of the resources, the capacity to exploit the base in order to increase supply in the future, the degree of tradeoff and the extent of intensifying factors. For most developing countries which are characterized by a limited current supply of the resources, high tradeoffs to enhance their supply (satisfy demand) and several factors intensifying the tradeoffs, understanding the link between the three resources is a more critical and prevalent concern than advanced nations. From the systems perspective, the three resources are highly interrelated where one is input for the other in several cases. Estimates from previous studies show that around 80-90% of the world's surface and groundwater abstraction is made for food production which is the largest of all consumptive water uses. As well, energy production in the form of fossil fuels, biofuels and hydropower is responsible for 8% of global water extractions. In turn, energy is required for various steps of clean water preparation. Moreover, the food production and supply course require energy where the complete chain of food production and supply accounts around 30% of total global energy demand. Different crops are also used to produce energy in the form of biofuels (Hoff, 2011). According to Bazilian et al. (2011:2), the three resources have many shared attributes in terms of existing access, change in demand, supply constraint, spatial and temporal availability, tradability and market structure. Particularly, limited current access accompanied by persistently increasing demand, constrained supply due to natural resources scarcity as well as lack of infrastructure and operation in highly regulated markets are common for the three resources.

However, against the inherent interlink among WEF systems, important decisions about the three resources often lack coordination due to existing institutional structures such as separate governing bodies (Davis, 2014). The fragmented governance of the three resources usually leads to the design of policies and strategies that do not consider sustainability challenges in an integrated way disregarding the inevitable linkages among WEF systems. But, such governance structures and resulting sectoral policies (or the so-called a 'silos' approach) which usually assume abundant resource inputs from the other sectors, is no more viable enough in today's dynamic world (where population and economic growth, as well as climate change, has placed a mounting pressure on resources)[1] (International Renewable Energy Agency (IRENA), 2015a). Insight of these, recently 'WEF nexus' is introduced as a new approach and has been strongly promoted as a "global research agenda and emerging development paradigm" (Leck et al., 2015:445). The World Economic Forum is among the first to evoke 'nexus thinking' indicating the inevitable link between the three resources in their report titled "Water Security: The Water–

[1] Forecasts indicated about a 40% shortage of water supply by 2030 (United Nations (UN), 2013), as well as a 70% and 40% rise in demand for food and energy respectively is expected to be faced by 2050 at global level (Hoff, 2011).

Food–Energy Climate Nexus" (World Economic Forum, 2011a). In addition, the forum has presented the potential risk associated with WEF resources in the Global Risks report alerting the international society about the possible dangers posed by resources scarcity and the need for integrated management (World Economic Forum, 2011b). Consequently, several global and regional events (conferences, meetings, and workshops) were conducted stressing the interdependencies between the three resources as well as land and the environment (Bizikova et al., 2013). Particularly, the Bonn 2011 Nexus Conference (and the background paper by Hoff, 2011) has made a major contribution in popularizing and well describing the nexus concept. The Rio+20 conference which was held in June 2012 and more recently the Bonn 2014 conference are other major events which gave further emphasis to the WEF nexus concept (UN, 2015a).

According to Hoff (2011), by integrating management and governance across sectors and scales, the nexus approach provides a framework that balance among competing and different goals, interests, and needs of people and the environment. The key issues within the nexus approach are natural resource scarcities, system interdependence (tradeoffs and synergies), resource use efficiency, externalities, and policy coherence (Hoff, 2011; Leck et al, 2015). Particularly, given increasing natural resource scarcity and interlink across sectors, the main idea behind the nexus approach is to increase resource use efficiency through reduced negative externalities with the aim to promote security in three sectors (Hoff, 2011). The core idea of nexus thinking which emphasized integrated management of natural resources is not completely new, previous frameworks such as Integrated Water Resource Management (IWRM) also had fairly the same principle (Ringler et al., 2013; Allouche et al. 2014; Davis 2014; Stringer et al. 2014). The IWRM framework was an early response to deal with the interlinkage between water and other resources. The conceptual framework emphasized balancing water allocation to different uses (including cultural and ecological needs) through integrated and coordinated water and land management approaches. However, the IWRM is criticized to give priority for the water sector and water-related development issues over the others sectors, which thus underpins traditional sectoral approaches (Ringler et al., 2013; Food and Agriculture Organization of the United Nations (FAO, 2014a)). Accordingly, considering WEF as a holistic system, the nexus approach was ideally proposed to give equal emphasis to all the three sectors. In practice though, nexus framing and analysis usually starts from one dimension and then endeavors to assimilate others (Bazilian et al., 2011) where for example in Hoff (2011) water is taken as a core component while in Ringler et al. (2013) food is considered to be central. Yet, as any dimension can be taken as a starting point in nexus framework, it is proposed to be more engaging (of other sectors) than IWRM framework (Leck et al., 2015).

Apart from its focus on sectoral interlinks among WEF systems, the nexus approach also has spatial and regional dimensions (Hoff, 2011). Such dimensions are especially crucial in transboundary basins where the existence of diverse and competing national interests (concerns) and upstream-downstream tradeoffs add more complexity to the WEF nexus analysis. Riparian countries in a river basin usually are characterized by diverse resource endowment, access and use, different level of economic development, complex water politics, and uneven power possession as well institutional capacity for making decisions. Applying the nexus approach in a river basin context thus needs to consider all these complexities that are inevitable in transboundary river basin management. If so, the approach can provide opportunities for new insight and options for solutions to WEF security issues. In addition, by identifying key development drivers and challenges as well as major tradeoffs in transboundary river basins, the approach can provide a useful framework for addressing challenges based on regional and river basin approach. This is however in theory, the key river basin characteristics mentioned above combined with limited information exchange and lack of sufficient basin scale knowledge makes the practicality of WEF nexus analysis in a river basin context considerably challenging (Bach et al., 2012; Rasul, 2014).

1.2. Problem Statement

Extending through eleven countries, the Nile is the longest river in the world and a base of livelihood for millions of people living in the riparian states (Appelgren et al., 2000; Awulachew et al., 2012; Paisley and Henshaw, 2013). The Eastern Nile region is an important sub-section of the Nile Basin as it supplies up to 90% of annual flows of the Nile River (Nile Basin Initiative (NBI), 2012a). The region extends across the North Eastern African countries of Ethiopia, Sudan, South Sudan, Egypt and a small portion of Eritrea with an estimated total population of approximately 245 million in 2015 (UN, 2015b). In the basin, the issue of WEF nexus is one of the most complex and critical issues as tradeoffs and synergies between the three resources are not only sectoral but also have a geopolitical dimension. Indeed, the Nile Basin as a whole is identified as one of the regions in the world with high existing tension, emerging peril and security threats regarding the three most important resources of WEF (UN, 2013). The basin is facing escalating challenges and pressures regarding issues of water management and sharing (Swain, 2011). Demand for WEF is increasing, intensified by high population growth and climate change in the region (NBI, 2012a).

Most of the upper stream economies of the basin are highly dependent on agriculture and water availability is the issue of survival for these countries while the same is true for downstream riparians who are highly dependent on water originating from upstream (Martens, 2011). The increasing demand for the three resources in the Eastern Nile is also partly attributed to the higher economic growth witnessed recently in some countries of the basin. Climate change is going to pose an additional challenge to the issue of WEF nexus in the basin by affecting the supply of and demand for the three resources (Conway, 2005). It is expected that water resource management in the Eastern Nile will become increasingly complex as these economic, climate and demographic changes continue. The existence of a high interlinkage between the WEF sectors within and between countries in the Eastern Nile basin calls for an approach that tackles security problems in the three sectors and riparian countries together, reducing potential tradeoffs that could arise with sectoral actions and exposing potential synergies of concerted efforts. The nexus approach is proposed to integrate the management of limited resources across sectors and bring cooperation among countries along the basin in order to ensure adequate provision of food, energy, and water for the basin's growing population (Bach et al., 2012).

With the aim of satisfying the existing suppressed demands and growing future needs in the basin, several multi-purpose projects are under construction and proposed to be developed in the future. Irrespective of other factors, these developments will require a substantial amount of additional water (as well as energy in the case of irrigation projects) to be operational. Given the fact that the existing water resource in the basin is already largely exploited (mainly by downstream countries), the proposed investments are expected to have adverse impacts on existing water use and users if they are not developed and managed in a cooperative manner. Single sector and unilateral development plans and actions could exacerbate the hydropolitical tension in the basin and create conflicts. Therefore, meeting current and future demand by peoples in the basin will require an approach which enhances and ensures the adequate supply of the three resources. By integrating the management of the limited resources across sectors and bringing cooperation among countries along the basin, the nexus approach is expected to give a way forward for adequate provision of WEF for the basin's expanding population (Bach, 2012). The underlying issue in modeling the nexus between WEF is quantifying the extent of tradeoffs and possible synergies across sectors and countries along the basin. Such attempt can help to avoid some of the "negative implications of poor sectoral coordination, institutional fragmentation, and inadequate capacity as well as to address sectoral and regional interests in a more efficient manner" (FAO, 2014a: 13).

Accordingly, this study attempts to apply the WEF nexus concept in the Eastern Nile basin to assess and quantify tradeoffs and synergies in the basin across sectors and between riparian countries. The general objective of the study is to conduct an empirical examination of inter-sectoral and transboundary links between WEF in Eastern Nile basin by combining qualitative and quantitative approaches. Qualitative method is used to assess knowledge and opinions of policymakers and practitioners on challenges and opportunities across the WEF nexus in the Eastern Nile region. Quantitative method is applied to analyze whether sectorally and regionally coordinated water resource developments increases benefit from irrigation and hydropower production in the basin compared to unilateral actions across sectors and riparians. In addition, as climate change is a key future challenge for the basin, its impact on agricultural (irrigation) and hydropower productivity, and hence economic benefits obtained from the two sectors are also examined. The results from this study are expected to increase the understanding of the interdependencies across both the WEF sectors and basin countries. Such understanding can lead to informed and transparent decision-making as well as the advancement of appropriate policies and strategies allowing the achievement of development goals related to WEF. Also, the study is believed to provide evidence-based recommendation towards better management and collaboration of the three sectors in basin countries.

1.3. Foundations of WEF Nexus Concept

It can be contended that the nexus concept makes its foundation on the economics of resource scarcity, institutional economics, and systems theory. The issue of resource scarcity and its implication on economic growth as well as human wellbeing has been emphasized back in the days of Thomas Malthus where he argued that growth in population will surpass food productivity leading to subsistence and dire leaving conditions for most people (Malthus, 1798). Malthus mainly based his argument of resource scarcity on the principle of diminishing marginal returns to factors. According to him, as the available land resource is fixed, applying more labor and capital on it will eventually result in a decreased marginal return to variable factors (and as productive or fertile lands are already largely captured, extending into a new land will not be a solution). The Malthusian resource scarcity is however criticized to be pessimist as it doesn't take into account factor substitution and technological progress (Barbier, 1989). Similarly, the Ricardian resource scarcity is based on incessantly diminishing quality of resources, i.e., first resources with higher productivity (like fertile land) will be used for production and as demand continues to rise less productive resources (marginal land) will be used demanding more and more input application to much previous level of production (Hall and Hall, 1984). The Malthusian resource scarcity is often termed as absolute scarcity while the Ricardian scarcity is associated with relative resource scarcity (Barbier, 1989).[2]

The issue of resource scarcity and diminishing marginal return leads to the notion of resource use efficiency. Different schools of thoughts have provided theories on how to achieve economic efficiency (allocative or productive efficiency). The classical market-oriented approach is on such dominant theory. In their "laissez-faire" motto they underline the central role that market plays in achieving economic efficiency stating if markets are left alone without any government intervention[3] they will lead to efficient allocation of resources. However, other schools of thoughts which advocate government intervention relying on issues of business cycle and market failure (including transaction cost, externalities, public goods and information asymmetry) were also prominent. Among these, the Keynesian economics which supports government intervention in stabilizing business cycle (and the resulting failure of the economic system to yield optimal outcomes) can be mentioned (Landreth and Colander, 2002).

Much of the empirical work on resource scarcity focuses on its implication for economic growth. The book 'Scarcity and Growth' (Barnett and Morse, 1963) which was sponsored by Resource for Future is an early work which examined trends of natural resource scarcity and how it could impair economic growth. Consequently, the Club of Rome has published 'The Limits to Growth' by Meadows et al. (1972) which predicted a halt in economic growth by the twenty-first century if the current growth trends in world population, industrialization, pollution, food production, and resource depletion continue. Further, in response to growing environmental concern in industrial countries, the 'sustainable development paradigm' has emerged in the mid-1980s perpetuating the resource scarcity agenda. The sustainable development paradigm has called for a holistic and integrative approach in planning and decision making to balance environmental, social, and economic development goals (Dernbach, 2003).

Similarly, the nexus approach can be taken as a recent effort to renew the natural resource scarcity concern. The approach stresses the scarcity of water, energy, land and other resources largely due to increasing demand (as a result of population growth and economic development), resource degradation and depletion. Predictions by the World Economic Forum and the following Bonn Nexus conference showed that if current demand, supply and resource management pattern continues, sever resource scarcity will be evident in a few decades

[2] Absolute natural-resource scarcity occurs when a resource is physically available in finite amount and gets depleted due to its use continuously in economic activities. On the other hand, relative natural-resource scarcity would occur due to mismatch between the limited availability of a natural resource and the unlimited want of human being resulting increasing scarcity relative to demand (Barbier, 1989).

[3] Expect protecting private property, enforcing contracts, providing public good and performing regulatory roles.

threatening sustainable economic growth. The approach suggested that significant changes towards more sustainable production and consumption patterns could be achieved through an integrated approach of natural resource management which is crucial in enhancing system efficiency leading to increased productivity of resources (Hoff, 2011).

In addition to resource scarcity, new institutional economics can also be taken as the conceptual basis for WEF nexus analysis.[4] This strand of the literature considers market failures in the form of transaction costs and externalities in its analytical framework, which are quite common in natural resource-dependent sectors (Taylor et al., 2013). Transaction costs and externalities determine the quantity and quality of water available in space and time which are key issues in river basin resource allocation (Lee and Dinar, 1995). Since water has characteristics of a common pool resource, parties cannot be precluded from using the resource. Private sector activities in these sectors typically do not internalize or compensate for externalities, and transaction costs for doing so are high. Thus, due to the existence of market failures, especially the water and energy sector operate under significant public sector involvement. Optimizing public policy and investments across sectors and scales is demanding and it also has its own transaction costs (von Braun and Mirzabaev, 2016). From an economics perspective, the presence of market failures due to externalities and transaction costs in WEF sectors results in sub-optimal allocations and lower aggregate social welfare. The new institutional economics focus on minimizing transaction cost across sectors rather than optimizing independent systems (von Braun, 2016). The nexus approach which takes into account the interdependencies among WEF sectors is a viable way to address such complex linkages reducing negative externalities and transaction costs across sectors and scales (Hoff, 2011).

Nexus thinking also makes its foundation in systems theory. General systems theory was first introduced by von Bertalanffy in 1950. According to him, a system can be defined as “a complex of interacting elements”. Von Bertalanffy (1968) indicated that systems can be found everywhere including nature, society, science, and economic contexts. Systems theory is an interdisciplinary theory dealing with all systems and a framework which can allow investigating phenomena from a holistic perspective. Knowing the interactions between different parts of an entity is the main focus of systems theory which is important to understand the organization, functioning, and outcomes of the entity (Mele et al., 2010). The theory contends that reductionism (i.e. trying to understanding a phenomenon by breaking into small parts) will not be enough to get full comprehension about a phenomenon and hence there is a need to follow holistic approach (von Bertalanffy, 1968). Likewise, the nexus concept emphasized planning and decision-making approaches which follow ‘socio-ecological systems’ perspectives and system-wide approaches (Davis 2014). Instead of achieving resource use efficiency in separate WEF sectors, the nexus concept promotes system-wide efficiency through reduction of transaction cost and externalities across multiple sectors (Hoff, 2011).

[4] One major tenet of the old institutional school is holistic perspective of the economy. According to the school, “the economy must be examined as a whole, rather than examined as small parts or separate entities isolated from the whole. A complex organism cannot be understood if each segment is treated as if it were unrelated to the larger entity. Economic activity is not merely the sum of the activities of persons motivated individually and mechanically by the desire for maximum monetary gain, but there are also patterns of collective action that are greater than the sum of the parts” (Brue and Grant, 2013:398).

1.4. Global Empirical Literature on WEF nexus

There is a considerable body of empirical literature concerning WEF as the three resources are a basis to sustain life in the globe. Given the breadth of the research in the area, in this section, only a brief systematic review of the relevant empirical literature on WEF nexus will be provided. The existence of common characteristics and interlink between the WEF resources calls for an empirical assessment which takes into account the complex and dynamic interaction between them to forward recommendations which could result in appropriate decisions and actions in each sector. In practice, however, the nexus consideration is often carried out with "two at one time" analysis. For instance, energy-water nexus is analyzed through a two-way interaction in the use of water for energy production and, the use of energy for water abstracting and processing. The same is also true in the case of water-food nexus and food-energy nexus analysis (Bazillian et al., 2011). There are quite extensive studies on the link between water and food as a proper understanding of the water-food link is particularly important, given that agriculture remains the major consumptive water user (Hoff, 2011). In addition to water use in agriculture, a larger amount of water is also used for industrially produced food (World Economic Forum, 2011). Water-food nexus modeling has been pursued based on household level models, farm level agronomic crop models, basin-level river models and at the global scale (Ringler et al., 2013). Findings from all scale of analysis showed that water has an apparent indispensable role in agricultural productivity and its scarcity often have an adverse impact on food security (Chaves and Oliviera, 2004; Rosegrant et al., 2009).

There are also increasing studies on the water-energy nexus provided that both are becoming scarce and their inter-linkage in terms of one being input for the other is increasing over time (Ringler et al., 2013). The water–energy (both hydropower and biofuel) interactions have implications on water allocation, groundwater depletion, food security, farm income, rural livelihoods and the environment. Previous assessments concluded that there exist serious conflicts concerning allocation of these resources at sectoral, basin and regional level and also there are important synergies among many goals of the water and energy systems that should be given due emphasis (Hellegers et al., 2008). Analysis of water input into energy production is conducted at country/sectoral level (see e.g. Carter, 2010, Li et al., 2012; Siddiqi and Anadon, 2011), industry level (e.g. Pan et al., 2011) and end users level (e.g. Malik, 2010). And overall the studies indicated that water use for energy is substantial. For example, Carter (2010) shows that the energy sector in the United States of America (USA) is the single biggest user of water in the economy. Ackerman and Fisher (2008) indicate weak water-energy nexus but strong energy-environment nexus in the western USA. Also, Li et al. (2012), reported that China's wind energy consumes a large amount of water and produce considerable emission. The need for significant quantities of water for energy-processing activities like refining oil products or manufacturing synthetic fuels (Thirlwell et al., 2007) and production of biofuels (Murphy and Allen, 2011) is also asserted. Moreover, increased biofuel production causes Land Use Change (LUC) and, affects water balance and water quality (Babel et al., 2011; Pacetti et al., 2015).

Global energy use for water abstraction is also considerable. In the Middle East and North Africa (MENA) region, Siddiqi and Anadon (2011) found a relatively weak reliance of energy systems on fresh water but a strong dependence of water abstractions and production systems on energy. The study estimated that in the case of Saudi Arabia, groundwater pumping and desalination consumes up to 9% of total annual electrical energy. About 5 to 12% or more consumption of electricity is also estimated for the other countries in the Arabian Gulf for water desalination. Bazilian et al. (2012) also show an increasing dependence on energy-intensive water desalination as a source of potable water and irrigation, especially in fast-growing areas. Hardy et al (2012) made calculations for both energy used in the water sector and water needed to operate the energy sector in Spain and found that close to 5.8% of total electricity use is in the water sector while the energy sector accounts for 20% of country's water withdrawal in 2008.

Cuellar and Webber (2010) argued that due to mechanization, increased use of fertilizer, irrigation and other inputs, the energy consumption of today's agriculture is becoming substantial. For example, food production in the USA accounts almost 8% of all energy consumed of which 2% of energy is wasted in unconsumed food. In addition, energy is used in food production in post-harvest stages (Canning, et al., 2010). Also, there is a tradeoff between energy production in the form biofuels and food production because the two usually compete for land, water, and labor (Hellegers et al., 2008; Gerbens-Leenes et al., 2009; Bazilian et al., 2012). Studies indicated that biofuel production will have a relatively minor impact on the global food system and water use; but, local and regional impacts could be substantial due unbalanced spatial distribution of land and water resources. Countries like China and India, which are the largest producers and consumers of many agricultural commodities in the world, and accounts a considerable percentage of current and future energy demand, are expected to face substantial limitations to expand biofuel. The two countries already faced severe water limitations in agricultural production and yet both have plans to increase biofuel production (de Fraiture et al., 2008; Muller et al., 2008). Not only first generation biofuels which are produced using food crops (Yang et al., 2009) but also cellulose-based biofuel (known as second generation biofuel) competes with food and food-related demand, and agricultural production in China and Japan (Koizumi, 2013).

Increased biofuel production also has implications on the price of agricultural commodities. Some studies indicated that global food price has already shown a rise due to increased demand for biofuel (Schmidhuber, 2007) while others found no significant impact of biofuels production on feedstock prices (Ajanovic, 2010). In developing countries, the energy-food linkage also has a gender component. In Arndt et al. (2011), a significant trade-off between biofuel production and food availability appears when female labor is largely used in biofuel production leading to higher food prices in Mozambique. Synergetic relationships between biofuel expansion and food security are also documented in some studies. Negash and Swinnen (2013) found that castor production significantly improves farmers' food security (in rural Ethiopia) through its positive income effect. Similar synergetic effect of biofuel development and food security is also indicated in Botswana due to the availability of idle land for biofuel expansion (Kgathi et al., 2012).

Studies which assess water and energy use for irrigated agriculture show that changes in the price of energy (electricity or diesel) seem to have serious implication on the extraction of water and food production, and hence on the livelihood of farmers. Mukherji (2007) have assessed the 'energy-irrigation nexus' in West Bengal, India and showed that increase in diesel prices led to the shrinkage of water market transactions in villages that dominantly use diesel to extract groundwater. Moreover, increased diesel price resulted in a change in the cropping pattern away from cultivation of the water-intensive *boro paddy* (most profitable and food secure crop) to less water-intensive crops. Forcing majority of the farmers to depend on diesel for groundwater pumping, the low rate of rural electrification has been indicated to result in economic scarcity of groundwater due to a steep increase in diesel prices over the last few years. This, in turn, resulted in serious negative impacts on crop production and farm incomes. In Wang et al. (2012), about 70% of the irrigated area in northern China was indicated to be fed by groundwater pumping which is an important source of greenhouse gas (GHG) emissions. However, country-wide energy use both directly and indirectly in providing non-agricultural water currently represents only a small fraction of China's total energy consumption (Kahrl and Roland-Holst, 2008). Globally, Zhu et al. (2007) found that increased energy prices have little impact on groundwater pumping resulting in a small reduction in global cereal production. The study found a similar result at river basin scale (Dong Nai basin in southern Vietnam) where a small decline in food production was observed despite the simulated large increase in energy price, mainly attributed to the small share of groundwater pumping cost in total cost of agricultural production in the basin.

In river basin context, studies which analyze the sectoral water allocation conflict between hydropower and irrigated agriculture shows that even if generation of hydroelectric power has little impact on the quantity of water available for downstream users, its generation frequently conflicts with other uses, especially irrigation, since its release schedule does not always correspond to the timing of other water needs. Unilateral efforts to maximize hydropower production in the upstream of the basin are shown to impose a significant cost to downstream irrigations (e.g. Molle et al., 2008 and Bekchanov et al., 2015). However, with joint management of reservoirs in a basin, using water for multiple purposes (such as hydropower, irrigation, and salinity control) is also shown to be possible with some tradeoffs (e.g. Cai et al., 2003a). In addition to irrigation, dams constructed for hydropower could have an impact on other economic activities such as fishery. A study by Orr et al. (2012) examined the potential impact of proposed hydropower dam construction in the Lower Mekong basin on fish catch (the resulting loss of protein and calories) and, its implication on land and water use to replace lost fish protein with livestock products. Basic food security was indicated to be potentially at a high risk of disruption in the basin if proposed hydropower developments do not consider sustaining important ecosystem services.

The interaction between WEF resources involves and has implication for the ecosystem (Rasul, 2014). Global analysis on the environmental footprint of food production indicated that increased production came with more use of land, fossil energy, water, and fertilizer inputs, making a considerable footprint on the environment (Khan and Hanjra, 2008). The global rice production, for instance, uses considerable energy input and generates significant environmental footprints. The situation is predicted to get worse with rapid growth in global population (with predicted 50% rise in 2050), climate change, changing diet preferences (with wealthier and richer populations changing their diet preferences to higher meat consumption) placing significant pressure on limited water resources. Conditions are expected to be more intense in developing countries due to their poor economic environment, weaker institutions and limited access to capital, technology, and information. Moreover, results show that tradeoffs exist between agricultural (rice) yield and energy usage in the sense that high energy inputs are required for high yield (Khan and Hanjra, 2008; Mushtaq et al., 2009). Investments that enhance water productivity and energy use efficiency in crop production are suggested as possible pathways to reduce the environmental footprints of water and energy inputs in food production (Khan and Hanjra, 2008; Khan et al., 2009).

In general, the literature on WEF nexus so far has underline the inevitable and increasing interconnection between WEF across the globe both in the present and in the future and emphasized the relevance of nexus thinking for those having inadequate access to these resources as well as for emerging nations with escalating demand for the three resources (Hoff, 2011; World Economic Forum, 2011; Bazilian et al., 2012; Rasual, 2014; Ringler et al., 2013, Bizikova et al., 2013; UN, 2013; FAO, 2014a; Finley and Seiber, 2014). Previous studies emphasized that future challenges will require nexus approach as actions taken to ensure adequate supply (that meets demand) in one sector without taking into account the interconnectedness among sectors will compromise the same efforts in other sectors and it is deemed to be unsustainable.

1.5. WEF Nexus Literature for the Eastern Nile Basin

The vast body of empirical literature on the Nile Basin revolves around issues of (1) biophysical interactions (hydrology, soil and the climate), (2) hydropolitics, transboundary governance, institutional settings and cooperation, (3) water resource management, and (4) upstream-downstream linkages. The WEF nexus issue is partially and implicitly raised by river basin modeling studies which principally focus on issues of water allocation and management (Guariso and Whittington, 1987; Whittington et al., 2005; Georgakakos, 2007; Blackmore and Whittington, 2008; Jeuland, 2010; Goor et al., 2010; Block and Strzepek, 2010; Nigatu and Dinar, 2011; Satti et al., 2014; Arjoon et al., 2014). However, studies which make an explicit assessment of the WEF nexus in the basin are very limited. Recently, few works had emerged on the WEF nexus in the region which applied various approaches and methodologies. Al-Saidi et al. (2017) provided anecdotal evidence on WEF nexus in the Eastern Nile basin highlighting the tight link between WEF resources in the basin and the need for transboundary cooperation to address the resource scarcity concern in the region. Stein et al. (2014) qualitatively analyze the interaction of different actors in WEF nexus in the Upper Blue Nile of Ethiopia. The dominance of biomass-based energy and issues of agricultural water management and environmental sustainability are presented as three interdependent challenges of WEF nexus in the study area. Particularly, it is indicated that biomass-based energy and water management in agriculture holds central nexus place and emphasis should be given to their linkages across sector and scales.

Combining Water Evaluation and Planning (WEAP) and Long-range Energy Alternative Planning (LEAP) models, Karlberg et al. (2015) has examined the effect of three alternative development scenarios (business as usual, national plan and nexus) on agriculture, energy, and the environment in Ethiopia's Lake Tana Sub-basin. The study indicated the existence of interdependence and some degree of competition between agriculture and energy development. Particularly, agricultural intensification will lead to more dependence of agriculture on energy while biomass-based energy continues to dominate the energy sector having implication on land available for food production. A considerable tradeoff is observed regarding water needed for energy and agricultural production, and to maintain ecosystem services mainly induced by water scarcity. The study also shows that without proper management and coordination among relevant stakeholders, upstream irrigation water withdrawal will reduce water availability for other uses.

1.6. Research Gap and Contribution of the Study

Even though several examples around the globe have been documented which substantiate the interdependence between WEF, empirical attempt to quantify the extent of interlink (tradeoff and synergies) as well as actual actions in harmonizing the three sectors is so far limited (Bizikova et al., 2013). Much work has been done in developing alternative frameworks which map the interconnection between the three sectors and can be used as a guide for future empirical studies (see Bizikova et al., 2013; Biggs et al. 2015 and UN, 2015a for a comprehensive review of various conceptual frameworks developed for WEF nexus analysis). The scope, objective and identified WEF nexus drivers vary across these conceptual frameworks (FAO, 2014a). Empirical applications that go beyond conceptualization are however few. The discussion in the last section shows that previous literature which is framed within the WEF nexus concept is scarce for the Nile basin in general and the Eastern Nile basin in particular. The existing couple of studies which examined the WEF nexus in Ethiopia's section of the Blue Nile sub-basin gave important insights on the interlinkages between the three sectors (Stein et al., 2014; Karlberg et al., 2015). However, these studies have limited geographical coverage (considering only one sub-basin or part of a sub-basin), and either look the nexus only from the social perspective using qualitative approach (Stein et al., 2014) or focus purely on biophysical nexus interactions (Karlberg et al., 2015). Given that the WEF management in the basin is highly complex involving natural, socio-economic, technical, governance and hydropolitical issues (domains), a study with a broad perspective and comprehensive spatial coverage is required. Accordingly, this study adds to the WEF nexus literature in the basin by doing a qualitative and quantitative analysis to address the various aspects of the nexus in the Eastern Nile basin. A qualitative approach is used to cover the governance aspects while an integrated hydro-economic model is used to study the technical and economic dimensions of the WEF nexus in the basin.

1.7. Research Questions

This study is intended to answer the following main research questions;

- What are the opinions of key stakeholders in WEF sectors about challenges and opportunities across the WEF nexus in Eastern Nile region?

- Could sectorally and regionally coordinated WEF developments increase economic benefits from water use in irrigation and hydropower generation in the Eastern Nile basin?
    - How would new water resource developments in the basin change existing water allocation and economic benefits of sectors and countries?
    - How would water allocation that maximizes economic benefit in one sector (say irrigation) only impact benefit obtained in other sectors (say energy)?

- How would water allocation that maximizes economic benefit in one country (say Ethiopia) impact benefits of the other riparians (Sudan and Egypt)?

- How would climate change affect the WEF nexus in the Eastern Nile basin?

Answering these questions is important for the following reasons. First, the issues of understanding the WEF nexus is vital for most riparian countries (especially, Ethiopia, Sudan and South Sudan) where the supply of these resources is by far less from satisfying the existing demand of agricultural production, industries, and residents. Second, ensuring WEF security in Eastern Nile region cannot be achieved with unilateral strategies and action as countries share a significant amount of one key resource, which is water. For Ethiopia and most of the other basin countries, ensuring a sustainable supply of WEF is not something which worries them in the future only, but rather an ongoing issue which requires immediate and integrated actions. The complex interdependence between the three resources on hand and the countries in the basin on the other hand thus calls for a research which explores the extent of the link and tradeoffs across sectors and member countries of the basin using a comprehensive approach. In the basin, there is a great need to understand the WEF nexus to develop strategies and take investment actions that can enhance synergies and reduce tradeoffs among WEF systems and riparian countries. And this calls for appropriate quantifications of tradeoffs and synergies across sectors and scales. Moreover, the Sustainable Development Goals (SDGs) set by UN can only be achieved if the nexus concept is duly considered. The SDGs are highly interlinked but particularly three goals namely zero hunger, clean water and sanitation and, affordable and clean energy are directly related to the issue of WEF nexus.

1.8. Methodology and Data

This study applies a combination of qualitative and quantitative approach to assess the issue of WEF nexus in the Eastern Nile basin. Given that WEF resources involve different stakeholders, institutions, and governance structures, qualitative analysis is used to assess the views and concerns of these parties to understand the status quo of resource management, existing links, and challenges across sectors and basin countries. To analyze the extent of sectoral as well as transboundary tradeoffs and synergies, a quantitative analysis is conducted mainly using an integrated hydro-economic model called the Eastern Nile Multipurpose Option Scoping (ENMOS). The model is used to establish optimal allocation of resources that maximize the benefit across Eastern Nile countries and serves as an instrument to examine whether joint WEF development and management is a better approach than unilateral actions by sectors and riparian countries. ENMOS is also used to analyze the potential impacts of climate change on WEF nexus in the basin. The study used primary and secondary data gathered from different sources. Primary data was collected from key stakeholders in WEF sectors in Ethiopia, Sudan, and Egypt through e-survey and key informant interviews (KIIs). Secondary data is obtained from various institutions including ENTRO, Ethiopia's Ministry of Water, Irrigation and Electricity (MWIE), Electricity Holding Company of Egypt (EEHC), Egyptian Ministry of Agriculture and Land Reclamation (MoALR), Central Statistical Agency (CSA) of Ethiopia, Egypt's Central Agency for Public Mobilization (CAPMAS), IFPRI's survey on "Energy in Agriculture", and relevant publications. Data obtained from the e-survey and KIIs are used to assess the views of main stakeholders in WEF sectors in the three riparian countries and, support our scenario formulation in the hydro-economic model. The ENMOS and Eastern Nile Multi-Sector Investment Opportunity Analysis (MSIOA) database from ENTRO are mainly used for the reconstruction/reformulation and updating of the hydro-economic model. In addition, secondary data obtained from various sources are used to give an outlook on key nexus issues by providing an overview of the current state and use of the three resources and their inter-linkage, making the baseline situations and trends explicit. Detailed descriptions of the methodologies and data sources are given in each chapter of the thesis.

1.9. Conceptual Framework

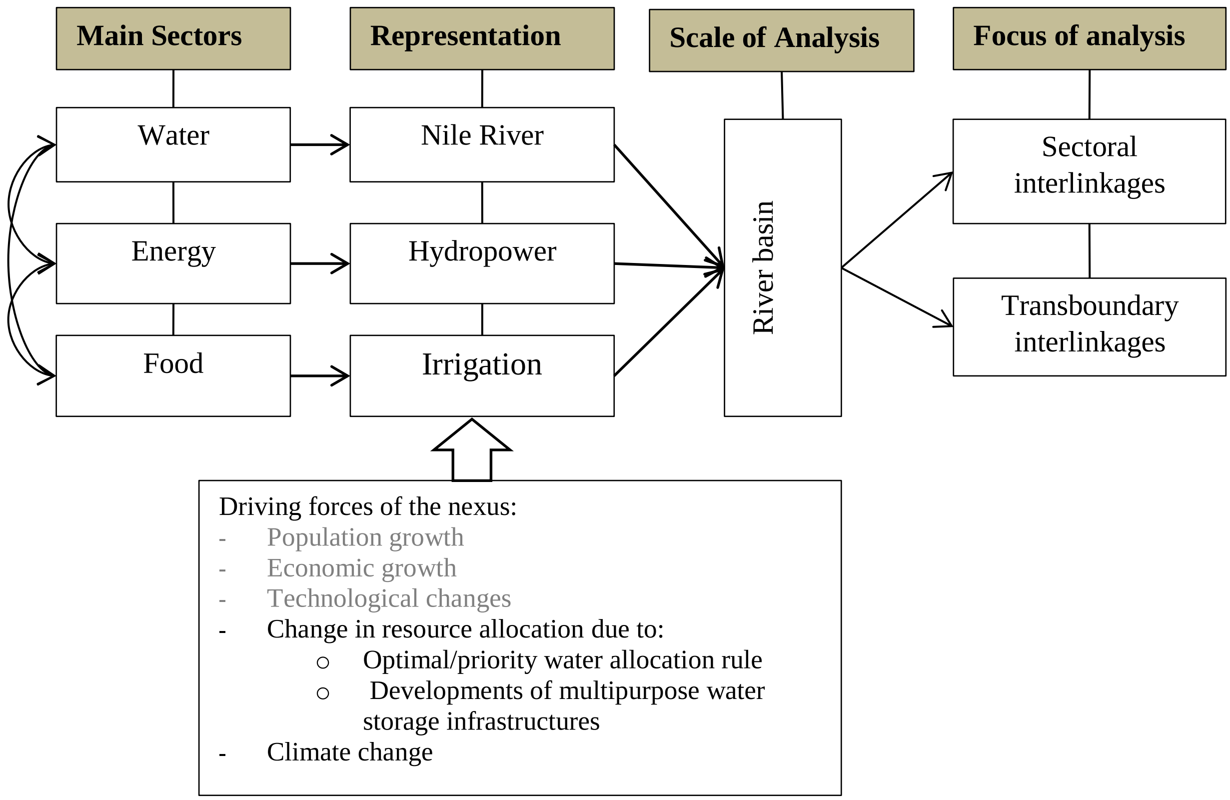
The discussions in the previous sections show that the issue of WEF nexus is a broad and complex topic involving several factors that need due consideration. This study is however limited to examining the sectoral and transboundary interlinkages between WEF resources in a river basin context. Therefore, the conceptual framework for the study is developed in accordance with its objectives and the specific context in the Eastern Nile basin (Figure 1.1). In the basin, the Nile River is the main source of water which ties riparian countries, and hydropower and irrigated agriculture are the two most important users of water. Hence, WEF are represented by the Nile River, hydropower, and irrigated agriculture respectively in this study. Water as a sector is also represented by municipal and industrial (M&I) water demand in Egypt which is treated as a fixed constraint that should be satisfied. In the context of a transboundary river basin, WEF nexus has both sectoral and regional dimension. Tradeoffs are not only between sectors of WEF within one country but it is also across countries which are part of the basin and such tradeoffs are overlapping in nature. Stakeholders in each sector have the goal of ensuring a sustainable supply of resources that meet current and future demands. Such action will cause tradeoffs across sectors given the strong interlinkages among WEF resources. For example, the main goal of stakeholders in the food sector is to ensure food security through the allocation of water and other resources which are sufficient to meet such goal irrespective of other sectors.

Regarding the transboundary tradeoffs, issues of water availability and quality, and the supply and demand goals of each country play a key role within the WEF nexus. From the viewpoint of an upstream country (Ethiopia), storing water to maximize hydropower production could be ideal but downstream countries need the timely release of water for irrigation (Sudan and Egypt). The upstream-downstream tradeoff is not necessarily between different countries, it could also occur between different uses and users of water in the same country.[5] Such factors will also have a direct impact on economic benefit that can be obtained from different sectors by different users (countries). Two main factors which stimulate both sectoral and transboundary (upstream-downstream) tradeoffs are considered: change in allocation of water (either due to optimal/priority allocation rules or water resource infrastructure developments) and climate change. For example, change in allocation of water due to the construction of water storage facilities involving increased withdrawal for irrigation could lead to higher water consumption by one sector or country in competition with other sectors and downstream users. These in turn

[5] Environmental constraints such as required flows to the sea and wetland requirements are additional factors that could shape sectoral and transboundary linkages.

will have impact on economic benefit from different sectors across countries. Also, through its impact on the existence and sustainability of resources, climate change can initiate or intensify both sectoral and regional WEF tradeoffs. Lower upstream precipitation due to climate change could for example result in less water availability (flow) for all sectors as well as downstream users having adverse impact on sectoral economic benefits across countries.

Figure 1.1: Conceptual Framework of the Study



Source: Author’s illustration

1.10. Organization of the Study

The rest of this study is organized as follows. Chapter 2 provides the general description of the Eastern Nile basin and key WEF nexus issues in a river basin context. In Chapter 3, results of the e-survey and KIIs will be presented discussing the views of key stakeholders on challenges and opportunities across the WEF nexus in the Eastern Nile basin. Chapter 4 will examine whether sectorally and regionally coordinated WEF developments are better than unilateral actions based on an integrated hydro-economic model. The description of the hydro-economic model and results from it will be presented and discussed in the same chapter. The potential impact of climate change on WEF nexus in the basin is discussed in chapter 5. General conclusions are given in Chapter 6.

2. General Description of the Eastern Nile Basin and Issues Related to WEF Nexus

2.1. Geographic Location and Associated Features

The Nile basin covers an area of 3,176,541 km^2 and it is divided into two major sub-basins namely the Eastern Nile and the Nile Equatorial Lakes sub-basin. The Eastern Nile basin possesses a total area of approximately 1.9 million km^2 which is 60% of the total Nile basin area. It is located between 27^0 and 40^0 eastern longitude and 4^0 and 32^0 northern latitudes. The basin covers countries of Ethiopia, Sudan, South Sudan, Egypt, and a small part of Eritrea (see Figure 2.1). The largest territory of South Sudan (96%) and Sudan (74%), and about one-third of Ethiopia's and Egypt's territory is part of the Nile basin (Table 2.1). The Eastern Nile Basin encompasses wide varieties of landscapes and ecosystems ranging from high mountains and afromontane forests with large average rainfall to lowlands and arid deserts having little average precipitation as well as high evaporation. Dense forests are mainly found in south-eastern part of the basin while the north and central parts are largely characterized by barren or sparse vegetation accounting about 50% of the entire basin. Elevation in the basin varies from highlands which are beyond 4000 masl to 0 masl in the delta where the Nile River runs into the Mediterranean Sea (ENTRO, 2014a). Temperature varies by elevation ranging from an average of 17^{0}C in the highlands of Ethiopia to above 45^{0}C in central and northern Sudan (Hassan, 2012; Johnston, 2012).

Table 2.1: Area distribution and water resource availability in the basin

Variables	Ethiopia	Sudan	South Sudan	Egypt
Total country area (Km^2)	1104300	1879360	644330	1001450
Area part of the Nile basin (Km^2)[a]	365,318	1,396,230	620,626	302,452
Area within the Nile basin as % of country area [a]	33.1	74.3	96.3	30.2
Area within Nile basin as % of basin area [a]	11.5	43.9	19.5	9.5
Arable land (Km^2)	151190	172200	-	27380
Cultivated area (Km^2)	162590	173650	-	37610
Cultivated total country area (%)	14.72	9.24	-	3.756
Long-term average annual precipitation (BCM /year)	936.4	469.8	579.9	51.07
Total renewable surface water (BCM /year)	120	35.8	49.5	56
Total renewable groundwater (BCM /year)	20	3	4	2.3
Total renewable water resources (BCM /year)	122	37.8	49.5	58.3
Water dependency ratio (%)	0	96.13	65.79	96.91

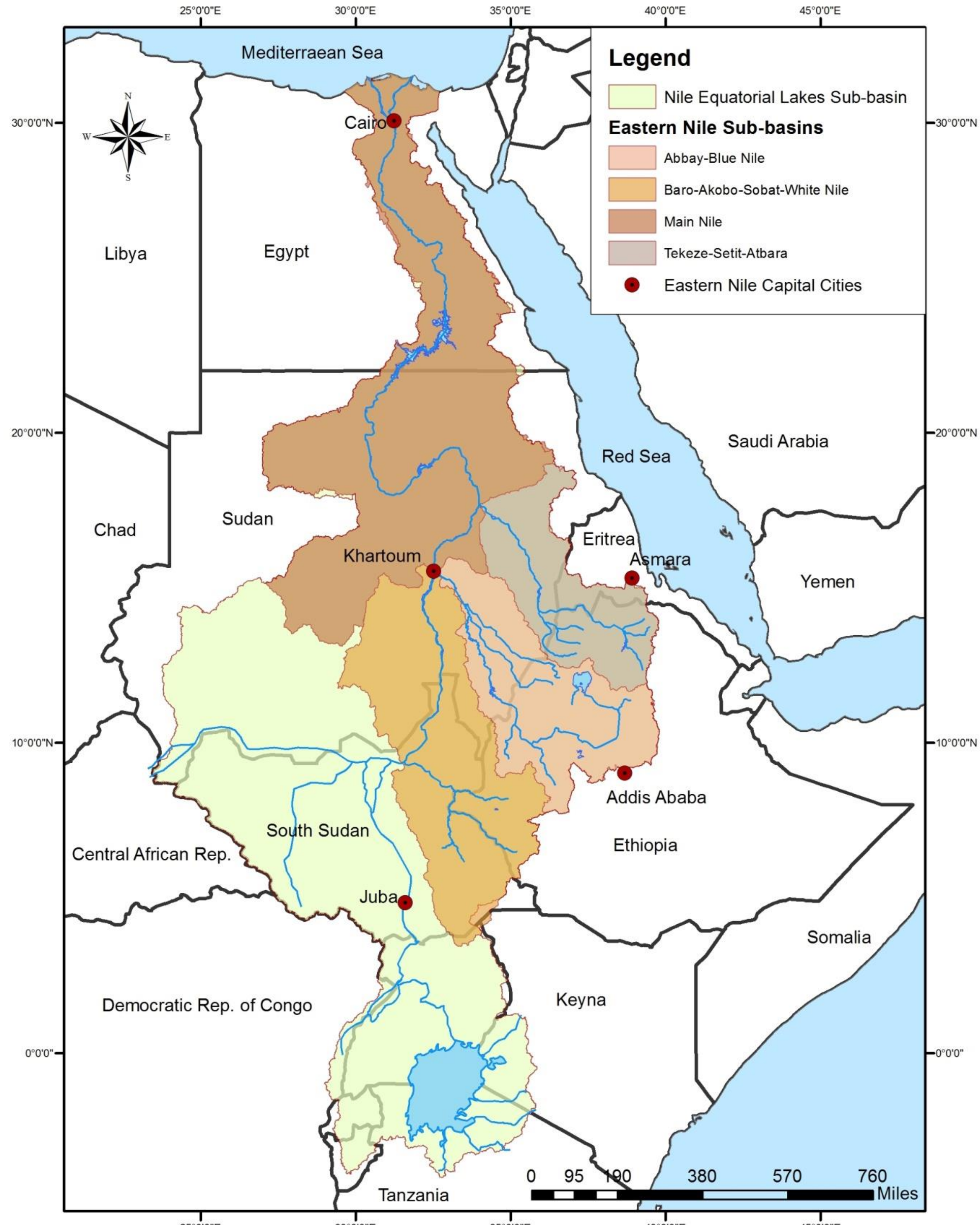
Source: AQUASTAT, 2013-2017, unless otherwise indicated as [a] (NBI, 2012a)

The Nile river flow in the Eastern Nile basin originates from the Ethiopian highlands. On average, Ethiopia contributes over 85% of the annual Nile flow reaching the Aswan dam in Egypt. The Blue Nile which originates from Lake Tana of Ethiopia contributes the largest 56%

of the main Nile flow while the Sobat and Atbara rivers which also sourced from tributary rivers in Ethiopia contributes 14% and 16% of the Nile flow respectively (Moges and Gebremichael, 2014). The reaming flow is contributed by the White Nile originating from Lake Victoria in Congo. The Nile flow is highly seasonal where almost 80% of the flow is generated within four months (Ethiopia's rainy seasons of June, July, August, and September). In the remaining months, only 20% of the flow is available making the development of water storage infrastructures essential for regulating flows and, ensure efficient and sustainable utilization of water. High water loss is also prevalent in the basin which is mainly due to evaporation from lakes, rivers, reservoir, canals and irrigation systems. Each year, about 19 BCM of water is estimated to be lost due to evaporation from man-made reservoirs (Blackmore and Whittington, 2008). High evaporation losses are also due to the low irrigation efficiency (both conveyance and on-field) in the basin. The high evaporation rate resulted in low water yield despite substantial rainfall in the upstream of the basin.[6] Downstream riparians of the basin are characterized by high water dependency ratio. Especially, more than 95% the water resource in Sudan and Egypt originates outside their territory creating strong upstream-downstream linkages. So far, water use in the basin is mainly for agriculture (rain-fed and irrigated) and hydropower production. Though relatively small, a significant amount of Nile water is also abstracted for M&I uses mostly in Egypt. Fishery, livestock, and navigation are additional uses of the Nile water (NBI, 2012a).

[6] Water yields from the major sub-basins are relatively small, ranging between 10 and 20% of total rainfall. For example, the annual precipitation on Lake Victoria is estimated to be 100 BCM, however due to high evaporation only a small fraction of it reaches to the Nile River system (i.e. less than 15% of the Nile flow) (ENTRO, 2014a).

Figure 2.1: Map of the Eastern Nile Basin within the Nile Basin and its Main Sub-basins



Source: Based on ENTRO (2014a)

2.2. Sub-basins of the Eastern Nile Basin

The Eastern Nile basin is classified into four main sub-basins: the Abay-Blue Nile, Tekeze-Setit-Atbara, the Baro-Akobo-Sobat-White Nile, and the Main Nile (Table 2.2). These sub-basins vary with their geographical features, natural resource endowment, climate, the extent of existing infrastructures and potential for future developments. In consecutive sections, each of these sub-basins will be briefly described.

Table 2.2: Sub-basins of the Eastern Nile basin: area and water availability

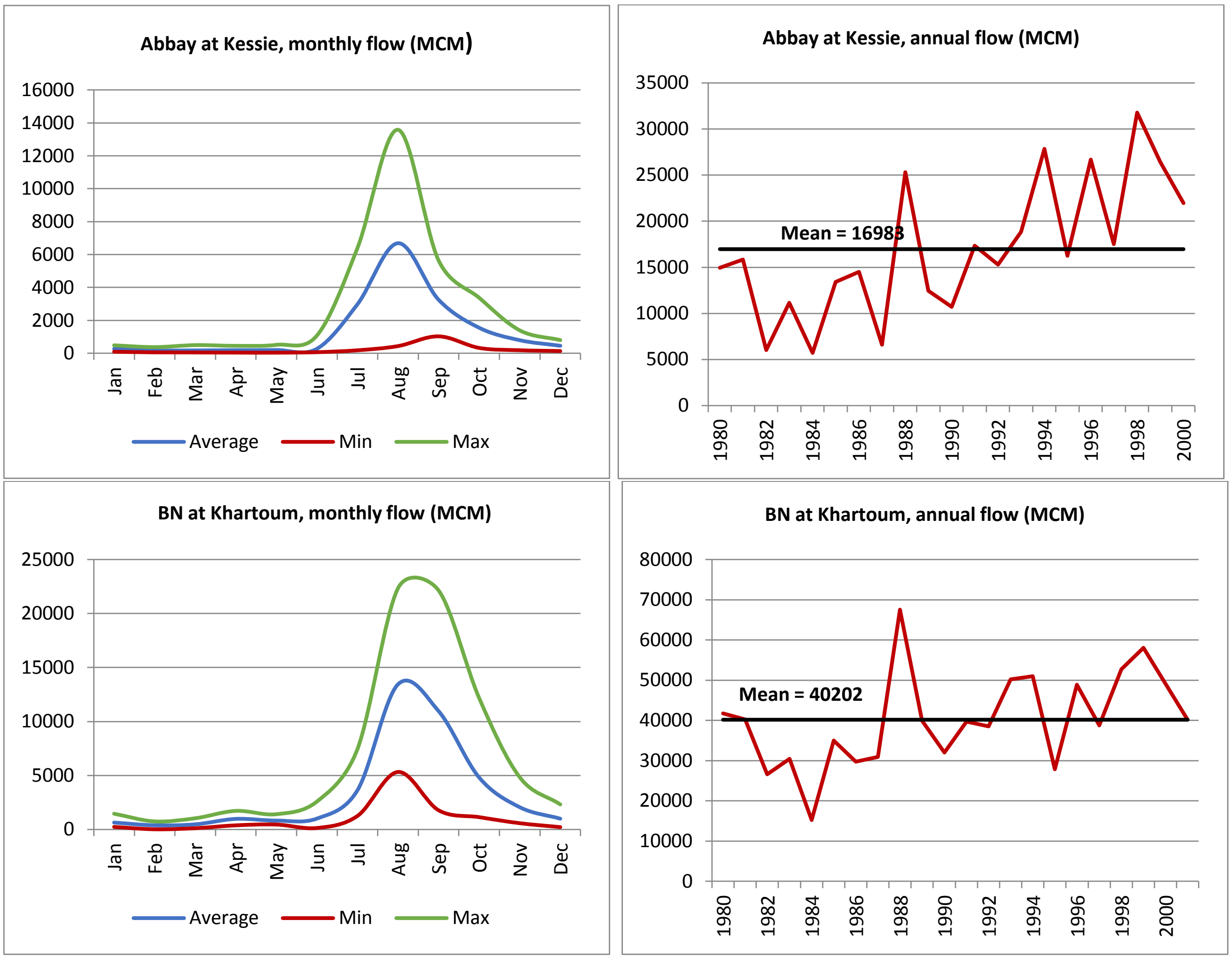
Sub-basins	Catchment Area(km2)	Share in EN basin (%)	Annual Precipitation(mm)	Average Flow(BCM)*
Abay-Blue Nile	311,548	18.7	500 – 1800	54
Baro-Akobo-Sobat & White Nile	468,216	28.1	500 – 1750 <300 – 500	28
Tekeze-Setit-Atbara	227,128	13.7	200 – 1500	12
Main Nile	656,398	39.5	0 – 200	84

Source: ENTRO (2014a)
* Indicates the flow of Nile measured at the major gauging station in the respective sub-basins.

2.2.1. Blue Nile (Abay) sub-basin

The BN sub-basin falls within the boundary of Ethiopia and Sudan with a total area of 311, 548km² accounting about 18% of the Eastern Nile basin. It is located in the middle-eastern part of Eastern Nile basin. This sub-basin contributes the largest share of water to Eastern Nile system where the mean annual flow measured at the Ethio-Sudan border is about 51 BCM. In the sub-basin, rainfall is erratic resulting high seasonal and yearly hydrological variability. River flow often reaches its peak in August with low discharges between January and March (see Figure 2.2). Rainfall also has significant spatial disparity ranging from about 2,000 mm/yr in the Ethiopian highlands to less than 200 mm/yr at the Blue Nile's junction with the White Nile (ENTRO, 2014a). Temperature also varies by elevation wherein the western highland plateau of Ethiopia average yearly temperature ranges between 17^0C and 19.5^0C whereas around Khartoum, Sudan temperature varies from 28.5^0C to 30.5^0C (Hassan, 2012). The main river in this sub-basin is Abay which is called the Blue Nile in Sudan. The Blue Nile (Abay) has several tributaries where the major ones in Ethiopia are Gilgil Abay, Megech, Ribb, Gumera, Beshlo, Wolka, Jemma, Muger, Guder, Chemoga, Fincha, Angar, Dura and Belese (Awulachew et al., 2008; Melesse et al., 2011). Dinder and Rahad rivers which rise to the west of Lake Tana also join the Blue Nile below Sennar dam in Sudan. The sub-basin is characterized by high sediment flows where estimates show that annually the Blue Nile carries more than 100 million tonnes of sediment downstream (Betrie et al., 2011).[7] Rugged topography with steep gorges is the salient geographical feature of the sub-basin creating a large potential for hydropower generation. Estimated hydropower potential in the Abay sub-basin reaches up to 13,000 MW (Desalegn et al. 2011).

Figure 2.2: Average monthly runoff and annual runoff of Abay (BN) River at Kessie, Ethiopia and Khartoum, Sudan (1980-2000)



Source: Based on Shenkut (2006) and Ahmed (2006)

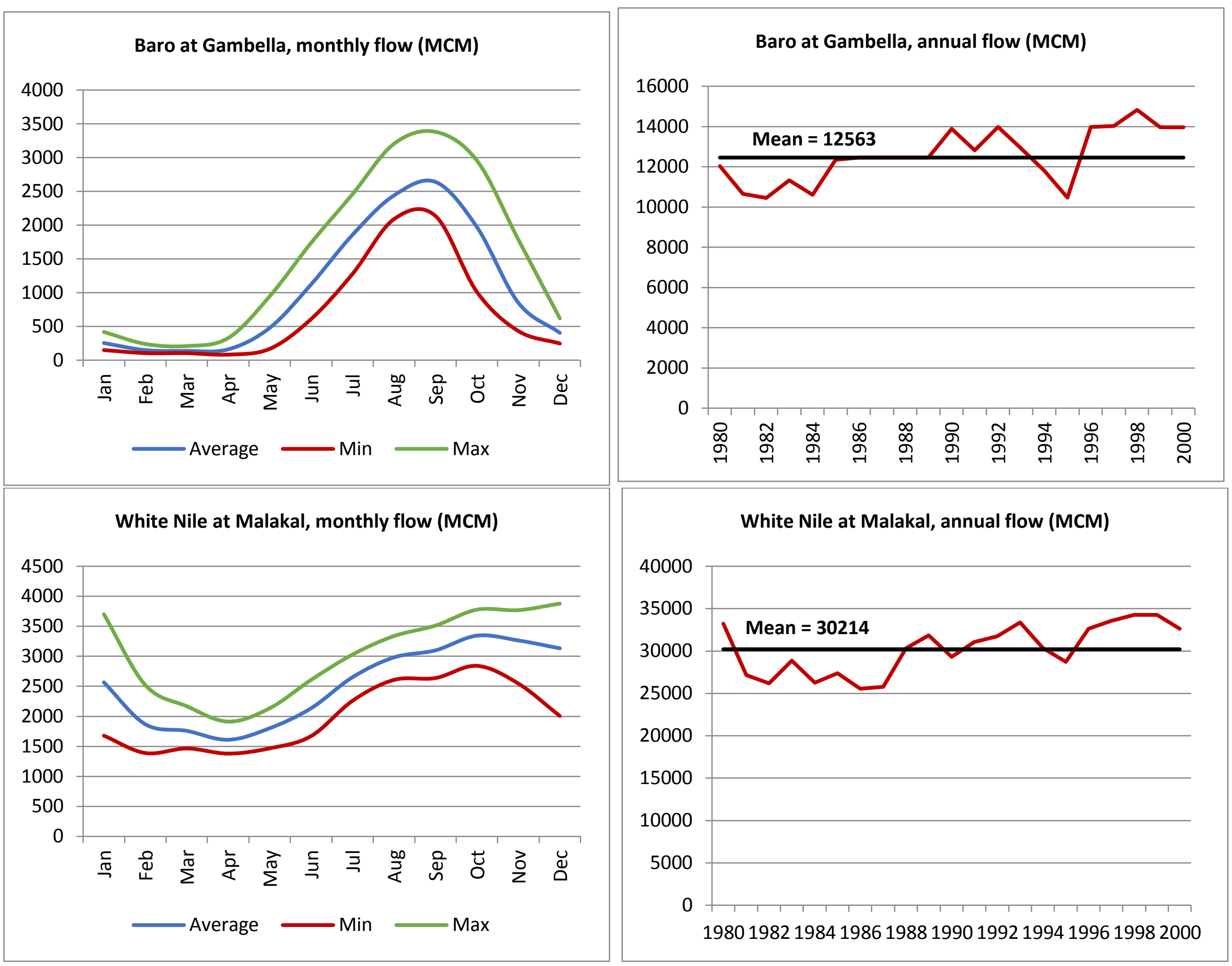
2.2.2. Baro-Akobo-Sobat and White Nile sub-basin

Located in the southern part of the Eastern Nile basin, the BASW sub-basin possesses a total area of 468,216 km2 which is 28% of the total basin area. It is shared by Ethiopia, Sudan and South Sudan (ENTRO, 2014a). The main rivers in the BASW sub-basin are Baro and Akobo where Birbir, Huwa, and Geba are the main tributaries of the Baro River while Dima is the

[7] The sediment load is estimated to be 131 million tonnes in Betrie et al. (2011). This high sediment transportation results siltation of the downstream reservoirs leading to high maintenance costs and reduced hydropower production.

tributary of river Akobo. Together with Gilo and Pibor rivers, Baro and Akobo form the river Sobat in South Sudan which feeds into the White Nile system. The basin is well endowed with water resource and is the second largest contributor of water to the Eastern Nile system. The climate in the highland plateaus of the sub-basin is identified to be sub-tropical with pleasant temperature rarely exceeding 20^0C while in the lowlands it could go beyond 36^0C during hot months. The rainfall pattern shows seasonal variability where high rainfall is often registered between months of June and September. Mean annual precipitation ranges between 600 mm in the lowlands (less than 500 masl) and 3,000 mm in the highlands (over 2,000 masl) showing the existence of significant spatial rainfall variability. The mean annual flow of the Sobat River measured at Doleib hill (upstream of the Malakal gauging station) is 13.7 BCM and combined with 16.8 BCM inflows from Sudd swamp, on average it contributes 30.5 BCM inflows to the White Nile system per year. Sedimentation problem is significant in the upper course of the Baro sub-basin and it is estimated to range between 35tonne/km^2 and 324tonne/km^2 annually (Hassan, 2012).

Figure 2.3: Average monthly runoff and annual runoff of Baro River at Gambella (1986-2006) and White Nile River at Malakal station (1980-2000)



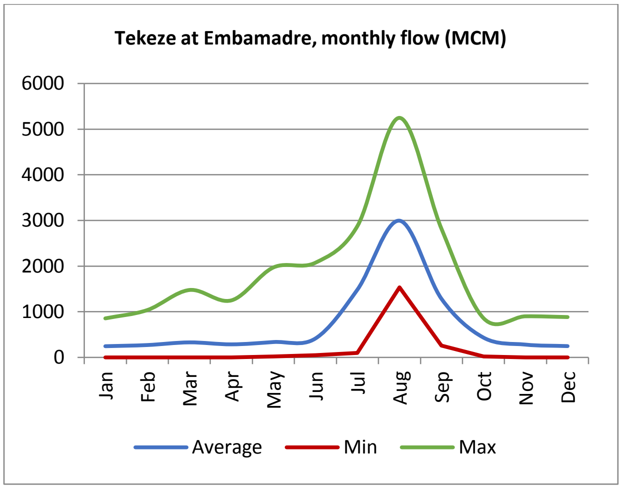
Source: Based on Shenkut (2006) and Ahmed (2006)

The sub-basin contains important wetland areas such as the Machar and Sudd marshes. A large amount of spillage (3.03 BCM/yr) from the lower course of Baro River forms the Machar wetland where return flow from the wetland to the Baro and White Nile rivers is estimated to be large. Sudd is another important wetland in the sub-basin and one of the largest in the world with estimated average area coverage of 30,000km^2 (Rebelo and McCartney, 2012). Current infrastructure development in the basin is low. However, the availability of high rainfall, fertile land, several rivers and flat topography creates a large potential to develop irrigated agriculture in the sub-basin. Also, total hydropower potential of the sub-basin in the Ethiopian part is estimated to be 19,826 GWh/year (Hassan, 2012).

2.2.3. Tekeze-Setit-Atbara sub-basin

The TSA sub-basin covers approximately 227,128 km² area which is 14% of the Eastern Nile basin. It is located in the north-eastern segment of the Eastern Nile laying within the territory of Ethiopia and Sudan. The sub-basin ranked third in its contribution of water into the Eastern Nile system. All the main rivers in the sub-basin originate from Ethiopia which includes Tekeze (also known as Setit) and its tributaries Goang and Angereb where these rivers join and form the Atbara River in Sudan (ENTRO, 2014a). The basin contains areas with the lowest average monthly temperature that could go as low as 3^{0}C, mainly located in the Ethiopian highlands. Similar to the BN sub-basin, rainfall and river flow patterns of the basin are highly variable both temporally and spatially. Mean annual rainfall ranges from 2120 mm near the source of the river (highlands of Ethiopia) to below 50 mm near its connection with the Main Nile (Hassan, 2012). The average flow of the sub-basin measured at El-Girba station in Sudan is 11.45 BCM with high seasonal variability even compared to the BN and BAS sub-basins. Also, sediment flows are extensive mainly due to soil erosion from agricultural lands in the upper course of the basin. Average annual sediment load at Atbara is estimated to be 58.43 million tonnes (ENTRO, 2014a). The coexistence of areas with high and low elevation creates significant potential for developing small to medium-scale hydropower and irrigation projects in the sub-basin.

Figure 2.4: Average monthly runoff and annual runoff of Tekeze River at Embamadre, Ethiopia (1994-2014) and Atbara River at El-Girba station, Sudan (1986-2000)



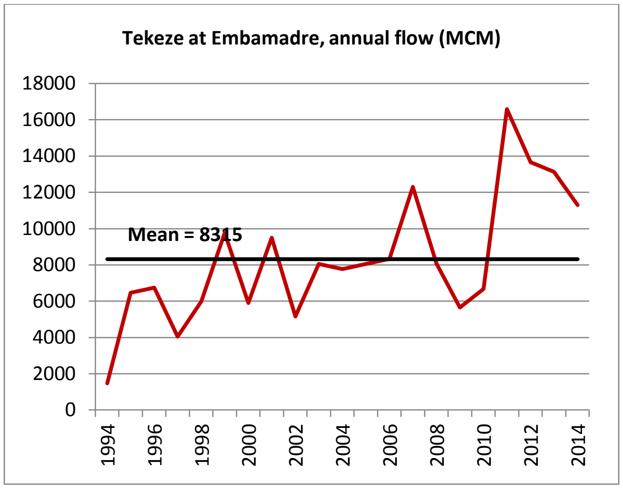
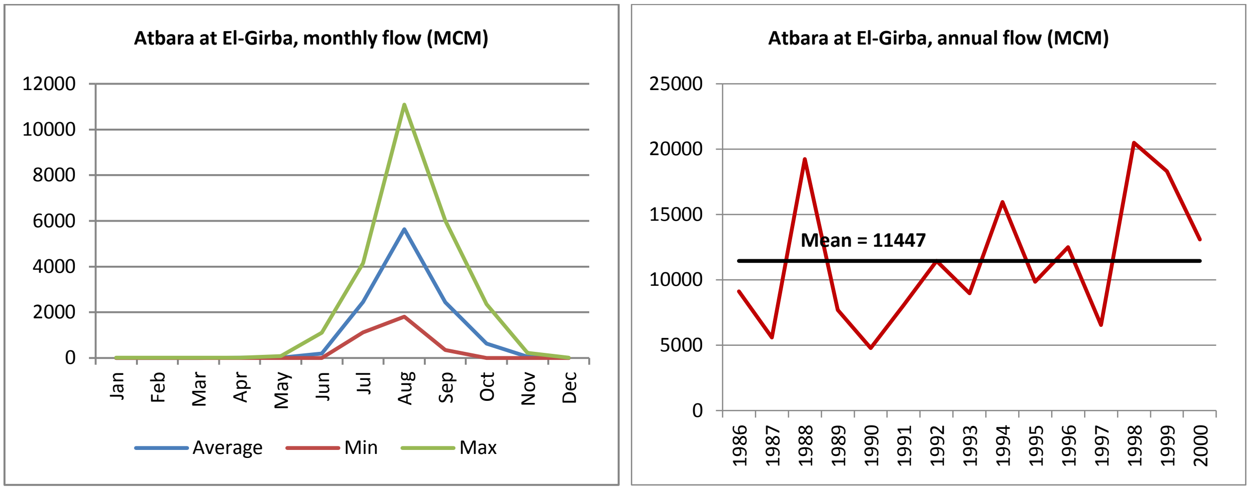


Figure 2.4 continued …

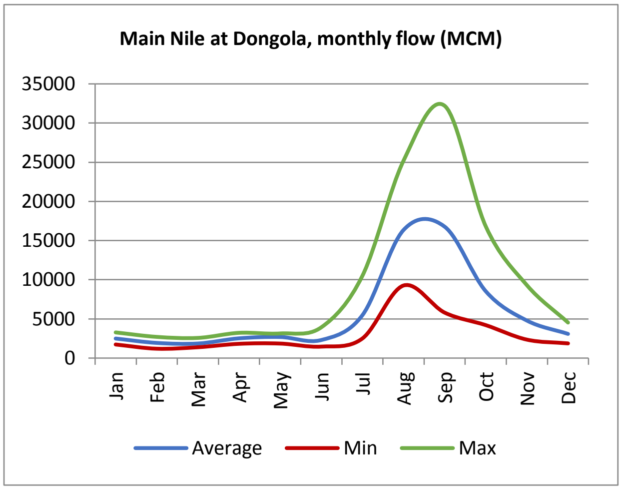


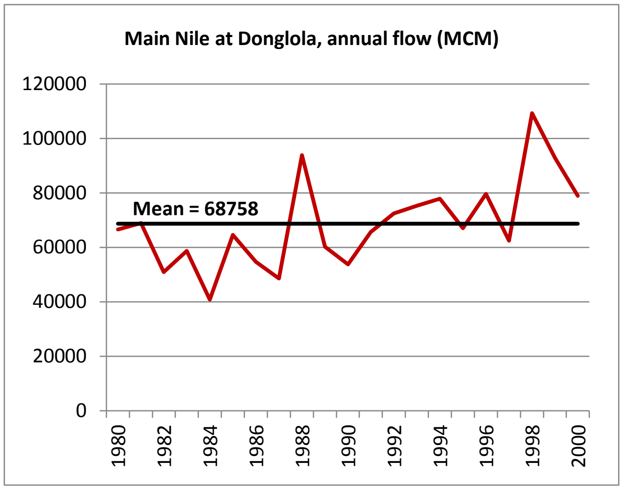
Source: Based on Ahmed (2006) and MWIE (2016)

2.2.4. Main Nile sub-basin

Covering an area of 656,398 km² (40% of the Eastern Nile Basin), the MN sub-basin is the largest of the four sub-basins. Sudan and Egypt contribute the area of the sub-basin. As a part of the Eastern Nile basin, the MN sub-basin starts at Sudan's capital Khartoum following the confluence of the White Nile and Blue Nile systems making the Nile the only main river in the sub-basin. Below the confluence of the two rivers, the only major tributary of the Nile is the Atbara River. The climate in the sub-basin is arid with very low rainfall and high evaporation rate. There is almost no runoff generated in this sub-basin (NBI, 2012a). Average annual rainfall ranges from 400mm in the southern part of Sudan to less than 5mm at Dongola (northern Sudan) and the High Aswan Dam (HAD) in Egypt. Only 17% of the sub-basin obtains mean annual rainfall more than 100mm while in over 65% of the sub-basin rainfall is less than 50mm. Evaporation in the sub-basin is substantial where Egypt's HAD alone is responsible for 10 to 14 BCM evaporation loss from the system annually. Because a substantial portion of this sub-basin is desert, high temperature that goes above 30^0C is prevalent especially in northern Sudan and Upper Egypt. However, a moderate temperature is also experienced in the coastal areas of Egypt such as Alexandria with a mean annual temperature of 18^0C (Hassan, 2012). The average annual inflow of the main Nile system at HAD is estimated to reach 84 BCM (NBI, 2012a). The MN sub-basin is the most developed section of the four sub-basins. Several dams and barrages are already built to generate hydropower and store water for irrigation. Due to the existence of large irrigation systems, water withdrawal in this sub-basin is extensively higher compared to the other sub-basins.

Figure 2. 5: Average monthly runoff and annual runoff of the Main Nile River at Dongola, Sudan (1980-2000)





Source: Based on Ahmed (2006)

2.3. Socio-economic Situations in the Eastern Nile Basin

2.3.1. Population and Access to Basic Services

The Eastern Nile basin is generally characterized by high population growth where average growth rate between 1950 and 2015 was estimated at 2.6%. The total population of the basin countries is estimated to be 245 million in 2015. The medium projection of UN shows that the total population of the basin countries will reach 330 million by 2030 and 446 million in 2050. Majority of the population in South Sudan (81.2) and Ethiopia (80.5%) still lives in rural areas and to a lesser extent in Sudan (66.2%) and Egypt (56.9%). Although rapid urbanization is expected in the future, the dominance of rural population is projected to persist until 2030 in most of the basin countries. In the lower riparian countries, population settlement pattern follows the river leading to high population density in the Nile Valley and Nile Delta in Egypt, which represent only 5% of the country's total area. Similar settlement pattern is also observed in the northern part of Sudan where most people live along the Nile River, in the Khartoum area, and in the irrigated areas south of Khartoum. Water availability also determines the settlement pattern in upstream countries where population density is high in areas with abundant rainfall. The rapidly growing and rural-dominated population which is largely dependent on agriculture as a means of livelihood resulted in mounting pressure and adverse impact on the natural resources of the basin. The scarcity of productive natural resource (such as land) in rural areas is also creating a high rural-urban migration, placing escalating stress on infrastructures and services in urban areas (NBI, 2012a).

Table 2.3: Key Socio-economic indicators

Indicators	Year	Ethiopia	Sudan	South Sudan	Egypt
Total population (in 1000) [a]	2015	99391	40235	12340	91508
Average population growth [a]	1950-2015	2.7	3.0	2.4	2.3
Human Development Index(HDI)[b]	2014	0.44	0.5	0.48	0.69
HDI Rank out of 188 countries of the world [b]	2014	174	167	169	108
GDP per capita (current US$)	2015	619.1	2089	730.6	3617
Poverty headcount ratio, national poverty lines (%)	2009,2010	29.6	46.5	50.6	25.2
Urban (%)	2009,2010	25.7	26.5	24.4	15.3
Rural (%)	2009,2010	30.4	57.6	55.4	32.3
Gini index	2008-2010	33.2	35.4	46.3	30.8
Consumer price index(2010=100)	2015	209	348.9	331.2	156.8
Inflation, consumer prices (%)	2015	10.1	16.9	50.2	10.4
Agriculture, value added to GDP (%)	2015	40.9	39.3	-	11.2
Petroleum & natural gas, value added to GDP (%)	2010-2015	0.0	7.5	26.5	8.2
Employment in agriculture (%)	2011,2013	72.7	44.6	-	28
Unemployment (as % labor force)	2008-2012	17.6	14.8	13.7	12.7
Adult literacy rate (%)	2015	49.0	58.6	31.9	75.8
Global food security index rank (out of 113 countries) [c]	2016	98	98	-	57
Access to electricity (%)	2012	26.6	32.6	5.1	100
Urban (%)	2012	100	62.1	12.3	100
Rural (%)	2012	7.6	17.8	3.5	100
Access to improved sanitation (%)	2014,2015	28.0	23.6	6.7	94.7
Access to safe drinking-water (%)	2014,2015	57.3	55.5	58.7	99.4
Urban (%)	2014,2015	93.1	66.0	66.7	100
Rural (%)	2014,2015	48.6	50.2	56.9	99

Source: WB, World Development Indicators, unless otherwise indicated as [a] (UN, World Population Prospects: The 2015 Revision), [b] (UN data), [c] (The Economist Intelligence Unit (EIU), 2016)

Access to basic services of electricity, improved sanitation, and safe drinking water is also limited in Ethiopia, Sudan and South Sudan, especially in rural areas. In 2012, only 27%, 33% and 5% of the total population of Ethiopia, Sudan and South Sudan respectively are reported to have access to electricity. The percentage of rural population having access to electricity is very low in South Sudan (4%) and Ethiopia (8%). South Sudan has no national grid system until now; the country obtains its very limited electricity supply mainly from expensive diesel-powered generators (African Development Bank (AfDB), 2013). Access to improved sanitation is lowest in South Sudan (7%) and highest in Egypt (95%). More than 40% of the population in Ethiopia, Sudan, and South Sudan also do not have access to clean drinking water. Except for Egypt, level of education in the basin is poor as it is indicated by the low adult literacy rate. In Ethiopia and South Sudan, over 50% of the adult populations are illiterate.

2.3.2. Economy

The Eastern Nile basin is one of the least developed areas in the world (with the exception of Egypt who outperform the other basin countries in many socio-economic indicators). As it is indicated by the ranking of the Human Development Index (HDI), three countries out of four are grouped under 'low human development' category and are in the bottom 25. Gross Domestic Product (GDP) per capita in all the riparian states is low particularly in Ethiopia and South Sudan. Poverty is prevalent in the basin where a considerable percentage of the population in riparian states lives below the national poverty lines. The rate of poverty is highest in South Sudan and Sudan where 50.6% and 46.5% of their population respectively lives under poverty. In all the basin countries, the poverty rate is higher in rural areas than urban areas. The Gini index also indicates the existence of significant income inequality in the basin. Agriculture has a major role in the economy of riparian sates in terms its contribution to GDP, employment, and foreign exchange earnings. In 2015, agriculture contributed 41% and 39% of the total GDP and, 73% (2013), and 45% (2011) of the total labor force employment in Ethiopia and Sudan respectively. Relatively, Egypt has a more diversified economy with less reliance on agriculture in terms of its share in total GDP (11%) and employment (28%). In addition to agriculture, petroleum and natural gas are also important in the economies of basin countries with the exception of Ethiopia. In 2011, petroleum and natural gas accounted for 48%, 19% and 11% of South Sudan's, Sudan's and Egypt's GDP respectively. However, the contribution of the sector declined in the subsequent year noticeably in South Sudan and Sudan due to a reduction in world price and civil unrest in the countries. The poor macroeconomic performance of countries in the Eastern Nile basin is also reflected by the double-digit inflation and unemployment rate. Food insecurity is a critical problem in the basin where according to the global food security index of 2016, Ethiopia and Sudan ranked 98th among 113 countries which are considered in the assessment.

2.4. Water Uses in the Eastern Nile Basin

Water resource in the Eastern Nile basin is used for various purposes including agriculture, hydropower generation, domestic water supply, industrial production, livestock, and fishery. Agriculture and hydropower production are the two most important water uses in the basin. Both rain-fed and irrigated agriculture are practiced in the basin. In Ethiopia and South Sudan, green water is largely used for agriculture since rain-fed agriculture is dominant in these countries. Sudan has a large area of both rain-fed and irrigated agriculture while in Egypt agriculture is almost entirely irrigated. Since green water use has relatively less importance in river basin management, our discussion in this section will focus on water use in irrigated agriculture. In addition to water use for irrigation, a brief discussion on other important uses of water in the basin will also be provided in subsequent sections.

2.4.1. Irrigation

In the Eastern Nile basin, irrigation is the largest consumer of water accounting more than 70% (approximately 78BCM) of total water withdrawal (ENTRO, 2014a). The total irrigated area in the Nile basin is estimated to be between 4.9 to 6.4 million hectares (Johnston, 2012). Currently, large-scale irrigation is mainly practiced downstream of the basin where Egypt has the largest irrigated area (3.4 million hectares) and together with Sudan (1.8 million hectares) they encompass close to 97% of the basin's total irrigated area. The Nile water is the principal source of irrigated agriculture in Egypt and Sudan. Smallholder and commercial irrigation systems which vary in size from medium to large-scale are dominant in downstream of the basin. Land holdings in medium to large-scale smallholder systems range from 1 ha to 20 ha and water is mostly transported through earth canals by diverting rivers or from dams via gravity. Such systems are characterized by high cropping intensity and, yield varies across schemes and households. In the medium to large-scale commercial irrigation systems, land holdings are above 1000 ha and water is conveyed based on gravity and pumping. Yields are high in the commercial irrigation systems owing to mechanization and large use of yield improving inputs (NBI, 2012a). Irrigation efficiency widely varies in the basin wherein highly efficient schemes it goes beyond 70%. However, this high efficiency is not attributed to the efficiency of irrigation system but rather to the repeated use of recycled water especially in Egypt. Yet, conveyance, distribution and field level efficiency are low mainly due to the prevalence of open and unlined canals which are indicated to create huge conveyance loss through evaporation and seepage[8] whereas the dominance of surface irrigation systems (mostly small basins) result in considerable on-field evaporation loss before the water reaches plant roots (Appelgren et al., 2000).

Table 2.4: Water use in the Eastern Nile basin

Water uses	Ethiopia	Sudan	South Sudan	Egypt
Agricultural water withdrawal (BCM /year)	9.69	25.91	0.24	67
Industrial water withdrawal (BCM /year)	0.11	0.08	0.23	2.00
Municipal water withdrawal (BCM /year)	0.63	0.95	0.19	9.00
Total water withdrawal (BCM /year)	10.55	26.93	0.66	78.0
Agricultural water withdrawal as (%) of total water withdrawal	91.82	96.21	36.47	85.9
Industrial water withdrawal as (%) of total water withdrawal	1.00	0.28	34.19	2.56
Municipal water withdrawal as (%) of total withdrawal	7.10	3.53	29.33	11.54
Total water withdrawal per capita (m3/inhab/year)	106.1	714.1	59.92	910.6

Source: AQUASTAT (2010-2016)

Almost the entire agriculture in Egypt is irrigated and its withdrawal amounts to 86% (67BCM) of total water use in the country (Table 2.4). Egypt's water resource comprises of 55.5BCM

[8] Annual conveyance losses directly from the river channel in the basin are estimated at 20-23 BCM (Blackmore and Whittington, 2008).

surface water from the Nile, 6.9BCM groundwater, 11.7BCM recycled agricultural water, 1.3BCM recycled sewage water, 0.9BCM rainwater and 0.1BCM desalinated seawater (CAPMAS, 2014/15). Large irrigation systems are found in the Nile valley and Nile delta which are known as old lands. The new lands constitute desert areas that have been reclaimed since 1950's (Gersfelt, 2007). The HAD is the principal source of water for irrigated agriculture which has a maximum storage capacity of 162 BCM.[9] Eight barrages are located downstream of HAD which are used to regulate and divert water into a wide network of canals which distribute water to irrigation fields. Surface irrigation (small basins and furrows) are used as field water application mechanism in the old lands whereas sprinkler and drip irrigation are used in the newly reclaimed desert lands. Yields are high in most irrigation schemes of the country (see Figure 2.6) and significantly increased over time (FAO, 2016). Extensive drainage systems are used to collect and dispose of water that drains from irrigated fields which plays a vital role in reducing waterlogging and salinity problems. Although the drainage systems significantly reduced the amount of irrigated areas that are affected by salinity and waterlogging,[10] salinity continues to be high in areas with large use of ground and drainage water, and due to saltwater intrusion from the sea (such as the Nile Delta region) having an adverse impact on yields. Cropping intensity in Egypt is also high reaching up to 180% which makes yearly cultivated area about 6 million ha (ENTRO, 2014a). There are three agricultural seasons which are winter (November-May), summer (April/May-October) and *Nili* (July/August-October). Wheat, clover, and berseem are the main winter crops whereas maize, rice and cotton are the main summer crops. Rice, maize, pulses, groundnut, and vegetables are often grown in *Nili* (Johnston, 2012 and FAO, 2016).

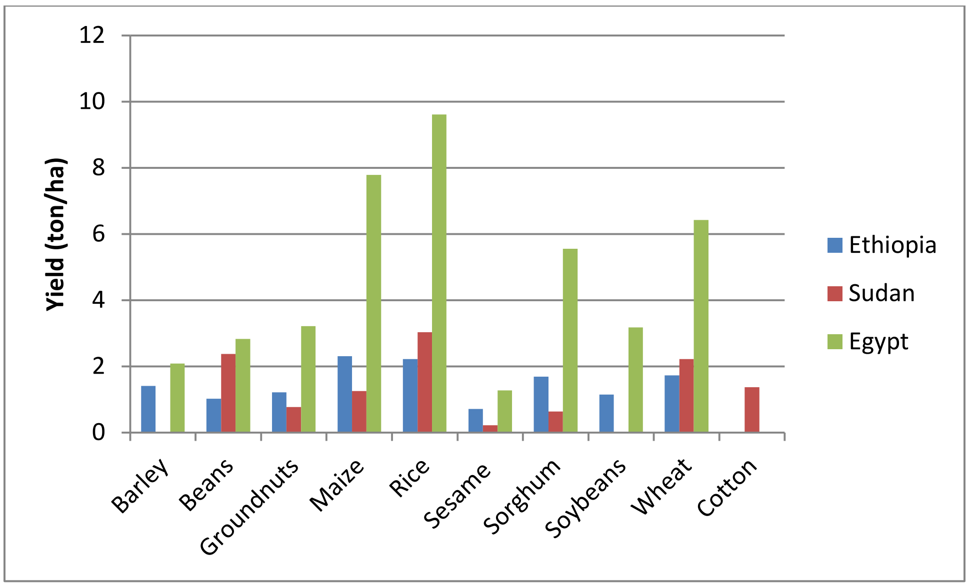
In addition to the existing vast irrigation schemes in Egypt, there are large new irrigation projects which are planned and under construction. Insight of the growing population of the country, an ambitious project called the New Valley Project or Toshka Project has begun in 1997 and set to be completed up to 2020. The main goal of the Toshka project is to create a new Nile Valley and increase the country's inhabitable area from 5% to 25% by extending irrigable land based on 'excess' water diverted from the Lake Nasser. The project involves building a system of canals (extending 310 Km) which transport water from Lake Nasser to irrigate part of the Sahara Desert in the southwest of Egypt. The Mubarak Pumping Station which is the main part of the Toshka project was inaugurated in 2005. When completed, the project will require additional 5.5 BCM water annually to irrigate 250,000 ha land. It is expected to become home to about 3 million people and reduce the high population density in the Nile Valley and Delta (Wahby, 2004; Blackmore and Whittington, 2008; Conniff et al., 2012; Abo-Khalil and Ahmed, 2016). However, the project has raised concerns and controversies both domestically and internationally. The fact that the project basis on the 'excess' water from Lake Nasser makes its sustainability questionable given the future possibility of no spill water available to be conveyed to the New Valley having disastrous consequences (Wahby, 2004; Conniff et al., 2012). Skepticisms are also reflected over the attempt of reclaiming land in the hottest part of the

[9] Groundwater is also used mainly in the oases lands (FAO, 2016).

[10] Still, about 35% of agricultural land in Egypt suffers from various levels of salinity (International Centre for Agricultural Research in the Dry Areas (ICARDA), 2011).

country where the temperature reaches up to 50^{0}C. This quest for developing water hungry agriculture is also in spite of the ongoing dispute between the riparian countries of the Nile on how to equitably develop the scarce water resource of the basin.[11] Another large irrigation expansion project in Egypt is the Al-Salam Canal which aims to irrigate marginal lands in North and South Sinai. The canal starts west of the Suez Canal and extends 262 Km eastwards, passing below the Suez Canal. Under the first phase of the project, 92,400 ha of desert land was planned to be reclaimed west of the Suez Canal and more than 70% of it is already under cultivation. In phase II, an additional 168,000 ha of desert land in the North Sinai is planned to be irrigated and could require 4.5 BCM additional water were half of it is stated to be sourced from the Nile and a half from recycled water (Conniff et al., 2012; Johnston, 2012).

Figure 2.6: Yields of major irrigated crops by country



Source: Based on FAOSTAT data (2010-2014)

In Sudan, agriculture is the largest water consuming sector accounting 96% of total water withdrawal. About 9-10% of the countries cultivated area is irrigated (Mahgoub, 2014) and surface water is the main source of irrigated agriculture (less than 5% is based on groundwater) (FAO, 2016). Large-scale irrigation systems are mainly located in the northern part and around Khartoum (NBI, 2012a). Traditional irrigation in the form of recession agriculture has been practiced for centuries using the annual flood waters of the Nile. Spate irrigation is also common where water from seasonal streams is diverted and applied to arable lands (FAO, 2016). With the construction of the Sennar Dam in 1918, modern irrigation began under the Gezira scheme (Conniff et al. 2012). The Gezira scheme (with the Mangil extension) is one of the largest in the world with a total command area of more than 900 thousand ha (Bastiaanssen and Perry, 2009). Through time (mainly in the 1970s) a number of large-scale irrigation schemes have been established and the major ones are Rahad, New Halfa, El Suki, Kenana, and Assalaya. Several small-scale schemes were also developed along the Nile system. Surface irrigation mainly in the

[11] www.water-technology.net

form of small basins is used to allocate water on the fields. Furrow method is also used in some schemes for field water application such as in the Kenana private sugar plantation. Though the total land equipped for irrigation in Sudan is estimated to be 1.8 million ha, due to low cropping intensity, the average area which is actually irrigated amounts only 60% (1.1 million ha) of the total area (ENTRO, 2014a). The low cropping intensity combined with poor farming techniques resulted in low productivity in most irrigation schemes (Bastiaanssen and Perry, 2009).[12] The short duration of the rainy season (which varies across different ecological zones of the country) also puts a limit on the extent of growing season resulting in low agricultural productivity. Cropping pattern varies annually where often cereal crops occupy close to half of the harvested area. Sorghum, cotton, fodder, vegetables and wheat are the main irrigated crops (ENTRO, 2014a). Irrigation practice often coincides with the wet summer period because in the dry seasons most reservoirs has insufficient storage and flow for irrigation propose (Johnston, 2012). High evaporation is the main reason for the shortage of stored water for irrigation purpose in the dry season, annual evaporation from the reservoirs in the country is estimated to be 5 BCM. Sudan is considering rehabilitation of existing irrigation schemes as most of its reservoirs and associated schemes are substantially affected by siltation. The Rahad and New Halafa schemes which are irrigated based on water from Roseires and Khashim El Girba reservoirs respectively are among the main irrigation sites which need rehabilitation work (Conniff et al. 2012). Horizontal expansion is also planned on Rahad and Kenana schemes. In addition, new irrigation developments are proposed in Upper Atbara and, North and South Dinder with a total command area of 330,000ha. The planned expansions and new irrigation developments are estimated to require about 9 BCM additional water per year (ENTRO, 2014a).

Table 2.5: Existing and Proposed Irrigation Area and Water Requirement in the Eastern Nile basin

Country	Existing		Planned	
	Area (Million ha)	Water req. (BCM/yr.)	Area (Million ha)	Water req. (BCM/yr.)
Ethiopia	0.14	1.1	1.59	18
Sudan	1.8	10.0	1.17	13
South Sudan	0.042	0.46*	1.5[a]	-
Egypt	3.35	67[b]	0.42**	10**
Total	5.33	78.6	4.68	41

Source: ENTRO (2014a), unless otherwise indicated as [a] (AfDB (2013), potential irrigable area for the whole country), [b] (CAPMAS, 2014/15)
*The Aweil irrigation scheme water requirement is not included, **estimated planned irrigation area and the associated water requirement for Egypt in ENTRO (2014a) reaches up to 1.12

[12] Low yields and cropping intensity are attributed to a number of factors including poor condition of infrastructures like canals, water shortage due to diminished storage capacity of existing reservoirs (because of siltation), competing releases for hydropower and high evaporation, weak drainage systems and reduced water quality as a result of salinity (ENTRO, 2014a).

million ha and 20 BCM per annum respectively, here only planned irrigation expansions in Egypt which were verified in other documents are considered.

Current irrigation developments in Ethiopia and South Sudan are very limited compared to their potential. Yet, agriculture (including livestock) water withdrawal is the largest of all water uses in both countries, noticeably in Ethiopia (92%). Estimates show that Ethiopia has about 3.7 million ha land that can be irrigated and half of it (1.9 million ha) is in the Eastern Nile basin. So far, only 5-6% of the potential has been developed (Awulachew et al., 2007). The existing two large-scale irrigation schemes in Nile basin of Ethiopia are Fincha Sugar and Koga which are located in the Abay (BN) sub-basin. Several small-scale irrigation schemes are also found in the Abay (BN), BAS and TSA sub-basins. Overall irrigation area developed in the Ethiopian part of the Eastern Nile is estimated to be about 140,000 ha. Among this irrigated area, only 12% (17,000 ha) is encompassed by large-scale irrigation schemes (10,000 ha by Fincha and 7,000 ha by Koga) whereas the remaining 88% is covered by small-scale schemes which are mostly traditional. Water is mainly conveyed via gravity (river diversion or from micro dams) and it is disturbed to irrigation fields through earth canals. In the small-scale irrigation systems, water control structures are absent and diversions are often made with local materials (such as stones and tree trunks) which are highly vulnerable to seasonal flood damages. In such schemes, unlevelled basins and short furrows are used to allocate water on the field. In large-scale irrigation schemes; basins, long furrows and sprinkler irrigation are used as field water application mechanisms (ENTRO, 2014a).

Cropping patterns in small-scale irrigation systems are quite similar to rain-fed agriculture where food crops such as cereals and pulses are cultivated in most seasons. Industrial crops like sugarcane and cotton are mainly grown in the large-scale schemes. Crop yields both in rain-fed and irrigated agriculture are generally low though it is relatively higher in the latter one.[13] Rain-fed agriculture is practiced in the two wet seasons of *Meher* and *Belg* where the former is the main rainy season (June to September) and the latter is a production season within the short rainy period (February to May). Irrigation and rainwater harvesting supplement the rain-fed agriculture and are also used in the dry season (ENTRO, 2014a). In most regions of the country, farmers produce only one crop per year due to the seasonality of rainfall and lack of water storage infrastructures. Crop failure and drought incidences are common in dry seasons because of poor water storage facilities and irrigation practice. A combination of financial, technical, institutional, social and geopolitical factors has played a role in the limited development of irrigation in Ethiopia (Awulachew et al., 2007; 2010). To meet the growing food demand in the face of growing natural resource scarcity and bring sustainable food security, Ethiopia now plans to expand irrigation at different scales. Country-wide there is a plan to expand irrigation area by 3 million ha where 1.6 million ha is within the Eastern Nile basin requiring estimated 18 BCM water per annum. Water for the planned schemes is expected to come from various multi-purpose dams which are under construction and planned for future development (Awulachew et al., 2007).

[13] The main reasons for the low agricultural yield include poor design, construction, operation and maintenance of infrastructures, use of antiquated irrigation and farming technologies, limited expertise of irrigation management and access to information, inadequate research and extension services, and lack of yield enhancing agricultural inputs (ENTRO, 2014a)

South Sudan has immense potential for irrigation development given its abundant water and land resources, where a huge share of it remains unutilized. Before 1983 (i.e. the breakout of the second civil war), there was a plan to irrigate about 270,000 ha of land in Southern Sudan. However, due to long-lasting instability, none of the planned irrigation schemes become fully operational and most of them are not functional now (AfDB, 2013). Currently, there are only two existing irrigation sites; Aweil and the Northern Upper Nile Irrigation Schemes (NUNIS) with a total equipped area of 42,500 ha (ENTRO, 2014a). But, since most areas these irrigation schemes are abandoned due to civil war, the current irrigated area overall the country is estimated at 32,100 ha, the exact share that lies within the Eastern Nile is not certainly known. Sorghum, wheat, fodder, vegetables and rice are the main irrigated crop in the country and yields are generally low. The overall irrigation potential for the country is estimated to be 1.5 million ha land. Several areas which are suitable for irrigation development are identified across the country where the Eastern and Western floodplains (600,000ha), the Nile-Sobat Rivers area (654,700ha), the Green Belt zone (500,000ha) and Mangalla (250,000ha) areas are indicated as the best ones. Some of these potential areas, however, encompass wetlands and forests which have great environmental significance, and hence developments efforts in the future should be cautious (AfDB, 2013).

2.4.2. Hydropower

Hydropower production is an important non-consumptive water use in the Eastern Nile basin. The Nile basin in general and the Eastern Nile, in particular, have a vast potential for hydroelectric power generation though most of these potential remain underexploited. The estimated hydropower potential for the entire Nile is over 20,000 MW where a significant share of it exists in the Eastern Nile region (NBI, 2012a). Ethiopia possesses the largest share of these potential and overall the country’s economically feasible capacity is estimated at 45,000 MW where about 29% of it is in the Abay (BN) sub-basin. The existing installed capacity of electricity production in the whole country reaches 3810 MW (less than 10 % of the total potential)[14] out of which about 1076 MW (28%) is within the Eastern Nile basin. Currently, there are six hydropower plants in the Ethiopian part of the Eastern Nile; five in the Abay sub-basin and one in TSA sub-basin. The Fincha multipurpose dam is the first big dam in the country which became operational in 1973 with installed hydropower generation capacity of 134 MW. The Tis-Abay I and Tis-Abay II hydropower plants which are located downstream of Lake Tana were commissioned in 1964 and 2001 having respective installed capacities of 11.4 MW and 73 MW. Subsequently, the Tekeze Dam was completed and became operational in 2009 with a capacity of 300 MW (Conniff et al., 2012). A recent development in the basin is the Tana-Beles run-of-river hydropower plant which was inaugurated in 2010 and became fully operational in 2012 with an installed capacity of 460 MW. After the completion of the Tana-Beles station, the Tis-Abay hydropower plants became standby plants and only used in emergencies or when lake levels are very high (McCartney et al., 2010). The Amerti-Neshe hydropower plant which was completed in 2011 with an installed capacity of 98 MW is also another recent development in the basin.

[14] Including the newly (December 17, 2016) inaugurated Gibe III dam, with installed capacity of 1,870 MW becoming the biggest existing and functional hydroelectric dam in the country.

Currently, the largest hydropower dam in Africa, the Grand Ethiopian Renaissance Dam (GERD) which is located within the Abay (BN) sub-basin is under construction. The construction of the dam has started in April 2011 and when completed it will have a maximum water storage capacity of 74 BCM. The main purpose of the dam is stated to be for hydropower generation and initially, its proposed installed capacity was 5,200 MW which has now increased to 6,450 MW due to design upgrading did twice. The dam is expected to benefit all the riparian states of the basin by alleviating the power shortage faced in the region (through regional power trade) as well as providing more consistent water supply to downstream riparian by regulating water flows and reducing siltation. However, serious oppositions were raised over the construction of dam both by Sudan and Egypt. The major concerns which were raised are reduced water level of Lake Nasser leading to less power generation at HAD and irrigation deficit in dry seasons and arid areas at impounding phase of the dam (International Panel of Experts (IPoE), 2013). Yet, both the potential negative impacts of the dam as well its expected benefits which were stated in the early periods of the dam construction were not on the basis of detailed scientific studies. Accordingly, the report released by the IPoE in 2013 recommended conducting comprehensive environmental and socio-economic studies to certainly assess the impacts of the dam.[15]

With expected lobbying from downstream countries, external finance was not secured for the construction of the dam from international funding organizations. Nevertheless, Ethiopia has continued with the construction based on domestic finance largely obtained from the contribution of its people (through issuing long-term bonds) and as of February 2017, around 56% of its construction was stated to be completed. Two turbines of the dam each with an installed capacity of 375 MW are expected to become operational soon. As the construction of the GERD progress, Egypt changes its target from preventing the construction of the dam to reducing its size and later to mitigating potential adverse impacts mainly through negotiation on the dam's filling horizon and operation rule. Tripartite negotiations have been resumed since 2014 and a 'declaration of principles' was signed in March 2015 by Ethiopia, Sudan and Egypt.[16] In the coming 5 to 25 (beyond) years, Ethiopia also has plans to construct several additional hydropower plants in different sub-basins of the Eastern Nile. Nine are located within the Abay (BN) sub-basin; seven in BAS sub-basin and two in the TSA sub-basin with combined installed capacity of about 9,000 MW. Additional reservoirs which will only be used for irrigation purpose are also identified for potential future construction mainly in the BAS sub-basin.

[15] Subsequently, several studies were conducted which assessed the potential impact of the GERD on downstream countries using a range of methods (see e.g., Arjoon et al., 2014; Kahsay et al. 2015; Habteyes et al., 2015; El Bastawesy et al., 2015; Soliman et al., 2016; Wheeler et al, 2016; Jeuland et al., 2017)

[16] Negotiation between riparian countries is still undergoing and a French consultancy firm is hired to study the impact of the dam, after the previous Dutch consultant named Deltares had terminated the job.

Table 2. 6: Existing and Planned Hydropower Developments in the Eastern Nile Basin Part of Each Country

Country	Existing			Planned & Under construction
	Installed capacity (MW)	Average generation capacity (GWh/yr)	Exploited (% of total potential)	Installed capacity (MW)
Ethiopia	1076	5091	8	15,450
Sudan	1924	8475	45	2300
Egypt	2842	16,071	96	32-57[a]

Source: based on ENTRO (2007; 2014a); [a] Liu et al. (2013)

Sudan has seven reservoirs in the Eastern Nile basin namely; Sennar, Roseries, Jebel Aulia, Merowe, Khashm Al Girba, Rumela and Burdana where most of them store water for multipurpose use including water supply, irrigation and hydropower generation. The first two are located in the BN sub-basin while the last three are in TSA sub-basin. The remaining two dams (Jebel Aulia and Merowe) are within sub-basins of BASW and MN respectively. All of the country's existing hydropower generation lies in the Eastern Nile basin and the total existing capacity amounts to 1,924MW. The Merowe (2009) multipurpose dam possesses the largest generation capacity of 1,250MW followed by 280MW at Roseires (1966),[17] 30MW in Jebel Aulia (1936), 26MW at Sennar (1924) and 18 MW by Khashm Al Gerba (1964). In April 2017, Sudan had inaugurated the Upper Atbara and Sitet dam project which constitutes two reservoirs; Rumela and Burdana having a combined water storage capacity of 2.7BCM and 320MW hydropower generation capacity.[18] The dams started operation with the first 80MW turbine and the remaining three turbines are expected to become operational until August 2017.[19] In the future, close to 2,300MW additional hydropower generation capacity is planned to be created and a large share of it is within the Eastern Nile basin. Proposed hydropower schemes include Sabaloka (120MW), Shereik (420MW), Dagash (312MW), Dal (400MW) and Kajbar (360MW) (ENTRO, 2014a). However, the Kajbar and Dal dams which are planned to be placed on the lands of ancient Nubia faced series oppositions mainly from the Nubian people who could be adversely impacted by the construction of the dams. It has been pointed out that the project will submerge the only fertile section of land in Northern Sudan, displace more than 15,000 people and destroy about 500 archaeological sites. The Aswan reservoir had already grabbed large Nubian territories and the construction of these new dams is said to bring the distinctive and ancient Nubian culture (which dates back to over 5,000 years) close to extinction.[20] In South

[17] Roseires dam was heightened by 10m to store additional 4 BCM water (McCartney et al., 2012) and irrigate 420,000 ha additional land (Conniff et al., 2012).

[18] Additional anticipated benefits of the project include expansion of irrigated area in the New Halfa scheme, flow regulation and reduction of flood (Conniff et al., 2012).

[19] HydroWorld.com, 2017

[20] Conniff et al. (2012) and internationalrivers.org, 2015

Sudan, the existing total installed electricity generation capacity is only around 24MW (3MW per million people) which is entirely obtained from diesel generators. Five mega hydropower plants with aggregate capacity of 2,590MW are proposed to be developed including the Grand Foula, Shokuli, Lakki, Bedden and Juba Barrage where all of them are on the White Nile (AfDB, 2013).

Egypt has largely exploited its hydropower potential which is mainly located on the Nile River. The existing installed capacity of electricity generation is close to 30,000 MW; hydropower having a share between 8-11% (2842 MW)[21] which is 96% of the total 2952 MW estimated available potential.[22] Currently, there are five main hydropower generation plants in operation, all of them located on the Main Nile. These are the Aswan I dam (1960), the HAD (1968), Aswan II dam (1985), Esna barrage (1993) and Naga Hamadi barrage (2008) with an installed capacity of 322 MW, 2,100 MW, 270MW, 86 MW and 64 MW respectively. The High Aswan hydropower plant produces more than half of Egypt's total hydropower supply.[23] The Assuit hydropower plant on Assuit Barrage is under construction which has a capacity of 32 MW and expected to be operational in 2017. Egypt has planned to increase electricity generation mainly from renewable sources. The country's Renewable Energy Strategy of 2008 targeted to increase the share of electricity generated from renewable energy in total electricity mix to 20% by 2020. Given that the available hydropower potential is almost entirely exploited, more than 12% (about 7,200 MW) of the contribution should come from other renewable sources such as wind, solar or through regional power trade to meet the target (National Association of Regulatory Commission (NARC), 2010; Hedman et al., 2014).

2.4.3. Livestock and Fishery

2.4.3.1. Livestock

Livestock plays an important role in the economy of Eastern Nile countries in terms of its contribution to income, employment, and foreign exchange earnings. The basin countries possess the largest livestock population in Africa, Ethiopia being the first and Sudan the second. Livestock use in the basin is numerous including food, draft power, transportation, bio-fertilizer, fuel, cash income as well as social prestige in pastoral areas (ENTRO, 2014a). Rain-fed livestock production systems are prevalent in the Nile basin (94%) where close to 61% is grouped as livestock-dominated and the remaining 33% as a mixed crop-livestock production. Only less than 2% of the Nile basin land is under the irrigated crop-livestock system and such systems are mostly situated in arid areas of Middle Egypt and the Delta and, in Sudan along the Nile River

[21] According to different sources (NARCU, 2010; Hedman et al., 2014; Ministry of Electricity and Energy (MoEE), 2011/12 and ENTRO, 2014a)

[22] More than 80% of electricity generation in Egypt is from thermal plants (MoEE, 2011/12)

[23] There are an ongoing upgrading works to prolong the operational life of HAD's turbines by about 40 years and increases its generation capacity to 2,400 MW (Hedman et al., 2014).

banks (Peden et al., 2012). Livestock rearing is an important livelihood strategy for many people in riparian states leaving in arid areas (mostly occupied by Sudan and Egypt) which are not suitable for crop production. But, even in areas with high rainfall, livestock remain important and mixed crop-livestock farming systems are common mainly in the upstream of the basin (i.e., Ethiopian highlands).

Water adequacy and quality are important factors for livestock production. Drinking water and water contained in the feed are the two most important livestock water uses. About 56 million cattle, sheep and goats in Tropical Livestock Unit (TLU) are estimated to exist in whole Nile basin and annual drinking water requirements (assuming 50 lit. per day per TLU) is estimated to be 1 BCM which is less than 1% of total basin rainfall. Compared to drinking water, animal feed production requires much greater water which is 90 times more under conventional feed consumption (5 kg. per day per TLU) and theoretical evapotranspiration (450m3) needed for its production. However, in parts of Sudan with an extremely arid climatic condition, feed water requirement could reach 400 times more than water for drinking. Livestock feed water use in the Nile basin is estimated to be only 4% of the basin's rainfall although it widely varies across production systems. In rain-fed systems (both in livestock-dominated and mixed crop-livestock), feed production consumes less than 12% of rainfall while in arid and hyper-arid irrigated areas, it is about 40% and 65% of annual rainfall, respectively (Peden et al., 2012). In arid systems, rangelands are usually poor and the main sources of food for livestock are fodder crops (such as clover/berseem, alfalfa, sorghum and sudangrass) and crop residues cultivated on the irrigated lands. In Egypt, rangelands provide only 5% of animal feed and as a result, annually 20% of the cultivated land (1.2 million ha) in Egypt is covered by fodder crops mainly clover (FAO, 2010a).

2.4.3.2. Fishery

Fishery and aquaculture are additional important water-dependent activities in the Nile basin. They are significant sources of employment, income, food (affordable animal protein, especially for the poor) and export earnings for basin countries (Hamza, 2014). Inland and marine fishing, as well as aquaculture, are practiced in the basin. In landlocked countries of the basin (Ethiopia and South Sudan) fisheries are entirely dependent on fresh inland water bodies of lakes, rivers and reservoirs. In Ethiopia, Lake Tana, the Rift Valley Lakes (Ziway, Langano, Hawassa, Shalla, Chamo and Abiyata), rivers (Abay, Wabi Shebele, Genale, Awash, Omo, Tekeze, Mareb, Baro, and Angereb) and reservoirs (such as Fincha, Koka, Melka Wakena, Gilgel Gibe, Tekeze, and Alwero) are the main sources of fish. Among these, Lake Tana and, Tekeze and Alwero (Abobo) reservoirs are located in the Eastern Nile Basin (FAO, 2014b). Lake Tana, the largest lake in Ethiopia is also the leading source of fish in the country with an estimated potential of 10,000 tonnes per annum, yet current annual catch is only about 1,000 tonnes (Berhanu et al. 2001; Janko, 2014; FAO, 2014b). Continues increase in commercial fishery has adversely affected the fish stock in the lake (Hamza, 2014). In addition, the construction of the Chara Chara weir, increased water abstraction, climate change and the recent lake's infestation with an invasive weed called water hyacinth (*Eichhornia crassipes*)[24] had contributed to changes in water level of the lake and fish stock, disrupting fishery activities. The construction of the Chara Chara weir which regulates water outflow from the lake towards the Tis-Abay hydropower plants downstream changed the lake's natural level. The year 2003 has witnessed the lowest level ever recorded (1,784.4 masl) which was a drought year in most of Ethiopia. The reduced lake level resulted in decreased fish production, expansion of agricultural activities on the exposed lakebed and destruction of significant areas of papyrus reed (McCartney et al., 2010). Despite the large potential, aquaculture is underdeveloped in Ethiopia. There are some subsistence farms around Lake Tana area and other parts of the country but there share to the total fish production is still marginal (FAO, 2014b).

Sudan has both inland (lakes and reservoirs) and coastal marine fisheries (red sea). The Nile River system is the main source of the inland fisheries in Sudan contributing over 90% of the estimated production potential of the country. In central and northern Sudan, there are several man-made lakes or reservoirs which are formed by the existing dams on the Nile and its tributaries which are major fishing grounds in the country. These are the reservoirs behind the Roseires, Sennar and Marowe Dams on the Blue Nile, the Jebel Aulia Dam on the White Nile, the Khashm al Girba Dam on Atbara River and the portion of Lake Nasser in Sudan (Lake Nubia) on the main Nile River. The estimated yearly potential of fish production from the five man-made lakes located within the network of the River Nile and its tributaries is 23,700 tonnes per year. Jebel Aulia Reservoir has the highest fish potential (15,000 tonnes/year) followed by Lake Nubia (5,100 tonnes/year), Roseires (1,700 tonnes/year), Sennar Reservoir (1,100 tonnes/year) and Khashm al Girba (800 tonnes/year). Marine fishery at the Red Sea coast is the second source of fish in Sudan and total marine catch of 5700 tonnes was recorded in 2009. Aquaculture activities in Sudan are currently limited though increasing local market demands is encouraging the development of large-scale aquaculture. The existing aquaculture activities in the country constituent both mariculture and freshwater fish farming where total harvest amounts to 2000 tonnes in 2010 (FAO, 2014c; Hamza, 2014). In South Sudan, the main sources of the inland fishery are major rivers (Nile, Sobat, and other tributaries), lakes, wetlands (Sudd and Mechar) and floodplains. The fishery stocks in these water bodies of the country are indicated to be vast, stable and underexploited. The current estimated total catch from inland fisheries is 143,000 tonnes where two-thirds of which are harvested during the peak fishing season of April to September. So far, aquaculture development in the country is limited, however, there is significant potential for development, particularly in the Green Belt area where there is perennial rainfall, suitable landscape (mainly sandy clay soil and gravity fed water supplies) and ideal climate for aquaculture. If well developed and managed, potential fish production from the aquaculture sector could reach up to 250,000 tonnes per year (FAO, 2014d).

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[24] This invasive weed poses crucial hazard to biodiversity in several water bodies around the world; changing ecosystem services and processes, endangering native species and reducing genetic diversity of ecosystems (United Nations Environment Program (UNEP), 2013a). The weed's high evapotranspiration rate poses a serious danger to Lake Tana which is a shallow lake with mean depth of 8m and maximum 14m. In addition, by covering the lake surface, the weed is blocking sunlight and reducing the oxygen level in the water creating hostile environment for reproduction of fish and microorganisms which serve as fish food threatening the biodiversity of the lake as well as livelihood of communities (Anteneh et al., 2014).

In Egypt, the fishery sector constitutes inland, marine and aquaculture sub-sectors. The main sources of inland fisheries in Egypt include the Nile River, Lake Nasser which is formed behind the HAD, irrigation channels, the Nile branches (Rosetta and Damietta), Northern Delta Lakes and some water bodies in the Western part of the country. Fish production from this sub-sector was 260,000 tonnes representing about 24% of the total fish production of the country in 2009 (FAO, 2010b). More than 50% (140,000 tonnes per year) of the total freshwater fish catch is contributed by the Northern Delta Lakes. Lake Nasser contributes 10% (28,153 tonnes per year) of the total inland fish catch while the Nile branches and irrigation channels account about 34% (Hamza, 2014). Fisheries in lakes make about two-thirds of the inland catch while fishing in the Nile River System account about one third. Marine fishery is also another important fishery sub-sector in Egypt and the Mediterranean Sea contributes about 60% of the marine catch while Red Sea fisheries contribute about 40%. Aquaculture is practiced in Egypt since 1930 and most farms are found in the northern and eastern parts of the Nile Delta making use of both fresh and brackish water. Aquaculture is currently the largest source of fish supply in Egypt and in 2009, the total annual fish produced from this sub-sector was 705,000 tonnes, almost 65% of the total fish produced in the country. In 2008, Egypt was the eleventh largest aquaculture producer in the world by quantity and leading in Africa, accounting about 74% of the continent's production volume (FAO, 2010b).

In general, fishery is an important sector in all of the Eastern Nile countries in terms its contribution to livelihoods and national economy. However, there are some existing and emerging problems facing the sector. Declining water levels, pollution and overfishing due to open access are some of the serious problems in the basin which are negatively affecting fishery and associated economic gains. In shallow water bodies, variation in water level is critical which is important for the lifecycle of several fish species. Also, pollution from irrigation and M&I discharges pose a problem for fishery productivity in the basin. Safeguarding the sustainability of the sector thus require cooperation among responsible bodies of the riparian countries to develop joint solutions (Karimi et al., 2012).

2.4.4. Municipal and Industrial Water Use

M&I water use is currently the least consumptive water withdrawing sector in the Eastern Nile basin. Larger uses are mainly in Egypt (about 97%) wherein 2014, an estimated 11.2 BCM (where 10 BCM is municipal and 1.2 BCM is industrial) water is withdrawn for M&I use (CAPMAS, 2014/15). In Egypt, Municipal water requirements mainly include water supply for major urban and rural villages. Surface water mostly from the Nile system (diverted either through canals or direct intakes on the river) supplies about 83% of total municipal water demand while groundwater provides the remaining 17%. Only about 1 BCM of the water diverted for municipal use is actually consumed while the rest returns to the system through sewerage. Similarly, only a small portion of water diverted for industrial use (0.7 BCM) is consumed through evaporation in the production process and the remainder returns to the system mostly in a polluted state (Ministry of Water Resources and Irrigation (MWRI, 2014)). The efficiency of the water delivery networks is indicated to be as low as 50% and even lesser in some areas. Improvement work on the water distribution network is considered as a significant way of reducing the cost of treating municipal water in the future. Desalination has been used to provide adequate water supply in some remote areas, tourism villages and resorts located along the Mediterranean Sea, Red Sea coasts and the Sinai Peninsula. Relative to other water sources, desalination has a high cost of production and the capacity of the desalination plants currently operating in Egypt is much less than 1 BCM where it supplies water only to municipal uses. However, with the adoption of new technologies and development of alternative energy sources such as solar and wind energy, desalination can become a significant source of water for Egypt in the future (El-Fellaly and Saleh, 2004; MWRI, 2014). Due to population pressure, economic growth and the associated increase in per capita water use, substantial basin-wide increase in M&I water demands are expected in the future (NBI, 2012a). Meeting this mounting demand require a combination of technological, economic and institutional measures to be taken by countries in the basin.

2.5. Water Allocation and Management Treaties on the Nile: Historical Trends and Institutions

This section provides a brief review of water management history of the Nile and regional institutions involved in managing water resources across the basin. Insight of the transboundary nature of the Nile River, starting the end of 19th century, several water treaties were made regarding the management of the Nile water including those between colonial powers, between colonial powers and independent states[25], and agreements involving independent riparian states of the basin only (Okidi, 1994; Arsano, 2007). The Anglo-Italian Protocol of 1891 which was signed by Great Britain and Italy is the first documented agreement on the Nile water management with the aim to assure the continued flow of the Tekeze/Atbara River to British Egypt. Article 3 of the treaty demands the Italian government not to involve in the construction of any water infrastructure that could significantly change the flow of Tekeze/Atbara River into the Main Nile. In 1902, a treaty was signed between Britain and Ethiopia where its main objective was delimiting the border between Ethiopia and Sudan. Besides the main aim of the treaty, the Nile water issue was included under Article 3 of the agreement which obligated Ethiopia (under the leadership of Emperor Menelik II), not to engage in or allow any development which could disrupt the flow of Blue Nile and Sobat/Baro-Akobo River into Sudan without obtaining agreement from Britain (Okidi, 1994; Swain, 1997; Okoth-Owiro, 2004; Arsano, 2007).

The aforementioned treaty which gave no mutual benefit for Ethiopia apart from heavily constraining its water use right was followed by the Tripartite Treaty of 1906 which was made between Britain, France, and Italy in which the three countries agreed to divide the territory of Ethiopia, Eritrea and Somaliland among themselves. The issue of Nile was stated under Article 4 (a) of this treaty which safeguards the interests of Britain and its colony Egypt over the Blue Nile concerning the regulation of the river and its tributaries (without harming the Italian interests) while denying the sovereignty of Ethiopia over the water resource. The followed Anglo-Italian

[25] I.e. between colonial powers and Ethiopia (the only sovereign state when early water agreements were signed and never been colonized afterwards), and later with independent Egypt who until 1922 was under British Colony.

agreement of 1925 has perpetuated the two imperial powers co-recognizing the Italians ambition to colonize Ethiopia and Britain's interest over the Nile Basin of Ethiopia (Okidi, 1994; Okoth-Owiro, 2004; Arsano, 2007). In 1929, an agreement was made between the newly independent Egypt and Anglo-Egyptian Sudan[26] which allocates the estimated annual 84 BCM Nile water flow between Egypt (48 BCM) and the Anglo-Egyptian Sudan (4 BCM) while the remaining 32 BCM left unallocated. The agreement gave Egypt full right to monitor the Nile flow from source to sea; to undertake Nile River related projects without the consent of upper riparian states; and the right to reject any construction work on the Nile that could adversely affect its interests (Whittington and Guariso, 1983). The 1929 treaty was rejected by Ethiopia stating that the right to use its own water resource cannot be halted by any country (Kidane, 1999).

The 1959 agreement between Sudan and Egypt is the first Nile agreement which involves independent basin countries only. After being administrated by a civilian government since independence, a pro-Egyptian military regime had takeover Sudan in November 1958 which fosters the signing of the 1959 Nile agreement between the two countries (Swain, 1997). The agreement granted Egypt's plan to construct the HAD (which can store the entire annual flow of the Nile) and allow Sudan to construct the Roseries Dam on the Blue Nile. Unlike the 1929 treaty, this agreement allocated the full estimated 84 BCM annual Nile flow between Egypt (55.5 BCM) and Sudan (18.5 BCM) with 10 BCM estimated evaporation losses while no water being reserved for the upstream riparian countries. The agreement, however, stated that in a case where other riparian made claim on the water, the resulting reduction in water flow will be equally shared by the two countries. Being completely ignored in the process of the agreement, Ethiopia invalidated it and requested the amendment of its content. The agreement was also protested by Tanzania, Uganda and Kenya after gaining their independence in the early 1960s from Britain. The countries declared that they will not acknowledge any Nile water agreements which are signed while Britain was administrating their countries (Okidi, 1994; Swain, 1997; Kidane, 1999, Arsano, 2007). Even though the treaties made by colonial powers and by downstream Nile states have been continuously challenged and denounced by the majority of the riparian countries and, even with the knowledge that a treaty is only binding for those states who sign it, the treaties continued to impede opportunities and new agreements which involve Ethiopia and other upstream countries for the subsequent decades, until 1993 (Beyene and Wadley, 2004). In December 1992, the Technical Cooperation Committee for the Promotion of Development and Environmental Protection of the Nile Basin (TECCONILE) was established with six member states of Egypt, Sudan, Rwanda, Uganda, Tanzania and Zaire while Ethiopia, Kenya, Eritrea, and Burundi were observers (Swain, 1997).

The year 1993 marked a signing of a framework agreement between Ethiopia and Egypt which stipulated that both countries should refrain from undertaking development works which may adversely affect the other country's supply of Nile water. In addition, the two countries agreed to consult and cooperate on development projects that will increase flows of the Nile River and reduce water losses, as well as act according to international water laws. However, the agreement was undermined by subsequent moves of Egypt such as massive irrigation expansion projects (the Toshka project for example) that are implemented without any consultation with Ethiopia. Overall, both the treaties made by the colonial powers and the bilateral agreement between

[26] Sudan who was under joint rule of Britain and Egypt

Sudan and Egypt in 1959 were to the advantage of Egypt. Even the 1993 agreement between Egypt and Ethiopia favored Egypt because the 'consult and cooperate' clauses stated in the agreement implicitly applies only to Ethiopia given that Egypt had already undertaken extensive developments on the Nile (such as HAD) before the agreement was signed. As downstream countries (mainly Egypt) endure with their will to perpetuate the 1959 agreement and upstream countries stand with their decision not to accept agreements in which they were not participated in, the Nile hydropolitical tension continued up to present (Arsano, 2007).

Following various efforts which were made between 1997 and 2001 to institutionalize the Nile water resource management, the NBI was launched in 1999 replacing the TECCONILE. The NBI is an intergovernmental partnership which pursues to achieve regional peace and security by promoting cooperative and sustainable development as well as management of water and related resources through the provision of joint platforms for consultation, collaboration and benefit sharing among basin states. The establishment of the initiative was considered as an important historical step for cooperation on the Nile water resource management because all the 10 basin riparian countries (Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda) were included as members where Eretria participates as an observer. The NBI comprises three main programs: the Shared Vision Program (SVP), the Eastern Nile Subsidiary Action Program (ENSAP) and the Nile Equatorial Lakes Subsidiary Action Program (NELSAP). The activities of the initiative are mainly guided by objectives that are stated in these programs. Each of these programs enclosed several projects under them.[27] The NBI has three parallel bodies: the governance called the Council of Ministers of Water Affairs of the Nile Basin States (Nile-COM); the Technical Advisory Committee (Nile-TAC) and the Secretariat (Nile-SEC). In addition, there are two centers which manage subsidiary programs; the ENTRO based at Addis Ababa, Ethiopia and the NELSAP Coordinating Unit (NELSAP-CU) at Kigali, Rwanda (Cascão, 2012; Morbach et al., 2014).

The NBI is playing important role in facilitating the Cooperative Framework Agreement (CFA), also called the Entebbe Agreement by providing platforms and suitable environments for the negotiation among countries. The main aim of the CFA is to allow all the riparian countries to gain mutual benefit from the use of Nile water. Its content basically echoes the principles of 'equitable and reasonable use' and 'no significant harm' that are stated in the UN Framework Convention on the Law of the Non-Navigational Uses of International Waterways (NBI, 2010). The principle of equitable and reasonable use is reinforced by upstream countries such as Ethiopia, while the principle of no significant harm is sustained by downstream countries mainly Egypt. From the Egyptian perspective, no significant harm refers to maintaining the water allocation set in 1959 agreement. In an attempt to reconcile the principles of equitable use and no significant harm, the CFA also contains a third principle on 'water security' which recognizes the "right of all the riparian Nile states to reliable access and use of the Nile River system for health, agriculture, livelihoods, production and environment". Egypt and Sudan opposed this

[27] The SVP for example included Applied Training Project, the Nile Transboundary Environmental Action Project, Nile Basin Regional Power Trade Project, Water Resources Planning and Management Project, Confidence-Building and Stakeholder Involvement Project, Socio-economic Development and Benefit Sharing Project and Shared Vision Coordination Project (Cascão, 2012; Morbach et al., 2014).

principle and demanded the amendment of Article 14 of the CFA in which the water security principle is contained. In particular, they requested the amendment of Article 14 (b) which stipulates “not to significantly affect the water security of any other Nile Basin State” to “not to adversely affect the water security and current uses and rights of any other Nile Basin State” (Cascão, 2012; Stoa, 2014).

Despite these disagreements which created a stalemate in the negotiation process, the CFA got signed by six countries (Ethiopia, Burundi, Uganda, Rwanda, Tanzania and Kenya) until 2011 and ratified by three; Ethiopia (June 13, 2013), Rwanda (August 28, 2013) and Tanzania (March 26, 2015). To enter into enforcement, the CFA needs to be ratified by two-third or six countries of the basin (Stoa, 2014). Objecting the signing of the CFA by the six countries, Egypt withdraws from its membership of the NBI in 2010. The CFA negotiations are still undergoing while Egypt showing an interest to re-join the NBI after its seven years of absence. Although the NBI was launched as a provisional institution until the CFA negotiations are finalized and a permanent institution, the Nile River Basin Commission (NRBC) is established, almost two decades have passed from its establishment without fully ratifying the CFA and realizing the commission.

2.6. Key WEF Nexus Issues and Challenges in a River Basin Context

The WEF nexus analysis is more complex in the transboundary river system, compared to analyzing it in the context of small water systems which only deals with local issues (Bach et al., 2012). Adequately addressing the additional challenges that exist at the larger basin scale thus requires a different approach and consideration which balance local needs with those of the wider society. Among many, the main issues in the transboundary river basin scale include variability in resource base, water scarcity, the difference in socio-economic conditions among riparian states, upstream-downstream impacts and conflicts, environmental quality, climate change and institutional capacity (Lee and Dinar, 1995; Bach et al., 2012). In consecutive paragraphs, the main issues that show the importance of WEF nexus analysis in a river basin context are discussed.

Variability in resource base and access: a river basin is usually characterized by differences in a resource base and access among riparian countries. In certain cases, part of riparian countries has abundant natural resources in terms of water, forest coverage, rainfall, and cultivable land while others have few of these resources or are highly dependent on resources emanating from other riparian states. In the Eastern Nile region, Ethiopia contributes more than 80% of the main Nile flow and is endowed with abundant water resources and cultivable land with a great potential for irrigated agriculture (Awulachew et al., 2007). In addition, the country has a huge potential of renewable bioenergy (Guta, 2012). Sudan and Egypt, on the other hand, are highly dependent on water that originates from upstream countries, mainly the Ethiopian highlands. Substantial parts of downstream riparian are characterized by an arid environment with little natural forest coverage (Martens, 2011) implying a low potential for renewable biomass-based energy. However, despite this resource base disparity, access to water, energy and food is much better in downstream countries especially in Egypt than Ethiopia. For example, Egypt’s electricity consumption per capita is more than 10 times higher than that of any of the other riparian countries in the Nile (Bach et al., 2012). Until very recently, the downstream countries have utilized the lion's share of the Nile water (mainly for irrigation purposes), whereas Ethiopia has only used a marginal share of the Blue Nile water resources (Arsano and Tamrat, 2004). Thus, analyzing the WEF nexus in a river basin context should take into account differences in the natural resources base and, capacity to exploit and access the base. The capacity to exploit the water resource base is largely determined by the availability of financial and human capital to construct water management infrastructures. In addition, emphasis should also be given to the scope for exploiting the potential given the existing water resource. In this regard, though the potential for irrigation in the Eastern Nile was estimated to be vast, given established water uses, there is only limited scope for increasing irrigated agriculture without causing too much of a stress (ENTRO, 2014a).

Water Scarcity: most transboundary river basins in the world are facing water scarcity and thus water security issues causing either conflict or cooperation (Mohamoda, 2003). According to Varis (2000), the Nile basin is by far more water scarce than any basin in China, Southeast Asia and West Africa. In addition to economic water scarcity which is common in much of Africa, the Nile basin also incorporates riparian countries which face physical water scarcity such as Egypt (Martens, 2011). In the case of physical water scarcity there is simply no enough water to meet all demands including environmental flows while in the case of economic water scarcity though sufficient water is available, scarcity prevail either due to poor investment in water (lack of capital to satisfy the demand for water) or its inequitable distribution across space (FAO, 2012). The existence of a riparian country with physical water scarcity makes the management of water in the Nile basin more tense and complex. In particular, upstream water uses and developments are usually seen with high caution by downstream countries which are susceptible to physical water scarcity. In the basin, water scarcity is aggravated by demand-side factors such population and economic growth and hence urbanization (Parkes, 2013). From the supply side, the basin is susceptible to the effect of climate change and climate-induced water scarcity (Eckstein, 2009). The issue of water scarcity is highly linked with food and energy security, and economic development in Eastern Nile.

Upstream-downstream linkages: in a river basin, the use of water for different purposes by upstream riparians may have an impact on downstream users. Water use can be classified into consumptive use and non-consumptive use. Consumptive water use refers to the amount of water extracted from a source and not restored while non-consumptive water use includes water uses for hydropower generation, boating and fishing (Hoff et al, 2011). Consumptive water use by the upstream party will affect the quantity and quality of water available across sectors, within sectors and regionally. Also, non-consumptive water use may have an impact on the quality of water and its availability in time (Lee and Dinar, 1995). Examples could be the filling stage of reservoirs and the disposal of waste by upstream users which reduces the temporal quantity and quality of water respectively for downstream users. There is no incentive for upstream parties to reduce the negative externality (pollution in this case), due to the failure of agents to internalize all the benefit and costs that stem from their decisions (Lee and Dinar, 1995; Taylor et al., 2013). Therefore, any water use by an upstream country must consider the possible negative externalities and impacts on the downstream state. In the Nile basin, due to socio-economic development in upstream states, water demands and abstraction in these regions have increased, which created disagreement on water allocation (Bach et al., 2012). Water withdrawal for irrigation is one key component in the upstream-downstream linkage. Water and food security have strong linkages in Nile basin (Appelgren et al., 2000). In the Eastern Nile, the dominance of rainfed agriculture in upstream Ethiopia is repeatedly discussed. The problem with rainfed agriculture is that it is vulnerable to climate change and involves considerable food insecurity concerns. Measures which are taken to address food security concerns in rainfed agriculture, usually involve the construction of water storage facilities which increases water consumption in competition with other sectors and downstream users.

Another component in the upstream-downstream linkage is energy production. Hydropower and renewable bioenergy, the two viable sources of energy in Eastern Nile, are both dependent on water resource though the former is non-consumptive.[28] Despite high hydropower potential in the Eastern Nile, electricity coverage is generally low with the exception of Egypt. Particularly, in rural areas of the upstream riparian states, only a small fraction of the population has access to grid electricity (NBI, 2012a). To meet the unsatisfied and growing electricity demands of (urban and rural) residential and industrial users, dams are being constructed in upstream countries. If not integrated, the release from hydropower plants might not match with irrigation water demands. Thus, there is a need to make developments which takes multipurpose use of water resources into consideration so as to maximize benefits and minimize negative cumulative impacts (Lee and Dinar, 1995). Yet, the construction of dams upstream that recognizes the multipurpose use of water resources is beneficial as it helps to undertake and expand power trade based on comparative advantage between riparian states. This will assist in alleviating power shortages and reducing electricity costs creating a more robust electricity supply. By regulating water flows, constructions of dams up streams also have additional benefits of reducing evaporative losses and minimizing flood in downstream areas (NBI, 2012a).

Upstream-downstream linkages also include soil conservation practices upstream, which reduce soil erosion and sediment accumulation downstream. Water and land management are highly interrelated in the basin implying the importance of land in the WEF nexus. In the Eastern Nile basin, lack of appropriate soil conservation in the upstream areas had led to onsite effects of reduced soil depth and fertility as well as a diminution of groundwater mainly associated with high soil erosion. The offsite effects of surface runoff and sedimentation which leads to flooding, reduced capacity of reservoirs, obstruction of hydropower inlets and irrigation canal, and reduced water quality in downstream areas are also substantial (Kidane and Alemu, 2015). Particularly, soil erosion from upstream catchments of the BN has important implications (in terms of water availability and quality) for downstream water uses within Ethiopia and for the remaining riparian (Awulachew et al., 2009; Steenhuis et al., 2012). Soil erosion and land degradation have a detrimental effect on sustainable improvement of agricultural and energy (i.e. hydropower) productivity. Studies show that sedimentation and siltation pose a serious challenge for newly developed small and large reservoirs (both for irrigation and hydropower generation) in Ethiopia and downstream riparian countries.

Climate change and shocks: one of the major issues which pose a challenge to water management in a river basin is climate change. By shaping the existence and sustainability of resources, it will certainly affect the inter-linkage across WEF resources (Bach et al., 2012). The Nile basin is characterized by spatial diversity and, temporal and changing climate. Rainfall patterns immensely influence Nile flows. The highly temporal variability of rainfall and rising

[28] Expect in the filling stage of the hydropower dams, which has a (one-time) consumptive element

temperatures adversely determine the productivity of rain-fed agriculture and people's livelihood. In the basin, climate change upsurges; agricultural water requirement, evaporation losses, drought risks and land degradation. Runoff trends in the basin are highly uncertain, which have implication for hydropower and irrigation potentials in the future (NBI, 2012a). Impacting water availability, agricultural productivity and energy generation, climate change will necessitate the application of adaptation measures. However, adaptation measures taken to mitigate climate change in one sector has an impact on other sectors (e.g. use of fertilizer and pesticides to increase agricultural productivity may pollute water for other uses) or downstream user (e.g. adoption of irrigation agriculture upstream) affecting the WEF nexus. Also, if each riparian country responds independently to a changing climate it might have implication for the other member states.

In addition to climate change, drought and flood are two important shocks which affect water availability in the Eastern Nile basin. Historical incidents indicated that all countries of the basin are highly prone to drought and flood which are the manifestations of the extreme hydrological variability and seasonality in the basin. Ethiopia and Egypt are highly prone to drought since the ancient times. Before the construction of the HAD, drought in Ethiopia and Egypt used to coincide given Egypt's arid climate (with virtually no rainfall), and the resulting high dependence on annual flow of Nile water from Ethiopia. Through time, the incidence of droughts is increasing in several regions of Ethiopia and in the overall basin due to evolutionary and anthropogenic climate change (Webb and von Braun, 1990; WB, 2006). The basin also has prolonged history of flooding associated with the highly seasonal flow of the major tributaries of the Nile where in high rainfall seasons (July to September) the main rivers in the basin rise to an immense scale and cause flooding especially in the floodplains of the Sudan and Ethiopia. Often, flooding results in huge socio-economic crisis largely associated with displacement of societies, interruption of social services, increased infestation with a waterborne disease as well as heavy loss of lives, livelihoods, infrastructures, and properties (ENTRO, 2014a).

Ecosystem and environmental quality: ecosystems provide a natural infrastructure service which supports water, food and energy security. Indeed, ecosystem services are at the center of the WEF security nexus though their role is often overlooked. There is a need to incorporate the costs and benefits of the natural infrastructure functions of the ecosystem in WEF nexus analysis by quantifying the services they provide and estimating their economic value (Bach et al., 2012; Rasul, 2014). In river basin context, developments made in river basin to exploit nexus benefits such as the use of water for energy production and irrigation so far resulted in reduced environmental quality. For example, increased settlement and agricultural activities along river banks in the Nile basin due to population pressure resulted in high environmental degradation. Reduced water quality due to wastewater and other pollutants from growing populations and industrial development can be mentioned. Water quality in the Nile Basin is also affected by sedimentation and salinity problems which are usually induced by human activity. The enormous soil erosion mainly from highlands of Ethiopia adversely impacts the quality of surface water especially during flood seasons creating high turbidity and suspended solids in the river making the water unsuitable for drinking and other domestic uses (Ahmed, 2006). Salinity is a common issue in areas practicing irrigation agriculture and in the Nile basin, it is mainly a problem in Nile Delta of Egypt mostly due to saltwater intrusion from the Mediterranean Sea. The three main reasons that can lead to saltwater intrusion are lower freshwater flow during the dry season, growing water withdrawal for irrigation and climate change induced sea level rise (Fahmay, 2006). In addition to sedimentation, the release of inadequately treated or entirely untreated M&I wastewater, return flow from agricultural fields with leached pesticides and fertilizer substances also affect the water quality of the Nile River. Also, the construction of water regulating infrastructures such as dams changes the natural course of river flow and sediment conveyance affecting environmental flows. One manifestation could be challenges posed to fisheries due to fish migration, and loss of habitats and hence livelihoods of local communities' dependent on fishery (Bach et al., 2012).

Socio-economic differences: another important issue in WEF analysis in river basin context which is partly related to having access to the three resources is the socio-economic difference. In the Nile basin, socio-economic conditions are characterized by large inequalities, both among the basin states and within the individual countries. The socio-economic disparity is manifested by the difference in GDP, per capita income, inequality indicators (Gini coefficient), infrastructures and development. As an example, the per capita income in Egypt is 20 times higher than in the Democratic Republic of Congo (NBI, 2012a). Similar disparities are observed in Eastern Nile where for instance, agriculture is a basis of livelihood for about 85% of the population in Ethiopia which is largely rainfed, less productive and smallholder subsistence farming. In Egypt however, only less than 50% of the labor force is engaged in agricultural production, which is mainly irrigated, highly productive and dominated by large commercial farming (Martens, 2011; NBI, 2012a). Fair allocation of water in the river basin should consider such socio-economic inequalities among countries. Future water allocation and uses thus should not be only based on historical rights and possible downstream impacts that are determined based on existing uses but rather should also consider the difference in current socio-economic status of countries and the need to improve lives of people in all riparian states.

Institutional capacity and cooperation: WEF nexus analysis in river basin context and its implementation demands strong institutional capacity. The analysis requires considerable data and information as input which calls for cooperation across sectors and regional scales. Also, appropriate tools and models which are suitable to analyze the WEF nexus in a river basin context must be developed. Cooperation among basin riparian is needed to have well understanding of externalities across the nexus sectors and spatial scales. However, the difference in national interests and institutional capacities, as well as power inequalities between riparian states, pose specific challenges. These translate into a constrained exchange of information and limited basin-wide knowledge thereby resulting in a weak institutional capacity to enforce decisions (Bach et al., 2012). The establishment of international agreements and institutions (organizations) like the NBI are a pertinent mechanism to make an exchange of ideas and information among member states. Moreover, international agreements are believed to stabilize and enhance WEF security at the regional level and promote sustainable development (Paisley and Henshaw, 2013). In general, carrying out integrated WEF analysis demands enhanced competence and there is a need to establish firm institutions having the capacity to implement policy options developed based on such analysis (Bach et al., 2012).

3. Addressing Transboundary Cooperation in the Eastern Nile through the Water-Energy-Food Nexus: Insights from an E-survey and Key Informant Interviews[29]

3.1. Introduction

WEF resources are facing growing stress and conflicts as demand outstrips their supply in many places. As a result of the growing scarcity and variability of resources, interactions between these resources are strengthening, along with the possibility of positive or negative unintended or unanticipated impacts from interventions in one of these resources on others (Ringler et al., 2013). Although this challenge is global, it is more pronounced in developing regions such as the Eastern Nile economies, where ambitious development plans are putting stress on all of these resources while supply is not keeping up. To strengthen positive synergies across these resources and sectors, and to reduce or avoid negative interactions, developments in the WEF sectors need joint planning and implementation with stakeholder involvement across sectors and riparian countries.

Such cooperation requires appropriate institutions that can facilitate cooperation among stakeholders across sectors nationally as well as across national boundaries. Several developments in the region, such as the energy power pool, food trade, and joint management of water resources, are examples of potentially significant nexus opportunities in the Eastern Nile region. However, the existence of diverse sectoral and national interests, goals, policies, and strategies concerning WEF systems makes taking advantage of such nexus opportunities challenging. From a governance perspective, the nexus concept can be interpreted as a "process to link ideas and actions of different stakeholders under different sectors for achieving sustainable development" (Endo et al. 2016:3). Meeting the competing needs between uses and users of WEF resources requires understanding the viewpoints of key stakeholders in these resources and understanding the trade-offs related to allocating resources between competing needs (McCartney et al. 2010). Developing such an understanding involves engaging relevant stakeholders in the course of identifying key WEF nexus issues across sectors and scales, in order to build common goals and decide on appropriate response options when potential conflicts of interest arise between sectors (FAO 2014; Endo et al. 2016). Engaging key stakeholders in WEF nexus analysis is also important for understanding the level of regulation in resource use and the extent of harmonization and coherence of policies (FAO 2014).

Usually, policies and actions in WEF sectors lack coordination in both their planning and allocation processes. Weak communication and collaboration between different institutions governing resource allocation leads to inefficiency because single-sector plans can undermine progress in other sectors. In practice, policy and decision makers generally do not follow or even have access to a holistic or inclusive framework that can engage relevant stakeholders and account for the multiscale character (ranging from local to regional, national, or global) as well as the complex and dynamic nature of the WEF nexus. Providing policymakers and practitioners

[29] This chapter was published as an IFPRI Discussion Paper and ZEF Working Paper.

with such a framework could allow them to properly identify and quantify linkages across sectors, and to design inclusive policies and strategies that could result in more efficient allocation of resources. For improved resource use across sectors, however, collaboration between key stakeholders is not an end in itself. There is also a need to properly communicate scientific findings to the relevant parties so they can integrate new knowledge into their plans for evidence-based actions (Mohtar and Daher 2016). Ideally, the WEF nexus approach is expected to offer an opportunity to engage various stakeholders, allowing them to make evidence-based and inclusive decisions in their respective sectors.

Assessing the views of different stakeholders (either through policy dialogues or through conducting surveys or interviews) is important for (1) revealing the diverse plans, targets, interests, and resource uses in different sectors, thus providing information to address potential trade-offs; (2) involving and bringing together different stakeholders from various sectors and levels of governance, thereby building a common understanding of challenges and opportunities at different scales; (3) ensuring that interventions are consistent with the needs and priorities of different sectors at different scales; (4) assessing and making connections with ongoing plans and actions; and (5) creating a feeling of ownership by relevant stakeholders through attaining more favorable outcomes in decision-making processes. The stakeholders in WEF systems include government bodies, nongovernmental organizations (NGOs), regional organizations, local and international research institutions, universities, civil society, and the private sector (FAO 2014).

This chapter describes nexus opportunities and challenges identified by selected stakeholders, with a focus on government agencies at the national and regional levels in the Eastern Nile Basin. The information was collected through an e-survey and KIIs conducted in the three Eastern Nile countries of Ethiopia, Sudan, and Egypt.[30] The tools were designed to gather in-depth knowledge and opinions from policymakers and practitioners on challenges and opportunities across the WEF nexus in the region. Particularly, the study attempts to identify the frequency and nature of interactions between key stakeholder organizations in the WEF sectors as well as the most influential organizations operating in the WEF space in the three countries; to understand the relevance of collaboration among the three sectors and among riparian countries, and the main steps needed to improve cooperation between countries in the Eastern Nile; and to discern the investments and actions the three countries should make to ensure adequate supplies of WEF resources to meet current and future demand. The rest of this chapter is organized as follows. Section 3.2 discusses the methods used to gather the data and information for this study. Section 3.3 presents key findings from the e-survey and the KIIs. The last section discusses the results and concludes.

3.2. Methods

The study used an e-survey that was disseminated to key stakeholders in the Eastern Nile countries. Stakeholders surveyed belonged to a range of organizations whose mandate is the development and management of agriculture, water, and energy in the Eastern Nile, mostly with

[30] Activities could not be implemented in South Sudan for various reasons.

national-level mandates. To expand on views expressed in the e-survey, follow-up KIIs were conducted among respondents to the e-survey who expressed interest in an in-depth interview. The e-survey was designed to gather information on the frequency and nature of interactions across WEF sectors and among countries in the Eastern Nile, such as personal communications between staff, attendance at conferences, and joint work on program design or implementation. In addition, respondents were asked to identify the organizations they perceived as the most influential in the three WEF sectors. The survey also gathered respondents' opinions about the importance of collaboration and coordination across sectors and countries to minimize sectoral and transboundary trade-offs. It asked about the steps needed to improve coordination between sectors and across basin countries for more effective natural resource management. Finally, the instrument elicited opinions on investment, knowledge, and capacity needs in the Eastern Nile region.

The e-survey was geared toward participants working in government agencies, local and international NGOs, research institutions, regional organizations, and other stakeholder organizations involved in the WEF sectors. Participants were identified mainly through previous networks created by the International Food Policy Research Institute and its partners under a nexus project supported by the federal government of Germany. In the e-survey, respondents were asked whether they were interested in participating in a follow-up KII. Those who responded positively were later contacted for an interview. Participation in the e-survey and KIIs was voluntary, and the identity of the respondents was kept confidential.

The e-survey was organized in four sections and consisted of a total of 25 questions. The first section asked for general background information on participants, including the name of the organization they worked in, its type, the country or countries on which the organization focuses, its primary sector, its most relevant area of work, and any additional sectors to which the respondent's organization contributes. Section two inquired about the frequency and type of interactions the respondent's organization has with other organizations across sectors. Section three requested respondents' opinions regarding the adequacy of existing collaboration and coordination across sectors and countries as well as the perceived importance of such collaborations for better resource management in the region. Section four gathered opinions about national and regional investments as well as knowledge and capacity needs required to ensure the supply of WEF resources to meet current and future demands in the Eastern Nile region.

The survey contained both closed and open-ended questions and was sent to more than 100 identified stakeholders in each basin country. In all three countries (Egypt, Ethiopia, and Sudan), the response rate was high, at about one-third of all the people who were invited (30 responses from Ethiopia, 31 from Sudan, and 36 from Egypt). Moreover, 15, 17, and 16 individuals from Ethiopia, Sudan, and Egypt, respectively, indicated interest in participating in the KIIs. A total of 14 interviews were completed, 5 in Ethiopia, 3 in Sudan, and 6 in Egypt. The KIIs aimed at gathering in-depth information about the program, projects, and research activities of participants; understanding the type and extent of their collaboration with stakeholders in other sectors; and eliciting their opinions on the need for collaboration between WEF sectors as well as for investments in the three sectors, for each riparian country specifically and for the region as a whole.

3.3. Results from the E-survey and Key Informant Interviews

This section discusses the results from the e-survey and KIIs, starting with the background of survey respondents.

3.3.1. Background of E-survey Respondents

In all three countries, the e-survey was sent out to a range of individuals who had participated in previous events focused on the WEF sectors. As a result, the government and academic sectors were overrepresented, and the private sector and representatives of end users, such as farmer organizations, were underrepresented. Thus, although this e-survey does not present the views of all stakeholders in the Eastern Nile Basin, it captures the opinions of key policy and decision makers and of the research community that is generating evidence for these leaders. A summary of respondents' characteristics is provided in Table 3.1. In Ethiopia, slightly more than a third of respondents worked in government agencies (mainly as experts and policy makers), and in Sudan, the share was more than half. In Egypt, on the other hand, the largest share of responses was from the academic community.

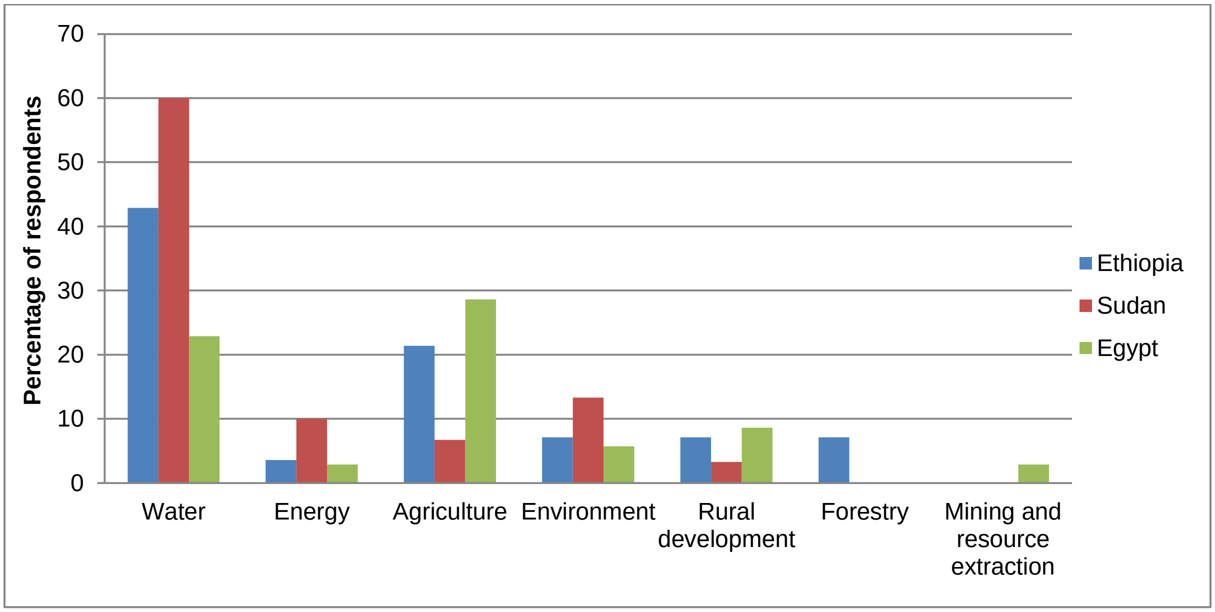
Table 3.1: Survey respondents' organizational types

Organization type	Ethiopia		Sudan		Egypt	
	Freq.	%	Freq.	%	Freq.	%
Private company	0	0.0	2	6.9	1	2.9
Government agency	11	36.7	17	58.6	5	14.7
National agricultural research institute	1	3.3	1	3.4	1	2.9
Academic or research institution	7	23.3	5	17.2	16	47.1
International NGO	2	6.7	0	0.0	2	5.9
Local NGO	1	3.3	2	6.9	0	0.0
Regional organization	4	13.3	1	3.4	0	0.0
Other (please specify)	4	13.3	1	3.4	9	26.5

Source: Authors' e-survey (2016).
Note: NGO = nongovernmental organization.

Respondents were also asked to state the number of countries their organization focused on. Responses show that 70–80% of the organizations represented focused on only one country, with the remainder being regional organizations focused on two to several countries. The e-survey respondents also reported the primary sector their organization focused on (Figure 3.1). Water was indicated most often in Ethiopia (43%) and Sudan (60%), agriculture in Egypt (29%). Within these sectors, respondents were asked to describe their primary work areas (Figure 3.2). Water (hydrology, hydrodynamics, water management) was the area of work listed most frequently in Ethiopia and Sudan. In Egypt, it was socioeconomic development (including income, welfare, and social protection). Other key areas included environmental conservation and crop production.

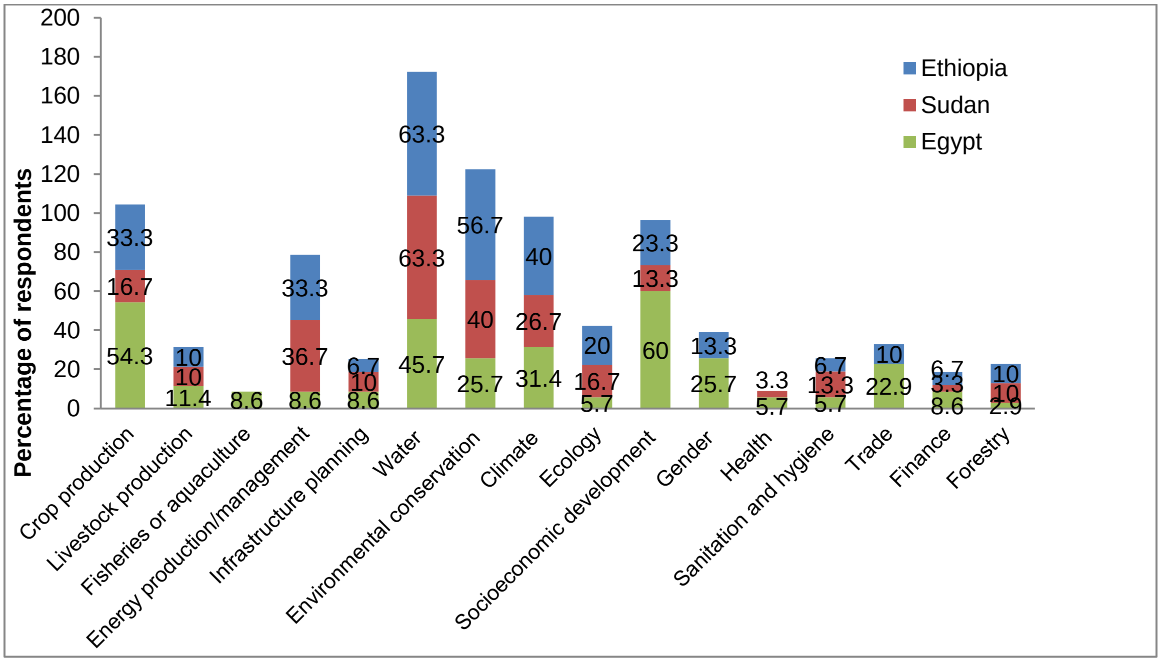
Figure 3.1: Respondent's primary sector



Source: Authors' e-survey (2016).

A further question asked to which additional sectors respondents contributed beyond their primary area of work. More than half of the Ethiopian and Egyptian respondents indicated that they contributed to the environment, agriculture, energy, and water sectors in addition to their primary sector of focus. Responses from Sudan were similar, but several respondents also mentioned forestry as an additional sector they engage in. In both Ethiopia and Sudan, a significant number of respondents whose primary sector of focus was water indicated that they also contribute to energy, agriculture, the environment, and rural development. Specifically, a large number of respondents in these two countries who listed water as their primary sector mentioned linkages to energy. In addition, respondents from Ethiopia primarily focusing on agriculture also linked to water and rural development, whereas responses from Sudan suggested that those working on water and the environment also contributed to the forestry sector. Respondents from Egypt who focused on agriculture indicated that they also contributed to water, the environment, and rural development; those focusing on water mentioned energy, agriculture, and the environment as additional areas they contributed to. Based on these responses, respondents already link across sectors, generally across water-energy-environment and forestry, but no linkages were indicated between the food and energy sectors in the three countries.

Figure 3.2: Areas most relevant to respondent's current work



Source: Authors' e-survey (2016).

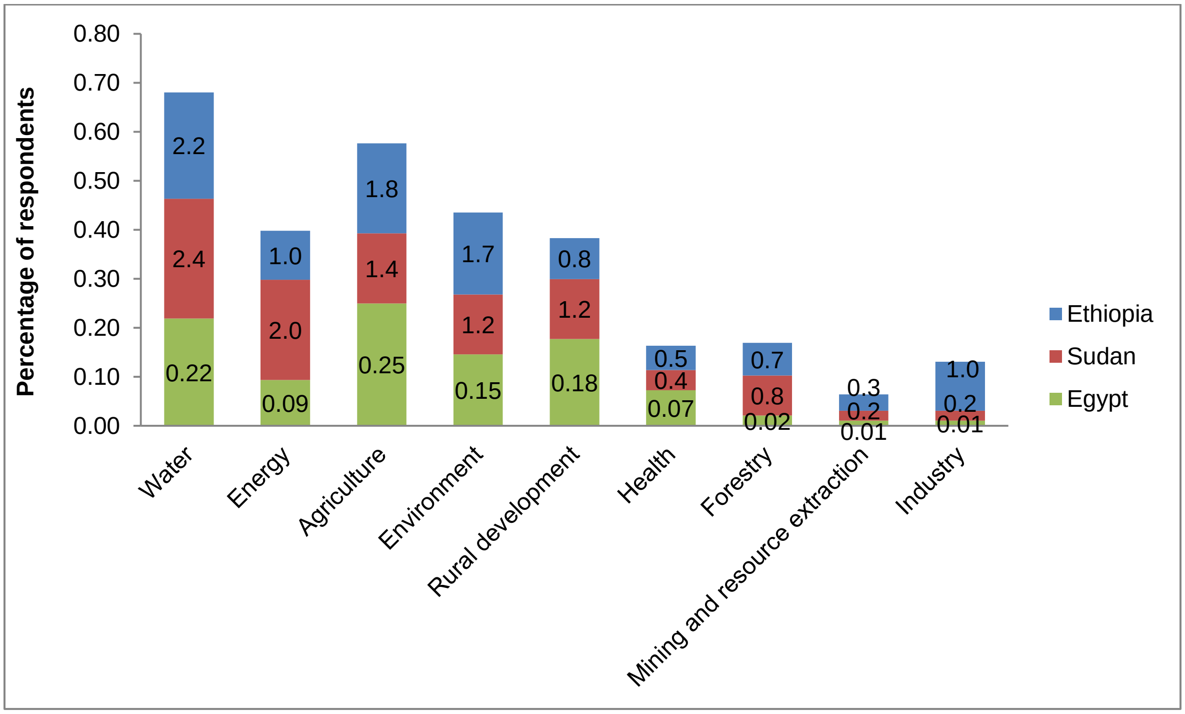
The KII participants ranged from executive directors of regional organizations to experts and researchers in government agencies to those working in local and international research organizations. Participants in the KIIs were involved in various areas of work, such as improving agricultural productivity (crop and livestock), watershed management, climate change and risk management, multipurpose water resource development assessment (mainly irrigation and hydropower), renewable energy, natural resource management (such as forestry), enhancing the productivity of marginal resources, clean water supply, livelihood improvement, regional economic integration, and gender issues.

3.3.2. Cross-sectoral Interactions and Influential Organizations

This section discusses the extent and types of interactions between different organizations, based on responses to the e-survey and KIIs as well as the organizations considered to be most influential in the WEF nexus space. Respondents characterized the extent of interactions with organizations in other sectors with responses ranging from "never" to "frequently." Figure 3.3 summarizes responses indicating frequent interactions (five or more times per year).[31] In general, interactions were most frequent with the water and agriculture sectors, followed by interactions with the environment sector. Sudanese respondents additionally reported frequent interactions with the energy sector.

[31] In all three countries, a large number of interactions were reported with organizations in the same sector (such as water organizations with water organizations), even though the question asked for interactions with organizations in other sectors. These responses can be taken as an indication of significant interactions with other organizations in the same sector.

Figure 3.3: Interactions across sectors, five or more times per year



Source: Authors' e-survey (2016).

In addition to the number of interactions, respondents were also asked about the types of interactions with other organizations. Table 3.2 presents the number of responses for each type of interaction by sector and country. Most interactions took place within the water sector and between the water and other sectors. The agriculture sector ranks second in terms of interactions, yet there are few or no linkages between the energy and agriculture sectors. In general, there seems to be limited consultation on planning and decision making in the water sector of Egypt, but the number of responses is too small to draw any conclusions. Responses from most KII participants noted that interactions with government agencies (mainly ministries) were largely in the form of conducting joint projects (research), exchanging data,[32] and communicating findings (and receiving feedback)[33] through workshops and conferences. KII participants also reported that collaboration with various government agencies was important for understanding and following the development agenda of the country.

[32] For example, respondents from Ethiopia mentioned that they used input data on climate, hydrology, and water resources from the National Meteorology Agency and the Ministry of Water, Irrigation and Electricity.

[33] Responses from Ethiopia indicated that organizations allow government agencies to give feedback on findings of research work as well as to present relevant research papers from their side. For example, one respondent mentioned working closely with the country's Environmental Protection Authority and allowing the agency to evaluate studies by the respondent's organization.

One respondent from Ethiopia who was primarily working in the agriculture sector mentioned that his organization had an innovation platform where relevant stakeholders from different sectors could meet and discuss new ideas. Similarly, a respondent from Egypt working primarily in agriculture stated that collaboration with relevant stakeholders from various sectors included planning for future projects, diagnosing and analyzing common problems, and identifying potential solutions. He also mentioned that his organization was gathering the opinions of farmers, the private sector, and NGOs about current and future investment opportunities.

Table 3.2: Types of interactions with organizations in other sectors and with other stakeholders in the same sector (number of responses)

Panel A. Interactions with water sector

	Primary sector								
	Water			Agriculture			Energy		
Type of interaction	**Eth.**	**Sud.**	**Egy.**	**Eth.**	**Sud.**	**Egy**	**Eth.**	**Sud.**	**Egy.**
Interact through professional conferences	9	8	7	5	2	5	0	0	0
Interact one-on-one with professionals in the sector	6	7	6	3	2	3	0	1	0
Collaborate on planning	6	7	3	0	0	2	0	2	0
Collaborate on project or other implementation	8	7	7	0	1	7	0	1	0
Collaborate on research	8	5	8	1	2	6	0	1	0
Provide policy advice/influence	6	8	5	2	0	1	0	0	0
Consult on planning / decision making	8	6	2	0	1	1	0	0	0

Panel B. Interactions with agriculture sector

	Primary sector								
	Water			Agriculture			Energy		
Type of interaction	**Eth.**	**Sud.**	**Egy.**	**Eth.**	**Sud.**	**Egy.**	**Eth.**	**Sud.**	**Egy.**
Interact through professional conferences	7	7	7	5	2	5	1	1	0
Interact one-on-one with professionals in the sector	4	4	5	4	2	4	0	0	0
Collaborate on planning	6	6	1	3	2	3	0	0	0
Collaborate on project or other implementation	3	3	5	3	2	6	0	0	0
Collaborate on research	3	3	5	5	2	7	0	0	0
Provide policy advice/influence	3	3	3	5	2	4	0	0	0
Consult on planning / decision making	6	6	1	2	2	5	0	0	0

Panel C. Interactions with energy sector

	Primary sectors								
	Water			Agriculture			Energy		
Type of interaction	**Eth.**	**Sud.**	**Egy.**	**Eth.**	**Sud.**	**Egy.**	**Eth.**	**Sud.**	**Egy.**
Interact through professional conferences	7	6	2	0	0	5	0	1	1
Interact one-on-one with professionals in the sector	4	5	1	0	0	1	1	2	0
Collaborate on planning	6	4	0	0	0	1	0	2	0
Collaborate on project or other implementation	3	4	1	0	0	1	1	3	1
Collaborate on research	3	2	2	0	0	1	0	2	1
Provide policy advice/influence	3	4	1	0	0	1	0	3	0
Consult on planning / decision making	6	4	0	0	0	1	0	2	0

Source: Authors' e-survey (2016).

Table 3.3 lists the three most influential organizations in the WEF sectors as identified by respondents. Most respondents indicated that government ministries are the primary and most influential organizations in all WEF sectors, and the most influential agency in each sector was generally clearly identified by a wide margin. In the agriculture sector, in addition to the ministry, Ethiopian and Egyptian respondents identified the Agricultural Transformation Agency and the Food and Agriculture Organization of the United Nations, respectively, as influential organizations. In addition, in all three countries, at least one research organization was among the top three most influential organizations identified in the sector.

Table 3.3: Three most influential organizations in the WEF sectors as identified by respondents (number of responses)

	Ethiopia		Sudan		Egypt	
Sector	**Name**	**Freq.**	**Name**	**Freq.**	**Name**	**Freq.**
Agriculture	Ministry of Agriculture and Natural Resources	23	Ministry of Agriculture and Forestry	15	Ministry of Agriculture and Land Reclamation	21
Agriculture	Agricultural Transformation Agency	11	Ministry of Water Resources and Electricity	8	Food and Agriculture Organization of the United Nations	14
Agriculture	Ethiopian Institute of Agricultural Research	8	Agricultural Research Corporation	6	Agricultural Research Center	12
Water	Ministry of Water, Irrigation and Electricity	22	Ministry of Water Resources and Electricity	21	Ministry of Water Resources and Irrigation	20
Water	Ministry of Agriculture and Natural Resources	8	Ministry of Agriculture and Forestry	3	National Water Research Center	10
Water	River basin authorities	5	Dams Implementation Unit	3	Ministry of Agriculture and Land Reclamation	3
Energy	Ethiopian Electric Power Corporation	22	Ministry of Water Resources and Electricity	15	Ministry of Electricity and Renewable Energy	10
Energy	Ministry of Water, Irrigation and Electricity	18	Ministry of Energy and Mining; Ministry of Petroleum and Gas	11	Ministry of Petroleum	7
Energy	Ministry of Mines, Petroleum and Natural Gas	7	National Center for Energy Research	4	International companies / private sector	6

Source: Authors' e-survey (2016).

Interestingly, in Sudan, two different ministries were considered to be the most important players in all three sectors. Moreover, one ministry, the Ministry of Water Resources and Electricity, was considered to be among the most important organizations for all three sectors, suggesting substantial potential for intraministerial as well as cross-ministerial collaboration for joint WEF management in the country. In the water sector, responses from Ethiopia and Sudan suggest that, in addition to ministries, river basin authorities and a dams implementation unit, respectively, are important entities, while in Egypt a national research body, the National Water Research Center, is ranked third. For energy, all three countries listed two ministries in addition to a national authority, a research center, and the private sector.

Similarly, responses from the KIIs reveal that most organizations work closely with government bodies at both the federal and regional levels. Almost all respondents from Ethiopia mentioned that they collaborate with the Ministry of Agriculture and Natural Resources; the Ministry of Livestock and Fisheries; the Ministry of Water, Irrigation and Electricity; the Ministry of Foreign Affairs; and the National Meteorology Agency. In addition, CGIAR centers; universities; and regional bureaus of irrigation, agricultural, and natural resources, as well as for livestock and fisheries, were listed as important collaborators. From the private sector, NGOs, private investors, farmers, suppliers, and various service providers and manufacturers were also identified as engaging in WEF sectors in responses from both Ethiopia and Egypt.

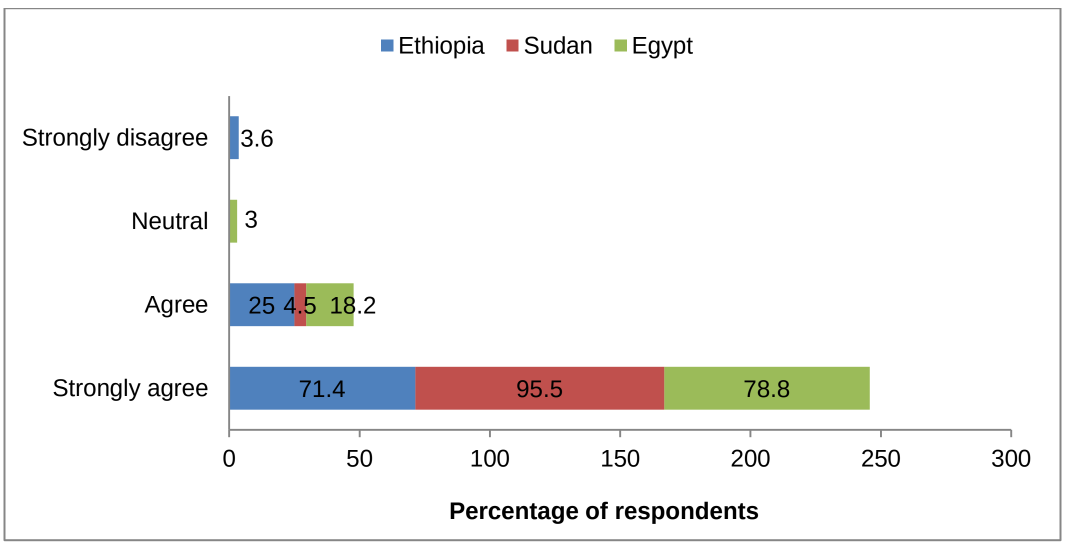
3.3.3. Collaboration among the WEF Sectors

This section describes respondents' perceptions about the need for, importance of, and adequacy of cross-sector national and regional collaborations.

3.3.3.1. National Collaboration

Respondents were asked whether national collaboration across the WEF sectors was essential for resource management in the region and whether national coordination efforts across the WEF sectors were sufficient. Figure 3.4 shows that the majority of respondents in all three Eastern Nile countries strongly agreed that collaboration across the WEF sectors throughout the region is essential for planning and decision making to improve resource management in the region.

Figure 3.4: Responses to the statement "Collaboration across the WEF sectors is essential for improved resource management in the region"

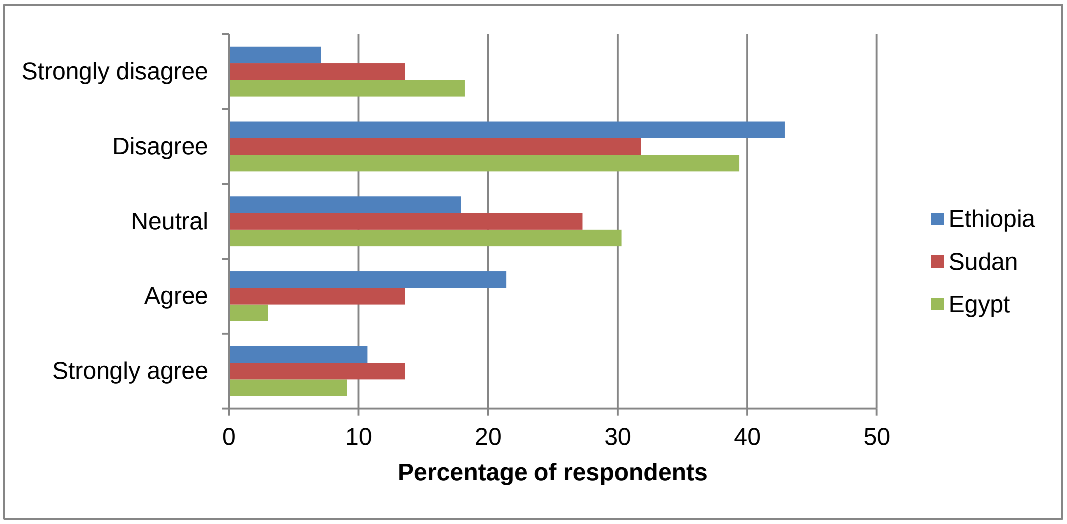


Source: Authors' e-survey (2016).

On the question of adequate existing coordination, there was no consensus, but the majority of respondents felt that coordination needs improvement. For example, 43% of respondents from Ethiopia, 32% from Sudan, and 39% from Egypt disagreed that national policies, plans, and decisions are well coordinated across WEF sectors (Figure 3.5). A further 18% of respondents from Egypt, 14% from Sudan, and 7% from Ethiopia strongly disagreed with the notion that policies, plans, and decisions are well coordinated at the national level. A considerable number of respondents did not voice a specific opinion on the question, and several respondents from

Egypt (12 %) and around 30% of respondents from both Ethiopia and Sudan agreed or strongly agreed that coordination across the WEF sectors was working well.

Figure 3.5: Responses to the statement "National polices, plans, and decisions across the WEF sectors are well coordinated"



Source: Authors' e-survey (2016).

Responses from the KIIs provide several examples of weak coordination across the WEF sectors at the national level. A respondent from Egypt summarized the feelings of several Ethiopian and Egyptian respondents:

> *Currently there is an ongoing competition on who will be leading an irrigation project planning to cultivate 1.5 million feddan [about 0.63 million ha]. They shift the priorities given back and forth between the Ministry of Agriculture and Land Reclamation and the Ministry of Water Resources and Irrigation. This is not a very good policy, though; a better strategy would be to have an integrated team that has expertise from both ministries working together. Thus, this kind of cooperation is not yet feasible and is not likely to be, in my opinion, unless a newer way of thinking takes the lead. For example, when they designed the water security strategy, there were no people representing the agricultural sector; similarly, there were no people from the water sector represented when the food security strategy was discussed.*

The responses obtained from the KIIs also provide some of the reasons for the strong consensuses reached about the need for collaboration across sectors. First, respondents noted that the three sectors are naturally interlinked, making collaboration essential. A respondent from Ethiopia (working in a government agency) mentioned that "basically water, energy, and food are interdependent; one can't stand or operate alone without the other, and hence collaboration or integrated work among them is very important." Integration among sectors was reported to be vital to getting the maximum benefit from investments in all sectors. A respondent from Egypt mentioned that coordination across sectors helps to harmonize planning by reconciling conflicting and overlapping ideas. Respondents also indicated the importance of collaboration for sharing experiences and learning from others.

> *To illustrate how lack of integrated work can cause serious problems, I can give the case of the Tana Beles project as an example. The concept of Tana Beles is as follows: the water that goes out from Lake Tana passes through the Chara Chara Weir and goes to the Tis Abay I and II hydropower stations with a capacity of 84 MW. However, instead of staying at 84 MW, a tunnel was built at the back; making it possible to generate more energy (460 MW) with less water (the former uses 100m^3/sec, whereas the tunnel uses only 77m^3/sec). And there are two irrigation projects just downstream: the Upper and Lower Beles projects. Together, up to 140,000 ha can be developed under these projects. However, when the projects were first designed, no mechanism was conceived to transfer the water to the irrigation fields in times when the hydropower doesn't operate. So, in the middle of the project it gets redesigned and a bypass tunnel is built at additional cost. In times when the hydropower is not operational, the water will pass through the bypass tunnel for irrigation. If this had not been fortunately discovered in the middle of the project, the irrigation project downstream was going to fail completely. Thus, integration among the three sectors is important to avoid problems like this from the beginning and obtain the maximum possible benefit.* ***-KII response from Ethiopia***

Another KII respondent from Egypt emphasized the need for collaboration between WEF sectors because the three resources are highly interdependent in the country. He stressed that irrigation in Egypt is dependent on energy because water abstraction for that purpose often uses diesel for running pumps. The respondent stated that the "situations in Egypt are closely intertwined because at the end of the day in order to produce food, we need water, and in order to get water into the field we need electricity." Accordingly to the respondent, connecting farmers in the delta with electricity (for pumping water) is a challenge limiting irrigation. As a result, solar panels are being considered as an alternative.

> *Higher means of cooperation among sectors would solve a lot of problems related to planning, where we happen to have a lot of problems in Egypt. For instance, ideas coming from different ministries might overlap. Thus, more collaboration and connectivity is needed in this regard in order to efficiently manage our limited natural resources.* ***-KII response from Egypt***

Improving resource use efficiency is a further important factor reported to support collaboration across WEF sectors. One respondent, from Ethiopia, mentioned that most natural resources are nonrenewable and need to be used in an efficient manner, which requires cooperation across sectors. Another respondent, from Egypt, explained that there is a need to promote efficient use of water by adopting crops with low water requirements. He mentioned that even if efficient natural resource management should primarily be based on the concept of economic efficiency (particularly marginal productivity), social factors should also be given emphasis and need to be integrated into nexus analysis. He presented an example of sugarcane production in Upper

Egypt: from an efficiency perspective, sugarcane should not be grown there, but it is difficult to move out of sugarcane due to local traditions and the crop's associated social value. The respondent stated, "Making a change in the cultivation cycle should be preceded by a study of social aspects, but usually decisions on removing crops are made without taking this social aspect into account. Farmers are not going to make changes without having these three questions answered and taken into consideration: First, is it economically wise or profitable? Second, is it socially acceptable? And third, is it environmentally valid?"

> *I will address the question of the need for collaboration among different sectors from the perspective of our main work: technology development. I believe any technology produced should take into consideration the available resource potential. For example, let's say we produce a certain crop technology. To be effective, the technology should be able to fit the resource potential available in the area where it is going to be introduced. So we need reliable and appropriate data on resource potential to produce suitable technologies. However, usually the data produced by different ministries are not sufficient for our purposes. One major problem is the difference in spatial scales. Most data are available at an aggregated scale, but the technology we produce is site specific and we need data that are compatible. For example, we need site-specific soil information for different analysis; the data we get are usually aggregated (for a certain region or sub-basin). Also, most of the time we obtain model based data and not observed data. We face the same problem with the National Meteorology Agency. It has only a limited number of stations countrywide, and the data they produce are not representative of Ethiopia (especially given the fact that Ethiopia's topography and climate is very diverse). Therefore, information should be planned and produced jointly in a way that everybody can use the information. Otherwise, it will be very difficult for one entity to take and use information or technology that is produced by another party. **-KII response from Ethiopia***

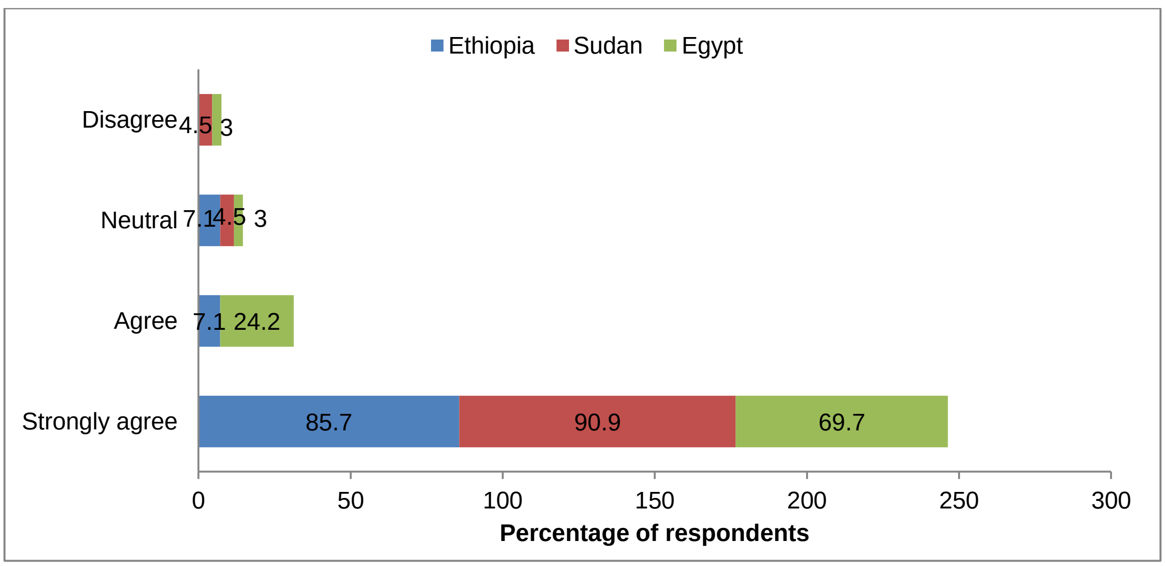
Some KII respondents also reported that collaboration among WEF sectors is not enough in the sense that other factors (such as climate change and basic infrastructure development) should also be integrated into nexus thinking. KII participants also mentioned natural resource degradation and depletion, and the question of sustainability, as a rationale for collaboration among WEF systems. One respondent from an international research organization in Ethiopia pointed out that development activities in any of the three sectors should not adversely affect the natural resource base. Mitigation and rehabilitation efforts are thus needed to ensure that development activities in one sector do not adversely affect outcomes in another.

KII participants also discussed several challenges that hinder collaboration. Respondents reported that even if greater collaboration and integration between sectors is theoretically ideal, in practice it is very challenging. Major challenges include the existence of sector-specific policies, mandates, responsible authorities, and institutional setups, as well as the lack of incentives for cooperation. In many cases, several separate and independent bodies work on what are essentially the same issues, making collaboration difficult because each body has its own goals and institutional setup. As an example, respondents from Ethiopia mentioned the case of irrigation: medium- and large-scale irrigation projects are managed by the Ministry of Water, Irrigation and Electricity, whereas small-scale irrigation is handled by the Ministry of Agriculture and Natural Resources. Such segmentation, respondents indicated, has shortcomings, including difficulty in getting consistent data. Respondents pointed out that in practice, different institutions focus on working per their mandate because in the end, their work will be evaluated based on what they achieved under the mandate. Finally, professional or disciplinary biases were noted to be another obstacle to cross-sectoral, multidisciplinary collaboration.

3.3.3.2. Regional Collaboration

Next in the survey came questions on the importance of regional cooperation for WEF security. Figure 3.6 shows wide agreement on this topic, with 70–91% of respondents, by country, strongly agreeing that collaboration is important to meet WEF needs. Again, respondents from Sudan, the country in some ways in the middle between Ethiopia and Egypt in the Eastern Nile Basin, felt the strongest need for such coordination. Egypt's response on this question was slightly weaker than the country's response about the need for national cross-sectoral collaboration, possibly because the country chose a few years back to leave one of the key regional coordination bodies, the NBI.

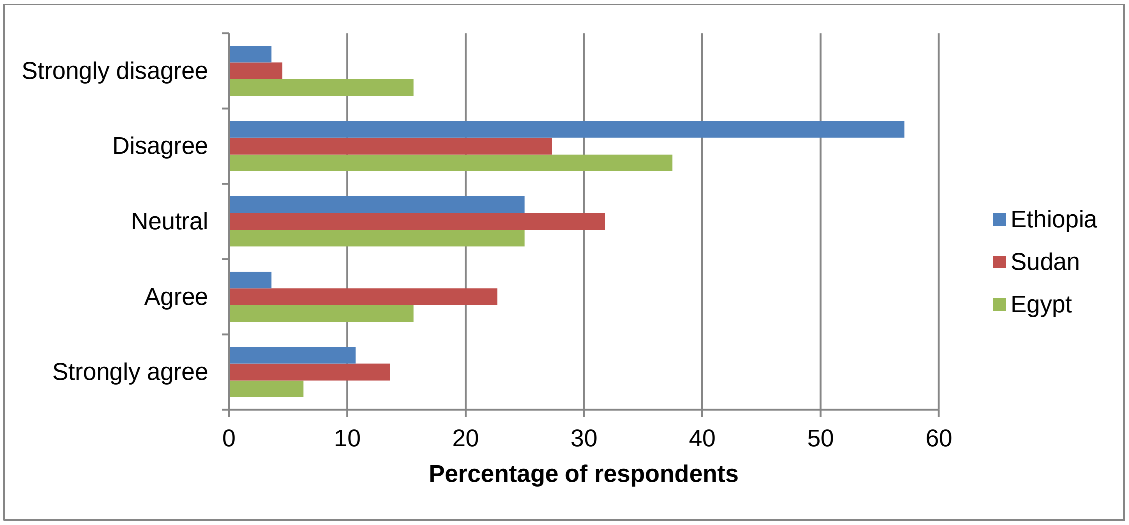
Figure 3.6: Responses to the statement "Collaboration among countries in the Eastern Nile Basin is important for adequate provision of food, energy, and water"



Source: Authors' e-survey (2016).

Similar to the question on adequacy of national collaboration, respondents from the three countries were somewhat divided on the adequacy of current regional cooperation, although most of them characterized it as inadequate (Figure 3.7). More than half of all Egyptian and Ethiopian respondents disagreed or strongly disagreed that cooperation is adequate, and 32% of Sudanese respondents disagreed or strongly disagreed. Approximately one-quarter to one-third of respondents felt neutral on this topic, whereas the rest agreed or strongly agreed that cooperation is sufficient. Among the three countries, Sudanese participants in the e-survey felt most strongly that ongoing cooperation is adequate.

Figure 3.7: Responses to the statement "Ongoing regional cooperation between countries in the Eastern Nile Basin is adequate"



Source: Authors' e-survey (2016).

Responses obtained from the KIIs largely support collaboration among countries in the Eastern Nile. Most respondents mentioned that any development in the basin will ultimately have implications for the rest of the basin (which could be either beneficial or harmful) and the benefit could be increased, or damage reduced, through joint planning and actions. A respondent from a regional organization based in Ethiopia gave his take on the importance of collaboration between basin countries: "Unilateral actions usually cause conflicts, and conflict has its own cost. So if we take the cost of conflict into account, collaboration is mostly better than unilateral actions. Collaboration across the sectors and the basin countries also brings what we call 'benefit beyond the river,' such as increased trade and tourism, better technical cooperation, and improved infrastructure."

> *There is no doubt that resources should be used in a coordinated manner by all the four riparian countries [Egypt, Sudan, South Sudan, and Ethiopia]. Each country has its own comparative advantage, and hence a multilateral approach is highly beneficial. I remember a very nice article regarding this. It's by Harry Verhoeven (2011), and he argued that Ethiopia has a comparative advantage in hydropower production, while Sudan has the same in agriculture (oil as well), and Egypt should provide the finance. Then regional trade between the three countries would benefit all the countries. I do not agree with all his arguments, but I think he has a great point. I believe utilizing this difference in comparative advantage between nations is the only way to bring about collaboration across sectors within the basin. In general, though past experiences are not very*

encouraging, a multilateral approach is the only sustainable option for this basin.
-KII response from Ethiopia

Given the fact that downstream countries are largely dependent on water originating from upstream areas, one KII participant suggested joint investment in watershed management upstream as an area in need of collaboration. A respondent from Ethiopia explained that the demographic, environmental, and economic situations in upstream countries are expected to further degrade natural resources, in turn impacting downstream countries:

In the past, floods and sedimentation have occurred on several occasions, and they could continue in the future if appropriate management of resources is not practiced upstream. There should be strong natural resource conservation upstream. Rapid population growth in the highlands will further reduce the natural resource base for individuals, leading to overutilization and associated degradation. It will be important to find new income opportunities for the highland population outside the agricultural sector to ensure that fragile hillsides are preserved. This will require joint development programs by riparian countries. Because the environmental consequences of upstream natural resource degradation are not local (but stretch to the Mediterranean Sea), joint interventions are needed for the sake of global existence.

In general, KII responses from Ethiopia pointed out that the transboundary nature of the river should be given due emphasis in national plans and that the basin should be managed as one system.

KII responses from Egypt were also in favor of collaboration among riparian countries. For example, respondents identified trade between basin countries as a key form of cooperation. A respondent from a research institute in Egypt mentioned that trade is the right tool for cooperation between Eastern Nile countries and suggested that the private sector, not the government, has to be the main player in this area. He mentioned foreign investment by the Gulf countries in the agricultural sector of Sudan as a good example that can also be practiced by the basin countries through establishing joint agricultural projects between Egypt, Sudan, and Ethiopia.

I believe we have major areas that we can collaborate on, based on the resource base in each of the [Eastern Nile] countries. For example, livestock has a large amount of virtual water content in comparison with other commodities. Making use of the rainfed agriculture in Ethiopia, we can jointly develop livestock projects (including animal rearing, forage development, slaughterhouses, and processing) there and import the meat, which will allow us to save this high amount of virtual water use in Egypt. The same collaboration can also be made with Sudan. Importing livestock from these two countries will also allow us to utilize the land currently planted with clover (which is used mainly for animal feed) to be planted with wheat instead, which will improve the country's food self-sufficiency/security. We can also collaborate to improve the productivity of

> *rainfed agriculture in Ethiopia and Sudan, such as by promoting rainwater harvesting, which could help to increase cropping intensity. **-KII response from Egypt***

Respondents suggested that because Ethiopia and Sudan possess relatively abundant resources for agricultural production, projects can be established in these two countries with Egypt providing technical assistance (because Egypt possesses better knowledge and experience, especially in irrigated agriculture) (see KII responses for further details).

Another KII respondent from Egypt mentioned that the riparian countries face common problems, such as soil erosion, salinity, and water shortages, which require joint solutions. Moreover, responses from KII participants in Egypt reflected that collaboration between basin countries should center not only on water but also on other sectors. Further, some suggested that integration across countries should include joint operation between the technical and the political realms. One respondent stated, "Even if the technical aspects are well studied and imply the need for more collaboration, at the end of the day the decision maker is the politician and hence the two should work together."

One respondent from Egypt also mentioned that cooperation is needed in the region regarding the operation of water infrastructures that are planned or currently under construction. He gave the Owen Falls Dam on Lake Victoria in Uganda as an example, mentioning that it was partially funded by Egypt. The purpose of the dam is hydropower generation, and its water release is determined through collaboration between Uganda and Egypt. The respondent said, "Over the last 60 years, Egyptian engineers have been engaged in the monitoring and decision making over water releases from the dam. This is an example of the kind of cooperation I would hope to see with other countries in the basin in the future. Inevitably, all the three countries will attempt to maximize control over the water resources, and thus the main issue would be how to do it for the benefit of everyone."

> *Water resource developments in the basin are going to proliferate. Currently we have three dams upstream under construction along the Blue Nile main course. At the moment, each country is developing the river unilaterally, but when the infrastructures become operational, a greater degree of coordination is required between countries. If the operation of such developments is not coordinated, it will pose a serious problem to countries. Take the Grand Ethiopian Renaissance Dam as an example. Its operation should be in line with the water use and operation of dams in Sudan and Egypt. If not, the benefit that is expected to be obtained by the three countries from the dam might not materialize at all. Thus, coordinated management of cascade dams is an issue that needs high emphasis. - **KII response from Ethiopia***

Some KII respondents also reported challenges that hinder collaboration between Eastern Nile countries. One such factor is water politics between upstream and downstream countries. Respondents also listed the lack of common databases, joint analysis tools, and platforms as a challenge that creates mistrust, tension, and conflicts of interest between basin countries. Other barriers that respondents identified include lack of finance and weak existing regional institutions.

3.3.4. Actions and Investment Options

This section discusses national actions, national and regional investments, and steps to enhance cooperation as proposed by the e-survey and KII respondents. Tables 3.4 through 3.7 summarize the responses given by the e-survey respondents. Regarding national steps that need to be taken to improve coordination across WEF sectors (Table 3.4), respondents from all three countries emphasized the need to identify common areas of interest; set clear objectives, policies, and strategies; and then move to joint planning and implementation. Respondents from Sudan and Egypt also mentioned raising the awareness of decision makers on the importance of cooperation as a mechanism to avoid duplication of work and unjustified competition for resources among sectors. Similarly, respondents from both of these countries indicated that involving relevant stakeholders in planning and implementation processes is important to improve coordination across WEF sectors. Respondents from Ethiopia and Egypt also reported that creating platforms to facilitate multistakeholder dialogue could improve cross-sectoral collaboration.

Table 3.4: National steps needed to improve coordination across the WEF sectors, respondents' suggestions, by country of respondent

Ethiopia	Sudan	Egypt
Identify common goals and set clear missions and visions	Study areas of common interest and set common objectives as well as clear policy and strategies	Conduct research for providing evidence on the linkages
Form integrated plans and implementation	Perform joint planning and implementation (integrated water resources management)	Perform joint planning and coordination of strategies, interventions, or implementation
	Raise decision makers' awareness of the importance of cooperation for improving sectoral performance	Raise stakeholders' awareness of the importance of coordination among sectors
	Involve relevant stakeholders and empower concerned authorities	Have stakeholders participate in the planning and implementation process
Create a platform for policy debate among policy makers and experts (stakeholders)		Facilitate multistakeholder dialogue
Enhance the capacity of planners, decision makers, and experts working in different sectors	Develop partnerships among sectors with clear roles and responsibilities	Provide incentives for information and data sharing among ministries, and more transparency in decision making
Document and share the potential gains from coordinated efforts		Develop a coordination mechanism between various ministries and regularly monitor its progress
	Give responsibilities to qualified professionals and focus on scientific decisions	

Source: Authors' e-survey (2016).

The survey participants also identified national investments to help ensure that the supply of the three resources meets current and future demands. Respondents from all three countries mentioned investments in water infrastructure (such as dams). Participants from Egypt and Sudan suggested investments in renewable energy as well as in enhancing resource use efficiency (such as improving irrigation systems). Respondents from Egypt and Ethiopia mentioned investments in research and education to facilitate evidence-based decision making. Ethiopia-based respondents pointed to investments in sustainable natural resource management (such as watershed management) as well as in holistic approaches and enhanced institutional setups for the planning and management of resources, taking into consideration all sectoral demands. Respondents from Sudan also mentioned a need to invest in the coordinated management of cascade dams (Table 3.5).

Table 3.5: National investments or actions needed to balance supply with needs along the WEF sectors, by country of respondent

Ethiopia	Sudan	Egypt
Carry through with planned large-scale investment in water infrastructure	Build multipurpose dams	Develop integrated investments and implementation plans across the water, energy, and food sectors
Pay attention to sustainable natural resource management (such as effective soil and water conservation strategies)	Invest in renewable energy and irrigated agriculture	Invest in renewable energy and irrigation systems
	Improve water management for existing projects (invest in irrigation systems that improve water use efficiency)	Increase resource use efficiency, such as by investing in water-saving technologies and water desalination projects
Institute strong coordination and joint planning among the sectors	Encourage water harvesting	Invest in enhancing water quality
	Invest in in-depth study of the benefits of regional power trade	Reduce food waste, especially postharvest losses
Provide opportunities for private-sector investors	Develop an optimum operating schedule among existing Sudanese dams in the light of the Grand Ethiopian Renaissance Dam (GERD) operating schedule	Improve agricultural production and marketing
Set up institutions in a way that helps avoid conflicts		
Create public awareness and promote experience sharing	Invest in careful feasibility studies of proposed new dams in Sudan, considering the impact of GERD	
Invest in research (to provide appropriate evidence) and education	Invest in science and technology	Invest in education, research, and capacity building

Source: Authors' e-survey (2016).

In addition to general investment needs for balancing WEF demand and supply, respondents were also asked to state the primary investments that need to be made by each country to ensure WEF security. The responses are very similar to those listed as general investment needs. Respondents from Ethiopia and Sudan mentioned large-scale investments in water and other infrastructure as primary investment needs, those from Ethiopia and Egypt pointed to investments in renewable energy and soil and water conservation, and respondents from Sudan and Egypt recommended investments in enhancing resource use efficiency and rainwater harvesting technologies (Table 3.6).

Table 3.6: Primary national investment needs for ensuring WEF security, by country of respondent

Ethiopia	Sudan	Egypt
Water storage programs (small and large reservoirs)	New dams for electricity generation and irrigation	
Irrigation	Expansion of irrigated agriculture	Irrigation development
Renewable energy (hydropower, wind, solar, geothermal)		Developing renewable sources of energy
New technologies in all sectors	Science and technology	
	Improvement of water management in existing projects through use of modern technologies	Increasing water use efficiency Water desalination projects
	Development of drought-resistant varieties of staple food crops	
Infrastructure (such as roads and telecommunication)	Development and upgrading of infrastructure	
Soil and water conservation (such as afforestation)		Reducing land degradation and improving soil fertility
	Rainwater harvesting technologies	Rainwater harvesting

Source: Authors' e-survey (2016).

The responses obtained from the KIIs largely support the types of national investment needs that were pointed out in the e-survey. KII respondents from Ethiopia mentioned investment in water storage infrastructure (for either hydropower or irrigation) and watershed conservation. Regarding water infrastructure, one respondent explained the following:

> *About 86% of the Nile flow is contributed by Ethiopia. But when we look at this flow, almost 80% of it is generated within three to four months (the rainy season of June, July, August, and September). In the remaining eight months, only 20 % of the flow will be available. When the flow is at 80 %, Ethiopia doesn't need the water for agriculture because usually rainfall is enough. If we want to use it for hydropower, it should be generated for the entire year. It is possible to generate hydropower for three to four months as run-of-river, but that is not beneficial at all because it is not sustainable. Thus, there is a great need for water storage infrastructure in Ethiopia that appropriately accounts for downstream impacts.*

In addition, respondents indicated investment in watershed management as crucial to ensuring the sustainability of the built water infrastructure.

KII respondents from Ethiopia also emphasized the role of the government in infrastructure development to create a conducive environment for private-sector participation. One respondent mentioned that even though private-sector involvement in all sectors of the economy is very important, such investment is not robust, especially in large infrastructure development, such as hydropower plants, which require a very large capital investment. Infrastructure, such as roads, was also identified as crucial for the development process. Regarding roads, another respondent from Ethiopia indicated their role in making the movement of people, resources, and products (both input and output) cheap and easy: "Better road access gives a farmer an opportunity to easily access additional markets for his products, which will provide him with more income, initiating more investment. It will also give him a chance of being exposed to new ways of thinking and operating." Respondents also underlined that the primary role of government investment should be creating an enabling environment for the private sector. Investment in research and education was also reported to be essential for successful investments by either the government or the private sector. Respondents suggested that knowledge and science are important prerequisites for appropriate investment choices, and hence schools, universities, and research centers should be formed to develop knowledge and technologies.

Even though KII respondents were supportive of the integrated development of WEF sectors, several respondents pointed out that among the three, food security should be given priority. As stated by one respondent from Ethiopia, "it is always preferable and vital to have integrated development that considers all the sectors in a parallel manner, but it is a fact that [among these] food is most essential for human survival. You can live without electricity but you can't survive many days without food."

Some KII respondents from Ethiopia also discussed the challenges to investment in irrigation in the country. They identified institutions, policies, and geographic features of the country as the main constraints on irrigation development. Another barrier mentioned was the fragmented administration of irrigation (with medium and large irrigation projects administered by one ministry and small-scale irrigation by a different one). In addition, informants identified limited experience with irrigation among policy makers, technical advisors, and farmers as a further hindrance to development. Lack of investments in education and research were also identified as factors limiting the capacity to transform the agricultural sector in Ethiopia. As one participant mentioned, "If we increase irrigation development, we have no agronomists who specialize in irrigated agriculture. This is because in the last 40 years, the focus was on how to become self-sufficient by increasing the productivity of rainfed agriculture, and mainly that of cereal production. As a result, the knowledge that most agronomists have is on rainfed crops. We thus need to invest in educating agronomists who specialize in irrigation."

> *Currently Ethiopia is focusing on investments for hydropower production. For example, we are going to use the Grand Ethiopian Renaissance Dam only for hydropower generation and there are limited water infrastructure developments that are intended for irrigation purposes. There are arguments that we have low water use efficiency for irrigation and we will waste water. However, I believe we should invest more in construction of dams for irrigation purposes. We should be able to increase agricultural productivity and become food self-sufficient. Also, given that we are now storing water through the constructed dams, artificial lakes*

are being formed. Depending on demand, such lakes can be used for tourism, navigation, and fishery. But all of these uses need agreement among countries to avoid potential conflicts and ensure that investments are secured. Benefits and risks from such investments should be distributed (shared) proportionally among countries. Therefore, political will for integration is needed before there can be effective technical cooperation. ***-KII response from Ethiopia***

KII responses from Egypt highlighted the need for investment to improve the productivity of those crops for which Egypt is a net importer, such as fodder, wheat, and oilseeds. Investments in agro-industry and marketing projects were also identified. Respondents also noted the need for investment in renewable energy, including hydropower and other energy alternatives such as solar energy. A respondent from a research center in Egypt mentioned that investment to increase food and agricultural productivity by treating and making use of marginal resources such as saline water and marginal soils is important for Egypt. One respondent described the need to balance investment in human resources with investment in infrastructure: "Comparing investment in infrastructure and investment in human resources, I give priority to the latter because effective utilization of infrastructure requires manpower that can understand, operate, and manage it."

I believe the potential investment areas for Egypt are improving irrigation systems, reducing agricultural waste, contract farming, and establishing biogas projects. There is a need to improve irrigation efficiency at both the canal and field levels. There is also a need to replace or relocate crops based on their water requirements (that is, crops with a high water requirement should be identified and replaced with crops with relatively lower requirements). This will allow us to save water and utilize it in newly reclaimed lands. More water for irrigation can also be obtained by treating and reusing wastewater and water drained from agricultural fields. Food losses at different stages of production are also significant; especially postharvest losses in food crops are substantial. We can reduce such losses by establishing more efficient agroprocessing industries, which we have in limited number currently. Reducing food loss is another mechanism for saving water and land resources. The development of biogas plants is also related to the productive use of waste, which will have an indirect effect on increasing agricultural productivity. ***-KII response from Egypt***

Moreover, KII respondents from Egypt reported investment in science and technology, rural development, open information-sharing systems, and civil society engagement as important ways to improve management of the three resources. These respondents also recommended investment in modern irrigation systems. One of them mentioned that instead of building new physical infrastructure to store water, for Egypt, it would be preferable to invest in improving existing infrastructure, such as irrigation programs, by introducing more efficient water conveyance systems. This respondent also suggested the need for continuous investment in research to assess ways of increasing the efficiency of water use in agriculture. Finally, respondents from Egypt suggested involving local communities in decision-making processes, which has been shown to be effective for more efficient resource allocation than processes whereby decisions are made entirely by some higher central body.

In addition to steps needed to improve cooperation among WEF sectors, e-survey respondents were also asked to suggest steps needed for better cooperation between Eastern Nile countries. There were a lot of interesting similarities among responses obtained across the three countries. Promoting existing regional organizations; creating joint scientific forums for sharing ideas and information; crafting joint policies, strategies, and development plans; and making coordinated investments based on the specific needs of the countries were mentioned by respondents from all three countries as important steps to improve cooperation among riparian countries. Respondents from Ethiopia and Egypt also indicated the need to strengthen existing technical and economic cooperation as well as to build trust and confidence among basin countries. Respondents from Ethiopia and Sudan suggested carrying out in-depth studies to assess the status of WEF resources. Respondents from Egypt and Sudan expressed similar views, noting also the need to rely on evidence and expert opinions when making decisions in the WEF space (Table 3.7).

Table 3.7: Steps needed to improve cooperation between countries in the Eastern Nile, by country of respondent

Ethiopia	Sudan	Egypt
Continue with the current cooperation and promote existing cooperative platforms (such as regional basin organizations)	Promote benefit-sharing regional organizations such as an Eastern Nile power pool	Establish good means of communication such as additional basin management organizations
Strengthen existing technical and economic cooperation		Promote economic integration and interdependence (encourage regional trade, establish free trade areas)
Create a forum to facilitate communication among scientists and experts in the water, energy, and food sectors in the three countries	Establish joint forums and committees	Build a network for scientists in the region
Expedite implementation of investment projects with regional significance	Set joint projects, policies, and strategies	Develop a joint vision and strategy based on facts and evidence, and jointly design large cross-border development projects
Carry out in-depth studies to show the extent of resource scarcity and poverty in the region	Review the status of water, energy, and food in the countries	
	Establish effective follow-up mechanisms to ensure integrated implementation of policies and action plans	Encourage transparency and flexibility among countries in the negotiation and coordination of national plans
Adopt win-win strategies in natural resource development and management	Coordinate to ensure equitable allocations based on actual needs in each country	Make countries consider where they have mutual interests in terms of water, energy, and food
	Allow specialists and experts to decide on management issues	Build the capacities of the countries' professionals and rely on technical advice from experts on mutually beneficial solutions
Build trust and confidence among riparian countries		Build trust and confidence among riparian countries

Source: Authors' e-survey (2016).

Finally, e-survey respondents were asked to report on potential joint investments that can be undertaken by countries in the Eastern Nile. Overall, respondents considered joint investments based on the comparative advantages of countries and enhanced regional trade to be the key elements for transboundary collaboration. Also, responses from all countries indicated that the riparian countries can make joint investments to improve resource use efficiency and sustainability. In addition, respondents from Ethiopia pointed to joint investment in trust building as essential, and respondents from Egypt mentioned the importance of research-based collaboration and investment in renewable energy as well as food security (Table 3.8).

Table 3.8: Potential joint investments across the Eastern Nile, by country of respondent

Ethiopia	Sudan	Egypt
Invest in benefit-sharing projects, such as storage dams for hydropower generation in Ethiopia and large-scale irrigation projects in Sudan: - Virtual water trade programs	Base investment in the three sectors on comparative advantages: - Hydropower in Ethiopia, agriculture in South Sudan and Sudan, industry and marketing in Egypt - Regional trade	Base joint investment in infrastructure on comparative advantages
Adapt efficient water utilization strategies: - Improve irrigation efficiency - Optimize the operational rules of dams in the basin	Focus on sustainability and enhancing the quality of resources	Reduce losses by enhancing resource use efficiency
Practice good watershed management, especially in upstream catchments	Invest in watershed management	Take coordinated action to maintain ecosystem sustainability
Invest in building trust so that stakeholders consider the basin as one unit, irrespective of political boundaries		Launch a major coordinated research effort to assess upstream and downstream costs and benefits of water resource developments
		Invest in renewable energy (solar, wind, and so on)
		Invest in improving food security (such as adapting high-yield crops)

Source: Authors' e-survey (2016).

The question on joint investments by Eastern Nile countries was also posed to KII respondents. Particularly, respondents were asked to elaborate on the joint investment options that they had mentioned in the e-survey. Respondents from Ethiopia emphasized construction of multipurpose dams (either micro or mega) as well as investment in other infrastructure, such as roads and telecommunications, as highly important for attracting further investment to the basin. Investment in environmental protection works, especially in relation to newly constructed water storage infrastructure, was also mentioned, as was the need to carefully study potentially adverse environmental consequences of new infrastructure development and to institute mitigation measures before development starts. Joint investments in watershed conservation in upstream catchments were also mentioned as essential for the sustainable operation of water infrastructure. In explaining this point, one respondent from Ethiopia stated, "If we do not do intensive catchment rehabilitation and watershed management in upstream catchments, any investment we do downstream will not be profitable as well as sustainable. If we take the Grand Ethiopian Renaissance Dam as an example, unless upstream watershed management is done to the extent needed, the dam will become obsolete in a few years."

A KII respondent from Ethiopia also mentioned joint investment in appropriate water resource management, including storage, conveyance, and use, as crucial, for example to reduce water losses to evaporation. Improved irrigation systems, for instance, can greatly reduce water losses in the basin. One respondent stated, "About 70% of the Nile water is used for irrigation and hence the irrigation system, which includes conveyance and on-field water use, should be greatly improved. If we see the conveyance system in the basin, it is mostly unlined canals, which lead to a lot of water loss through seepage. The canals are also open, leading to high evaporation losses. On fields, flood irrigation is usually practiced, which is not efficient at all. More efficient irrigation types, such as sprinkler and drip, should be adopted. In general, a considerable amount of water can be saved through coordinated polices and proper water resource management." KII respondents from Ethiopia also identified virtual water trade schemes based on comparative advantages as a joint area of investment.

> *First the issue of integration should be conceptually developed. By integration I am not referring to political integration; my emphasis is more on economic integration. For countries in the Eastern Nile region, separate economic advancement is not possible; they should develop jointly. Economic integration will provide them with bigger markets (because the population of the region is very huge, it has a great potential to create large markets). Especially a landlocked country like Ethiopia should be careful regarding its relations with neighbors. We should be able to integrate our economy in the region. Infrastructure developments that link these countries (railways, roads, and so on) and regional trade agreements that could allow free movement of goods are essential. Investments in alternative energy sources and power trade based on comparative advantages are highly beneficial for all countries. However, such joint development efforts should be appropriately managed to avoid the dominance of one country over the others. Economic integration could also bring about cultural integration, which is important in facilitating cross-border investments and collective development actions.* ***-KII response from Ethiopia***

Ethiopian KII respondents also discussed some challenges that hinder countries from making joint investments. Lack of goodwill and trust among countries is one such challenge, hindering trade-based solutions such as growing livestock or crops in relatively cooler Ethiopia for export to Egypt. Financial constraints were mentioned as another key limiting factor for collaborative efforts. Respondents noted that transboundary studies, mostly funded by international donor organizations, have been characterized by a lack of continuity and seldom considered to be of practical use.

> *For the Eastern Nile region, increasing agricultural productivity for raising food self-sufficiency levels is one important area of investment. It is important that*

conditions and plans for agricultural projects not be set by foreign investors. They should be determined in advance by the countries themselves, with clear plans and visions reflecting priority needs in the region. This is very crucial to get optimal results from investments in the region. Investments are also needed in awareness creation and negotiation to ensure a higher level of cooperation across sectors and countries in the basin. Awareness concerning natural resource scarcity is not something required only in ministries; individuals in each country should also be aware of the ongoing and future trends of natural resource scarcity. In this way, efficient utilization of resources and cooperation among different resource users can be achieved. ***-KII response from Egypt***

KII respondents from Egypt recommended joint investments in natural resource management to reduce degradation of resources such as land and shocks such as droughts. They also considered joint investments that balance development and environmental concerns to be vital. One respondent from Egypt described regional needs in this way:

Investment in research seeking win-win solutions for water management in the Nile basin is important. There have been several research activities since the 1980s that focus especially on dam construction in the basin. There have also been debates, particularly in Ethiopia, over which kind of investment should be pursued for better water resource management. Debates range from whether to build mega dams or many micro dams for storing water or to focus instead on reforestation, which could also serve the purpose of water conservation. Such debates over investment choices should be made at the regional level, and final investment decisions should be undertaken jointly, facilitated by a regional organization such as the NBI. Joint decisions are needed not only in terms of where and what kind of dams to build but also regarding their management.

3.4. Conclusions

With rapid economic development and concomitant growth in natural resource scarcity, enhanced collaboration among the countries sharing Nile waters, particularly those in the Eastern Nile Basin—Egypt, Ethiopia, South Sudan, and Sudan—is urgently needed. Due to a history of hydropolitical tensions, direct cooperation on water resources is challenging. However, a recent concept, that of the WEF nexus, might find wider acceptance because it is not focused solely on sharing one particular, contested resource, but allows for broader discussions, including identifying synergies that can be strengthened across sectors and countries, and trade-offs that can be avoided. This paper used an e-survey and KIIs to elicit insights on the potential of this concept, both nationally in Egypt, Ethiopia, and Sudan, and regionally across these three countries.

Although the responses are not representative of all stakeholders in the WEF sectors in the Eastern Nile Basin, and although the respondents are similarly not representative of all stakeholders in government and research organizations, we believe the responses represent useful insights into the potential for collaboration across the WEF sectors, both nationally and across the Eastern Nile Basin. Assessing the views of different national stakeholders helped identify key constraints and opportunities for collaboration nationally, garner insights on the potential for cross-sectoral collaboration both nationally and regionally, and ensure that regional suggestions are consistent with national needs and priorities.

Even if the objective of the paper and much Nile diplomacy is to move beyond water as the sole topic of discussion, national cross-sectoral interactions clearly indicate that water remains the best-connected sector in the nexus. Both energy and agricultural specialists engage frequently with the water sector, and given the breadth of water specialists' expertise, water-sector experts also frequently engage with other specialists in the sector. Of interest, the energy and agriculture sectors currently do not dialogue much at the national levels, and the potential for cooperation between them is likely similarly limited at the regional scale.

There is a strong consensus that cross-sector collaboration is essential at the national level, but overall, levels of coordination remain unsatisfactory despite the identified benefits of working jointly across sectors, such as these: (1) sectors are naturally linked in important activities such as groundwater pumping, (2) collaboration can conserve natural resources, and (3) harmonizing strategies can reduce the need to retrofit investments later on. These same benefits also apply at the regional level. Respondents proposed a series of measures that can enhance cross-sectoral collaboration at the national level. These steps would also likely support regional collaboration. Key steps identified include raising awareness of the benefits of cooperation, involving relevant cross-sectoral stakeholders in planning processes, and creating institutional frameworks to support cross-sectoral collaboration. Suggested investments to ensure national WEF security could either support or hinder regional cooperation, depending on the cross-sectoral and transboundary connections being made during such investment planning. Key investments proposed include multipurpose dams and food security projects (Ethiopia and Sudan); soil and water conservation and rainwater harvesting (Ethiopia and Sudan); and more efficient irrigation infrastructure, postharvest loss reduction, and renewable energy projects (Egypt). All three countries propose to increase investment in education, research, and capacity building, including building the capacity for better management of infrastructure.

Respondents saw an equally strong need for cross-sectoral collaboration at the transboundary level. Such collaboration is currently being held up due to (1) politics; (2) lack of common databases, joint analysis tools, and platforms; (3) lack of measures to build trust; (4) lack of sustained national financing for regional collaboration; and (5) resulting weak regional institutions. Moreover, most specialist agencies with mandates in water, energy, or food have only national mandates or operate only at the national level. To fruitfully engage national expertise in transboundary nexus collaboration, new networks that integrate these sector specialists will need to be developed. Specific steps that respondents proposed for enhanced transboundary collaboration on WEF issues were remarkably similar across the three countries and include the following:

1. Strengthen existing technical and economic cooperation (for example, the Eastern Africa Power Pool (EAPP))

2. Review the status of WEF in the region and carry out in-depth studies to show the extent of resource scarcity and poverty in the region
3. Develop joint projects, policies, and strategies that have common benefits, and implement effective follow-up mechanisms to ensure the implementation of integrated policies and action plans
4. Establish continuous communication and frequent meetings across countries, for example, through a forum to facilitate communication among scientists and experts in the WEF sectors in the three countries, and ensure that technical experts are involved in decision making
5. Share information and data across countries
6. Allow specialists and experts to decide on management issues
7. Continue to develop trust-building mechanisms

Once these measures are established, investments can be taken forward that mirror many of the same investments already identified to meet national WEF security goals, such as joint investments in (1) water storage projects with due consideration of and adjustments for upstream and downstream impacts; (2) catchment rehabilitation, watershed management, and environmental sustainability in general to ensure the sustainability of infrastructure investments; (3) food security projects, including regional trade in agricultural commodities based on the comparative advantage principle, as well as investment in higher-yielding varieties and irrigation efficiency measures; and (4) renewable energy security projects beyond hydropower, such as solar and wind, supported by regional energy trading.

4. Hydropower and Irrigation Developments in the Eastern Nile Basin: Sectoral and Transboundary Tradeoffs, and Potential Synergies

4.1. Introduction

In the Eastern Nile region, not only the livelihoods of millions of people directly depend on the water flows from the river, but there are also strong links between WEF, and hence welfare and economic development. In fact, the basin was identified as one of the five critical regions in the world for examining the interlinkages among water, food, poverty and urbanization (Vairs, 2000). The main factors that led to considering the basin as critical were escalating population growth, persistent water and food scarcity, large socio-economic inequality among riparian countries, volatile and changing climate, and a lack of strong institutions to govern cooperation and equitable water allocation (Vairs, 2000; Mohamoda, 2003). Among others, agriculture (including livestock and fish) is the main source of livelihood for basin countries and at the same time the largest water-consuming sector (Awulachew et al., 2012).

There is a need to improve agricultural productivity in the basin, notably through the adoption of irrigation (Appelgren et al., 2000; Conniff et al., 2012). The rain-fed agriculture, which is dominant particularly in upstream countries of the basin, is characterized by low productivity and high levels of risk due to variable climate and recurring droughts (NBI, 2012a). In Ethiopia for instance, the rain-fed agricultural is being challenged by continued degradation of the natural resource base, critical climate and hydrological variability as well as shocks, and climate change. Therefore, developing water storage infrastructures that can provide a year-round water supply for multi-purpose uses including irrigation are vital (Awulachew et al., 2007). Large areas of formal irrigation are so far developed only in Egypt and Sudan (Johnston, 2012). The agricultural developments in these downstream countries are highly productive and can be taken as an example for agricultural development in other Nile Basin countries. But, there are concerns that irrigation development in upstream countries could jeopardize existing production in downstream countries. Thus, the question of to what extent upstream agricultural development will impact on water availability in the lower basin is critical (Demissie et al. 2012). Furthermore, irrigation is energy-intensive as pumping water requires energy which adds to the WEF nexus interlinks in the basin. Current irrigation water requirement by all riparian countries of the basin is estimated at 78 BCM, together with M&I water demand and estimated up to 20 BCM water evaporation from reservoirs in Egypt and Sudan, the existing water use in the basin almost reached to the full capacity of the Nile River (ENTRO, 2014a).

From an interregional perspective, hydropower production is the most critical WEF issue. Hydropower is an important source of energy for most Nile countries. Still, only 26% of an estimated hydropower potential of over 20GW is currently developed in the Nile basin (NBI, 2012a). The largest share of this potential accrues to upstream Ethiopia, for which hydropower is also important insofar as the country has no exploitable fossil reserves discovered as yet. With the exception of Egypt, electricity supply in the Nile countries is low and the majority of the population remains dependent on biomass energy resources. The negative environmental impact of high dependence on biomass energy and the crucial role that energy (particularly hydropower) can play in economic growth and development necessitates appropriate exploitation of the basin's potential. Nevertheless, exploiting the vast hydropower potential of the region requires cooperation among riparian states. There is a need to balance interests of competing sectors and basin countries with appropriate consideration of environmental and social issues, a task which will require a nexus-based thinking.

In regions like the Eastern Nile which are characterized by high hydrological variability, water storage infrastructures are vital to ensure adequate and sustainable water supply for various uses. Dams and the resulting reservoirs buffer communities from the adverse impacts of erratic hydrological conditions such as droughts and floods. Water storage infrastructures (either micro or mega dams) could serve several purposes including clean water supply, hydropower generation, irrigation, flood and sediment control, tourism, aquaculture and navigation thereby supporting economic development (World Dam Commission (WDC), 2000; Bhatia et al., 2008; Lindström et al., 2012). Often, the major economic benefits of large water storage developments emanate from expansion of irrigated agriculture and hydropower production. Several studies around the world indicated that appropriately designed, implemented and managed irrigation developments can boost agricultural productivity by providing adequate and more regular water, bringing more land into cultivation and allowing multiple cropping. These will foster food security as well as increase income and employment within and outside the agricultural sector by stabilizing output in times of environmental shocks like drought (Schoengold and Zilberman, 2007).

Likewise, economically and environmentally sound and sustainable energy development is vital for the socio-economic advancement of countries (Stern, 2004). In regions where there is adequate rainfall and suitable geographical features, hydropower is one of the most important and preferable alternative source of renewable energy. The electricity generated from hydropower dams will provide households and various businesses with affordable and clean energy which will contribute to economic development and improved standard of living. In particular, adequate and sustainable supply of energy will encourage private sector investment in industrial sectors which often require high and uninterrupted energy input. Hydropower development creates employment both directly in its construction and operation, as well as indirectly through the productive use of energy by promoting industrialization and private sector development. The growth of manufacturing industries also facilitates trade in diversified commodities. Besides its economic importance, hydropower developments could also have positive environmental outcomes by reducing use of biomass based energy and the associated deforestation (Bhatia et al., 2008; Lindström et al., 2012; Koschel, 2012).

Insight of these, several dams are already developed, are under constructions and planned to be constructed in the future both in upstream and downstream countries (Conniff et al., 2012). However, if the impact of these unilateral projects on other riparian countries is not properly studied, they could become a source of conflict in the future. Making secure investments hence require creating a common understanding and trust among basin countries. Since the WEF nexus in Eastern Nile has a strong regional (upstream–downstream linkages) and sectoral dimensions, studying interactions (tradeoffs and synergies) across these domains is vital. Thus, the general objective of this chapter is to analyze whether sectorally and regionally coordinated WEF developments in the Eastern Nile Basin increases benefit from irrigation and hydropower production (the two most important water uses in the basin) based on an integrated hydro-economic modeling approach.

This chapter is expected to add to the literature by examining the sectoral and transboundary tradeoffs and potential synergies in the basin in cooperative and non-cooperative scenarios under various levels of water resource development. The cooperative scenarios are represented by system optimization which implicitly assumes the existence of full cooperation between sectors and riparian countries. Under this scenario, the basin is treated as one system and, each sector and country is given equal priority (weight). The non-cooperative scenario or the tradeoff analysis is formulated to analyze the case of unilateral or single sector actions in the basin which allows for assessing the WEF nexus in the basin. It constitutes sectoral and transboundary tradeoff analysis characterized by prioritization of one sector or country over the other respectively. Both the cooperative and non-cooperative (nexus) scenarios are examined under various levels of water resource developments which are given in terms of proposed hydropower and irrigation expansions in the basin.

For this purpose, an existing hydro-economic model (subjected to rigorous modification and upgrading work) called ENMOS is used. ENMOS was mainly designed to quantify the benefit of existing and proposed developments in the Eastern Nile basin. The model allows finding optimum combinations of development options that best meet the projected demand for water supply, agriculture, and hydropower production. ENMOS is an integrated optimization model where the objective is to maximize the net economic benefits from water use mainly in agriculture and hydropower subjected to a range of constraints in a river basin context (ENTRO, 2014b). ENMOS incorporates all the basic components of a hydro-economic model including hydrologic systems, demand sites, and water management infrastructures and their operation rules. In addition to studying sectoral and cross-country tradeoffs and synergies, the model allows examining potential implications and consequences of several proposed developments (such as reservoirs, hydropower plants, irrigation expansion) including the GERD in various combinations.

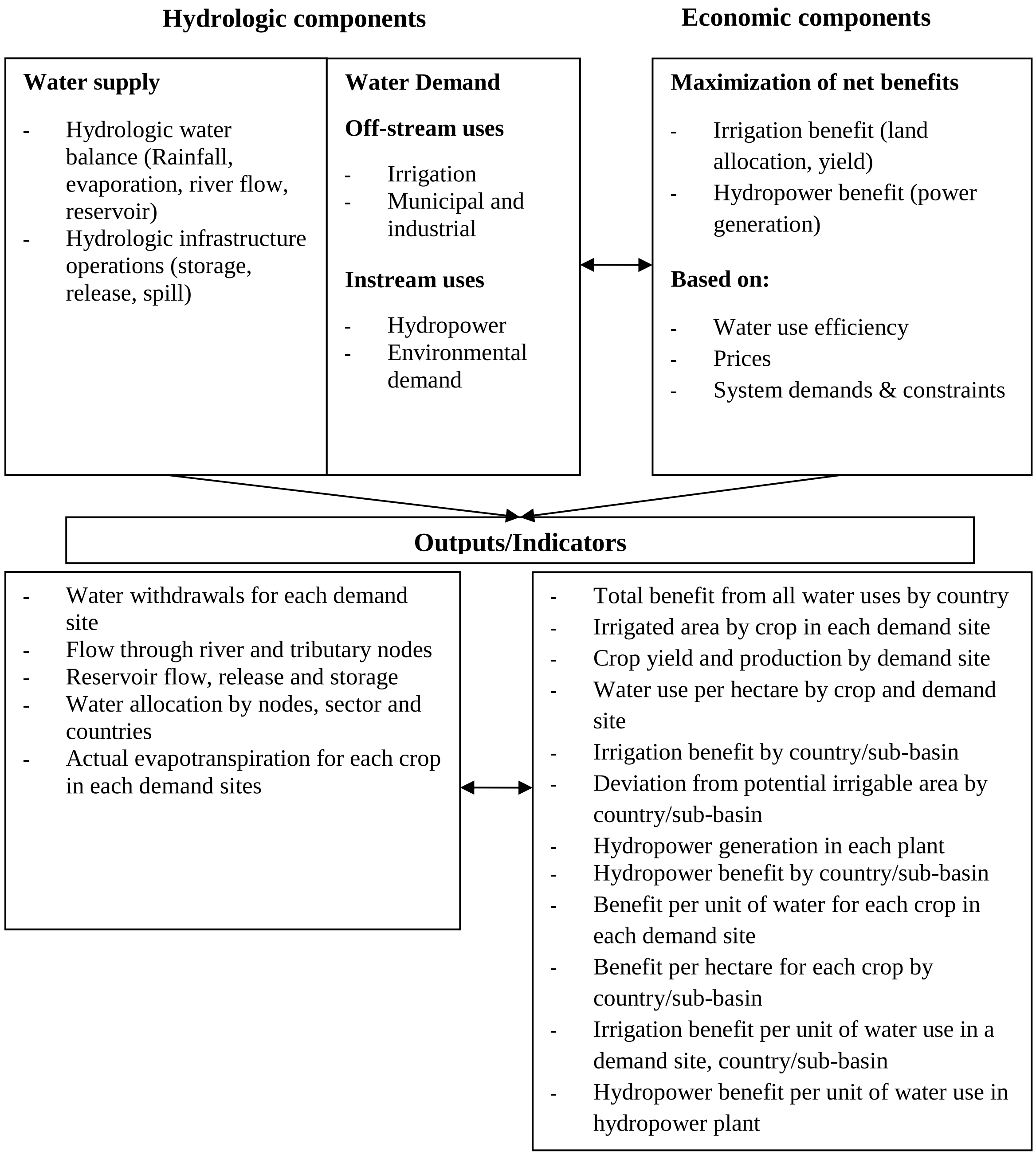
4.2. Hydro-economic Models and WEF Nexus Analysis

Efficient management of water resource in a river basin requires a comprehensive approach because there are several competing and conflicting objectives in such context. Water resource decision-making process usually involves tradeoffs in choosing between different objectives. For such decisions to be rational suitable analysis tools are needed and river basin models are one such tool (Lee and Dinar, 1995). Hydro-economic model is a type of river basin model which represent hydrologic, economic and environmental aspects of water resources systems at different regional scales (McKinney et al., 1999). As the name implies it contains both hydrologic and economic components where in particular economic concepts are applied in water resource management models. Water balance at inflow nodes, reservoirs, irrigation sites and end nodes are included under the hydrologic components while the economic components comprise calculation of water benefits from different uses and users. In addition, institutional rules and economic incentives which could influence hydrologic and economic components are also incorporated (Ringler, 2001). The design and formulation of a hydro-economic model can take different approaches depending on methods used, level of integration and representation of time (Harou et al., 2009). Simulation and optimization are two principal methods which are used in hydro-economic models. Simulation models are used to answer the question of "what if" by simulating varying hydrological conditions under a range of alternative scenarios given a set of rules that determine water allocations and management of infrastructures. On the other hand, optimization models are often applied to answer the question of "what is best" by finding the optimal or efficient allocation of resources given a predefined objective (could be maximization or minimization) and a set of associated constraints (Harou et al., 2009). Usually, optimization models also contain simulation component to represent the hydrologic process and are called integrated simulation and optimization models (McKinney et al., 1999).

Depending on the level of integration, hydro-economic models can be grouped as compartment (modular) and holistic. Under the modular approach, economic and hydrologic sub-models are developed separately and they are connected by transferring results from one sub-model to the other. The advantage of such models is that they allow representing issues in each sub-model in a detailed manner. However, there is a loose connection between the economic and hydrologic components, making analysis difficult. Under the holistic approach, both components are integrated in one modeling framework and they are tightly interlinked. Such models are advantageous as they are more efficient in representing causal linkages and interconnections. But, such models require sub-components to be represented in a highly simplified manner to avoid model solving difficulties (McKinney et al., 1999 and Harou et al., 2009). Under integrated optimization hydro-economic models, the main objective is to maximize benefit from various water uses while balancing water supply and demand. The hydrologic system (i.e. water balance in river flow nodes) determines the water supply whereas water uses in different sectors (i.e. irrigation, hydropower, M&I and environmental) determines water demand (Ringler, 2001). Figure 4.1 illustrates the general structure of a hydro-economic model.

In general, an integrated hydro-economic model developed for a river basin should ideally possess the following features. First, they should be able to provide adequate and realistic description of the whole river basin system which includes physical processes (mainly hydrologic process which involves appropriate description of spatial and temporal distribution of water supply and demand in source nodes, connection nodes and water demand sites), infrastructures and associated water uses, and operating rules and institutions that manage the hydrologic system. Second, they should assimilate hydrologic and economic interactions in an endogenous system thereby allowing calculation of the economic return from various water uses. Third, institutional setups, economic incentives and policy constraints that govern water allocation should be incorporated (McKinney et al., 1999; Ringler, 2001; Cai et al., 2001).

Figure 4.1: Basic Structure of the Hydro-economic Model



Source: Adapted from Cai et al. (2006)

Several studies have applied hydro-economic models to analyze the issue of water management in river basin context. Besides their use in water resource management issues, hydro-economic models can also be used as one tool for WEF nexus analysis as they; (i) model the trade-off between competing water using sectors, (ii) allows comparing basin-wide optimization versus business as usual and (iii) encompasses upstream-downstream linkages.

4.3. Review of Nile River Basin Models

A comprehensive and detailed review of hydro-economic models and their applications can be found in a number of previous studies (see e.g., McKinney et al., 1999, Jakeman and Letcher, 2003; Brouwer and Hofkes, 2008; Ward, 2009; Harou et al., 2009; Booker et al., 2012 and Bekchanov et al., 2017). In this review, only a brief discussion of hydro-economic models which are applied in the context of the Nile basin will be presented.

Previous river basin modeling effort using hydro-economic analyses is considerable in the Nile River basin. So far, a significant amount of hydro-economic models has been developed with a focus on evaluating the downstream impact of upstream water resource developments either for the entire Nile or sub-set of the basin. An early work by Guariso and Whittington (1987), examined the implication water resource developments in the Blue Nile of Ethiopia (i.e. the construction of four hydropower dams proposed by the U.S. Bureau of Reclamation (USBR) namely Karadobi, Mabil, Mandaya and the border dam) to Egypt and Sudan using a linear programming model. The main objective of the mode is to maximize hydropower production in Ethiopia and downstream agricultural water supply for irrigation demand in Egypt and Sudan. The model has a one-year horizon and used average monthly hydrological data where the main decision variables are the monthly releases and storage levels of reservoirs in the three riparian countries. The model approximates the operation of the four planned Ethiopian reservoirs by a single reservoir in which their combined capacities and hydropower production is solely determined by release of water according to the monthly pattern of agricultural water needs. Results from the study indicated that Ethiopia's increased hydropower generation would have a minor adverse effect on downstream riparian nations, rather it is beneficiary as it decreases water levels in the highly evaporative downstream reservoirs and hence increases total water availability for downstream riparian nations.

Subsequently, the Nile Decision Support System (DSS) which is a more advanced hydrological Nile River optimization model is developed by the Georgia Water Resources Institute (Georgakakos, 2007). One main component of the model, the River Simulation and Management System simulates the state of the Nile pertaining to various hydrologic, management and development scenarios thereby assessing the benefits and tradeoffs related to these scenarios. In addition to this component, the Nile DSS also includes agricultural planning model, hydrologic model and remote sensing. The Nile DSS is a proprietary software prototype which was developed to provide the 10 Nile riparian countries with a common tool of analysis thereby helping decision makers to design evidence-based and inclusive policies (FAO, 2004). An empirical application of the model was done by Blackmore and Whittington (2008) in order to assess opportunities for cooperative water resource developments in the Eastern Nile. They have used a modified version of the model to characterize the current and evolving conditions in the Eastern Nile, and analyze the impact of infrastructure development (irrigation schemes and hydropower) and climate change on hydropower generation, irrigation deficits, evaporation losses, storage levels, and flood control in Ethiopia, Sudan, and Egypt. Results from the study indicated that cooperative development of new infrastructures in the basin is beneficial for all riparian nations. The study also indicated that successful cooperative investments in the basin need to involve reducing the existing large water loss from the Nile system mainly due to evaporation from reservoirs and inefficient irrigation schemes which are mainly prevalent in downstream of the basin.

Another hydro-economic model developed for the basin is the Nile Economic Optimization Model (NEOM) presented by Whittington et al. (2005). The model was used to assess the economic implications of various infrastructural developments (mainly the four proposed dams in Ethiopia by USBR) within the basin and aims to maximize for basin-wide economic benefits from irrigation and hydropower production under status quo and various new water resource developments (where the latter assumes cooperation between basin countries). NEOM is a deterministic model with a one-year horizon and considers three hydrologic conditions (average, wet and dry year). Results from the study indicated that new infrastructure developments in the basin which entails cooperation among basin countries are highly beneficial for the basin compared to the status quo. Later, Wu and Whittington (2006) also integrated this model with the game theoretical approach and used it to study incentive compatibility and conflict resolution in the Nile basin. It assisted to identify incentive-compatible cooperative solutions for the Nile riparian countries based on estimated economic benefits under various assumed cooperation schemes. Recently, Wu et al. (2016) also used the model to assess the effect of political uncertainty on water resource developments while Jeuland et al. (2017) used it to analyze the impacts of the GERD in the Eastern Nile basin.

There are also recent modeling efforts that have focused only on the subset of the Nile basin or one country. The Sudan Hydro-economic Optimization Model (SHOM) was developed by Satti et al. (2014) is one example. The model embodies existing infrastructures and practices in the Sudanese part of the Blue Nile and was applied to assess the optimal allocation of surface water which maximizes the benefits obtained from hydropower and irrigation as well as examine tradeoffs between the two sectors within Sudan. Like the models discussed above, SHOM is deterministic and runs for one year with monthly time steps. The model contains only three reservoirs in Sudan; two located in the Blue Nile (Roseries and Sennar) and one on the Main Nile course (Merowe). Findings from the study also supported the benefit of collaborative water resource development. Also, Block and Strzepek (2010) introduced the Investment Model for Planning Ethiopian Nile Development (IMPEND) which focus on Ethiopia’s portion of the Blue Nile basin only. The model was used to calculate the economic benefit of developments (also the four USBR proposed dams) at the upstream portions of the Blue Nile. IMPED is also a deterministic model, but it contains strong new features including its ability to model the transient filling stages of reservoirs and staged introduction of the proposed dams into the system. In addition, the model is multi-year with 100 years simulation period allowing analysis to be done with variable historical hydrological conditions as well with climate change in the future. Results from the study emphasized that the filling stage and the stepwise introduction of proposed dams in the system are very important features that need to be considered in water resource planning models were ignoring such issues was indicated to overestimate economic benefits from proposed infrastructures.

Moreover, Goor et al. (2010) presented a hydro-economic model for the Eastern Nile in order to explore both the hydrologic and economic impacts of a range of proposed infrastructure alternatives. Particularly, the implications of proposed reservoirs in Ethiopia to the HAD are assessed based on economic benefits and costs associated with its operation. The model employed a Stochastic Dual Optimization Program which is argued to be important in understanding the effect of the hydrologic uncertainty, risk, and assessing relevant risk indicators, unlike most of the deterministic hydro-economic models. Results from the study revealed that the development of new large water storage infrastructures upstream of the Eastern Nile basin would beneficial for all riparian countries if the operations of the reservoirs are coordinated. The benefits include regulated flows (which reduces flood incidents in peak flow years and stabilized flows in low flow years), increased hydropower production in Ethiopia, increased irrigation benefits in Sudan, and water saving through reduced evaporation loss from HAD. Arjoon et al. (2014) used the same model to analyze the hydrologic and economic impact of GERD on downstream riparians and indicated that if managed cooperatively; the dam will have a positive impact for all basin countries.

Furthermore, Nigatu and Dinar (2011) had developed the Nile Environmental and Economic Optimization Model (NEEOM), a deterministic model which runs for a single year with monthly time step. It differs from previous models by including issues of resource degradation and the possibility of water trade in the optimization process. The results from the study confirm findings of previous studies that basin-wide cooperation (stated as "social planners welfare gain") is the most beneficial option for the basin. The study indicated that though basin-wide cooperation ensures efficient allocation of resource (and the highest economic gain) it might not guarantee equitable distribution. Accordingly, water trade between riparian countries is suggested as a solution to address issues of both efficiency and equity. Particularly, the study showed that water trade will ensure efficiency by allowing water transfer from a low-value to high-value uses and users, whereas it ensures equity by creating compensation mechanisms (through transfer payment) for those uses and users who forgo their lower-value water use for higher-value uses.

4.4. Limitations of Previous Nile River Basin Models and Research Needs

As it can be seen from the above review, so far there have been considerable river basin modeling efforts in the Nile River basin. Though we acknowledge the potent contribution of these studies to the issue of water resource management in the basin and that each of them has their own strength, they are not without limitations. First, all the previous models assumed fixed value per unit of water use (0.05USD/m^3) which was adopted from Whittington et al. (2005). This implicitly assumes a horizontal demand curve for irrigation water withdrawals where the value of water is constant across seasons, water uses, places (countries) and various infrastructure developments.[34] However, demand for water and its value differ by location, type and quantity of its use (irrigation, hydropower, M&I), and hydrological condition (dry, normal and wet season) (McKinney et al., 1999). This fixed water value assumption can be relaxed by including a crop production function where water is a variable input. In our model, the FAO crop production function (Doorenbos and Kassam, 1979) which depicts crop yield response to water relationships, developed based on field experiments conducted across an extensive variety of

[34] Often, crop yield is also constant (not responsive to water stress) in such models where irrigated area is the only decision variable (except in Goor et al., 2010 where yield is indicated to be modeled as a function of water supply)

crops is incorporated. Details of the crop-water production function are given in section 4.5.2.2. Second, there is no clear description of how the seasonal and spatial cropping patterns and intensities are determined in the modeling framework of previous studies. Detailed crop calendar and location matrix which are developed based on data obtained from various sources are included in our model (see section 4.6 for details on data sources). The crop calendar considers two cultivation seasons for Ethiopia (wet and dry) and three for Egypt (winter, summer, and *Nili* (river)). Third, previous hydro-economic models developed for the basin has limited spatial coverage which focuses on proposed infrastructure developments in the BN sub-basin. Especially, potential water storage developments in BASW sub-basin were not considered. Currently, there are only few water resource developments in the sub-basin. However, given that the basin is the second largest contributor of water for the Eastern Nile system coupled with the existence of a large potential for future development (both irrigation and hydropower), it is important to examine the implications of such water resource developments for WEF nexus in the basin. The hydro-economic model used for this study considers several proposed infrastructures in BASW sub-basin. In addition, unlike previous studies which mainly focused on planned hydropower developments in Ethiopia, our model includes proposed hydropower plants in Sudan as well. Lastly, given the objective of our study (i.e. WEF nexus analysis), we assess the intersectoral and transboundary tradeoffs and interdependencies in the basin by conducting sectoral and country prioritization scenarios under various levels of future infrastructure developments. Such analysis will add to existing literature on water management issue in the basin.

Insight of the fact that WEF nexus in a river basin context involve several issues ranging from appropriate identification and quantification of benefits and cost, and tradeoffs and synergies associated with resource allocation to various sectors and riparian countries to choosing between goals of "efficiency, equity, and sustainable resource use" a holistic and integrated optimization hydro-economic model is developed for this study building on an existing model named ENMOS which was first developed by ENTRO in 2014. ENMOS includes hydrologic, agronomic and economic components, and maximize economic benefit from various productive uses and users of water through optimal allocation of water subject to a set of constraints including natural or physical (such as mass balance, irrigable area), technical (such as crop water requirement, minimum and maximum cropping, release from reservoir, minimum reservoir level) and environmental (such as water flows to meet wetland requirement and to Mediterranean sea). Given that ENMOS is constructed at a river basin scale, it is an aggregate model where water supply and demand are represented by flows from major rivers (which has several tributaries) and large water withdrawing units (i.e. irrigation and M&I demand sites which lumped several households or communities) respectively, and economic benefits are provided by the water using units or sub-basins or at country level. The model incorporates all the Eastern Nile countries of Ethiopia, Sudan, South Sudan and Egypt. However, detail representation of the model is only for Ethiopia, Sudan, and Egypt. Originally, the model contains a total of 32 reservoirs (12 existing and 20 proposed including the GERD) and associated irrigation demand sites (ENTRO, 2014b). Several modifications and updating work are done on the model before applying it to WEF nexus analysis. The following are the major ones:

- Made multi-year with monthly time interval based on 102 years simulated flow data (1900-2002).

- Modifications are done on the schematics of the model based on the MSIOA (2014) study of ENTRO which makes is it more detailed.
- Input data on key reservoir characteristics are thoroughly checked and corrected (this includes estimation of elevation-area-volume equations for each reservoir in the model).
- Irrigation and crop data (crop type, yield, pattern, water requirement etc.) were revised and updated.
- The FAO crop yield response function is included to capture yield responses to water stress.
- Data on crop prices and crop cost of production has been updated.

Therefore, compared to previous hydro-economic models developed for the basin, the current version (updated and modified) of ENMOS has: (i) relatively comprehensive spatial coverage, (ii) detailed representations of the river basin network and water resource developments in the basin, (iii) well described reservoir characteristics and morphological relations, (iv) fairly exhaustive and more realistic presentation of the irrigation (agronomic) module[35], and v) allows to perform multiyear analysis. Details of model structure and formulation including the river basin schematic, objective functions, and constraints as well as the sources of data used for model parameterization and the scenario setups will be presented in the following sections.

4.5. Integrated Hydro-economic Model for the Eastern Nile Basin

4.5.1. The River Basin Network

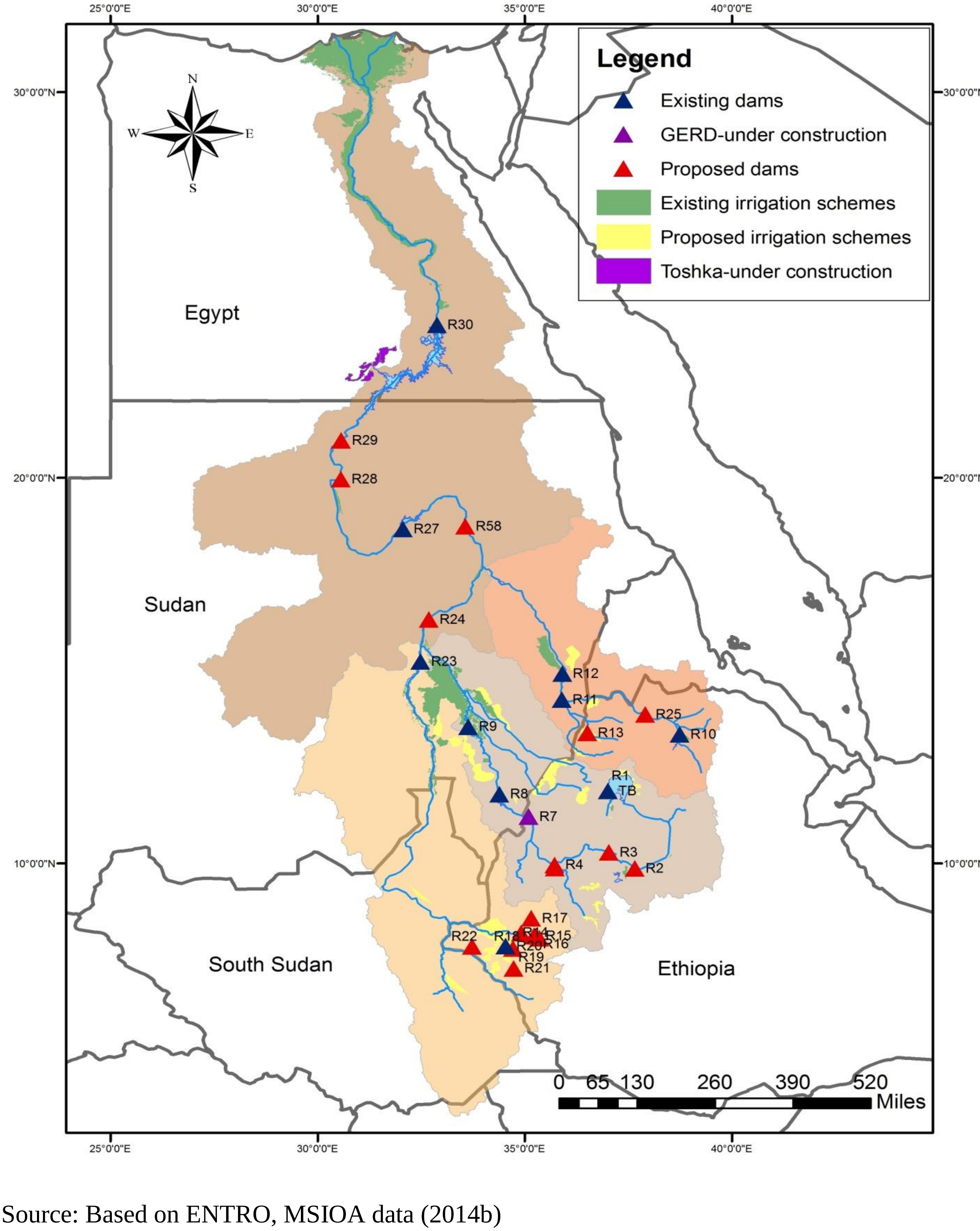
Developing a hydro-economic model at a basin scale essentially starts from representing the river basin system as the node-link network. A node-link network is "an abstracted representation of the spatial relationships between the physical entities in the river basin where nodes represent river reaches, reservoirs, and demand sites, and links represent the linkage between these entities" (Ringler, 2001:19, Rosegrant et al., 2000). The main nodes included in ENMOS are source (inflow) nodes, connection nodes, reservoir nodes, hydropower plant nodes, irrigation demand nodes and an end node. These nodes are spatially linked to the river basin network where spatial location of main rivers, reservoirs/lakes, diversions from and return flow to the rivers and important environmental flows needs be identified. Water supply in the model emanates from source (inflow) nodes which then go either directly into a reservoir or through connection nodes. Water withdrawal by irrigation sites could be either from reservoir/lakes or direct intakes from connection nodes. Water flow balances are determined for each of these nodes (i.e., source, reservoirs, irrigation, and hydropower nodes) at each time period, and the spatial connection in the river basin network will allow calculating flow conveyance from one node to the other. The spatial location of the hydrologic component is defined in a way to adequately reflect the spatial variability of water availability and demands while keeping the continuity and boundaries of the hydrologic system.

[35] Though groundwater use, drainage system and reuse of recycled water, and salinity issues (which are especially important in Egypt) are not considered

Both single and multi-purpose reservoirs are included in the model where some supply water either for hydropower production or irrigation while others serve both uses. The size of existing and proposed irrigation areas are used to delineate irrigation demand sites. At each of the irrigation demand site, water is allocated to various crops, based on their water requirements and economic value where both optimal crop area and yield are determined endogenously within the model. Both off-stream and instream water uses are included in the model where off-stream uses include water diversion for irrigated agriculture, and M&I water uses while instream uses include water required for hydropower generation, minimum flow for maintaining wetlands, and flow that should go into the Mediterranean Sea to regulate salinity in the Nile Delta due to saltwater intrusion. Given that M&I water use withdraws a negligible amount of water in the basin compared to other uses and since such water uses are usually prioritized over other uses (and hence less likely to compete in reality), in the model, M&I water use is treated as a fixed constraint divided equally across 12 months. Spills to two important wetland areas in the basin; the Twalor spill to Sudd swamp and the Mashar spill to Mashar marshes are included in the model.

Figure 4.2 illustrates the existing and proposed dams and irrigation schemes that are included in the hydro-economic model (ENMOS). Detailed model schematics of the river basin network are presented in Appendix B classified by the main sub-basins of the Eastern Nile. The model contains a total of 211 nodes: 36 inflow nodes, 29 reservoir nodes, including lake Tana (where 8 of them are multipurpose in which they serve both hydropower and irrigation water demand, 17 are only for hydropower while the remaining 4 are only for irrigation), 1 run-of-river hydropower plant, 49 irrigation demand sites, 86 connection nodes (gauging stations, where 36 are main stations), 6 barrages, 2 spill nodes to wetlands, one M&I demand node and an end node (Mediterranean Sea). Among the reservoir nodes included in the model, 10 of them exist and 19 are proposed for future construction. Also, of the irrigation demand sites included in the model, 28 are existing, 1 is under construction, and 20 are proposed to be developed. Out of 25 hydropower plants considered in the model, 9 of them exist, 1 is under construction and 15 are planned to be constructed. Some existing and proposed reservoirs and hydropower stations are excluded from the model either due to having a small size or lack of enough information to include them.

Figure 4.2: Existing and proposed dams and irrigation sites included in ENMOS[36]



Source: Based on ENTRO, MSIOA data (2014b)

[36] See Appendix B for detail model schematics

4.5.2. Components of the Hydro-economic Model (ENMOS)

In this section, the hydrologic, agronomic, and economic components of the model are presented briefly. Detailed mathematical formulation of the model is provided in Appendix C. The model has been coded in the General Algebraic Modeling System (GAMS) and the CONOPT solver was used to solve the model.

4.5.2.1. The Hydrologic Component

The hydrologic component of the model mainly contains water supply relations which are determined by the hydrological flow transport and water balance at different nodes. The main hydrologic associations and processes include: conveyance directly from rivers to irrigation sites or from rivers to reservoirs and then to irrigation areas; return flows from irrigated areas; evaporation from reservoirs and evapotranspiration from crop fields; releases for hydropower generation, and limits on water flows, storage and diversions. The model doesn't include the rainfall-runoff process assuming that water supply starts from rivers (inflow and incremental flow nodes) where effective rainfall is determined exogenously, and deducted from maximum evapotranspiration before the latter is included in the model. Observed flow data was found from some discharge and gauging stations which are found in the basin. However, the records at different stations are for different years and accessing consistent and recent data from all countries for all inflow and incremental nodes included in the model were not possible. As a result, the hydrological process in the model is represented by 102 (1900-2002) years simulated flow data with monthly time step.[37] Using time series flow data is important to capture variable and stochastic nature of water availability in the basin. The 102 years series includes both droughts and flood periods which allows examining how the system will behave in extreme hydrological conditions. Minimum annual flow to the Mediterranean Sea is fixed to be 10 BCM based on FAO (2011). Water balance at different nodes is given by the following general equations:

Water balance at source node;

$$Q_{n,t} = LR_{n,t} + RF_{n,t} \tag{5.1}$$

Water balance at reservoir node;

$$S_{n,t} = S_{n,t-1} + Q_{ni,t} - R_{n,t} - L_{n,t} \tag{5.2}$$

Water balance at irrigation node;

$$Q_{n,t} = Q_{ni,t} + LR_{n,t} + RF_{n,t} - QD_{n,t} \tag{5.3}$$

Where $Q_{n,t}$ is flow at node n in time t, $Q_{ni,t}$ is flow from i upstream nodes at time t, $LR_{n,t}$ is local runoff at time t (incremental flow), $RF_{n,t}$ is return flow to n at time t, $S_{n,t}$ is storage at reservoir n at time t, $S_{n,t-1}$ is storage at reservoir n in previous period, $R_{n,t}$ is release from reservoir n at time t, $L_{n,t}$ is loss (such as evaporation) from reservoir n at time t and $QD_{n,t}$ is irrigation water demand at node n at time t.

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[37] The RIBASIM hydrological model was used to simulate the 102 years flow data included in the model (Deltares, 2012).

4.5.2.2. *The Agronomic Component*

The agronomic component of the model is represented by an approach which captures the yield response of crops to different levels of water use. The approach to depict the crop yield-water stress relationship is first presented in the FAO Irrigation and Drainage Paper No.33 by Doorenbos and Kassam (1979). The relationship between crop yield and water consumption was addressed based on a simple yet innovative equation which relates relative yield reduction (actual yield (y_a) divided by maximum or potential yield (y_m)) to the associated relative reduction in water use (actual evapotranspiration (eta) divided by maximum evapotranspiration (etm)) through a yield response factor (ky), which is specific to crops and their growing stages. The yield response coefficient captures the complex relationships between crop yield and water use which involve various biological, physical and chemical processes. Its value is determined based on the assumed linear relationship between relative yield and relative evapotranspiration, for water deficits of up to around 50% or $1 - eta/etm = 0.5$. If $ky > 1$, the crop yield response is very sensitive to water deficit resulting more than proportional yield reductions to a reduction in water use due to water stress; if $ky < 1$ the crop is relatively tolerant to water deficit, leading to less than proportional reductions in yield with reduced water use, and $ky = 1$ indicates yield reduction is directly proportional to reduced water use. The following equation specifies the crop yield response to water use:

$$y_a = y_m * [1 - (ky * (1 - eta/etm))] \qquad (5.4)$$

Equation 5.4 implicitly assumes that water deficit is equally distributed over the total growing season and that deficit will have similar yield impact on different crop growth stages. However, yield response considerably varies depending on the stage the water stress occurs and hence to get optimal yield, water should be allocated according to crop growth season given the water requirements of the crop in a particular growth stage (Doorenbos and Kassam, 1979).[38] To account for this, stage water deficit (and associated relative yield reduction) is defined as;

$$Sdft_{dn,c,t} = kym_{c,t} * \left(1 - \frac{eta_{dn,c,t}}{10^{-5} * area_{dn,c} * etm_{dn,c,t}}\right) \qquad (5.5)$$

Where: $Sdft_{dn,c,t}$ is stage deficit for a crop at irrigation node dn at crop growth period t (i.e. growth stage), $kym_{c,t}$ is monthly yield response factor for crop c at period t and $area_{dn,c}$ irrigation area at node dn for crop c. In our model, crop growth stage is defined as one month. Defining relative yield rate (y_a/y_m) as $RY_{dn,c}$; actual yield [$y_{a(dn,c)}$] can be written as maximum yields at irrigation node dn for crop c [$y_{m(dn,c)}$] multiplied by relative yield rate at irrigation site dn for crop c ($RY_{dn,c}$) :

[38] Usually, the flowering and early yield formation period is the most sensitive stage of crops for water deficit whereas in vegetation and late growth stages (ripening) sensitivity to water stress becomes less intense. Thus, effective water management entails that water should be allocated to meet the full water requirements of the crop during the growth stage where it is most sensitive to water stress than distributing the water deficit equally across the overall crop growing period (Doorenbos and Kassam, 1979).

$$y_{a(dn,c)} = y_{m(dn,c)} * RY_{dn,c} \quad (5.6)$$

And $RY_{dn,c}$ is defined as;

$$RY_{dn,c} \leq 1 - msdft_{dn,c} \quad (5.7)$$

Where ($msdft_{dn,c}$) is maximum crop growth stage water deficit which is selected from the monthly stage deficits estimated in equation 5.5:

$$msdft_{dn,c} = max_t\{Sdft_{dn,c,t}\} \quad (5.8)$$

Therefore, the crop yield response to evapotranspiration which takes into account the stage crop yield response factors will be:

$$Y_{a(dn,c)} = y_{m(dn,c)} * [1 - msdft_{dn,c}] \quad (5.9)$$

4.5.2.3. The Economic Component

The economic component of the model performs the calculation of net economic benefits from water uses in different sectors and by riparian countries of the basin. The objective is to maximize the total net economic benefit (profit) from water uses for irrigation and hydropower generation. The objective function is given as:

$$Max\ Z = \sum_{\mathrm{dn}} NETIB(n) + \sum_{\mathrm{rn}} NETHB(n) \quad (5.10)$$

Where; Z is total net benefit, NETIB is net irrigation benefit and NETHB is net hydropower benefit.

Profit from the agricultural sector (i.e. irrigation demand sites) is calculated as crop revenue minus cost of crop production. In the equation 5.11 it is given as total production multiplied by the difference between crop selling price (producer price) and crop production cost.

$$NETIB(n) = \sum_{c} AREA_{c,dn} * YIELD_{c,dn} * (CROPPRICE_c - CROPCOST_c) \quad (5.11)$$

Where; $AREA_{c,dn}$ is irrigated area at irrigation site dn for crop c, YIELD is crop yield, CROPPRICE is crop selling price, CROPCOST is crop cost of production.

The net profit from hydropower generation equals to total profit from sales of power minus the cost of power generation. In equation 5.12 it is presented as power generation times difference between power selling price and power generating cost for each hydropower plant which could be reservoir based or run-of-river power stations.

$$NETHB(n) = \sum_{t} HPGEN_{rn,t} * (HPPRICE_{rn} - HPCOST_{rn}) \tag{5.12}$$

Where; $HPGEN_{rn,t}$ is hydropower generated at reservoir node rn at time t, HPPRICE is the hydropower selling price and HPCOST is the cost of hydropower generation.

4.6. Sources of Data

The data used for model parametrization is obtained from various sources. The Information Management System (IMS) of ENTRO (mainly from MSIOA study and the original ENMOS model database) is the principal source of data used for reconstructing the hydro-economic model. Data obtained from various ministries of the basin countries, relevant publications and IFPRI's survey on "Energy in Agriculture" are also used to update and modify ENMOS. Data on key reservoir characteristics including maximum dead and live storage, elevation-area-volume relationships, and installed capacity and average (firm) energy of hydropower plants are obtained from ENTRO's IMS. Effective rainfall, reference evapotranspiration (ET_o), and reservoir evaporation are obtained from Deltares (2012) whereas crop coefficient (K_c) is taken from ENTRO's IMS. Additional crops data such as crop types, pattern, calendar and yield are obtained from various sources. For Ethiopia, crop types, pattern, schedule and yield data in seven major (two to three per sub-basin) irrigation districts were obtained from the One–System Inventory (OSI) reports on water resource related data and information prepared under the auspices of ENTRO. For Sudan and South Sudan, crop related data obtained from the Statistical Yearbook (2009) of Sudan and FAOSTAT is used. For Egypt, the Spatial Production Allocation Model (SPAM) (2010-2012) data of IFPRI which was compiled based on data from CAPMAS published in Yearly Bulletin of Crop Area and Crop Production Statistics were used. The SPAM data on crop yield for Ethiopia and Sudan were also used for comparison and validation purpose. To convert observed yield to maximum or potential yields, the former is adjusted by a factor of 1.2. A total of 32 major irrigated annual and perennial crops which are cultivated in the four basin countries are included (see Appendix A for the list of crops included in the model). If the various cropping patterns of crops in each country (classified as dry and wet season for Ethiopia and, winter, summer and river (*Nili*) for Egypt) are considered separately, the total number of crops included in the model will add up to 51.

For all basin countries, crop price data (i.e. producer price) is obtained from FAOSTAT (2012). Finding consistent crop cost of production data for all basin countries was not possible and as a result the data for the respective parameter had to be either estimated or proxied for some countries. For Ethiopia, crop cost of production (fertilizer, seed and labor) is estimated based on household survey data conducted by IFPRI in 2012 on 948 households in the Ethiopian part of the Nile Basin. For Egypt, the data on the cost of crop production is obtained from MoALR, Economics Affairs (2014). For Sudan and South Sudan no cost data was found and hence the average cost of production from Ethiopia and Egypt is taken. Hydropower selling price and cost of generation data are taken from various sources including Foster and Morella (2001), NBI (2009) and EEHC (2015/16).

4.7. Scenarios

The model scenario contains two major types of analysis: system optimization (cooperation) and tradeoff (non-cooperation) analysis. In the case of system optimization, it is assumed that there is full cooperation between sectors and riparian countries, and economic benefits will be maximized basin-wide where the entire basin is considered as one system. Under the full cooperation scenario, it is implicitly assumed that benefits that are lost due to water allocation from low-value use and users to high-value use and users will be compensated through appropriate transfer mechanisms. The tradeoff analysis constitutes sectoral tradeoff analysis and cross-country (transboundary) tradeoff analysis which are designed to analyze the case of non-cooperation between sectors and countries, allowing to quantify the WEF nexus in the basin. Both the full cooperation and non-cooperation scenarios will be examined under various levels of water resource developments in the basin which results in a total of 42 scenario runs. The summary of the different levels of water resource development scenarios is described in Table 4.1 whereas the system optimization and tradeoff analysis scenarios which will be conducted for each of the development pathways are given in Table 4.2 below.

The water resource development scenario contains seven scenarios which are formulated in a logical and piecemeal fashion so that changes from one scenario to the other can be examined and explained. The first scenario (S1) depicts the baseline or existing situation in the basin and it includes only existing hydropower and irrigation developments. Scenario 2 (S2) adds the under construction hydropower development in the basin which is GERD. Given that currently GERD is highly contested water resource development, this scenario is formulated to analyze the impact of the dam on basin countries under cooperative and non-cooperative scenarios. In addition to infrastructures included in S2, scenario 3 (S3) includes the Toshka irrigation project in Egypt which have been under construction since 1997. Scenario 4 (S4) includes all proposed hydropower developments in the basin which are advanced to pre-feasibility and feasibility study stage in addition to those included in S3. This scenario includes hydropower developments which can be done with short (5-15 years) to medium term (15-25 years) period. Scenario 5 (S5) adds proposed hydropower developments that are either identified in country master plans or in reconnaissance study phase. These developments are assumed to be undertaken in the long run (after 25 or more years).

Up on S4, scenario 6 (S6) introduces proposed irrigation infrastructures for which pre-feasibility and feasibility study have been conducted while scenario 7 (S7) is S5 plus irrigation developments included in S6 and those either identified in country master plans or in reconnaissance study stage (three additional proposed reservoirs which are solely for irrigation purpose namely Itang, Dombong and Gilo 2 are also included in this scenario). Such analysis will allow assessing the cumulative and basin-wide economic and hydrological impacts of dam and irrigation projects in the basin which are often planned and implemented in piecemeal manner and managed unilaterally. Under scenario 6 and 7, we conduct a sensitivity analysis with improved irrigation efficiency and crop yield increment assuming that such large irrigation developments in Ethiopia and Sudan will not be economically attractive without significant improvements regarding agricultural productivity. It should be noted that the aim of this study is not to conduct a cost-benefit analysis on the economic, social and environmental feasibility of various combinations of infrastructure developments in the basin, but rather to assess whether different sectoral and regional objectives can be meet across different levels of water resource infrastructure developments, and alternative prioritization of sectors and countries, giving emphasis on potential economic tradeoffs between them. Also, the objective of scenario analysis is not to forecast the future but rather to map and understand alternatives futures by examining different decision or options under various potential future developments and management strategies. The transit filling stage of the new dams in the basin is not considered in this analysis; our study focuses on the operational phase of the reservoirs.

Table 4.1: Water resource development scenarios[39]

S. No.	Scenario	Description
S1	Baseline	Only existing hydropower and irrigation developments in the basin
S2	Ongoing hydropower development	S1 + under construction hydropower plants
S3	Ongoing hydropower and irrigation developments	S2 + irrigation developments which are under construction
S4	Short to medium-term hydropower developments	S3 + hydropower developments for which pre-feasibility or feasibility studies have been conducted
S5	Long-term hydropower developments	S4 + hydropower developments which are identified in country's master plans and/or are in reconnaissance study phase
S6	Short to medium-term hydropower and irrigation developments	S4 + irrigation developments for which pre-feasibility or feasibility studies have been conducted
S7	Long-term hydropower and irrigation developments	S5 + all irrigation developments including those identified in country's master plans and/or are in reconnaissance study phase

Table 4.2: Cooperation and non-cooperation scenarios (tradeoff analysis scenarios)

Scenario	Description
Full cooperation	Basin-wide system optimization
Non-cooperation	
Sectoral tradeoffs	Sectoral tradeoff analysis which assumes no cooperation between sectors
- HPP	Hydropower is prioritized over irrigation
- IRRP	Irrigation is prioritized over hydropower
Cross-country tradeoffs	Cross-country tradeoff analysis which assumes no cooperation between countries
- ETHP	Ethiopia is prioritized over Sudan and Egypt
- SUDP	Sudan is prioritized over Ethiopia and Egypt
- EGYP	Egypt is prioritized over Sudan and Ethiopia

[39] See Tables A.1 to A.4 in Appendix A for list of infrastructures included in the model and their status.

The tradeoff analysis between sectors and countries is done with weighting method where the primary objective function is multiplied by a relative weight which reflects the tradeoff or the marginal rate of transformation of sets of objective functions (Vedula and Mujumdar, 2005:125). In the sectoral tradeoff analysis, the level of tradeoff between hydropower and irrigation sectors in the basin will be examined. Accordingly, in the objective function the term representing the sector which is given priority will be weighted by a factor of 100 while the function for the other sector is kept the same. The cross-country tradeoffs scenarios aim to analyze transboundary (upstream-downstream) tradeoff. Similar to the sectoral tradeoff analysis, in this scenario the objective function for the country which is given priority will be multiplied by a factor 100 while the objective functions for the other countries remains unchanged. The sectoral tradeoff analysis is modeled as:

$$Max\ Z = W_{irr} * \sum_{\mathrm{dn}} NETIB(n) + W_{hp} * \sum_{\mathrm{rn}} NETHB(n) \tag{5.13}$$

Where W_{irr} and W_{hp} are irrigation and hydropower weights which takes value of 100 when the respective sector is prioritized and 1 when the other sector is prioritized.

The equation for analyzing transboundary tradeoffs is given as:

$$Max\ Z = W_{ci} * \left(\sum_{\mathrm{dn}} NETIB(n) + \sum_{\mathrm{rn}} NETHB(n) \right) \tag{5.14}$$

Where W_{ci} is country weight (in which i = Ethiopia, Sudan or Egypt) and takes the value of 100 for the country that is prioritized and 1 for the remaining riparians.

4.8. Results and Discussion

This section presents the results from the hydro-economic model which was discussed in the previous section. Particularly, changes in economic benefits and potential tradeoffs across sectors and riparian countries under various levels of water resource developments in the basin will be assessed. First, comparison of existing vs optimal results will be presented relying on selected key indicators followed by cooperation (system optimization) scenario results and non-cooperative (tradeoff) analysis results under different water resource development pathways. Our analysis gives insights into the potential hydrologic and economic impacts of alternative water resource development pathways across cooperative and non-cooperative scenarios reflected by system optimization and different sectoral and transboundary prioritization scenarios as well as varying hydrological conditions captured by a long time series water flow data.

4.8.1. Comparison of Existing Situation Vs Optimized Results

Before using the model for further analysis, the first step is to compare selected key optimized model results with observed historical data. We start with comparing observed flows with the pattern of flow in the case optimal water allocation at selected major gauging stations in the basin. Model results from the baseline scenario which represent the existing water resource developments and use in the basin are used for comparison with observed values (see Figure D.1 in Appendix D for comparison of average monthly and annual flows in optimal case vs observed flow). It should be noted that since optimization models show potential for improved water use, it does not replicate the reality and close match with observed flow patterns is not expected as in simulation models. Nevertheless, such comparison is important to see if changes in flow patterns in the case of optimal water allocation are within the practical limit (i.e. do not deviate largely from observed flow patterns). In most of the main checkpoints, the patterns of monthly and annual flow in the optimized model are in line with the observed flow patterns. Deviations are shown in gauging stations located after major water infrastructures where either higher or lower flows are projected in some months in the case of optimal water allocation compared to observed flows.

Table 4.3 presents estimated total benefit from hydropower and irrigation, water allocations and irrigated area under the current situation (CS) as well as model optimization. Total economic benefit in the basin increases by 25% (from 11.5 to 14.3 billion USD) in the optimized scenario compared to the existing situation. Basin-wide hydropower benefit increased by 8% while irrigation benefit raised by 26%. However, this increased total economic benefit is not attributed to all riparian countries. Particularly, total benefit for Sudan is 20% lower in the optimized scenario than under the existing situation which is mainly due to about 23% decrease in irrigation benefit in optimal case. Irrigation benefit for the remaining countries is higher in the optimal case and the same is true for hydropower benefit with the exception of Egypt where it is 6% lower compared to the existing situation. Relative to the existing situation, the model allocates more irrigation water to Egypt (14%) and South Sudan (80%) and less water for Ethiopia (-48%) and Sudan (-16%). Optimal basin-wide irrigated area in the baseline is estimated to be 6.5 million ha (assuming 180% cropping intensity in Egypt). Irrigated area in Ethiopia and Sudan decreased in optimal case while it increases in Egypt and South Sudan. At the baseline, the model estimates the total optimal water withdrawal in the basin to be 94.3 BCM which is the sum of water uses for irrigation (72.9 BCM) and evaporation loss from reservoirs (21.4 BCM). Such basin-wide optimization implicitly assumes the existence of an omniscient decision maker who maximizes basin-wide benefits or social welfare and a system to compensate less efficient sectors and countries that incurred loss due to water allocation from low valued to high valued uses and users in the benefit maximization process. In reality, such central decision maker with perfect foresight and, an effective and fair benefit allocation system is unlikely to exist due to the enormous transaction cost involved to generate information about the overall basin and the tradeoffs resulting from different inter-sectoral and transboundary water allocations (Ringler, 2001).

Table 4.3: Current vs optimized economic benefits, water allocation and irrigated area

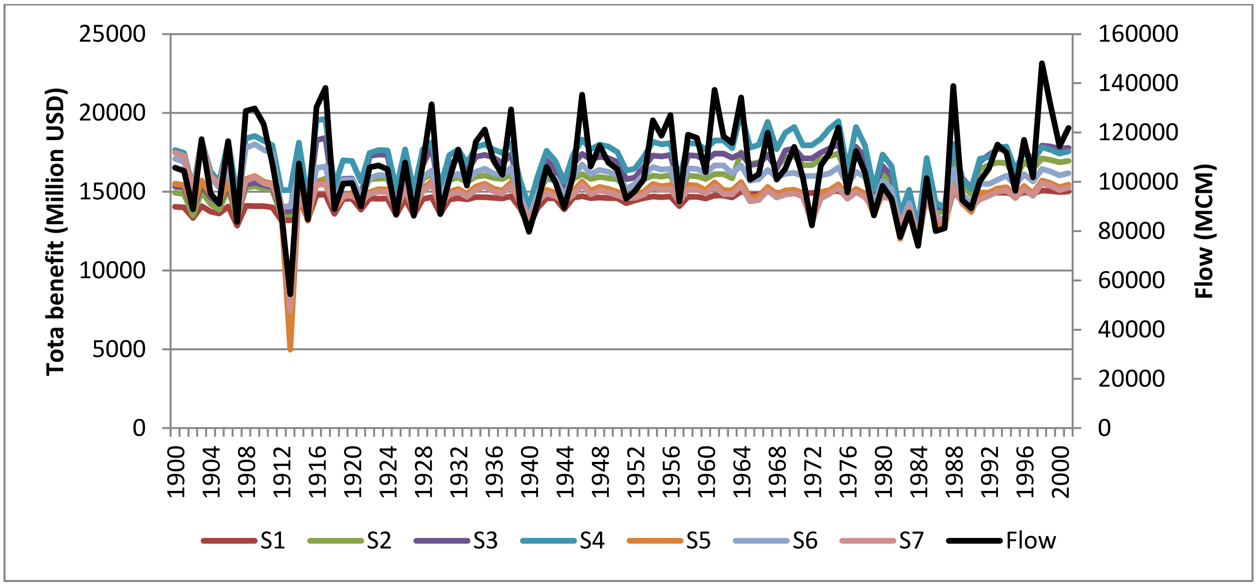
		Total benefit (Million USD)	Hydropower benefit (Million USD)	Irrigation benefit (Million USD)	Water use in irrigation (MCM)	Irrigated area (1000ha)
Ethiopia	CS	253.0	93.6	159.4	899.2	253.9
	Optimized	283.7	119.8	163.9	466.9	176.7
	%change	12.1	28.0	2.8	-48.1	-30.4
Sudan	CS	2252.5	186.5	2066.0	11433.3	1278.1
	Optimized	1804.2	211.2	1593.0	9592.1	633.9
	%change	-19.9	13.3	-22.9	-16.1	-50.4
South Sudan	CS	20.3		20.3	87.2	12.4
	Optimized	26.5		26.5	156.8	13.1
	%change	30.8		30.8	79.9	5.7
Egypt	CS	8990.8	207.0	8783.8	54919.7	5380.6*
	Optimized	12259.3	194.9	12064.5	62719.6	5740.6*
	%change	36.4	-5.9	37.3	14.2	6.7
Grand Total	CS	11516.5	487.0	11029.5	67339.3	6924.9
	Optimized	14373.7	525.8	13847.9	72935.5	6564.1
	%change	24.8	8.0	25.6	8.3	-5.2

Note: Optimized values are averages from 1900-2002 for the baseline scenario (S1). *With 180% cropping intensity

4.8.2. System Optimization (Cooperative) Scenario Results under Different Levels of Water Resource Development

Before presenting tradeoff analysis results which are the main interests of this study, we will briefly discuss results from various levels of water resource developments to evaluate whether changes in water demand by countries of the basin, reflected by different levels of hydropower and irrigation developments can result significant economic tradeoffs among water using sectors (mainly hydropower generation and crop production), and transboundary benefits and water allocations. The system optimization scenario assumes full (greater degree of) cooperation between the Eastern Nile countries and treats the basin as one unit. Therefore, for the entire water resource development scenarios, the model was run as a single system giving equal weights (priorities) to water demands in all riparian countries. Subsequently, results for net basin-wide and country specific economic benefits (from hydropower generation and crop production), water allocation to irrigation, evaporation loss from reservoirs and irrigated area under various water resource development scenarios will presented.

Figure 4.3: Total economic benefit and water availability over years



As we can see from Figure 4.3, total basin-wide economic benefit varies over years with total water availability in the basin measured by river flow. The result is quite intuitive suggesting that lower water availability generally leads to reduced economic benefits which indicate economic outcomes are highly dependent on the supply of water. For example, the year 1913 is a severe drought year where total water flow in the basin was almost 50% lower than the 102 years average. It is also the year where lower economic benefits are obtained in most of the model scenarios. High degree of correlation was found between basin-wide hydropower benefit and water supply wherein dry years, basin-wide hydropower production was largely reduced indicating the importance of climate variability and hydrological conditions for the productivity of the sector in the basin.

Yearly average economic benefits are also compared for countries under various levels of water resource developments in the basin (Figure 4.4). All comparisons are made with the results of the baseline scenario (S1). Total basin-wide benefit show increment in all scenarios compared to S1 where it is highest under S4. However, since the capital cost of investment and other detail cost-benefit analysis is not done, our results should not be taken to imply any infrastructure development pathway is superior to the other and should be selected for future development. Our objective is only to show the extent of upstream and downstream tradeoffs as well as within country sectoral tradeoffs that could emanate with the introduction of different water resource infrastructures. As most of the proposed infrastructure developments are in Ethiopia, the country gets the larger gain in all of the scenarios pertaining to different levels of water resource developments. Also, compared to the baseline, the economic benefit for Sudan has increased in all of the water resource development scenarios (except S3). Egypt however obtained lower economic benefit with new infrastructure developments in Ethiopia and Sudan under S5, S6, and S7. These imply that with the existing water use and management structure, there seem to be limited scope for implementation of all the planned irrigation and hydropower infrastructures in the basin that can lead to Pareto improvement if the amount of water allocated to countries is taken as a sole subject of negotiation.

With the introduction of GERD in the system (S2), total basin-wide benefit increases by about 9% and become 15.6 billion USD under system optimization. GERD increases the total economic benefit of all basin countries of Ethiopia (166%), Sudan (4%) and Egypt (5.8%) after being operational. Sector-wise, the dam increases Ethiopia's hydropower benefit by 382% while reducing existing irrigation benefit by 4%. This shows the potential existence of a within-country tradeoff between irrigation and hydropower in Ethiopia. GERD has increased both hydropower (15%) and irrigation (2%) benefits in Sudan. For Egypt, while it increases irrigation benefit by 5.9%, hydropower benefit declined by 1.5%. GERD results in more regulated year-round flow changing the patterns of inflow into and release from major reservoirs in Sudan (Roseries, Sennar and Merowe) as well as the HAD in Egypt. When is GERD in the system, inflow into Roseries increases between the months of June and December resulting increased hydropower production between February and May and release for downstream irrigation demand between October and May. Nearly similar flow and release change patterns are also observed at Sennar and Merowe. Also, evaporation loss from Sudan's reservoirs and HAD declined by 0.3 BCM and 1.5 BCM respectively. With optimal water allocation, HAD will operate at a lower level when GERD is in the system (storage declined by 15% on average) which results in reduced hydropower production. However, GERD will ensure more constant flow into HAD throughout the year which benefits irrigated agriculture in Egypt (see Figure D.2 in Appendix D).[40] Despite differences in modeling approaches, most of these findings are consistent with previous studies which analyzed the impact of the dam on downstream countries in its operational phase and indicate that GERD will not have significant adverse effect on hydropower and irrigation production in downstream countries (e.g. Mulat et al., 2014; Arjoon et al., 2014; Jeuland et al., 2017)

The introduction of the under-construction Toshka irrigation project in Egypt (S3) results in a slightly higher (15.8 billion USD) total basin-wide economic benefit compared to S2. The project did not significantly affect the total economic benefit of Ethiopia but resulted in lower total economic benefit for Sudan compared to both S1 and S2 (mainly due to reduced water allocation to irrigation in Sudan). It increases Egypt's total economic benefits by 7.2 percentage point compared to S2. However, given the complex and highly controversial nature of the project (related to reclaiming lands in hot deserts and developing water hungry agriculture in a water scarce basin), and several technical difficulties faced with implementing it (associated with the salinity level of the desert land and existence of underground aquifers) are not accounted into our modeling framework, the estimated benefit and cost either from basin-wide perspective or to Egypt should be taken with caution. Toshka is not just an agricultural project which aimed at expanding irrigation area; it is a vast and complex development which involves establishing new settlements and development of other non-agricultural sectors including industry, mining, tourism as well as alternative energy options (Wahby, 2004). Thus, tracing the actual and long-term impact of such multifaceted development project on the overall basin-wide water use or particularly to Egypt needs detailed and focused assessment.

[40] Note that additional (potential) important benefits of the dam to downstream countries in terms of flood control and, sedimentation and silt trapping are not considered.

Figure 4.4: Yearly average economic benefits by country

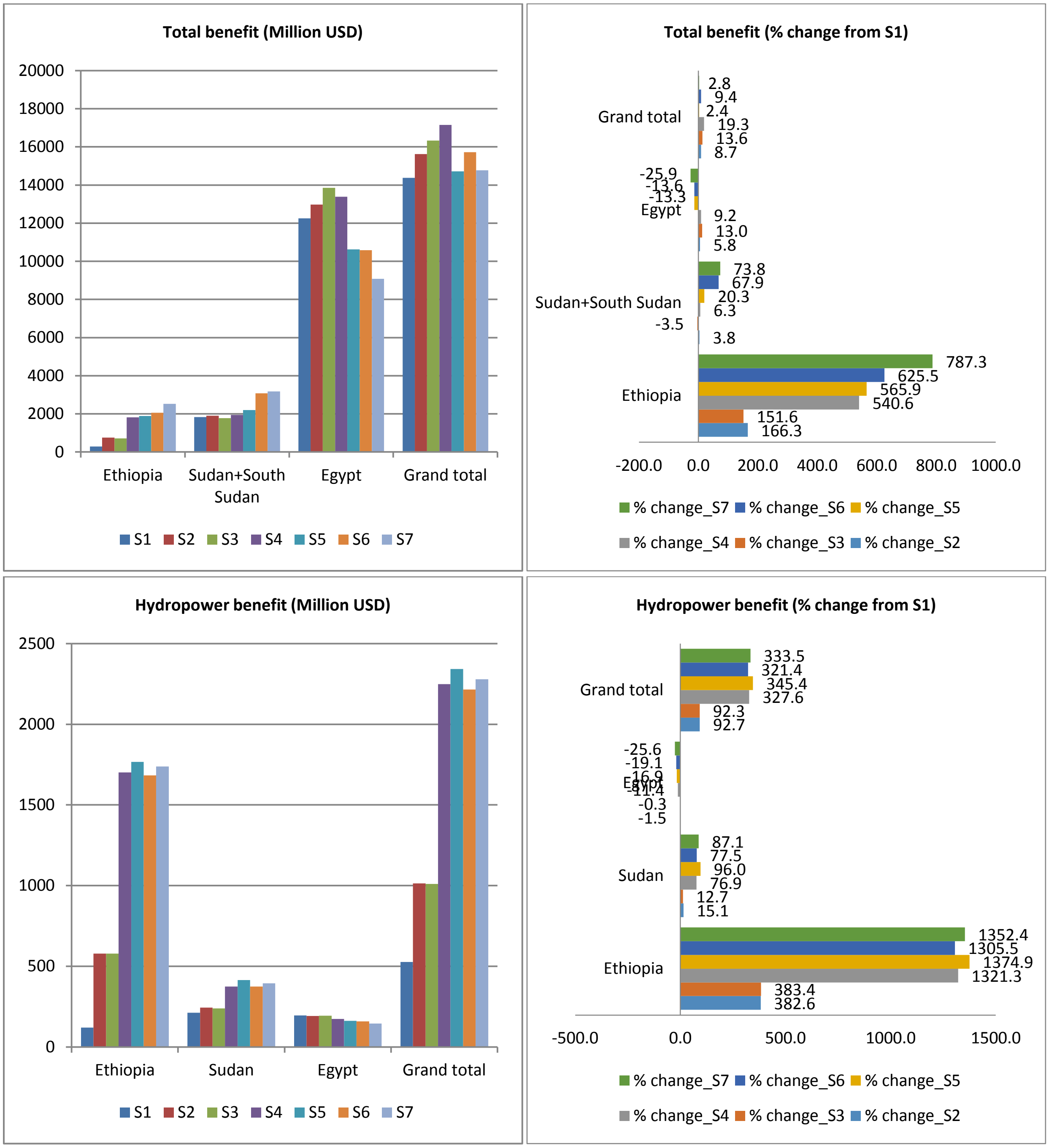
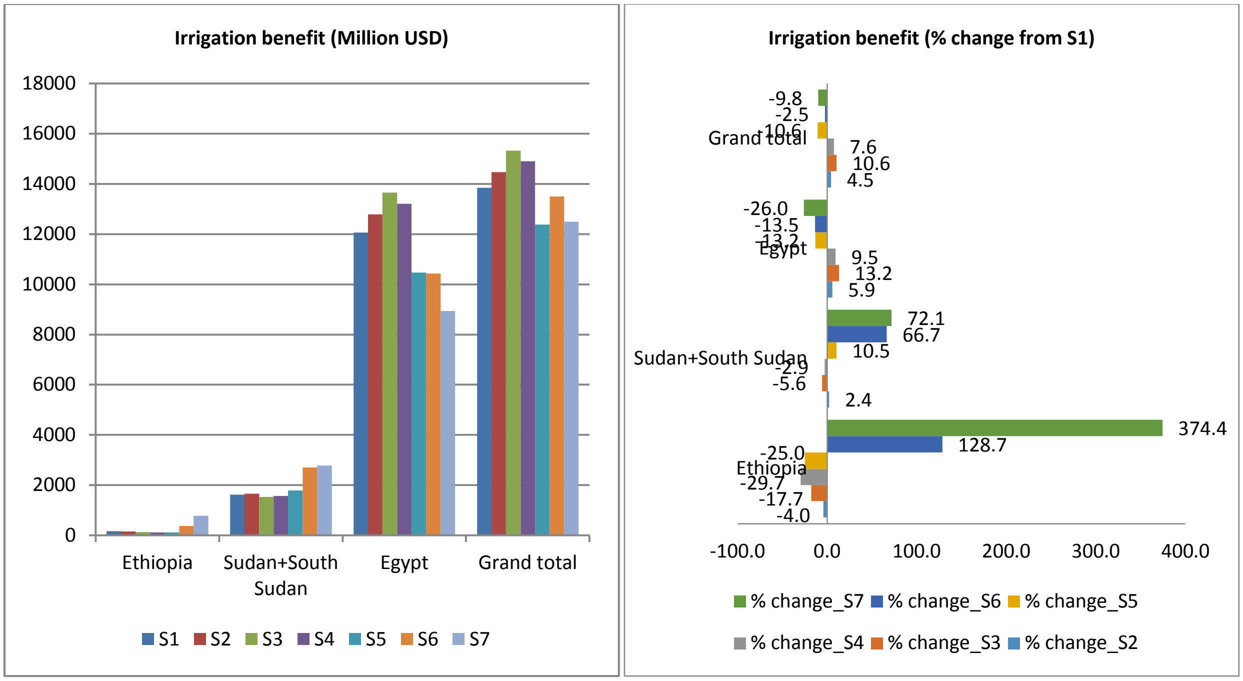


Figure 4.4 continued…



In S4, seven proposed hydropower plants that are advanced to pre-feasibility or feasibility study stage in Ethiopia (Karadobi, Beko Abo, Upper Mandaya, Lower Didessa, Baro I, Baro II and Genji) and three in Sudan (Kajbar, Dal and Shereik) are introduced in the system. Total basin-wide benefit shows further increment in S4 (19%) and reached 17.1 billion USD. Total economic benefit for all basin countries increased under this scenario. In S5, additional five proposed hydropower dams which are either identified in the countries master plan or progressed to reconnaissance study phase are included where four are in Ethiopia (Gambella, Gilo 1, TK7 and TK21) and one in Sudan (Sabaloka). Total economic benefits for Ethiopia and Sudan also increased under this scenario while Egypt's benefit declined. In both S4 and S5, hydropower benefit for both Ethiopia and Sudan increases while irrigation benefit declined in Ethiopia and increased in Sudan (S5). Introducing additional hydropower plants intensify the within-country tradeoff between irrigation and hydropower in Ethiopia. Given Ethiopia's comparative advantage is in hydropower, the model chooses to reduce water use in irrigation sites located upstream of hydropower plants. In order to maximize system value of water, model wants to capture the full benefit that can be obtained from hydropower production before water is abstracted for irrigation (Sadoff et al., 2002). Egypt's hydropower benefit declined in both S4 and S5 while irrigation benefit increases in S4 but showed a reduction in S5. These results indicate the existence of a large potential for developing a number of additional dams (yet not all that are proposed) for hydropower production in upstream countries of the basin which will increase basin-wide economic benefit without inflicting a significant cost on any riparian.

With the introduction of new irrigation systems in Ethiopia and Sudan, both countries make further larger gain under S6. The total basin-wide benefit under this scenario is estimated to be 15.7 billion USD. Similarly, in S7 more irrigation area is introduced in Ethiopia and South Sudan which results in an even higher economic gain for the two countries. However, Egypt's total economic benefit declined in the last two scenarios, where both hydropower and irrigation benefits exhibit significant reduction notably in S7. In both scenarios, even if Ethiopia and Sudan (South Sudan) obtained a higher total benefit, total basin-wide benefit declined compared to S4 due to a lower benefit obtained by Egypt. This indicates that future irrigation developments in Ethiopia and Sudan could have a potential negative impact on Egypt either by reducing the amount of water available or causing a mismatch between river flow patterns and irrigation water demand downstream. However, changes in water use efficiency, agricultural productivity, climate, hydrology, sectoral policies and other dynamic variables in one or more of the basin countries will shape the actual impact of future upstream irrigation developments. Particularly, adoption of new technologies and suitable policies which improved irrigation efficiency and agricultural productivity in the basin could lessen potential water stress created by new developments and might generate benefits for all riparians.

Looking at optimal water allocation under different water resource development levels, total water use increases in Ethiopia and Sudan (except in S3 for Sudan) while it decreases in Egypt (expectations – S2 and S3) in all scenarios compared to the baseline (see Figures 4.5). Estimated total basin-wide water use under different water resource development scenarios ranges between 94 and 100 BCM (including return flow from irrigation fields).[41] The largest share of this water withdrawal is for irrigation ranging between 63 and 78 BCM while the remaining is evaporation loss from reservoirs varying from 22 to 31 BCM. For Ethiopia, the increased total water use in S2 to S5 is attributed to evaporation loss from the newly introduced reservoirs into the system whereas in these scenarios Ethiopia's irrigation water use declines. For Sudan, irrigation water use increases in all the scenarios except S3 and S4. Similarly, evaporation loss from Sudan's reservoirs increases in most of the scenarios with the exception of S2 and S3. For Egypt, irrigation water use shows increment in S2 to S4 while it declined in the remaining scenarios. Evaporation loss from Egypt's reservoir (HAD) showed a reduction under all the scenarios compared to the baseline. Except in S4 and S5, total basin-wide irrigated area exhibited an increment where it varies between 5.9 and 7.1 million ha under different development pathways. For Ethiopia, irrigated area declined in S2 to S5 and increases in S6 and S7. In Sudan, irrigated area increases in all scenarios (except in S3 and S4) while in Egypt it shows increment in S2 to S4 and declined in the last three scenarios (S5-S7).

[41] Estimated flows into the Mediterranean Sea under different water resource developments are presented in Figure D.3 in appendix D. The lowest flow is observed under S4 where compared to the baseline, flow into the sea declined by about 34% in the respective scenario. In all scenarios, the minimum environmental flow requirement that should go into the sea (10 BCM) is satisfied.

Figure 4.5: Yearly average water allocation and irrigated area by country

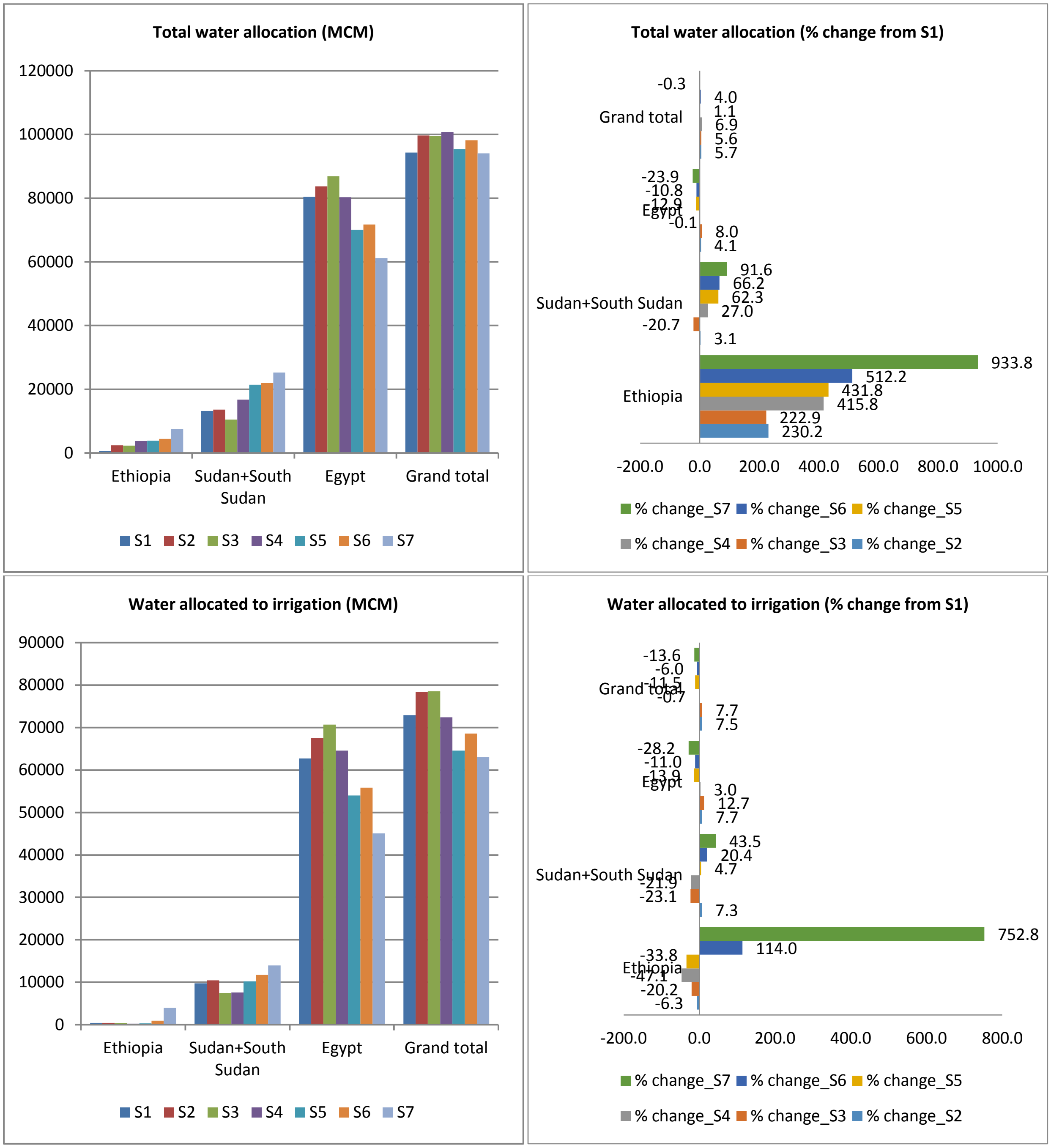
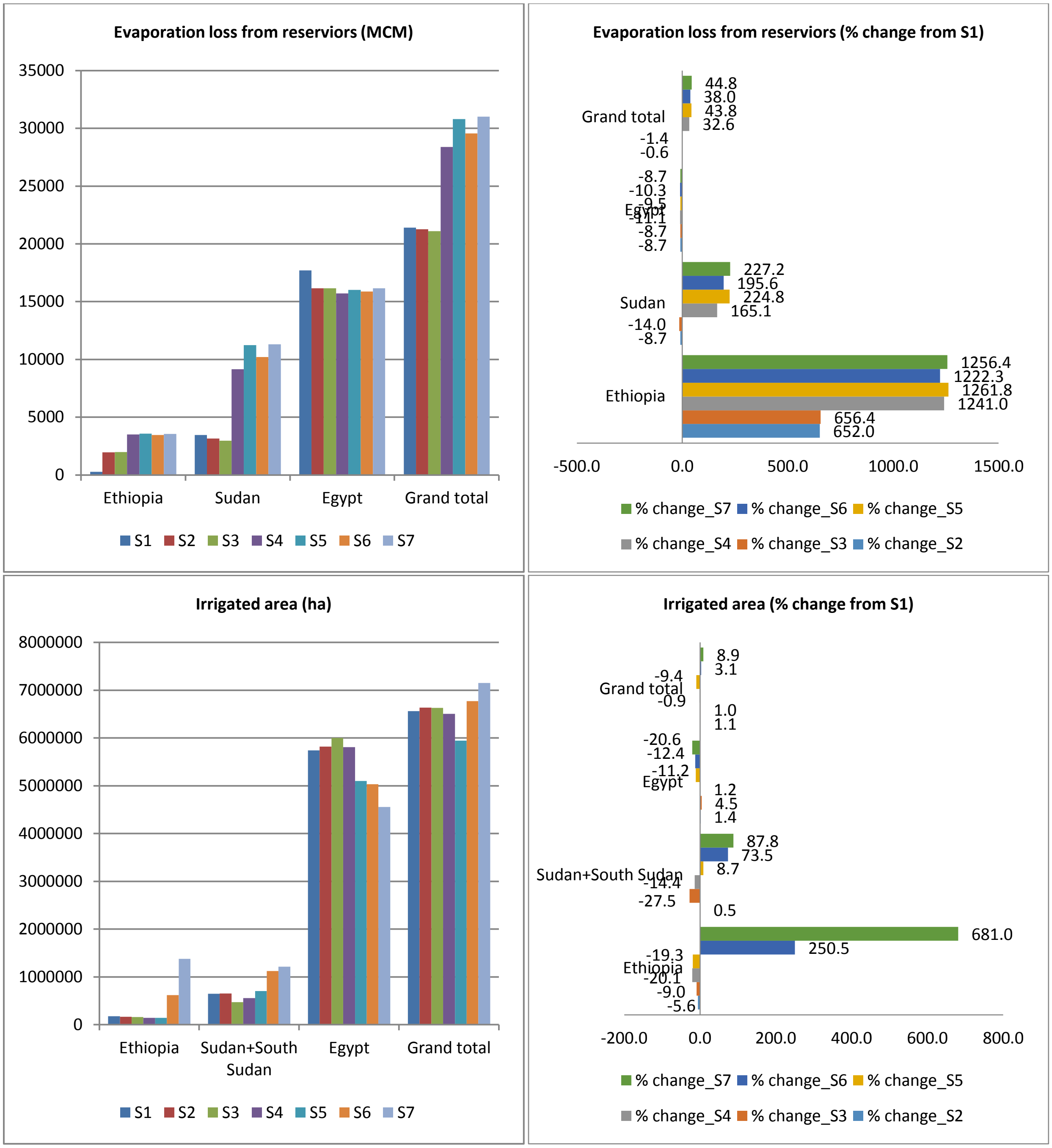


Figure 4.5 continued…



4.8.3. Sensitivity Analysis

Introducing large irrigation developments in Ethiopia and Sudan under Scenario 6 and 7 implicitly entails future sustainable agricultural intensification in the two countries. In particular, improved irrigation efficiency and crop yield increment (through various measures such as the use of improved seeds, fertilizer application and appropriate land management) need to be achieved for the proposed irrigation schemes to become feasible, efficient and profitable. As a result, we conduct a sensitivity analysis related to sustainable agricultural intensification in the two countries under S6 and S7. Our agricultural intensification scenarios are represented by 10-50% increment in irrigation efficiency and yield in Sudan and Ethiopia. The maximum increment (50%) is chosen by considering the existing level of irrigation efficiency and yield in Egypt as a benchmark. The assumption is that in the future Ethiopia and Sudan could at least reach the level of water use efficiency and crop yield which currently exist in Egypt. Table 4.4 and 4.5 presents results from 50% increment in irrigation efficiency (Irr_eff) and, combined yield and irrigation efficiency (Irr_eff&yield) improvements in Ethiopia and Sudan.

Compared to benefits obtained in S6 at the current level of irrigation efficiency, a 50% increment[42] of irrigation efficiency in Ethiopia causes 1.5% increase in total basin-wide benefit (hydropower benefit increases by 0.9% while irrigation benefit increases by 1.5%).[43] Country-wise, it results in higher total benefits for Ethiopia (7.4%) and Egypt (3.7%). Irrigation water use in Ethiopia (-8.5%) and Sudan (-24.8%) declines while it increases in Egypt (1.8%). Moreover, irrigated area increases in Ethiopia (1.7%) and Egypt (1.1%) whereas it declines in Sudan (-29.4%). Improved irrigation efficiency in Sudan also increases total basin-wide benefit by about 2%. In addition, improved irrigation efficiency both in Ethiopia and Sudan increases total basin-wide benefit by 3.3%. Similarly, total basin-wide benefit increases in all of the combined irrigation efficiency and yield scenarios. Particularly, a combined yield and irrigation efficiency improvement in Ethiopia increases total basin-wide benefit by 2.8% while the same improvement in Sudan and in both Ethiopia and Sudan, increase basin-wide benefit by 9.9% and 4.7% respectively (Table 4.4).

In S7, total basin-wide benefit increases in all of the agricultural intensification scenarios except in the case of combined yield and irrigation efficiency improvements both in Ethiopia and Sudan. Country-wise, improved irrigation efficiency in Ethiopia leads to higher total benefit in Ethiopia (6%) and Egypt (10%) while lower benefit is obtained by Sudan (-4%). With improved irrigation efficiency in Sudan, all countries obtained higher benefit and basin-wide total benefit increases by 4%. Similarly, due to improved irrigation efficiency both in Ethiopia and Sudan, all countries obtained higher benefits resulting 6% increment in total basin-wide benefit. In the entire combined yield and irrigation efficiency scenarios, Sudan attained higher benefits (ranging from 9 to 45%). Ethiopia also got higher benefits in these scenarios except in the case where the improvements are in Sudan. Likewise, Egypt's total benefit increases in most of the combined yield and irrigation efficiency improvement scenarios (Table 4.5).

[42] Baseline overall irrigation efficiency in all irrigation schemes of Ethiopia and Sudan is fixed at 50%.

[43] Regardless of the cost of improving irrigation efficiency

Table 4.4: Improved irrigation efficiency and yield in Ethiopia and Sudan under S6

	Irr_eff ETH	Irr_eff SUD	Irr_eff Eth&SUD	Irr_eff&yield ETH	Irr_eff&yield SUD	Irr_eff&yield_ ETH&SUD
Total benefit						
ETH	7.4	-0.4	1.8	12.4	3.2	15.1
SUD**	-10.4	1.5	5.8	-2.5	49.5	35.6
EGY	3.7	2.2	2.9	2.5	-0.4	-6.3
Grand total	1.5	1.7	3.3	2.8	9.9	4.7
Hydropower benefit						
ETH	-0.1	-0.1	0.3	0.4	-0.2	0.4
SUD	4.4	3.6	4.1	3.7	1.9	6.9
EGY	2.8	3.0	3.2	-0.6	2.4	5.2
Grand total	0.9	0.8	1.1	0.9	0.4	1.9
Irrigation benefit						
ETH	41.1	-1.8	8.4	66.1	18.6	80.7
SUD**	-12.5	1.2	6.0	-3.4	56.2	39.5
EGY	3.7	2.2	2.9	2.5	-0.4	-6.5
Grand total	1.5	1.9	3.7	3.1	11.4	5.1
Total water use						
ETH	-2.2	-0.7	-3.5	-5.9	0.9	-6.2
SUD**	-7.8	-9.1	-9.5	3.9	-9.0	-14.3
EGY	0.5	1.3	1.8	0.5	1.2	-1.1
Grand total	-1.5	-1.1	-1.0	1.0	-1.0	-4.3
Irrigation water use						
ETH	-8.5	-2.6	-15.6	-24.7	3.5	-25.8
SUD**	-24.8	-26.4	-27.2	-4.9	-21.3	-40.2
EGY	1.8	1.2	1.9	0.2	1.5	-2.3
Grand total	-2.9	-3.6	-3.3	-1.0	-2.3	-9.1
Evaporation loss						
ETH	-0.4	-0.1	0.0	-0.5	0.2	-0.6
SUD	11.7	10.8	10.9	14.0	5.2	15.5
EGY	1.9	1.9	1.5	1.6	0.2	2.9
Grand total	5.0	4.7	4.6	5.6	1.9	6.8
Irrigated area						
ETH	1.7	-0.5	5.4	1.7	0.8	-7.6
SUD**	-29.4	1.2	4.9	-12.0	-15.7	-32.9
EGY	1.1	0.6	1.3	1.0	-0.5	-11.1
Grand total	-3.9	0.6	2.3	-1.1	-2.9	-14.4

Note: All values are % changes from results in S6 without irrigation efficiency and yield improvement; **including South Sudan

Table 4.5: Improved irrigation efficiency and yield in Ethiopia and Sudan under S7

	Irr_eff ETH	Irr_eff SUD	Irr_eff ETH&SUD	Irr_eff&yield ETH	Irr_eff&yield SUD	Irr_eff&yield ETH&SUD
Total benefit						
ETH	5.9	0.7	1.3	1.7	-4.7	8.7
SUD**	-3.6	3.5	4.1	8.8	44.5	11.0
EGY	10.1	5.0	7.4	3.3	13.2	-15.4
Grand total	6.5	3.9	5.7	4.2	16.9	-5.6
Hydropower benefit						
ETH	1.1	0.5	0.8	1.3	0.5	0.8
SUD	1.3	6.3	6.5	-1.4	3.4	10.0
EGY	5.6	7.0	5.5	0.9	7.9	10.4
Grand total	1.4	1.9	2.1	0.8	1.5	3.0
Irrigation benefit						
ETH	16.6	1.4	2.5	2.6	-16.2	26.4
SUD**	-4.3	3.1	3.8	10.3	50.3	11.2
EGY	10.2	4.9	7.5	3.3	13.3	-15.9
Grand total	7.4	4.3	6.3	4.8	19.7	-7.2
Total water use						
ETH	-9.7	3.5	-2.1	-27.0	-6.1	-17.4
SUD**	-12.5	-15.7	-13.4	2.3	-21.5	-23.2
EGY	10.1	2.8	1.8	7.3	12.6	-1.3
Grand total	2.4	-2.1	-2.6	3.2	1.9	-8.4
Irrigation water use						
ETH	-18.7	7.2	-3.3	-51.5	-11.7	-32.2
SUD**	-20.3	-35.0	-32.9	9.9	-38.6	-55.1
EGY	13.9	3.5	1.8	10.5	17.5	-2.7
Grand total	4.2	-4.8	-6.2	6.4	3.2	-16.2
Evaporation loss						
ETH	0.4	-0.6	-0.7	0.4	0.2	-1.0
SUD	-3.0	8.2	10.7	-7.1	-0.4	16.4
EGY	-0.5	0.8	1.7	-1.7	-1.3	2.8
Grand total	-1.3	3.3	4.7	-3.4	-0.8	7.3
Irrigated area						
ETH	9.3	1.5	11.3	-13.2	-8.4	1.5
SUD**	-15.2	1.7	3.7	9.9	-26.9	-35.7
EGY	7.9	2.4	1.7	3.9	13.0	-5.5
Grand total	4.3	2.1	3.9	1.6	2.1	-9.3

Note: All values are % changes from results in S7 without irrigation efficiency and yield improvement; **including South Sudan

In general, both in S6 and S7, improved irrigation efficiency and yield mostly result reduced water use by Ethiopia and Sudan while at the same time basin-wide economic benefits increased.

These indicate investments in improving water use efficiency in particular and in sustainable agricultural intensification in general, could have a potential synergetic impact in enhancing the benefits of future water resource development in the basin. However, reduced water abstractions upstream (as a result of improved water use efficiency) does not necessarily translate into higher economic benefits downstream if water use and flow regimes are altered, and are not consistent with water demand patterns downstream. In some scenarios, for example, reduced irrigation water abstraction in Ethiopia and Sudan is accompanied by reduced irrigation water use (as well as benefits) in Egypt resulting in a large amount of unused water flow into the Mediterranean Sea. This is due to a mismatch between irrigation water demand in Egypt and, the changed water use and flow regime associated with improved water use efficiency in the upstream of the basin.[44]

4.8.4. Tradeoff (noncooperation) Scenario Analysis Results

4.8.4.1. Sectoral Tradeoff Analysis

Meeting the dual objectives of food and energy demands through expansion of irrigation and hydropower developments entails proper understanding about the consistency of power generation targets with providing adequate supply of water which is required for irrigated agriculture. Although hydropower production is not water consumptive (except in the filling stage of a new reservoir and evaporation loss due to water storage for power production), if its management is not well coordinated with irrigation developments, the operation rule of the reservoir for maximized power generation could be in conflict with irrigation water demand downstream. Poorly managed water releases from reservoirs can have a devastating impact on water supply for irrigation by changing the seasonal availability of water (Cai et al., 2003b; Tilmant et al., 2009; Bekchanov et al., 2015; Zeng et al., 2017). Tradeoff analysis between hydropower and irrigation sectors is done for each of the water development scenarios. In all cases, the tradeoff (noncooperation) analysis results are compared with the system optimization (cooperation) scenario results (Figure 4.6). Under S1, basin-wide economic benefit declined in the hydropower prioritization scenario (HPP) by about 8% and it showed only a slight (0.8%) reduction under the irrigation prioritization scenario (IRRP). Total benefit for Ethiopia and Sudan declined in both HPP and IRRP scenarios compared to system optimization. Sudan incurred a large loss of benefit under the HPP scenario where total benefit declined by 76% from the cooperation scenario. Looking at sectoral benefits, hydropower benefit for all countries increases when the sector is prioritized and declined when irrigation is prioritized indicating the existence of a significant potential tradeoff between the two sectors in the Eastern Nile basin. For Ethiopia and Sudan, irrigation benefit declined in both HPP and IRRP compared to the cooperation scenario while it increases for Egypt in both prioritization scenarios. Basin-wide irrigation benefit is 8% lower under HPP and around 1% higher under IRRP.

[44] This is however a static view, in reality farmers could gradually adjust their cropping season to cope up with the altered flow regimes and start using the additional water available due to improved water use efficiency in upstream countries.

Figure 4.6: Sectoral tradeoffs

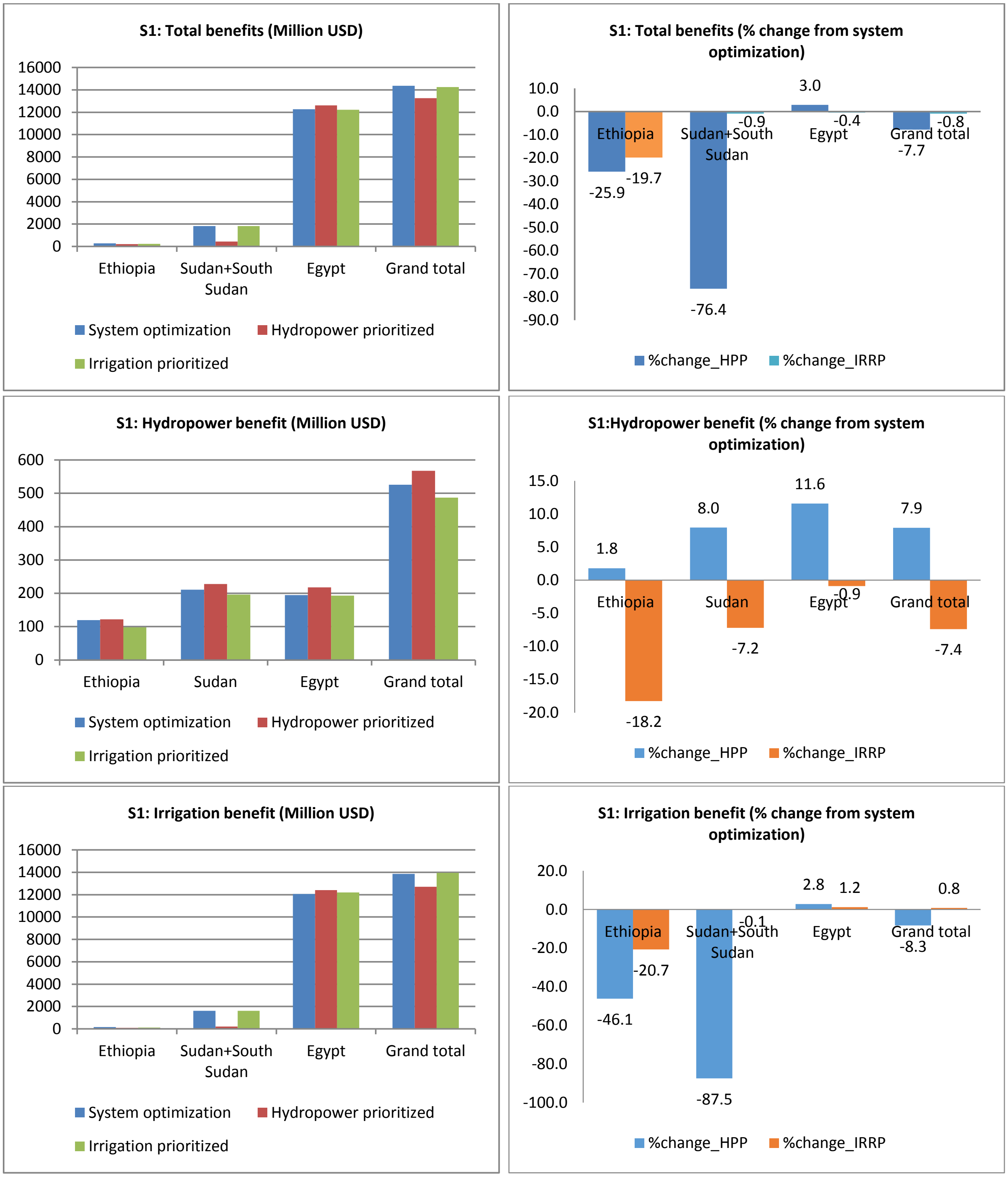
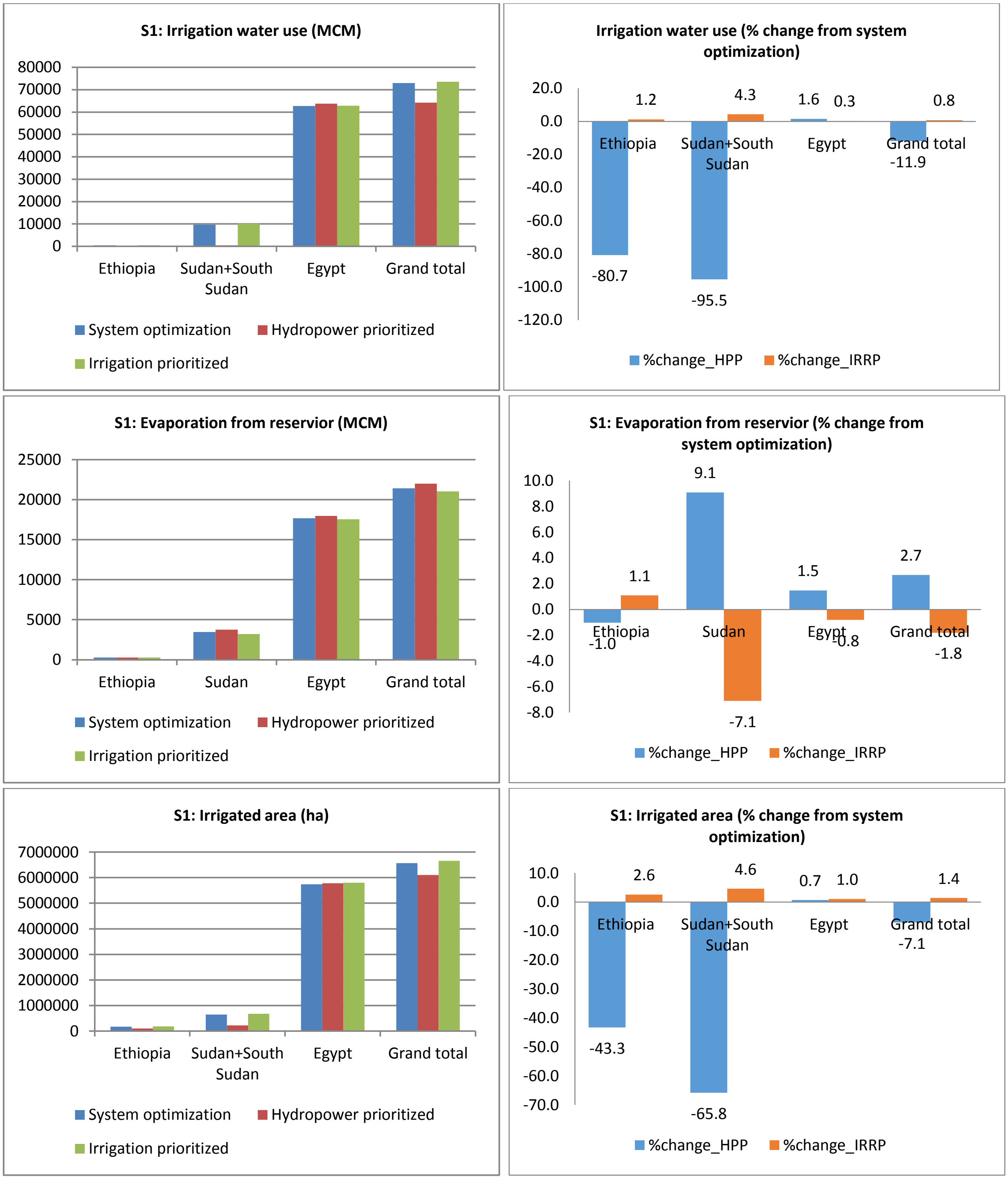


Figure 4.6 continued…



Results for changes in sectoral water use are intuitive where basin-wide irrigation water use is higher in the case of IRRP and lower under HPP while the reverse is true for evaporation loss from reservoirs. Also, for all basin countries, irrigation water use is higher under IRRP whereas evaporation loss from reservoir shows increment in HPP scenario. Total basin-wide water use marginally increases under the IRRP while it showed an 8% decline in the HPP scenario. The total basin-wide irrigated area is also higher in the IRRP (and lower in HPP) scenario compared to the system optimization scenario. At the baseline, cooperation between sectors results in higher benefit for Ethiopia and Sudan than unilateral sectoral actions whereas Egypt makes a slight gain in both sectoral prioritization scenarios. At the existing infrastructure development in the basin, hydropower prioritization creates large tradeoff and reduces basin-wide economic benefits. The tradeoff is more pronounced for Sudan in which hydropower prioritization entails increased release from the consecutive hydropower dams along the Main Nile resulting very little water allocation to irrigation fields which are located downstream of reservoirs. However, it should be noted that the result here shows an extreme case where water release from one reservoir goes directly to the next reservoir without any or very little water abstraction by irrigation fields between consecutive dams. In reality, even if hydropower is prioritized, such large reduction in irrigation water use (and hence irrigation benefit) may not be observed since it will be impractical to forbid irrigators from withdrawing water when it is released from an upstream dam. Similarly, the IRRP scenario is not beneficial for Sudan and Ethiopia at the existing level of irrigation development and agricultural productivity in the two countries. Egypt gained in the hydropower prioritization scenario because large amount of water remains unused by upstream countries resulting plenty of water for Egypt to use for production in both sectors.

In the various water resource development scenarios, similar trends of tradeoffs are observed between sectors. The sectoral tradeoff analysis results for S2-S7 are given in Table D.1 under Appendix D. The inclusion of GERD (S2) in the system creates a more pronounced hydropower-irrigation tradeoff for Ethiopia compared to the baseline (S1) which is reflected by the large (92%) decline in irrigation benefit under the HPP scenario. The remaining results are similar to S1 except that Egypt obtained a relatively less total benefit under HPP compared to system optimization. In S3, the total basin-wide benefit is lower in both sectoral prioritization scenarios compared to the cooperation scenario. With the introduction of additional reservoirs in Ethiopia and Sudan under S4 and S5, the sectoral tradeoff for Sudan gets more prominent wherein both scenarios more than 90% irrigation benefit losses are incurred compared to the cooperation scenario. In both scenarios, when hydropower is prioritized, Sudan only gets 5% of the irrigation benefit which was obtained in the case of system optimization. Tradeoff analysis under S6 and S7 also gives virtually similar results with the above scenarios. In both cases, total basin-wide benefit decreases in the sectoral prioritization scenarios compared to the system optimization scenario. Similar to S1, irrigation benefit for Egypt increases under both sectoral prioritization scenarios in S6 and S7.

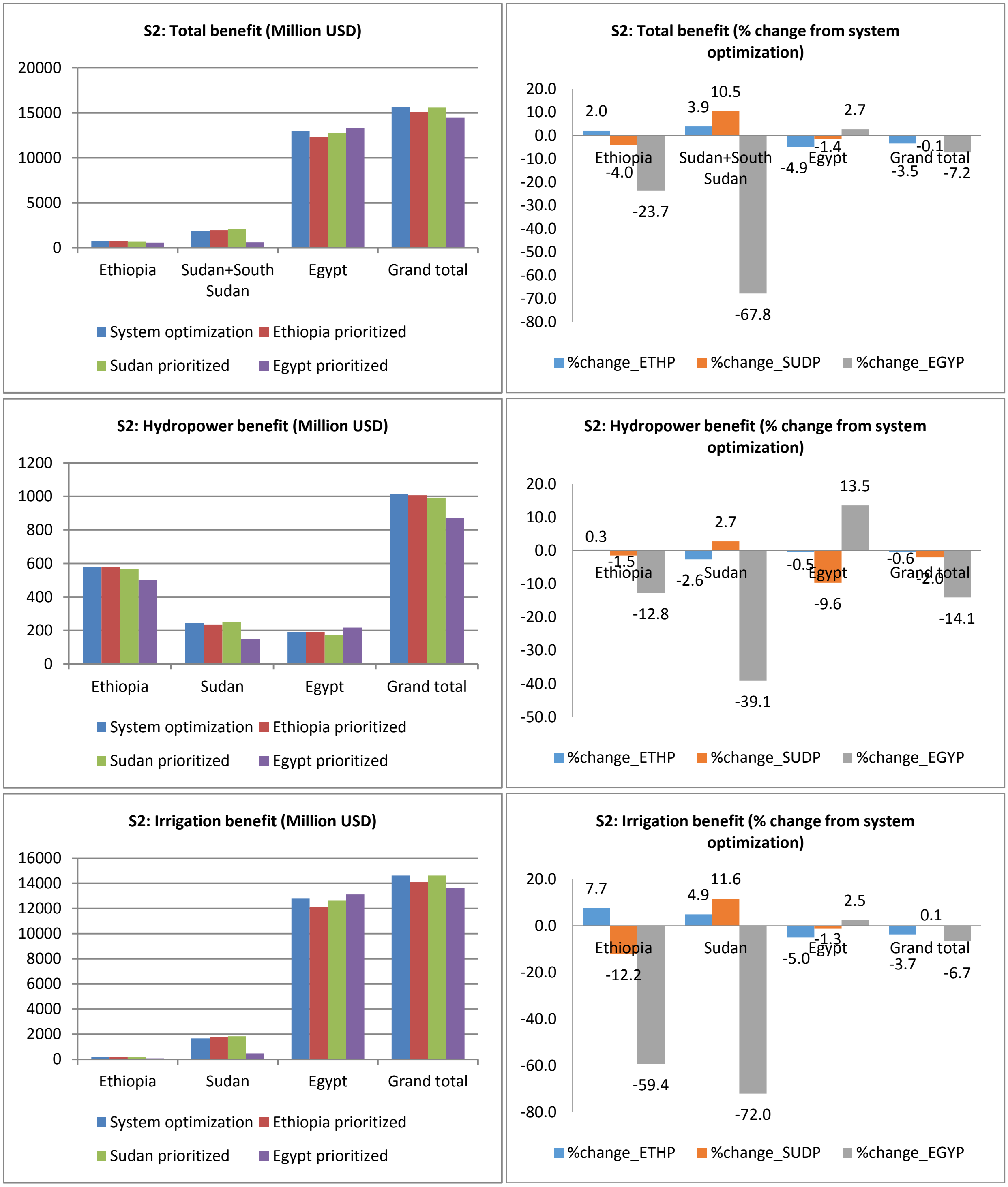
In general, in most water resource development scenarios total basin-wide hydropower benefit increases when hydropower is prioritized and decreases when irrigation gets priority. In contrast, total basin-wide irrigation benefit increases when irrigation is prioritized and decreases when hydropower gets priority. Thus, it can be concluded that there could be a considerable tradeoff between energy and food production in Eastern Nile basin if sectors are not managed in a cooperative manner. Even if the sector that gets priority gains, total economic benefits in the basin are lower in the case of noncooperation (sectoral and country prioritization) scenario than the cooperation scenario in most of the water resource development scenarios. Hence, cooperation between sectors is more beneficial for the basin than sector-specific actions.

4.8.4.2. Transboundary (Cross-country) Tradeoff Analysis

Similar to the sectoral tradeoff analysis, the transboundary tradeoff analysis is conducted for each of the water resource development scenarios and in each case, results are compared with the system optimization scenario. In S1, it is not meaningful to prioritize one country over the other because under the existing infrastructure development and water allocation in the basin, Egypt is already prioritized. Therefore, our transboundary tradeoff analysis starts from S2 where GERD is in the system (S2). As it is presented in Figure 4.7, total basin-wide economic benefit decreases in all country prioritization scenarios compared to the cooperation scenario. Ethiopia and Egypt get higher benefits when they get prioritized but lower benefits when the other countries are given priority. The same is true for Sudan except that Sudan also obtained higher benefit while Ethiopia gets prioritized. The same trends are observed in terms of total water use and irrigated area by countries. The results of the transboundary tradeoff analysis for S3-S7 are presented in Table D.2 in Appendix D. The change in total basin-wide benefit is also similar under S3 where basin-wide total benefit declined in all country prioritization scenarios compared to system optimization (except that in this scenario the total benefit for Sudan decreases under ETHP scenario as well). Total water use and irrigated area by countries show the same pattern of change as the total benefit of countries compared to the cooperation scenario.

The transboundary tradeoff analysis in S4 and S5 gives virtually similar result with the previous scenarios where total basin-wide benefit falls in all country prioritization scenarios compared to the cooperation scenario. Changes in country-wise benefits in these scenarios are similar to what is observed in S2 where countries gain when they are prioritized and lose when the other basin countries get priority with the exception that Sudan (in S4) and Egypt (in S5) also obtained a higher benefit under the ETHP scenario. The change in total water allocation for countries is also similar to changes in total benefit except that Sudan and Egypt also use more water in the case of ETHP in S4 and S5 respectively. Likewise, all countries irrigated more area when they get priority (though the irrigated area for Egypt slightly increases under the ETHP scenario as well). In S6, compared to the cooperation scenario, total basin-wide benefit increases under ETHP scenario and decreases in the remaining country prioritization scenarios. Changes in total benefits for countries are as expected in which they get a higher benefit when being prioritized and lower benefits when other riparian countries are given priority (Egypt also obtained a higher benefit under ETHP scenario). Also, total water allocation and irrigated area increase for the country which gets priority while decreases for the remaining countries (except for Egypt who uses slightly more water under the ETHP scenario too). In S7, the total basin-wide economic benefit is lower in all country prioritization scenarios than benefits under system optimization as it is the case in most of the previous scenarios. Irrigated area and water use for countries under this scenario also exhibit expected changes showing an increment for the prioritized country and a decline for the other riparians.

Figure 4.7: Transboundary tradeoffs



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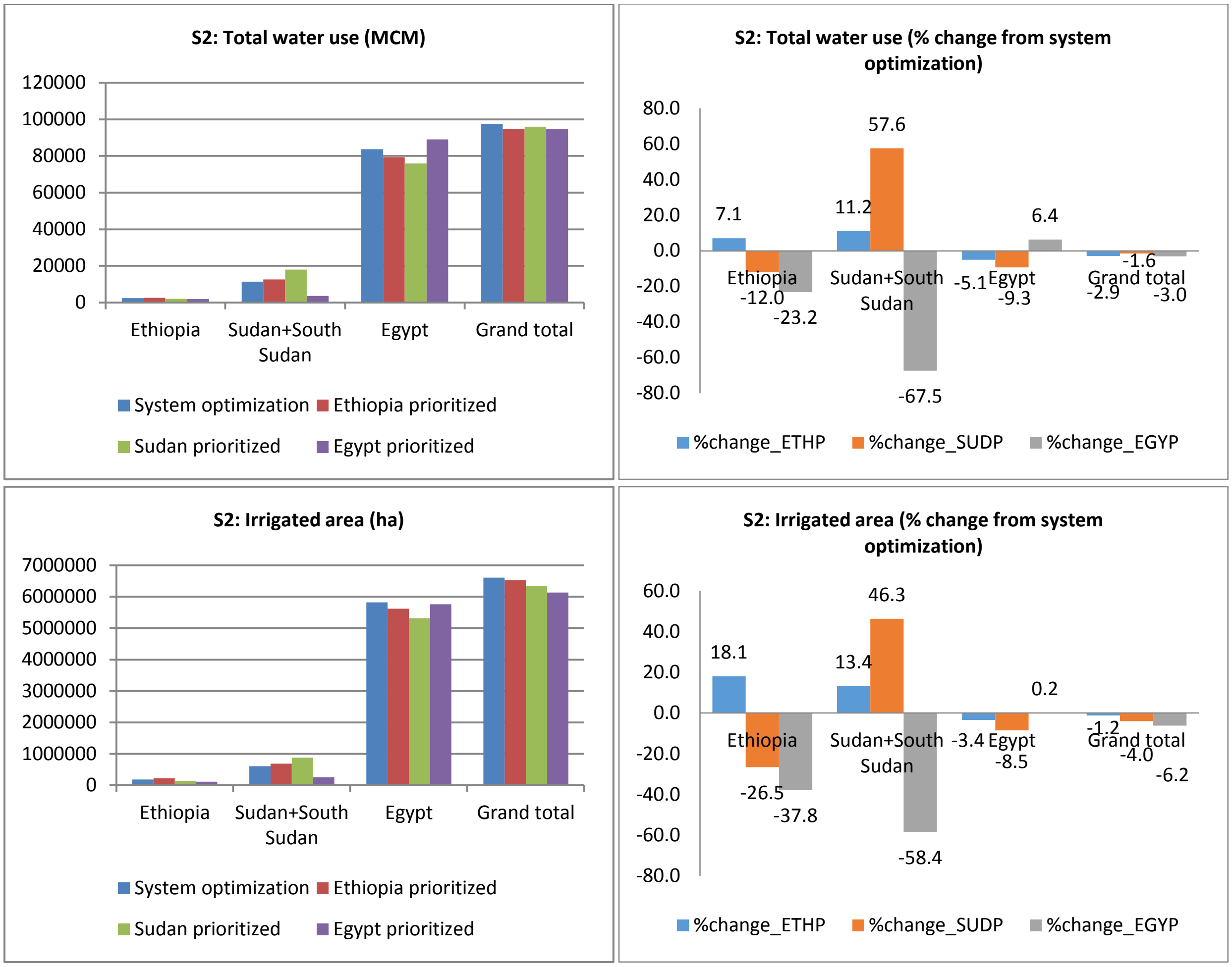


Generally, in all the water resource development scenarios, large transboundary tradeoffs are observed between Egypt and Sudan both in terms of hydropower and irrigation benefits. Also, the transboundary tradeoff for Ethiopia in terms of both irrigation and hydropower benefit is more intense with Egypt than Sudan. Among the country prioritization scenarios, lower basin-wide economic benefits were obtained when Sudan or Egypt gets prioritized implying that the current water allocation which favors the two countries over upstream nations is not efficient. In the majority of the scenarios, the total basin-wide benefit is higher in the cooperation case than country prioritization (exception – Ethiopia prioritization scenario under S6).

4.9. Discussion

The water resource of the Nile basin in general and the Eastern Nile, in particular, is already under immense stress from various water users and uses, and pressures are expected to increase considerably in the near future. This calls for continues investigation on the level of interdependence and tradeoffs across sectors and riparian countries. Ongoing and proposed new developments in different parts of the basin are adding to the complexity of WEF management in the region. So far, most developments are unilateral but a greater degree of coordination and collaboration is need when the infrastructures become operational (Blackmore and Whittington, 2008; Goor et al., 2010; McCartney et al., 2012; Arjoon et al., 2014). Results from the hydro-economic model used in this study suggested that under cooperation (system optimization), total (potential) basin-wide economic benefits from using the Nile water for irrigation and hydropower generation ranges between 14-17 billion USD (on average annually) in different water resource development scenarios. It should be noted that this does not account for construction and operating cost of infrastructures. Thus, financial assistance from the international community for building new water resource infrastructures is important so that the estimated economic benefits from the developments are quickly and largely captured by countries of the basin (Whittington et al., 2005). This is not, however, the case for GERD for example where Ethiopia has to cover the cost of constructing the dam from domestic resources. This coupled with the limited current domestic demand to absorb and utilize the electric power generated from the dam is expected to prolonged its repay period unless regional power interconnections deals are quickly implemented (J-WAFS, 2014; Jeuland, 2017).

Looking at the sectoral composition of economic benefits by country, in all the future water resource development scenarios, the largest benefit from hydropower production is attributed to Ethiopia whereas the largest irrigation benefit is generated in Egypt followed by Sudan. With existing agricultural productivity and irrigation efficiency in the basin (which determines the economic value of water in irrigation), Ethiopia’s comparative advantage is in hydropower production while Egypt’s and Sudan’s is in irrigation. Thus, basin-wide system optimization that ensures economically efficient allocation of water dictates a large amount of water use for irrigation in downstream riparian countries (after benefits from hydropower production are fully captured) than in the highlands of Ethiopia. Introducing additional hydropower plants in Ethiopia and Sudan (S2-S5) across the main course of the Blue Nile will likely increase the within-country tradeoff between hydropower and irrigation in Ethiopia. Expanded electricity for market through regional power trade may further increase the economic value of electricity from hydropower, and could potentially intensify the within-country tradeoff between the two sectors. Also, future agricultural intensification which involves improved productivity and irrigation efficiency in Ethiopia might significantly increase the economic value of water in irrigation (by reducing the crop water requirement per yield) and could create more within country hydropower-irrigation tradeoff at optimal water allocation (Whittington et al., 2005).

The results from this study show that under full cooperation, the development of dams that are going to be used for hydropower production in Ethiopia and Sudan could be beneficial for all riparian countries (S2 to S4). If managed cooperatively, upstream water storage facilities will increase irrigation benefits in downstream countries by providing more regulated year-round flow thereby increasing cropping intensity. Also, storage dams in upstream of the basin will significantly reduce evaporation losses from the Aswan reservoir in Egypt. Water saved from HAD due to upstream water storage is estimated to range between 1.5 and 1.9 BCM under S2-S4. These water savings will be compensated by increased evaporation loss from newly introduced reservoirs in Ethiopia and Sudan, but generating enormous hydropower benefit without inflicting a significant cost on any riparian. Upstream hydropower developments could provide increased access to affordable and clean energy supply in the region. It should be noted that evaporation loss per cubic meter of water stored in Sudan’s reservoirs is substantially higher than Ethiopia. In S4 for instance, estimated evaporation loss per cubic meter of water stored in Ethiopia is only about 3% of that in Sudan. Therefore, even if developing additional hydropower dams in Sudan may not cost downstream water users (mainly in Egypt), from system-wide efficiency perspective it is clearly preferable to store water in the colder Ethiopian Highlands with lower evaporation rate, than under arid climate of Sudan. These findings are consistent with most previous studies (Guariso and Whittington, 1987; Whittington et al., 2005; Blackmore and Whittington, 2008; Goor et al., 2010; McCartney et al., 2012; Arjoon et al., 2014).

Additional potential benefits of building upstream hydropower dams for downstream countries which are not addressed in our modeling framework include reduced sediment loads, and lower flood and drought risks (Blackmore and Whittington, 2008; Goor et al., 2010; McCartney et al., 2012; Tesfa, 2013; Arjoon et al., 2014). Some of these benefits could, however, have associated costs. For example, reduced sediment entering into reservoirs in Sudan and Egypt might extend the lifespan of the dams, cutback silt removal cost and improve water quality. But, trapping sediment upstream also means less fertile soil reaching to downstream croplands adversely affecting productivity, notably recession agriculture in Sudan (J-WAFS, 2014). How the massive soil erosion from Ethiopian highlands will affect the operation and lifespan of under construction (GERD) and proposed dams in Ethiopia also needs further investigation (Chen and Swain, 2014). Efforts to reduce soil erosion from highlands of Ethiopia like reforestation could affect the amount of surface runoff having unpredictable local and downstream impacts on water availability (Blackmore and Whittington, 2008). Increased evapotranspiration and infiltration due to improved forest cover may reduce the surface water yield (Guzha et al., 2018). Moreover, realizing the direct and indirect benefits of future water resource developments (aimed to enhance WEF security in the region) require significant basin-wide cooperation on their filling and operational phase. Several studies indicated that the transit filling stage of new dams in the basin is crucial and should be done in a manner that potential negative impacts on downstream users are minimal (see e.g. King and Block, 2014; Mulat and Moges, 2014; Habteyes et al. 2015; Zhang et al., 2015; Wheeler et al., 2016 on alternative filling options for GERD). Strong institutions which promote and govern greater cooperation in the basin will thus have a decisive role in maximizing positive externalities and minimizing costs (Cascão, 2009; 2012; McCartney et al., 2012).

New irrigation developments and expansions in Ethiopia, Sudan and South Sudan which are analyzed under S6 and S7 significantly increase benefits from the sector for the three countries compared to the existing situation. However, such upstream irrigation developments could have a negative impact on Egypt by changing either the amount or seasonal pattern of water flow. Irrigation will remain by far the largest user of water in the basin and future developments by upstream countries are inevitable given their indispensable need to increase agricultural productivity. Hence, given that the surface water resource of the Eastern Nile basin is almost entirely utilized, essential steps such as water saving from irrigation systems through adoption of more efficient irrigation practices and considering alternative water sources (like groundwater) are required to be taken (Blackmore and Whittington, 2008; Awulachew et al., 2012). Sensitivity analysis results showed that improving irrigation efficiency and crop yield (by 50%) in existing and new irrigation schemes of Ethiopia and Sudan could save up to 8.9 BCM (most of it from Sudan) water annually. However, translating this saved water into actual uses and benefits might require dynamic efforts such as changing cropping seasons by downstream irrigators.

The system optimization (cooperative) scenario results in general shows that most future developments in the basin are potentially beneficial to all riparian countries of the Eastern Nile basin and entail limited tradeoffs among sectors as well as riparians. However, this might not hold true if there are no integrated efforts across sectors and basin countries. The tradeoff (non-cooperative) analysis results indicated that there are considerable sectoral and transboundary tradeoffs in the basin when one sector or country is prioritized over the other. In most of the water resource development scenarios, the sector or country that get priority gains, but total basin-wide economic benefits in the case of non-cooperation (either sectoral or country prioritization scenarios) are lower than full cooperation scenarios. This implies unilateral developments and actions either by sectors or countries are not beneficial from basin-wide perspective. Unilaterally designed and managed developments could create significant conflicts of interests among various sectors and riparian countries, and conflict of any type has its own cost. Narrowly designed and, sector or country-specific projects that does not account the needs of and potential benefit from other use or users of resources will fail to capture the greater gains that could be obtained from development and management actions that follow system-wide approaches (Whittington et al., 2005, Wu and Whittington, 2006; Dinar an Nigatu, 2013)**.** In general, WEF nexus in the Nile basin is complex and tight which needs holistic and dynamic thinking and actions. Cooperation across sectors and scales is the most beneficial and sustainable pathway for the Nile basin. The next important questions thus will be how countries can cooperate, what means of cooperation are available, what are the challenges of cooperation and what mechanism can be in place to lessen those challenges and pave the way for better cooperation in the future. In the subsequent section, various means of cooperation, as well as their prospects and challenges, will be briefly discussed.

4.10. Potential Cooperation Mechanisms for the Eastern Nile Basin

4.10.1. Water Markets

From the economic realm, market-based solutions particularly establishing water markets relying on 'tradable water rights' were proposed as a pertinent mechanism to solve water allocation problems (Rosegrant and Binswanger, 1994).[45] For the Nile basin, in particular, the potential benefits of establishing regional water markets have been discussed in previous studies (Abate, 1994; Whittington et al. 1995 and Wu, 2000 cited in Nigatu and Dinar, 2011). Recently, Nigatu and Dinar (2011) has examined the possibilities of an intra-basin water trade based on the principle of "allocate-and-trade"[46] for the Eastern Nile basin and concluded that water trade can ensure economically efficient allocation of water in the basin. Though very appealing in theory,

[45] Water trade is believed to have potential to ensure efficient use of water by reallocating it from lower value uses to uses where it produces higher values (Saliba and Bush, 1987). Also, well designed and implemented water markets were argued to formalize and protect already established water rights, promote water conservation by realizing the actual opportunity cost of water for users, incentivize internalization of negative externalities and reduce transaction costs (Rosegrant and Binswanger, 1994; Easter et al., 1998).

[46] The "allocate-and-trade" concept involves two steps where first a river basin institution must define and allot water rights to countries of the basin, and then facilitate an intra-basin water trade (Nigatu and Dinar, 2010).

establishing water markets based on the principle of tradable water rights could be very challenging in reality. In this regard, Dellapenna (2000) argued that water is inherently a public good and markets for raw water is less likely to work where in reality water markets are rare and they are not truly free.

Several conditions such as well-defined private property rights, freedom of contract, legal and institutional structures which facilitate trade and basic water conveyance infrastructures for making water transfers are required to establish well-functioning water markets (Holden and Thobani, 1995). Considering water as an economic good is the first pre-condition for the existence of water markets and water yet has no established market value in Nile basin, mainly in irrigated agriculture which is the largest consumer of the resource. Water is usually seen as a public good and assigning either private or public property right to it is challenging. Especially, in irrigated agriculture, often farmers can access water for free or in some cases pay a very low subsided price. As a result, attempts to establish market prices are often received with strong opposition from existing irrigators (Randall, 1981 cited in Dinar et al., 1997). Additional challenges for establishing water markets include; the need for appropriate accounting of the available water resource, defining water rights that are in line with water constraints, executing water withdrawal rules, developing physical water transfer systems, intensified inequality due to trading of water-for-cash by poor farmers, negative externalities, and potential overutilization of water resulting environmental degradation (Dinar et al., 1997).

4.10.2. Benefit Sharing

Unlike solutions which mainly focused on improving and facilitating the actual amount of water allocated to countries, benefit sharing has been also presented as an alternative solution which is believed to alter the almost "zero-sum game of water sharing into a positive sum game" (see e.g. Ding et al. 2016; Arjoon et al. 2016). Instead of the actual volume of water allocated, the notion of benefit sharing focus on fair and equitable distribution of benefits emanating from water uses (Sadoff and Grey, 2002). Analytical approaches such as game theory (Wu and Whittington, 2006; Elimam et al., 2008; Dinar and Nigatu, 2013), parallel evolutionary algorithm (Ding et al., 2016) and bankruptcy theory (Arjoon et al. 2016) were considered as a benefit sharing mechanism for the Nile basin. Sharing of benefits in transboundary basins require a combination of market based and institutional mechanisms of cooperation. Institutional benefit sharing mechanism (also called pseudo-market approach) which involves a river basin authority with a role of central water system operator was suggested by Arjoon et al. (2016) for the Nile basin. This central authority will first identify economically efficient water allocation alternatives by gathering information on water use and productivity and then based on such information it will efficiently allocate water among various agents in the river basin. The authority will then charge water using units according to their bulk water use and reallocate the collected payments to users in an equitable manner (Arjoon et al., 2016).

Acknowledging the contribution of the study to the subject of benefit sharing in general and to the Nile discourse in particular, the practicality of the benefit sharing arrangement proposed in it, however, can be fairly contested. First, the transaction cost for such central body to gather all the information required to ensure efficient allocation, to collect bulk water charge and redistribute the payment will be obstructively large in reality. The approach also requires the existence of a river basin authority which manages the basin as one unit where all riparian countries are members and, they have full trust and confidence in the central authority. In this regard, the Nile basin portrays a dismal outlook given that almost two decades have passed without establishing the Nile River Basin Commission despite considerable effort through the NBI (Martens, 2011; Nigatu and Dinar, 2011). This implies that institutional benefit sharing solutions often based on static side payment concepts alone will not address the cooperation issue in the basin. Demographic and economic changes which alter demand patterns in basin countries might challenge the stability of agreements reached on monetary side payments.

4.10.3. Regional Trade

An alternative economic means of cooperation that can also be taken as a mechanism of benefit sharing is intra-regional commodity trade. Trade and economic diversifications are two major international mechanisms which can help to successfully reduce disagreements over transboundary water resources in water-scarce economies. Trade could improve or even ensure the water security of countries by allowing them to access commodities that are water-intensive indirectly giving them access to water which could not have been obtained through negotiations on water allocation (Allan and Mirumachi, 2010). The idea of ensuring water security through international trade of water-intensive commodities (mainly that of agricultural commodities), is first introduced in Allan (1997) named as virtual water trade. Virtual water refers to the water embedded in water-intensive commodities mainly agricultural products (Allan, 1997). After the introduction of the concept in the early 1990s, it has been among the most debated methods to quantify the water-food-trade nexus and deemed to shape decision-making regarding water allocation for agricultural production (IRENA, 2015a). Water endowment, water needed for the production of a commodity and water productivity greatly varies across countries or regions of the world which lead to the main premise of the virtual water trade concept that is “trade based on hydrological comparative advantage”. Accordingly, countries with less water endowment should import water-intensive products from countries having relatively high water endowment and productivity (Chapagain et al., 2006; Hoekstra, 2010).

The largest share of virtual water flow is due to international trade in agricultural commodities mainly crops (76%) and livestock (12%). Industrial products also account for about 12% of virtual water flows worldwide (Mekonnen and Hoekstra, 2011). Virtual water trade will generate direct positive gain to the importing country by saving water which could also be beneficial from the environmental, social and economic point of view (Hoekstra and Hung, 2005; Chapagain et al., 2006; Hoekstra and Chapagain, 2008).[47] The word “saving” however implies water saved in physical terms and has no direct economic interpretation. In reality, the potential for water saving through virtual water trade will not often translate into countries designing and adopting specific trade policies that could alleviate their water stress. This is because international trade in water-intensive commodities is not solely determined by water but rather via a range of additional

[47] Mekonnen and Hoekstra (2011) estimated that between the periods 1996-2005, globally 369 BCM water is saved annually due to trade in agricultural commodities and without trade each year an additional 98 BCM of blue water would have been needed to produce the same quantity of goods produced with virtual water trade.

issues such as availability and productivity of other factors of production (such as land, labor and, human and financial capital), tariff and non-tariff trade barriers, domestic consumption patterns, degree of economic diversification, market structures, and purchasing power (Chapagain et al., 2006; IRENA, 2015a)**.**

Allan and Mirumachi (2010) argued that solutions for transboundary water conflicts should also be explored outside of the river basin, the water sector and international water sharing laws where economic diversification and international trade are important part of such solutions. Especially in river basins like the Nile where there are significant water resource endowment and power asymmetries, it is very challenging to establish effective basin-wide cooperation purely through the water-centered institutional mechanism and intra-regional trade combined with economic diversification should be considered as an alternative means of cooperation. Generally, current trade among countries in the Eastern Nile basin is very limited accounting less than 5% of the total countries import and export (own computation based on COMTRADE data, 2005-2016). There is however a considerable potential for intra-basin trade in agricultural commodities and energy products (mainly hydropower, oil and natural gas) given the massive population of the basin and difference in comparative advantage between riparian countries (Wichelns et al., 2003). Intra-regional trade in agricultural commodities is being promoted by NBI and its subsidiary bodies for long as a means to improve the efficiency of water use in the basin. Specifically, assessment of opportunities for cross-border trade in various agricultural commodities and virtual water trade (or water footprint) analysis has been done by NBI under NELSAP's Regional Agricultural Trade and Productivity Project showing the existence of a large potential for intra-basin trade (NBI, 2012b; NBI, 2012c).

Estimates show that Nile basin countries already import a considerable amount of virtual water embedded in agricultural commodities (globally about 41 BMC per year between 1998 and 2004) where a large share of it was by Sudan and Egypt which is believed to have a considerable impact in lessening the water scarcity in the two countries. Virtual water import outside of the basin was found to have major importance to the downstream Nile riparian than those in upstream. This discrepancy between upstream and downstream countries concerning the relevance of virtual water import is evident as Egypt for example, imports about 40 times more virtual water (in agricultural products) compared to Uganda. Within basin virtual water trade was however indicated to be very little largely dominated by trade in rain-fed agricultural produce. Such limited intra-basin virtual water flow was not found as a significant solution in addressing the water deficits of lower riparian states of the basin. However, it was indicated that improving productivity of the rain-fed agriculture could become a major solution to alleviate the water scarcity problem in the future without putting stress on the blue water resource of the basin (Zeitoun et al., 2010).

Population and economic growth will change the quantity as well as quality (composition) of food and energy demand in the Nile basin. These coupled with the uneven distribution of resource and demand indicated that chances are less for all basin states to become food and energy self-sufficient suggesting the vital role of trade. Regional trade has a potential to encourage specialization based on comparative advantage thereby enhancing economies of scale in production which in turn increase employment. It could also increase consumer surplus by providing better access to cheaper commodities. By providing wider market access, intra-basin trade in agricultural products is particularly sought to be highly beneficial in improving the welfare of the vast number of households in the basin whose livelihood is principally dependent on agriculture. Most importantly, it will help in addressing the water scarcity issue in the basin (NBI, 2012a). Insight of this, regional trade organizations like the East African Community (EAC) and Common Market for Eastern and Southern Africa (COMESA) promote intra-regional trade in the Nile basin and advise various trade liberalization measures to be taken by member countries.

However, even if appropriate trade policies have an indisputable role in facilitating trade in the region, the real challenges facing the intra-basin trade comes from the profound productivity, infrastructure and market-related problems in the basin. So far, most of the basin countries are net food importers and it is uncertain that if they could produce a tradable surplus in the near future. Infrastructures (like road, railways and sea route) that link one riparian country to the other are generally in a poor state. Lack of proper means of transportation combined with poor storage facilities often results in excessive post-harvest losses. The market structure for most agricultural commodities is also highly unorganized characterized by information asymmetry and weak backward and forward linkages (value chain) (NBI, 2012a; NBI, 2012b). Nevertheless, these challenges do not preclude intra-basin trade from being a feasible proposition to partly resolve the water management and other broader economic issues in the Nile basin. Rather, it calls for quick and continues measures that address the productivity problem rooted in agriculture and other sectors of the economy. Investments are required in yield-enhancing innovations such as improved seeds and fertilizer. Since economic diversification is the key to trade, investment is also required in sectors outside of agriculture. Both physical and institutional infrastructures also need great improvements (NBI, 2012b).

In addition to trade in agricultural commodities, there are also viable opportunities to pursue energy trade between the basin countries. Regional power trade can improve energy security allowing greater access to renewable energy and encourage investment by boosting economies of scale in production (IRENA, 2015b). As hydropower is an important source of electricity in the basin, intra-basin power trade can also become part of a solution for the water allocation problem by shifting the focus from the amount of water allocated for hydropower production in a particular country to the amount of energy access regardless of the source (either from domestic production or trade). With aim of promoting power trade between the four Eastern Nile countries, the NBI through its subsidiary program, ENSAP conducted extensive assessment of power trade prospects under the Eastern Nile Power Trade (ENPT) project. The project had identified various investment options for power generation and transmission in the basin (NBI, 2001; 2009). Currently, power trade in the basin is mainly conducted either through regional power pools or bilateral deals created between countries. Ethiopia and Egypt are already involved in electricity export to neighbor countries. Since 2013, Ethiopia is exporting electricity to Djibouti (60 to 80 MW), Sudan (100 MW) and Kenya (10MW). In 2015/16, the country exported a total 511 GWh of electricity and earned 31.5 million USD (National Bank of Ethiopia (NBE), 2015/16). Egypt is also engaged in electricity trade and exchange mainly with Libya, Jordan, Lebanon and Syria through the North African and Middle East Power Pools. In 2015/16, Egypt exported 747 GWh of electricity and imported 54 GWh of electricity where part of it is electric exchange (EEHC, 2015/16).

There are also several proposed and committed deals between Nile basin states and other East African countries which are not part of the basin. The Ethio-Kenya transmission line is under construction (set to be completed in 2018) which has a capacity to convey up to 2000 MW of electricity where the transfer of 400 MW will be done in the first phase. Ethiopia also plans to export up to 400 MW of electricity to Tanzania through Kenya. A potential for 3,200 MW of electricity export from Ethiopia to Sudan and Egypt is also estimated under the Eastern Nile Power Trade Study, out of which 1200 MW is to Sudan and 2000 MW is to Egypt via Sudan (IRENA, 2015b). The EAPP which was established in 2005 is a major actor in facilitating power pooling (interchange of electric power based on difference in time of peak load over a large network of grid system) and trade between East African countries (EAPP, 2014; IRENA, 2015b). Egypt is also in the process of implementing a power exchange system with Saudi Arabia reaching up to 3000 MW based on the difference in timing of peak load between the two countries (EEHC, 2015/16). Since the basin also encompasses one of the world's major producers of oil and natural gas, energy trade beyond electricity is also possible in the region. A considerable trade in refined petroleum already exists between Ethiopia and Sudan.

4.10.4. Issue Linkage

Once strong economic and institutional connections are created in the basin, issue linkage which involves tying multiple issues in negotiation process can serve as important means of cooperation in the basin. The concept of issue linkage for long has been discussed as a way to facilitate and enforce international negotiations (Tollison and Willett, 1979; Haas, 1980; Davis, 2004; Poast, 2013). Issue linkage provides a wider range of options for negotiating parties and creates additional motivations for cooperation apart from monetary side payments (Dombrowsky 2010). Accordingly, it increases the likelihood of reaching an agreement between countries as well as their dedication to staying in it (Poast, 2013). In the case of transboundary basins, both intra-water (Dombrowsky, 2009; 2010; Bhaduri and Liebe, 2013) and non-water sector (Pham Do et al., 2012**;** Pham Do and Dinar; 2014) issue linkages have been suggested as potential means of cooperation. Intra-water issue linkage is shown to be effective means of cooperation in a bilateral context where riparians take reversed position (Dombrowsky, 2010). Given that the Nile basin is a liner river system, non-water issue linkages might be more effective for the basin than intra-water issue linkage. Using linked games approach, Pham Do et al. (2012) discussed how non-water issue linkage can promote stable agreements. Later, Pham Do and Dinar (2014) also showed linking water issue with trade issue can solve water allocation problem in the Mekong river basin.

Linking independent issues to water allocation negotiations in the Nile basin could avoid non-cooperative behavior and reduce conflicts. For instance, trade liberalization measures such as reducing import tax and lifting quotas can be linked to water issues to enforce cooperative behavior in the basin. Kahsay et al. (2017a) indicated that trade liberalization and facilitation (i.e. reduction of tariff and non-tariff trade barriers) results significant economic and welfare gain for all Nile basin countries. Thus, excluding a non-cooperative country from trade liberalization and facilitation deals which could result in loss of potential economic and welfare gains emanating from them might be used as credible threats to enforce cooperative behavior in water allocation issues. Trade cooperation issues can also take the form of countries specializing based on their comparative advantage. Wichelns et al. (2003) suggested that Ethiopia should concentrate in producing hydropower and livestock, Sudan in food crops (such as sorghum, wheat, and rice) and Egypt in higher-value crops (fruits and vegetables). Such measures could however be difficult to implement in the short-run as they implicitly demands restructuring the political economy of countries. In general, the effectiveness of linking trade or other issues to water issue in the Nile basin will depend on the strength of existing and future ties between countries of the basin regarding the linked issues.

4.11. Conclusion

The question of how can transboundary rivers best meet the WEF needs of riparian populations is crucial to answer. Such attempt will include quantifying tradeoffs and synergies between the WEF sectors so as to optimize outputs across sectors and scales. As most of the riparian countries in the Eastern Nile basin are faced with high poverty and serious ongoing problem in meeting demand for the three resources, empirical evidence on the WEF nexus is needed to improve resource use efficiency and avoid adverse impacts of single-sector development strategies. The nexus approach can be used as a mechanism for quantifying the tradeoffs and synergies between the sectors themselves and across countries. Accordingly, this study applied an integrated optimization hydro-economic model for analyzing potential economic impacts associated with various levels of water resource developments and, sectoral and country prioritization scenarios in the Eastern Nile basin. Particularly, changes in economic benefits and potential tradeoffs across sectors and riparian countries under cooperative (system optimization) and non-cooperative (sectoral or country prioritization) scenarios with various levels of water resource developments in the basin are assessed. A considerable number of previous studies have applied hydro-economic models developed for the basin to address various issues related to water resource development and management. This study made contributions to the existing literature by examining the implication of various levels of water resource developments under different sectoral and transboundary prioritization scenarios. Sensitivity analyses concerning potential future agricultural intensification (i.e. improvements in irrigation efficiency and yield) in Ethiopia and Sudan with large irrigation developments in the future are also conducted.

In general, results indicate that if managed cooperatively, upstream water storage developments for the purpose of hydropower production are beneficial for all basin countries. In addition to producing clean and affordable energy which are key for economic development, dams which are constructed for hydropower production could also have synergic impacts by providing additional benefits such as regulating water flows and, reducing drought and flood risks. However, future irrigation developments in upstream countries could inflict cost on downstream water users (mainly in Egypt) unless measures are taken to enhance irrigation efficiency in the basin. Also, there could be considerable sectoral and transboundary tradeoffs in the Easter Nile basin if resources and associated infrastructures are not managed in a cooperative manner. Results from the sectoral and transboundary tradeoff analysis show that the sector or the country which gets priority gains while the other sector or riparian countries incurred a loss. Total economic benefits in the basin are lower in the case of noncooperation (sectoral and country prioritization) scenarios than the cooperation scenario in most of the water resource development scenarios considered in the study. However, there are also potential synergies that can enhance the benefits of future water resource development in the basin mainly through developing upstream water storage facilities for hydropower production and, improving water use efficiency and productivity in existing and proposed irrigation schemes. Therefore, based on the results from our analysis we can reinforce the notion that cooperation between sectors and countries is more beneficial for the basin than unilateral actions which has been indicated by a number of previous studies. Given the complex and dynamic nature of WEF nexus in the region, various mechanisms of cooperation which combine technical, economic and institutional solutions are needed to bring effective collaboration in the basin.

5. Climate Change and the Water-Energy-Food Nexus in the Eastern Nile Basin

5.1. Introduction

The nexus between WEF is shaped by several driving factors which influence one or more of the individual sectors. Climate change, population growth, urbanization, rapid economic development, degradation and scarcity of natural resources (including water and land), and globalization are the main factors which influence WEF nexus worldwide (Hoff, 2011; Rasul, 2014; Leck et al., 2015). Among these cross-cutting issues, climate change is more complex because its impacts (direct or indirect) as well as mitigation and adaptation strategies, affect more than one sector (Hoff, 2011; Rasul and Sharma, 2016; Pardoe et al., 2017). Major global climate change projections include increasing temperature, declining snowpack, more frequent, severe and prolonged extreme events and sea level rise in the future (Intergovernmental Panel on Climate Change (IPCC), 2014). Such climate change induced occurrences will add to the complex WEF nexus relations by intensifying pressures on natural resources and creating more uncertainty. Particularly, rising temperature, changed precipitation patterns, and recurrent and intense droughts or floods will create high uncertainty in water supplies adversely impacting the reliability of productivity in WEF sectors (Holtermann and Nandalal, 2014; Carter and Gulati, 2014; Liu, 2016; Zhang et al., 2018). The relationship between WEF productivity and climate change is also bi-directional in the sense that changes in food and energy production which alter the use of water, land and other natural resources are often the main causes of climate change (Hoff, 2011).

The direct impacts of climate change on weather events and sustainability of ecosystems will ultimately impact the livelihood, vulnerability, and resilience of societies through its effect on production systems (WEF) they depend on (Biggs et al., 2015). Such impacts are expected to become more intense on people living in already exposed and marginal areas requiring mitigation and adaptation measures that safeguard future WEF security (Holtermann and Nandalal, 2014). However, climate change mitigation and adaptation policies, strategies and measures per se may in turn have implications for WEF security and often demand efforts beyond one sector to be effective (Hoff, 2011; Carter and Gulati, 2014; Pardoe et al., 2017). Climate change mitigation measures such as carbon sequestration (e.g. REDD+) and renewable energy developments (including biofuels and hydropower) can generate substantial new demands on water and land resources. Also, competition for water between food and energy sectors could become more intense due to climate change adaptation measures such as expansion and intensification of irrigation, increased water storages facilities, larger uses of groundwater and more water desalination activities which are highly energy intensive. Thus, nexus thinking is required for climate change policies be effective and has minimum negative externalities across various WEF domains (Hoff, 2011; Carter and Gulati, 2014).

Though the effect of climate change is predicted to be global, the type and extent of its actual impact will vary across regions (IPCC, 2007; IPCC, 2014). Some regions of the world are more exposed and vulnerable to climate change impacts, and the Nile basin is one such region. Several factors makes the basin particularly susceptible to impacts of climate change where the major ones are: (1) existence of very prone arid and semi-arid areas which account 40% of the basin, (2) high sensitivity of the Nile flows to changes in precipitation, (3) high incidence of and exposure to droughts and floods in the past, (4) food and energy (mainly hydropower) production systems which are heavily reliant on rain (upstream) or Nile river (downstream), (5) low coping and adaptation capacity of communities due to their high dependence on climate sensitive sectors mainly agriculture (including fishery and livestock) and (6) rapid population growth which will create more stress on natural resources (NBI, 2012a). So far, several studies have analyzed the potential impact of climate change on climate variables (mainly temperature and precipitation) and hydrology of the Nile basin using different techniques at various spatial scales (Conway and Hulme, 1996; Yates and Strzepek, 1998; Strzepek et al., 2001; Elshamy et al., 2006; Kim et al., 2008; Elshamy et al., 2009; Soliman et al., 2009; Beyene et al., 2010; Nawaz et al., 2010; Bhattacharjee and Zaitchik, 2015; Haile and Rientjes, 2015; Gebre and Ludwig, 2015; Mekonnen and Disse, 2016; Worqlul et al., 2017). Though these studies consistently indicated that climate change will result in a higher temperature in the basin, their findings regarding the extent and direction of change in precipitation and river runoff is diverse and inconclusive (Elshamy et al., 2009). Since the Nile basin comprises sub-basins with different climate and hydrological regimes, predicting how the collective responses to climate change from each sub-basin are going to affect the flow of the Nile is not straightforward (NBI, 2012a).[48] Studies which analyzed the impact of climate change on hydrological extremes in the future also found different results – both an increase and a decrease in episodes of high and low river flows – depending on the climate change model (General Circulation Models (GCMs))[49] and downscaling methods used (Taye et al., 2015).

Despite disagreements on extent and directions of changes however, findings of previous studies clearly show that climate change will considerably impact the environment and hydrology of the basin. Accordingly, to reduce the potential disrupting impact of climate change on socio-economic activities and livelihood of people in the basin, building water storage infrastructures (with multipurpose use) have been emphasized as relevant coping or adaptation mechanism among several other measures (NBI, 2012a). But, the performance of water storage infrastructures as a coping or adaptation mechanism will also be determined by climate change through its implication on water availability required for their operation (McCartney and Girma, 2012). Besides looking the impact of climate change on the weather and water resource of the basin, some studies went further and analyze the effect of such changes on the performance and operation of existing and planned water resource developments in the Nile basin (Jeuland, 2010; Block and Strzepek, 2010; McCartney and Girma, 2012; Jeuland and Whittington, 2014;

[48] Most of the previous climate change studies focused on the Upper Blue Nile sub-basin given that the sub-basin is the largest contributor of water to the Nile system (Kim et al., 2008; Elshamy et al., 2009; Soliman et al., 2009; Haile and Rientjes, 2015; Gebre and Ludwig, 2015; Mekonnen and Disse, 2016; Worqlul et al., 2017).

[49] As defined by the IPCC, GCMs are “climate models which represent physical processes in the atmosphere, ocean, cryosphere and land surface, and are the most advanced tools currently available for simulating the response of the global climate system to increasing GHG concentrations”.

Mostafa et al., 2016). These studies indicated that climate change will have a significant effect on irrigation and hydropower production in the basin. For the Blue Nile sub-basin, McCartney and Girma (2012) showed that with climate change, only less than 40% of the total irrigation water demand will be satisfied and close to 60% of potential hydropower will be produced by the late twenty-first century. Climate change will thus intensify uncertainty affecting the economic return and attractiveness (hence choice) of future water resource infrastructures in the basin (Jeuland, 2010; Jeuland and Whittington, 2014). It could also make some of the future hydropower and irrigation developments infeasible by altering the seasonal availability of water (Block and Strzepek, 2010). Therefore, the potential impact of climate change on large-scale water storage infrastructures and, food and energy production systems relying on them has important implication for WEF nexus analysis in the basin. In addition to its impact on water resources, climate change induced rise in temperature could also increase crop water requirement through its effect on crop yield and evapotranspiration rate. Potential reduction in quantity and quality of crop yield, increased rate of evapotranspiration and higher evaporation from reservoirs will put further pressure on resources touching major elements of the WEF nexus (Blackmore and Whittington, 2008; Holtermann and Nandalal, 2014).

Insight of these, the objective of this study is to examine the potential impact of climate change on water allocation and associated economic benefits across sectors and countries in the Eastern Nile basin by 2050 using an integrated optimization hydro-economic model, ENMOS (ENTRO, 2014b). To analyze the impact of climate change on economic benefits obtained from irrigation and hydropower generation, changes in river flow, crop yield, evapotranspiration and precipitation (effective rainfall) are taken into account, where the latter is considered to assess changes in irrigation water demand. Also, potential land subsidence due to climate change induced Sea Level Rise in the Nile delta and the associated reduction in irrigated area in Egypt is considered. In addition to climate change, population growth is also a key factor driving the WEF nexus as it accelerates demand for various resources. Capturing the full impact of the future change in the magnitude and composition of the basin's population (such as expanding middle class and concomitant changes in lifestyle and diet) is not possible in hydro-economic modeling framework. Thus, the impact of population growth is represented only by a projected increase in M&I water demand in Egypt by 2050. All of these changes are analyzed under the assumption of full hydropower and irrigation developments in the Eastern Nile basin. It is assumed that in 2050 all the proposed irrigation expansion and hydropower development projects in the Eastern Nile basin will be implemented. This entails the expansion of total installed hydropower capacity in the basin to 20,230 MW and irrigation area to about 6.6 million ha. The actual developments that will realize at the time could however be different from the assumptions made in this study.

This study will add to existing literature on potential effects and implications of climate change in the Nile basin by making the first attempt to analyze the impact of climate change predictions made based on IPCC's fifth report using an integrated hydro-economic model developed for the Eastern Nile basin. The hydro-economic model used for this study is relatively up to date (mainly in terms of input data) and contains relevant hydrologic, agronomic and economic components (see section 4.5 in chapter 4 for details). The hydrologic component well represents the basin's hydrology as it incorporates several inflow nodes that exist in major sub-basins of the Eastern Nile. The agronomic module is also fairly comprehensive because it incorporates a number of existing and proposed irrigation sites as well as 32 major irrigated crops which are cultivated in the four Eastern Nile basin countries. This allows us to map the projected climate changes impacts on crop yields as well as water uses to several irrigated crops in the basin. By doing so, the study will assess the effects of climate change on water use and economic benefits obtained from irrigation and hydropower production, and will provide insights on the role climate change plays in the WEF nexus in the basin.

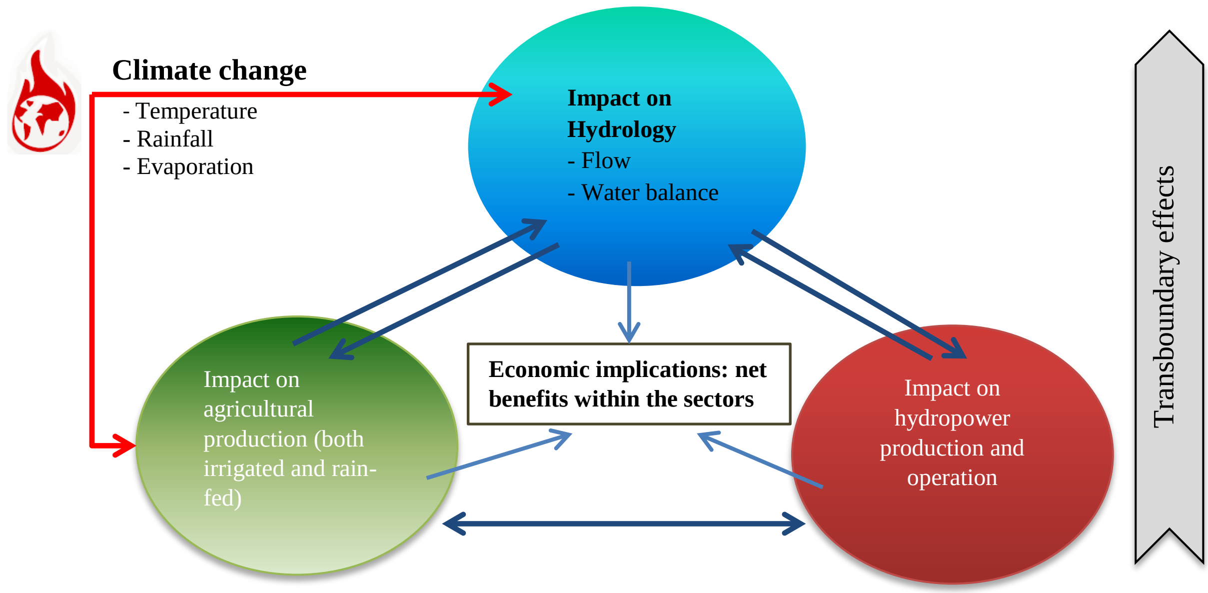
The rest of this chapter is organized as follows. In section 5.2, the conceptual framework used for the study is briefly discussed. Section 5.3 will present the data used and the steps followed to make the climate change analysis. Climate change related predicted changes regarding; river inflow, crop yield and irrigation water requirement will be described in section 5.4. Results from the hydro-economic model and a brief discussion of these results will also be given in section 5.5. Section 5.6 provides the main conclusions of the chapter.

5.2. Conceptual Framework

The impact of climate change works through many channels affecting both natural and human systems across the globe (IPCC, 2014). Figure 5.1 illustrates the conceptual framework used for this study to analyze the effect of climate change on WEF systems in a river basin context (Bach et al., 2012). The inter-linkage between WEF resources per se involves several externalities and climate change is a great addition. Climate change related changes in temperature and rainfall, as well as other climate variables, will have a direct effect on hydrological systems (surface and groundwater) though the extent and direction of the effect will largely vary across geographical locations. Lower water availability and, more frequent and extended dry seasons are projected for most countries in sub-tropical and tropical areas (IPCC, 2014). Increased temperature or lower precipitation rate (both) might result in less river flow thereby affecting the water balance. Such changes will have further influences on food and energy systems which are directly dependent on the availability of water. Climate change could also have a direct impact on agricultural productivity through its effect on crop yield and evapotranspiration rate. Also, the interaction between climate change induced changes in river flow and, food and energy production systems is multidirectional. For instance, increased irrigation water demand either due to lower crop yield or higher evapotranspiration rate will affect water available for hydropower production.

In river basin context, the effects of climate-induced changes are not limited locally; it will also have transboundary implications. Change in river flow in upstream countries due to climate change could have an effect on water availability in downstream riparian countries. Similarly, climate change related changes in water demand from food or energy sectors in one country will affect water available for use in other riparian by the same sectors. Also, climate change adaptation measures that are taken in each domain of the WEF nexus can have either positive or negative externalities on others. In general, direct and indirect relationships between climate change and WEF nexus could entail several tradeoffs (and potential synergies) across sectors and scales having complicated interactions and feedbacks with the overall ecosystem. Climate change induced changes in agricultural and energy production will eventually have economic implications because the benefits obtained from the sectors will be influenced.

Figure 5.1: Conceptual framework for impacts of climate change on WEF nexus



Source: Adapted from Bach et al. (2012)

The economic impacts of climate change work through its effect on the supply and demand of goods and services provided by the natural environment (Callaway et al., 2011). Besides being a habitat for humans and other species, the natural system (ecosystem) is the main provider of numerous raw materials (such as water and land) which are either directly consumed or used for production in major economic sectors. Physical impacts of climate change which may alter the quantity and quality of ecosystem services will have implications on major economic sectors of agriculture (including forestry, livestock, and fishery), energy, industry, tourism, and transportation (Watson et al., 1996).[50] Estimates show that climate change could result in significant damage to many developing and emerging economies leading to a permanent cut in consumption and economic growth globally (Stern, 2007). The extent of these damages will vary depending on current and future level of economic development and possession of physical and human capital (OECD, 2015). Valuing the macroeconomic costs or damages of climate change is not, however, an easy task. This is because the impact of climate changes on the economy works through several direct and indirect channels. The direct impacts are mainly reflected through damages on natural, physical and human capitals. These changes will have indirect effects by

[50] Climate change induced changes in the supply of and demand for goods and services in main sectors of the economy will then affect market prices having further influence on consumer and producer surplus. The cumulated impacts of climate change on individual producers and consumers will ultimately be reflected in aggregate economic indicators of GDP (economic growth), employment, inflation, consumer and government expenditure and, investments (OECD, 2015; Callaway et al., 2011).

disrupting economic activities which are dependent on the various capitals.[51] In general, both the supply of and demand for food and energy will be affected by climate change and changes in the specific sectors will have a consequence on other sectors relying on them. However, since this study uses a hydro-economic model for the analysis (which is a partial equilibrium model), only the production/supply side of climate change impacts on the two sectors is modeled.

5.3. Data and Analytical Approaches

The climate change scenarios used in this study are based on IPCC's fifth assessment report (IPCC, 2014). Data from five GCMs including GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5 – the medium and highest emission scenarios respectively) are used for the climate change analysis.[52] These are the same climate change scenarios which are applied in the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Robinson et al., 2015) where the original data was prepared under the Inter-sectoral Impact Model Intercomparison Project (Hempel et al., 2013). Details on the GCMs and downscaling procedures of the climate data can be found in Hempel et al. (2013). The IMPACT database provides comprehensive baseline projections (with no climate change) by 2050 with its base year in 2005, for 320 food processing units (FPU) in 159 countries and 154 basins including the Nile (Robinson et al., 2015). The climate change projections are also conducted out to the year 2050. For this study, climate change related data is extracted for Ethiopia, Sudan, South Sudan and Egypt for their territory lying in the Nile basin.

Figure 5.2 shows the procedures followed to make the climate change analysis. The implications of climate change on the water resources of the basin is assessed by mapping predicted changes from the five GCMs (under the two RCP scenarios) for each country of the basin to inflow nodes in the hydro-economic model, ENMOS. Similarly, climate change projections with respect to crop yield for several rain-fed and irrigated crops which were obtained from the IMPACT projections are mapped to irrigation nodes in ENMOS. Estimated responses of crop yield to climate change are based on climate change related changes in temperature, evapotranspiration, and precipitation for rain-fed crops and only temperature for irrigated crops (where changes in potential evapotranspiration, effective rainfall and applied irrigation water are captured separately for irrigated crops). The impact of climate change induced Sea Level Rise on irrigated area in Egypt is based on estimates made in Kahsay et al. (2017b) which predicted 4.3% reduction in irrigation land in Egypt due to 0.5m rise in sea level by 2050 (see Kahsay et al., 2017b for details on the assumptions for these prediction). M&I water use in 2050 for Egypt is

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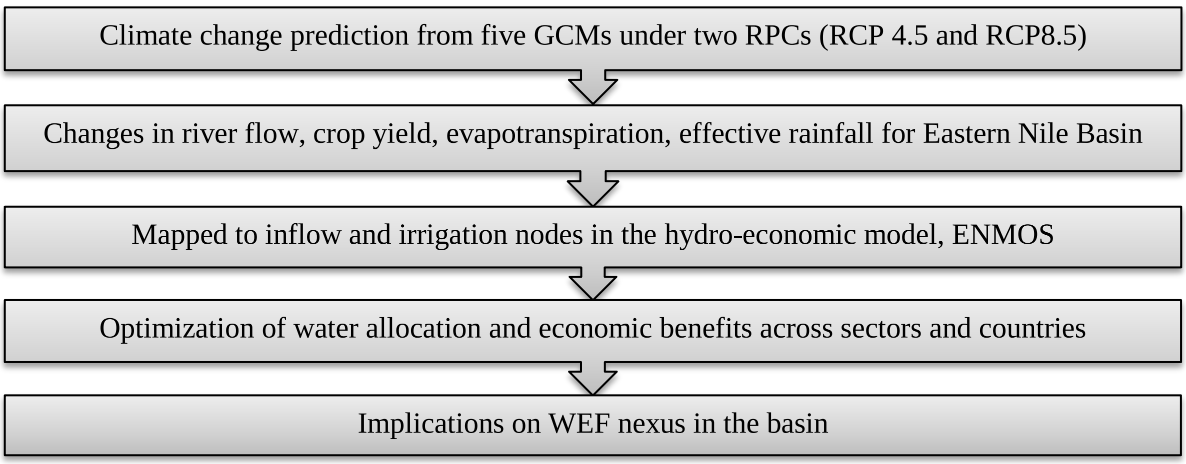
[51] Natural capital includes land and water where as physical capitals are infrastructures (roads, bridges, energy), assets (like houses), and industries (variable and fixed inputs). Climate change could result in displacement, migration, injuries (health problems) and death of people affecting human capital (the workforce). It could also affect features of life which are not directly related to economic activities such as human culture and security (OECD, 2015).

[52] RCPs are "potential levels of GHG emissions and atmospheric concentrations in 21st century which determine possible ranges of radiative forcing values (i.e. difference between sunlight absorbed by the earth and energy radiated back to space)" (IPCC, 2014).

estimated based on population growth projection data from the United Nation's World Population Prospects, 2015 Revision (UN, 2015b). After introducing these changes into the hydro-economic model, optimal water allocation and hydropower and irrigation benefits are determined under climate change (see section 4.5 for details on the optimization process of the hydro-economic model).

Figure 5.2: Steps of the climate change analysis



Source: Author's illustration

5.4. Predicted impacts of climate change for the Eastern Nile basin

In this section, the climate change predictions from five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M which will be shortened as GFDL, HGEM, IPSL, MIRC and NESM respectively in the rest of the paper) under two RCP scenarios (RCP4.5 and 8.5) regarding river flow, crop yield and irrigation water requirement are presented. Table 5.1 shows predicted percentage changes in river inflow (from simulated historical inflows) by major sub-basins of the Eastern Nile basin in 2050. These changes are calculated by imposing the projected hydrological impacts of climate change for the ten climate change scenarios on 102-year historical time series flow data (1900-2002) for each inflow node in the hydro-economic model (ENMOS). The predicted changes for total inflow in the basin greatly vary across GCMs and radiative forcing (RCPs) widely ranging between -7% to +136%. Reduction in total basin-wide inflow is predicted by two climate models (HGEM4.5 and MIRC4.5) while the remaining climate change scenarios predicted an increase in total inflow. Two climate change scenarios – IPSL4.5 and IPSL8.5 – predicted a dramatic increase in total basin-wide inflow (more than 100%).[53] Looking at inflow changes by sub-basin, relatively higher number of

[53] As it is discussed in Aich et al. (2014), the distinct increases in runoff predicted by the IPSL model is due to the large increase in precipitation, generated by the bias correction method used in Hempel et al. (2013). In some cases, the trend-preserving bias correction method is indicated to result extreme precipitation corrections (at the baseline) mainly in months following the rainy season, causing a very high increment in precipitation during the respective months in future scenarios (Aich et al., 2014).

climate change scenarios predicted increased inflow in all sub-basins. Reduced inflow from the Blue Nile sub-basin is predicted by four climate change scenarios (GFDL8.5, HGEM4.5, HGEM8.5, and MIRC4.5) ranging between 0.3% and 8%. For the Baro-Akobo-Sobat (BAS) sub-basin, about 4% and 2% reductions in inflow are predicted by MIRC4.5 and MIRC8.5 respectively. Also, decreased inflow from the Tekeze-Setit-Atbara (TSA) sub-basin is projected by four climate change scenarios (GFDL8.5, HGEM4.5, HGEM8.5, and MIRC4.5) varying between 3% and 11%. Thus, similar to previous studies, these results show the existence of great uncertainties in predicting the impact of climate change on the flow of river Nile.

Previous studies which predicted the impact of climate change on precipitation and runoff for the Nile region obtained very diverse results (see e.g., Conway, 2005; Taye et al., 2015; Barnes, 2017 for detail review of studies on the impact of climate change in Nile basin). The emission or RCP scenarios, the type and number of GCMs, the downscaling methods, the hydrological models, the spatial scale of analysis and the prediction timespan varies across studies making the comparison of results very difficult. The question of which GCM is more suitable or reliable in predicting the impact of climate change in the Nile region (mainly on the water cycles) is crucial but not easy to answer. So far, there are no studies that clearly indicate which GCMs perform well in all relevant evaluation criterions and suggested to be used for the Nile basin. Bhattacharjee and Zaitchik (2015) examined the performance of 10 GCMs regarding their ability to project precipitation for the Nile basin based on various criterions (i.e. how they capture rainfall amount and seasonality, inter-annual variability, precipitation teleconnections, and continental scale climate patterns). The study found that no model outperforms in all of these criterions and the GCMs which performed well in one of the metrics also make diverse predictions regarding precipitation changes. Accordingly, given that evaluating the regional performance of climate models is beyond the scope of this study, the climate change predictions from all the five GCMs will be analyzed using the hydro-economic model to address diverse possibilities of climate change impacts in the basin.

Table 5. 1: Inflow with climate change by sub-basin (% changes by 2050 from historical period)

Climate change (CC) scenarios	BN	BAS	TSA	Total
Average annual inflow under no CC*	54437.3	38247.6	12794.7	105479.6
GFDL_4.5	14.7	20.8	9.1	16.2
GFDL_8.5	-0.3	16.5	-3.0	5.5
HGEM_4.5	-7.0	5.1	-10.1	-3.0
HGEM_8.5	-1.7	10.9	-5.4	2.4
IPSL_4.5	116.5	90.0	104.9	105.5
IPSL_8.5	151.7	113.5	138.5	136.3
MIRC_4.5	-7.9	-3.5	-10.5	-6.6
MIRC_8.5	5.7	-1.6	4.1	2.8
NESM_4.5	22.1	11.9	20.3	18.2
NESM_8.5	11.8	5.9	11.2	9.6

*Absolute value in MCM, averaged over 1900-2002

Table 5.2: Yield of rain-fed and irrigated crops with climate change (% changes by 2050)

Crops by country	GFDL_4.5	GFDL_8.5	HGEM_4.5	HGEM_8.5	IPSL_4.5	IPSL_8.5	MIRC_4.5	MIRC_8.5	NESM_4.5	NESM_8.5
Ethiopia (irrigated)										
Maize	4.8	3.0	1.5	-1.0	7.2	3.3	5.3	1.9	3.7	4.0
Wheat	-7.3	-11.0	-13.5	-17.2	-10.0	-18.6	-8.5	-15.5	-4.5	-9.7
Other cereals (barely, rice)	-3.7	-5.6	-7.0	-9.0	-5.1	-9.8	-4.3	-8.1	-2.3	-5.0
Oilseeds (groundnut, sunflower, soybean)	2.1	-0.5	-2.5	-2.9	2.5	0.4	0.6	-1.6	3.4	3.1
Legumes (field peas, castor bean, lentils)	2.0	-0.3	-1.2	-1.4	2.1	0.3	0.5	-0.8	3.3	2.8
Potato	-1.1	-6.3	-16.0	-21.4	-6.5	-19.1	-5.0	-11.2	-4.0	-6.0
Sugarcane	4.8	3.0	1.5	-0.5	7.2	3.3	5.3	1.9	3.7	4.0
Onion	-6.7	-10.3	-13.1	-16.7	-9.3	-17.9	-7.9	-14.8	-4.2	-9.1
Fodder	8.7	13.0	12.6	13.3	11.4	11.2	10.6	11.5	10.0	10.8
Other crops (fruits, red-pepper, ginger, coffee, tobacco)	-3.4	-5.3	-6.8	-8.7	-4.8	-9.4	-4.0	-7.7	-2.1	-4.7
Ethiopia (rain-fed)										
Barley	-3.3	-4.7	-5.8	-6.3	-2.5	-9.9	-4.0	-9.1	-0.3	-4.7
Cotton	-5.5	-8.0	-10.2	-11.2	-3.7	-17.0	-7.0	-16.2	0.1	-8.2
Groundnut	11.6	12.1	8.7	6.5	13.0	16.2	-5.7	4.9	9.0	5.9
Maize	4.3	2.1	6.4	2.6	-2.5	-0.7	-0.1	5.3	3.5	7.6
Oilseeds (sesame, noug)	-5.5	-8.0	-10.2	-11.2	-3.7	-17.0	-7.0	-16.2	0.1	-8.2
Rice	24.6	34.4	34.4	34.4	34.4	34.4	26.4	28.3	16.5	19.7
Teff	-3.3	-4.7	-5.8	-6.3	-2.5	-9.9	-4.0	-9.1	-0.3	-4.7
Wheat	-57.4	-59.1	-60.3	-62.0	-58.7	-62.6	-58.0	-61.2	-56.2	-58.6
Sudan (irrigated)**										
Cotton	-15.0	-24.5	-28.5	-40.2	-17.3	-28.2	-17.6	-24.7	-12.6	-18.2
Oilseeds (groundnut, sunflower, sesame)	-16.3	-26.2	-28.9	-37.7	-18.0	-29.3	-17.0	-22.9	-12.9	-16.8
Rice	-14.8	-26.0	-29.3	-42.6	-15.4	-28.4	-10.0	-15.7	-6.7	-10.4
Sorghum (and fodder)	-15.5	-17.5	-18.6	-26.4	-13.2	-22.8	-11.7	-17.6	-8.0	-12.2
Sugarcane	-29.6	-38.9	-40.4	-43.1	-28.6	-42.1	-20.0	-27.4	-15.9	-21.6
Vegetables	-5.8	-30.5	-54.4	-67.2	-33.9	-63.3	-43.8	-67.2	-24.7	-46.5
Wheat	-11.6	-19.0	-26.5	-46.3	-14.6	-23.6	-18.5	-28.5	-11.7	-21.5
Egypt (irrigated)										
Fruits (apple, banana, orange)	-2.3	-5.0	-5.2	-9.0	-4.2	-10.1	-6.4	-7.7	-4.0	-5.9
Barley	-1.5	-2.7	-2.6	-4.4	-1.9	-5.2	-3.0	-3.2	-2.0	-2.8
Bean	-4.2	-6.9	-7.2	-10.2	-6.4	-8.0	-7.8	-11.4	-5.8	-8.0
Cabbage	-2.3	-5.0	-5.2	-9.0	-4.2	-10.1	-6.4	-7.7	-4.0	-5.9
Cotton	-2.3	-5.0	-5.2	-9.0	-4.2	-10.1	-6.4	-7.7	-4.0	-5.9
Maize	-10.4	-16.3	-17.1	-23.3	-19.5	-17.9	-18.8	-25.7	-15.2	-20.9
Peanuts	-7.4	-12.2	-13.2	-17.8	-11.8	-14.1	-13.7	-18.4	-10.5	-13.7
Potato	15.7	10.9	6.9	6.2	4.1	-4.8	8.8	-5.9	3.6	0.3
Rice	-2.9	-5.9	-6.0	-10.7	-5.6	-10.0	-8.5	-9.1	-4.2	-6.7
Sesame	-2.3	-5.0	-5.2	-9.0	-4.2	-10.1	-6.4	-7.7	-4.0	-5.9
Sorghum	-3.3	-4.0	-3.6	-5.4	-6.2	-5.8	-4.9	-7.3	-2.7	-6.1
Sugarcane	-5.3	-8.5	-9.0	-12.4	-10.2	-9.4	-9.9	-13.8	-7.9	-11.0
Sugar beet	-2.3	-5.0	-5.2	-9.0	-4.2	-10.1	-6.4	-7.7	-4.0	-5.9
Wheat	-3.0	-5.3	-5.2	-8.6	-3.7	-10.1	-6.0	-6.4	-4.0	-5.5

Note: ** **Including South Sudan**

The impact of climate change on the yield of major irrigated and rain-fed crops in basin countries which are incorporated in the hydro-economic model are given in Table 5.2. For rain-fed crops, predicted yield changes reflect climate change induced changes in temperature, evapotranspiration, and precipitation while for irrigated crops yield change reflects impacts from temperature only.[54] Though the predicted yield changes due to climate change vary across climate change scenarios, crops and basin countries, most projections show a reduction in crop yields by 2050. For Ethiopia, both irrigated and (partially) rain-fed crops (i.e. cultivated in wet seasons of the cropping calendar and supplemented with irrigation in dry growing seasons) are considered in the hydro-economic model. For irrigated crops in Ethiopia, a relatively larger decrease in yield is projected for cereals (wheat, barley, and rice) and vegetables (potato and onion) by all climate change scenarios. Except for one climate change scenario, yield increase is predicted for irrigated maize and sugarcane in Ethiopia. Similarly, for irrigated legumes, most climate change scenarios predicted yield increment. Significant yield reduction is predicted for most rain-fed crops (barely, cotton, oilseeds, teff, and wheat) in Ethiopia by all GCMs whereas all climate change scenarios predicted an increase in yield for rain-fed groundnut and rice. Yield increment is also anticipated for rain-fed maize by seven climate change scenarios out of ten. Relatively larger reduction in yield is predicted for rain-fed crops than irrigated crops. For Sudan, South Sudan and Egypt, only irrigated crops are included in the hydro-economic model. All GCMs in both RCP scenarios predicted substantial yield reduction for the entire irrigated crops included in the hydro-economic model for Sudan and South Sudan in 2050. The HGEM8.5 scenario predicts the largest reduction in yield for all crops. Up to 67% reduction in yield is predicted for vegetables whereas 40% to 45% reductions are anticipated for cotton, rice, sugarcane, and wheat. Similarly, notable yield reductions are predicted for all irrigated crops (except potato) in Egypt that are incorporated in ENMOS. Lager reductions in yield are predicted for irrigate Maize (up to 26%) and peanuts (up to 18%) in Egypt.[55]

For irrigated crops, the effect of climate change related changes in potential evapotranspiration and precipitation (effective rainfall) is modeled separately from yield impacts of climate change. Table D.3 in Appendix D illustrates irrigation water requirements by crop which is potential evapotranspiration (crop evaporation coefficient (Kc)*reference evapotranspiration (ET_0)) minus effective rainfall with climate change for major irrigated crops in ENMOS for each country of the Eastern Nile basin in 2050. Climate change related predicted changes in irrigation water requirement for irrigated crops in Ethiopia are diverse across crops and climate change scenarios. It should be noted that since climate change is predicted to result in a higher temperature in the Nile basin, its effect on potential evapotranspiration is always positive. Hence, any decrease in irrigation water demand is due to increase in effective rainfall. Compared to the baseline (no climate change), seven out of ten climate change scenarios predicted an increase in irrigation water requirement for irrigated barley, field peas, lentils, tobacco and wheat in Ethiopia. Also, increase in irrigation water requirement from groundnut, onion, potato, soybean, and sunflower is projected by six climate change scenarios. Both reduction and increment in irrigation water

[54] The carbon fertilization effect on yield is not considered, given large uncertainty associated with it (Long et al., 2005).

[55] In addition to quantity, temperature rise (heat-stress) also has an impact on quality (nutritional content) of crop yield which is difficult to compensate through irrigation (Fahad et al., 2017).

requirement are predicted by an equal number of climate change scenarios for irrigated castor beans, coffee, fodder, maize, rice, and sugarcane. For the remaining crops, a decrease in irrigation water requirement is predicted by most GCMs (six to eight scenarios). Like Ethiopia, predicted changes in irrigation water requirement due to climate changes in Sudan vary across crops and climate change scenarios. Increase in irrigation water requirement is predicted by all GCMs for rice, sunflower, and wheat while increments are also predicted for vegetables, sugarcane and fodder crops by six scenarios. For cotton, groundnut, sesame, and sorghum only four climate change scenarios projected increased irrigation water demand. In the case of Egypt, the direction of projected changes in irrigation water requirement are consistent across GCMs (and RCP scenarios) for all crops where it is predicted to be higher in 2050 either due to increase in potential evapotranspiration or decrease in effective rain-fall (or both).

5.5. Results and Discussion

5.5.1. Results

This section describes results from the hydro-economic model where the predicted climate change induced changes in river flow, crop yield, evapotranspiration and sea level rise, as well as increased M&I water demand due to population growth, are simulated to see their impact on optimal economic benefits, water allocations and irrigated area across basin countries. Table 5.3 presents percentage changes calculated by comparing optimal results for key variables of interest with and without climate change assuming full irrigation and hydropower development in the basin. Total basin-wide economic benefit decreases in seven climate change scenarios while it increases in the remaining three scenarios. The decline in total basin-wide benefits ranges from 6% to 18% where the largest reduction is predicted under the HGEM8.5 scenario. Predicted increases in total basin-wide benefit also vary between 4% and 17% where the largest increment is seen under the IPSL4.5 scenario. Country-wise, a decrease in total economic benefit for Ethiopia is predicted under six climate change scenarios. The largest decrease of 16% is seen under HGEM4.5 while the largest increase in total benefit (49%) is predicted with IPSL8.5 scenario. For Sudan (and South Sudan) an equal number of climate change scenarios predicted an increase and a decrease in total benefit. The largest increase and decrease in total benefit for Sudan are predicted under IPSL4.5 (30%) and HGEM8.5 (-35%) scenarios respectively. A decrease in total economic benefit is predicted under eight climate change scenarios for Egypt. Among, the GFDL4.5 scenario predictions cause the largest reduction of 17%. Increments in Egypt’s total benefit are predicted only under the IPSL scenarios (2% to 8%) which also predicted an immense increase in total basin-wide inflow.

Table 5.3: Optimal economic benefits, water allocation and irrigated area under climate change (% changes from baseline or no CC)

	With no CC*	GFDL_ 4.5	GFDL_ 8.5	HGEM _4.5	HGEM _8.5	IPSL_ 4.5	IPSL_ 8.5	MIRC_ 4.5	MIRC_ 8.5	NESM_ 4.5	NESM_ 8.5
Total benefit											
ETH	2517.0	3.8	-11.6	-16.1	-10.2	39.3	49.3	-12.9	-9.7	15.9	-2.8
SUD**	3181.4	22.1	1.2	-22.4	-34.8	30.3	5.9	-13.1	-24.8	10.1	-0.6
EGY	9078.4	-17.2	-6.4	-14.5	-13.5	7.6	1.9	-14.1	-8.6	-0.1	-4.8
Grand total	14776.9	-6.3	-6.6	-17.2	-18.1	16.7	9.8	-14.5	-13.0	3.8	-4.5
Hydropower benefit											
ETH	1739.3	11.7	-0.2	-6.4	-1.7	60.7	72.1	-6.9	5.8	18.1	10.3
SUD	395.0	8.6	-5.8	-12.1	-7.8	41.8	43.1	-18.2	-7.0	12.1	-2.0
EGY	144.9	7.8	-1.5	-10.3	-4.6	95.3	102.5	-11.6	-2.1	18.2	2.7
Grand total	2279.2	10.9	-1.2	-7.6	-2.9	59.6	69.0	-9.1	3.0	17.1	7.7
Irrigation benefit											
ETH	777.7	-13.8	-37.2	-37.9	-29.4	-8.4	-1.5	-26.2	-44.3	11.1	-32.2
SUD**	2786.4	17.8	-2.9	-27.8	-41.9	22.1	-4.8	-16.7	-31.1	4.2	-5.4
EGY	8933.5	-17.6	-6.5	-14.5	-13.6	6.2	0.2	-14.1	-8.7	-0.4	-5.0
Grand total	12497.7	-9.5	-7.6	-19.0	-20.9	8.9	-1.0	-15.5	-15.9	1.4	-6.8
Total water allocation											
ETH	7534.4	13.1	-8.8	-19.5	-2.3	43.1	48.4	-16.7	-9.9	9.1	-6.1
SUD**	25298.4	54.1	27.9	14.0	19.1	130.6	153.2	-0.6	15.5	29.9	35.0
EGY	61218.6	-3.1	8.8	0.0	7.0	32.1	30.7	0.5	9.0	16.8	11.4
Grand total	94051.4	13.6	12.6	2.2	9.5	59.4	65.0	-1.2	9.3	19.7	16.4
Irrigation water allocation											
ETH	3982.2	24.5	-16.7	-36.8	-4.7	77.7	88.1	-32.6	-20.8	14.9	-13.8
SUD**	13989.3	90.9	68.0	47.9	55.6	184.7	221.9	29.3	47.5	46.7	76.7
EGY	45060.1	-3.5	14.9	2.8	12.6	39.9	37.5	3.7	15.2	24.4	18.0
Grand total	63031.5	19.2	24.7	10.3	21.1	74.4	81.6	7.1	20.1	28.7	29.0
Evaporation loss from reservoirs											
ETH	3552.2	0.4	0.1	-0.1	0.3	4.2	4.0	1.2	2.3	2.7	2.4
SUD	11309.1	8.6	-21.7	-28.0	-26.0	63.6	68.2	-37.6	-24.1	9.2	-16.5
EGY	16158.5	-1.8	-8.1	-7.7	-8.6	10.2	11.6	-8.4	-8.1	-4.3	-6.8
Grand total	31019.8	2.2	-12.1	-14.3	-13.9	29.0	31.4	-18.0	-12.7	1.4	-9.3
Irrigated area											
ETH	1379.6	0.9	-11.2	-9.6	-5.2	16.2	21.8	-10.1	-5.7	0.0	-8.4
SUD**	1215.2	41.1	43.9	35.2	39.5	88.9	101.1	33.9	41.0	26.4	51.9
EGY	4555.2	-15.5	-6.0	-10.9	-6.3	9.8	9.4	-10.9	-3.7	2.5	-1.8
Grand total	7150.0	-2.7	1.5	-2.8	1.7	24.5	27.4	-3.1	3.5	6.1	6.1

Note: *absolute value with no climate change where economic benefits are in Million USD, water allocations in MCM and irrigated area in thousands of ha; ** including South Sudan

Looking at economic benefits by sectors, total basin-wide hydropower benefit is predicted to increase with six climate change scenarios compared to the baseline (no climate change). Large increments in basin-wide hydropower reaching up to 69% are seen under the two IPSL scenarios. A decline in basin-wide hydropower benefits ranging between 1% and 9% is also predicted under four climate change scenarios. Ethiopia's benefit from hydropower production is expected to increase under climate change by six scenarios. The highest increments are observed with the IPSL4.5 and IPSL8.5 predictions (61% and 72% respectively) which are expected due to the dramatic increase in river flow forecasted by the respective scenarios. Reduced hydropower benefits for Ethiopia, predicted by four climate change scenarios range from 0.2% to 7%. For Sudan, economic benefit from hydropower production is predicted to decline in six climate change scenarios (2% to 18%). The IPSL scenario predictions results the largest increment in hydropower benefit for Sudan as well (more than 40%). Egypt's benefit from hydropower is also predicted to decrease due to climate change by five scenarios ranging from 1% to 12%. Close to and more than double increments in Egypt's hydropower benefit is predicted by IPSL4.5 and IPSL8.5 respectively. Basin-wide irrigation benefit is predicted to decline under most (eight) of the climate change scenarios (1% to 21%). Except for NESM4.5, all GCMs predicted that climate change will reduce irrigation benefit for Ethiopia. The predicted reductions in irrigation benefits for the country widely vary between 2% and 44%. Similarly, for Sudan and Egypt irrigation benefit is expected to decline due to climate change as it is indicated by most of the scenarios (seven for Sudan and eight for Egypt). The largest reduction in irrigation benefit of Sudan is projected in HGEM4.5 (42%) while for Egypt it is foreseen under the GFDL4.5 scenario (18%).

In general, though most of climate change scenarios (except HGEM4.5 and MIRC4.5) predicted that total basin-wide inflow will increase due to climate change, in most cases it could be more than compensated by higher irrigation water demand resulting either from reduced crop yield or higher evapotranspiration rate (or both) thereby reducing sectoral and transboundary economic benefits. This is shown by the increase in total basin-wide water use (the sum of irrigation water use and evaporation loss from reservoirs) which is predicted by nine of the climate change scenarios (exception – MIRC4.5). Basin-wide irrigation water use saw an increment in all GCM predictions while evaporation loss from reservoirs increases only in four of the climate change scenarios. The highest increment in total basin-wide water use is again observed in the IPSL scenarios which anticipated a dramatic increase in river inflows due to climate change. Lower total as well as irrigation water use is predicted under six climate change scenarios for Ethiopia while in almost all scenarios (except HGEM4.5) higher evaporation loss from reservoirs is foreseen in the country. For Sudan, increase in total and irrigation water use is predicted under all climate change scenarios (except MIRC4.5 for total water use) whereas evaporation loss from reservoirs in the country is predicted to be higher only with four scenarios. Similarly, the increment in total and irrigation water use by Egypt is predicted under nine out of ten climate change scenarios. However, evaporation loss from Egypt's reservoir (HAD) is predicted to decline under all climate change scenarios except IPSL4.5 and IPSL8.5. The total basin-wide irrigated area is anticipated to increase with seven climate change scenarios where it saw a reduction in the remaining three scenarios. Six scenarios predicted a reduced irrigation area in Ethiopia while under all GCM predictions an increase in irrigation area is anticipated for Sudan. Egypt's irrigated area is predicted to decline due to climate change under seven climate change scenarios. Most of these reductions in optimal irrigation area are more than the assumed 4.3% loss of irrigable area in Egypt due to climate change induced sea level rise.

5.5.2. Discussion

Though the Nile basin is indisputably indicated to be highly sensitive to impacts of climate change, providing clear and conclusive answers to questions of how climate change will affect the water resource of the basin, how these impacts are distributed spatially as well as what implications it will have for future policies in WEF sectors and potential mitigation and adaptation strategies still needs continuous study (UNEP, 2013b). Also, how climate change will influence ongoing and future cooperation mechanisms or potential conflicts among riparian countries of the basin is uncertain (NBI, 2012a; Link et al., 2012). The key variables which are selected to indicate impacts of climate change in this study including water availability, optimized benefits from irrigation and hydropower generation, water use by sector and country, and irrigated land showed that climate change could result in future changes and uncertainties in the Nile basin. Such changes will affect productivity and economic benefits obtained from the basin's key sectors of agriculture and energy having unpredictable impacts on national and regional economies (Strzepek and Yates, 2000; Kahsay et al., 2017b). If river inflow in the basin declines in the future, total economic benefits in all basin countries will decrease as it shown by HGEM4.5 and MIRC4.5 scenarios. However, even with increasing inflow, total benefit for all basin countries shows a reduction under the HGEM8.5, MIRC8.5, and NESM8.5 scenarios mainly due to lower crop yield and higher evapotranspiration causing increased irrigation water demand notably in Sudan and Egypt.[56]

The productivity of both hydropower and irrigation are influenced by climate change. Climate change affects hydropower production by altering either the amount of yearly flow or its seasonal pattern (Zhang et al., 2018). Total basin-wide hydropower benefits show a reduction in four climate change scenarios. In two of these scenarios (GFDL8.5 and HGEM8.5), total river inflow showed an increment. Thus, the reduction in hydropower benefit under these scenarios is associated with increased water use in irrigation implying that climate change could potentially exacerbate tradeoffs between the two sectors. Irrigation benefit is also is predicted to decline by the majority of the climate change scenarios mainly due to lower productivity per unit of water. The dramatic increase in river inflow projected in two IPSL scenarios results in increased basin-wide water use and economic benefits of both irrigation and hydropower generation. Higher river flow in the basin is found to improve hydropower potential but its impact on irrigation seems uncertain. However, a substantial increase in river flow could result in massive flooding (and soil erosion) in the basin even under the assumed full water resource development. In Egypt, Strzepek and Yates (2000) showed that under wet climate conditions, excess water above 75BCM left unused mainly due to a significant decline in the marginal value of water. In this study, the amount of flow going into the Mediterranean Sea is predicted to be 57.8BCM and

[56] Lower productivity per unit of water due to crop yield reduction will result in decreased economic returns to water in the basin. However, the farmers' willingness to pay for irrigation water (or its price if water market exists) will depend on interactions between the market demand and supply of crops and the resulting change in their price irrespective of other factors.

80.9BCM under the IPLS4.5 and IPLS8.5 respectively. Such enormous increase in the flow of the Nile River might seem unrealistic, but it shows the potential danger that extreme increase in river flow could pose for peoples in the basin unless appropriate adaptation strategies are in place.

Climate change is only one of the several factors that could make the basin's future uncertain, other factors such rapid population growth and rising demand for water and other resources will also play an important role. Projections show that the Nile region could face up to 75% decline in per capita water availability in by 2100 (UNEP, 2006). The actual trend and composition of water resource developments that will realize in the future together with the transboundary nature of the Nile River will also create further challenges to water management in the basin (McCartney et al., 2012; Satti et al., 2014). Decreased agricultural productivity say due to lower crop yield could result in land use changes and unsustainable agricultural practices. Often, climate change and land use changes are simultaneous processes (Dale, 1997) and such parallel movement of the two is also indicated to be strong in the case of Nile basin (Sead et al., 2010; Barnes, 2017). If adaptation options such as shifting to less water consuming crops and diversifying livelihood into other non-agricultural sectors are not considered, climate change induced decline in agricultural productivity could result in unsustainable compensation measures such as the expansion of agricultural land into forest areas which may further aggravate climate change. Reduced forest cover mainly in the upstream of the basin could have several local and far-reaching consequences including intensifying soil erosion, lowering groundwater recharge, increasing sedimentation, reducing water quality and sea level rise. Future projections regarding climate change induced sea level rise makes the Nile Delta (the heavily populated region of Egypt which accounts up to 40% of the country's agricultural production) one of the vulnerable hotspots in the basin (UNEP, 2013b).

Although the climate change scenarios used in this study (as well as previous studies) makes uncertain predictions, they provide a range of important information that can be used for decisions regarding future investments regarding WEF sectors in the basin. Results from this study show that climate change could negatively affect WEF sectors in the basin, through its impact either on the availability of water or irrigation water demand. The fact that most models predicted a wetter climate in the basin implies that translating potential increase in river flow into beneficial uses and mitigating the possible incidence of floods will require investing on suitable infrastructures that can allow managing the additional water. Placing water resource infrastructures, however, is not an end in itself; their operation rules should be adjusted and coordinated in a way that they can handle the impacts of climate change (Block and Strzepek, 2010). Also, despite predicted increases in water inflow in the basin, total basin-wide benefits show a reduction in most cases due to increased irrigation water demand resulting either from lower crop yield or higher evaporation (or both). Given that currently irrigation is the largest consumer of water in the basin and will continue to be so in the future, investments in technologies which improve the crop yield and water use efficiency as well as productivity are crucial for the basin (Blackmore and Whittington, 2008). Some of the climate change scenarios also show possible future climate extremes in the basin, requiring investments that promote early warning systems and forecasting and prediction facilities supporting such systems (relaying both on scientific and traditional knowledge), as part of adaptation strategies (Amare and Simane, 2017).

The complex and ever-changing socio-economic and political conditions in the basin will also add to future uncertainty in the region making well suited and dynamic adaptation measures essential (Conway, 2005). With the current level of water resource developments and economic structure (dominated by climate-sensitive production systems) especially in upstream countries of the basin, the capacity of most communities to adapt with the potential adverse impacts climate change is limited (UNEP, 2004; NBI, 2012a). Future adaptation measures such as building new water resource infrastructures should consider important aspects of upstream-downstream interdependences and ramifications associated with them while addressing the impacts of climate change. In general, managing the potential impact of future climate change in the Eastern Nile basin will require integrated efforts across sectors and riparian countries. A cross-sectoral and basin-wide cooperation that could improve WEF governance and management will continue to play a decisive role in addressing potential problems arising from climate change.

5.6. Conclusion

Climate change is one of the global phenomena which could put pressure on the three most important resources (WEF) for human survival. There are already evidence which show the direct impact of climate change related events (such as more erratic rainfall pattern, recurrent, longer and more intense extreme weather occurrences, and rising sea levels) on WEF systems. The potential impact of climate change on these three sectors is expected to be more amplified via the linkages and interdependence among them. Though the impact of climate change is expected to be global, regions like the Nile basin which are already under immense stress concerning WEF resources will likely be more affected. Accordingly, this chapter examines the potential impact of climate change on water allocation and associated economic benefits across sectors and countries in the Eastern Nile basin in the year 2050 assuming full irrigation and hydropower developments in the basin. An integrated optimization hydro-economic model – ENMOS was used to analyze the predicted climate change induced changes from five GCMs namely GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M under two RCPs – RCP4.5 and RCP8.5. Predicted changes in river flow from the five GCMs are applied on 102 years (1900-2002) historical flow data for each inflow nodes in the hydro-economic model. In addition to changes in river flow, climate change related changes in crop yield, evapotranspiration, and effective rainfall are also mapped to irrigation sites in the hydro-economic model. Moreover, the potential impact of sea level rise on irrigated land in Egypt's Nile Delta and population growth represented by a projected increase in M&I water demand in Egypt by 2050 are taken into account. These changes are introduced in the hydro-economic model to assess the impact of climate change on water use by sectors and basin countries as well as economic benefits obtained from irrigation and hydropower generation.

Results of climate change predictions show great disparity across the ten climate change scenarios where both reduction (up to 7%) and increment (up to 136%) in total basin-wide inflow is predicted. Two scenarios predicted reduced total basin-wide inflow while the remaining anticipated an increment by 2050. Dramatic (more than 100%) increase in total basin-wide inflow is predicted by the two IPLS scenarios. Such results indicate high uncertainty involved in predicting the impact of climate change in the Nile basin in general and the Eastern Nile basin in particular partly attributed to the fact that the basin contains several sub-basins with varying climate and flow regimes, and partly to uncertainty introduced by downscaling methods. Similarly, the predicted impacts of climate change on crop yield and actual evapotranspiration vary across climate change scenarios, crops, and countries. However, most climate change models projected decreased yield and increased actual evapotranspiration for a significant number of crops in each basin country. Lager decrease in crop yield is predicted for major irrigated crops in Sudan while an increase in actual evapotranspiration is anticipated consistently across climate change scenarios and crops for Egypt. In Ethiopia, a relatively higher decrease in yield is predicted for rain-fed crops than irrigated crops.

The impact of climate change on water use in the basin and economic benefits obtained from major sectors (hydropower and irrigation) was assessed by introducing the predicted climate change related changes in river inflow, crop yield, evapotranspiration and effective rainfall into the hydro-economic model. Even if the majority of the climate change scenarios considered in this study predicted that basin-wide inflow will increase due to climate change, total basin-wide economic benefit (the sum hydropower and irrigation benefits) decreased in most cases. This is mainly due to higher irrigation water demand resulting either from reduced crop yield or higher evapotranspiration rate (or both). Total basin-wide water use (including irrigation water use and evaporation loss from reservoirs) was predicted to increase with nine of the climate change scenarios. Basin-wide irrigation water use show increment in all GCM predictions. The wide range of results from this study should not be interpreted as risks by policy makers without further analysis, they could be true risks but they may also represent uncertainties introduced by simplistic/unrealistic modeling (climate models). However, despite large uncertainties seen in predicting climatic changes impacts in Eastern Nile basin, results from this study has important implication for future WEF related investments that should be made in the basin to adapt with potential impacts of climate change. These include investing in technologies which enhance crop yield and water use efficiency. Such efforts should be complemented by investments in water resource infrastructures (and coordinating their operating rules) to make use of the potential excess water predicted by some climate models. Also, since climate change has an important implication on the feasibility and adaptation benefits of water resources development plans in the basin, continues research is required on the field. In general, the climate change scenarios assessed in this study indicated that together with population growth, climate change will play an instrumental role in the Nile basin and future adaptation measures should be holistic, dynamic and evidence-based to have a synergistic impact across sectors and scales.

6. General Conclusions

Understanding the multidirectional link between the three most important resources of WEF is essential to reduce inherent tradeoffs and enhance potential synergies among various uses and users. The nexus between WEF is characteristically complex at every scale of analysis. Yet, the degree of intricacy is even higher in the case of transboundary river basins involving independent states with their own development priorities, plans, goals, and policies in each of the three sectors. This study attempted to examine the sectoral and transboundary interlinkages between WEF in one of the most stressed and sensitive regions of the world regarding the issue of water allocation and management – the Eastern Nile basin (covering Ethiopia, Sudan, South Sudan and Egypt). The WEF nexus concept was applied to assess and quantify existing and, potential tradeoffs and synergies in the basin across sectors and riparian countries by combining qualitative and quantitative approaches. In the qualitative approach, an e-survey and KIIs were used to assess the knowledge and opinions of relevant stakeholders (from Ethiopia, Sudan, and Egypt) on challenges and opportunities across the WEF nexus in the basin. Also, an integrated hydro-economic model named ENMOS was mainly used to analyze whether sectorally and regionally coordinated water infrastructure developments increase benefit from irrigation and hydropower production in the basin compared to unilateral actions across sectors and riparian countries. ENMOS was also used to examine the impact of climate change on water use and hydropower and irrigation benefits in the basin.

The assessment of past trends and current status of supply and use of WEF resources indicated that sectoral and transboundary interlinkages in the basin are already tight. Responses from the e-survey and KIIs emphasized that the three sectors are characteristically interlinked both at national and transboundary levels where cross-sectoral collaborations and harmonized actions are strongly advocated at both scales. Such collaborative arrangements are specified to be vital for sustainable utilization of natural resources and reduce investments with adverse spillover effects. The results from the hydro-economic model also underpin the strong consensus reached by the e-survey and KII participants on the need for sectoral and transboundary cooperation in the Eastern Nile basin. Proposed and under construction hydropower and irrigation projects which involve building large water storage infrastructures will undoubtedly add to the complexity of WEF management in the basin. The cooperative (system optimization) scenario results show that most proposed developments in the basin will have a potentially favorable outcome to all countries of the Eastern Nile basin and involve limited tradeoffs among sectors as well as riparian countries. However, this might not be the case if resources and associated infrastructures are not developed and operated in collaboration. Results from the non-cooperative (tradeoff) scenario analysis revealed the existence of significant sectoral and transboundary tradeoffs in the basin when one sector or country is prioritized over the other. In most of the water resource development scenarios, the sector or country that get priority gains, but total basin-wide economic benefits in the case of non-cooperation (sectoral or country prioritization scenarios) are lower than full cooperation scenarios.

Respondents of the e-survey and KIIs suggested several areas of collaboration for the basin which include joint investments in; proper water storage projects, catchment rehabilitation and watershed management, food security projects (such as investment in higher-yielding varieties and irrigation efficiency improving measures), and renewable energy projects complemented by regional energy trading. The potential synergic role of cooperatively developing upstream water storage facilities mainly for hydropower production is also indicated by the results of the hydro-economic model. Under the assumption of full cooperation in the basin, upstream water storage developments for the purpose of hydropower production appear to be beneficial for all basin countries. Results showed that under cooperative management, upstream water storage facilities which are mainly used for hydropower generation could increase irrigation benefits in downstream countries by providing more regulated year-round flows. In addition, storage dams in upstream of the basin (primarily Ethiopia) could significantly reduce evaporation losses from reservoirs located in downstream countries with arid climate (Sudan and Egypt). Investing jointly in hydropower dams and engaging in regional power trade based on comparative advantage will provide access to an immense amount of clean and affordable energy thereby fostering economic development in the region. Hydropower dams could also have synergic impacts by providing additional benefits of lowering drought and flood risks and reducing siltation in downstream reservoirs. However, investment in hydropower dams will be economically attractive if rehabilitation measures are taken mainly in the upper catchments of the Blue Nile (in Ethiopia) to reduce the massive soil erosion from the sub-basin and ensure the sustainability of water storage infrastructures.

Although the development of upstream hydropower dams is shown to be synergetic, new irrigation developments or expansions in upstream countries will introduce additional consumptive demand in the already largely utilized water system of the basin and could be costly for downstream riparians (mainly Egypt). Results from this study indicated that irrigation expansion in Ethiopia, Sudan, and South Sudan significantly increase the countries benefit from the sector relative to the baseline. However, such upstream irrigation expansion could have an adverse impact on Egypt by resulting lower benefits compared to current situation. Future irrigation developments in the upstream countries are inevitable given their expanding population and climate change. Therefore, collaborative actions are needed to improve water use efficiency and productivity in existing and proposed irrigation schemes to save water. Improving conveyance structures and field water application mechanisms, as well as changing (adjusting) management systems and crop types can significantly reduce water loss from irrigation schemes. Replacing the unlined and open irrigation water canals with modern delivery structures could decrease water loss due to seepage and evaporation. Also, more efficient field water application technologies should gradually substitute unsustainable irrigation practices (such as flood irrigation) in the basin. Optimal crop type and pattern selection which recognizes relevant biophysical (climate, hydrology, soil type and crop water requirement) and socio-economic factors (without ignoring cultural aspects) in each riparian country could contribute to efficient utilization of water in the basin. In addition, alternative water sources (like groundwater and desalination of seawater) and solutions beyond the water and agriculture sectors (such as diversifying into other economic activities) should be considered in long-term plans. Such transformations will not, however, occur instantly, they will require continues collaborations and institutional reforms.

The nature of WEF nexus in the Eastern Nile basin is expected to be very dynamic due climate change and, rapid population and economic growth. The Nile basin as a whole is highly exposed to the impacts of climate change due to its vulnerable natural and the socio-economic systems. In this study, results from five GCMs with two RCP scenarios show the existence of high uncertainty in predicting how climate change is going to affect the water resource of the basin by 2050 where some (majority) scenarios forecast increased flow, while others project a reduction. Across scenarios, the predicted changes in river flow show great variations with a wide range. Likewise, the predicted impacts of climate change on crop yield and evapotranspiration vary across climate change scenarios, crops, and countries. Yet, most climate change scenarios projected decreased yield and increased evapotranspiration for a large number of crops in each basin country. Results from the hydro-economic model show that despite the predicted increase in total basin-wide inflow by the majority of the climate change scenarios, basin-wide total economic benefit decreased in most cases under the assumption of full hydropower and irrigation developments in the basin. This was mainly due to an increase in irrigation water demand resulting either from reduced crop yield or higher evapotranspiration rate (or both). Such findings indicated that climate change could potentially intensify the sectoral and transboundary tradeoffs in the basin. In general, given the high uncertainty involved in predicting the impact of climate change in the basin, mitigation and adaptation measures should be continues and broad in range accounting for all sorts of extreme possibilities. Climate change adaptation measures should also be holistic and require collaborative efforts across sectors and basin countries. It should be emphasized that policy makers should not directly take the range of results from this study as risks, but rather as uncertainty of the climate models or of expected reality (or both). Therefore, further researches (by physical scientists) which evaluate the regional suitability of GCMs are needed to provide clear predictions to planners and decision-makers so that proper adaptation pathways are identified.

Even if cooperation across sectors and riparian countries are promoted to be a beneficial and viable pathway for the basin, the current level of coordination is generally deemed to be inadequate. For these, several reasons are provided in the qualitative assessment including the complex hydropolitics in the basin; lack of common databases, joint analysis tools, and platforms; lack of measures to build trust; lack of sustained national financing for regional collaboration; the limited mandate of national institutions; and weak regional institutions. These will make the transaction cost of cooperation in the basin significantly large. Hence, it is mandatory to take measures that can improve cross-sectoral collaboration both at the national and regional scales. Key steps include creating an institutional framework that boosts trust and confidence among key stakeholders in the basin. Awareness on the benefits of cooperation should also be improved through regular and continues dialogues across countries. Such measures will promote data and information sharing which are crucial for cooperation in the basin. In addition to institutional solutions, existing technical and economic cooperation must be strengthened, and new ones should be created.

Technical collaborations can be in the form of joint planning, designing, building, operating and monitoring of projects that have mutual benefits. Such efforts will allow selecting the most effective projects thereby resulting in efficient utilization of resources. Egypt could play a major role in sharing its long-established knowledge, experience, and technology regarding water management (mainly in irrigation systems) with riparian countries of the basin. Technical cooperation will ensure that water resource developments in the basin are beneficial to all or at least not significantly harmful to any party. Also, it could lessen suspicions in the basin by clearing up details on various steps of development projects which have transboundary implications. Moreover, technical experts should be given a chance to collaborate with politicians in the decision-making process. Often negotiations and key steps taken in transboundary river context are dominated by politicians and associated flawed interests that may not be advantageous from a basin-wide perspective. The enduring hydro-political tension in the Nile basin could partially found a solution if the opinions of technical experts are given due consideration.

Economic means of cooperation include regional trade and cross-broader investments in various activities. Variations in cost and price of commodities due to differences in resource endowment (i.e. availability of factors of production or raw materials), production technology, efficiency and domestic demand patterns among basin countries should be exploited to create strong trade ties. Intra-regional trade based on the comparative advantage of each Nile riparian country can serve as one solution to the water management problem in the basin. Within the broad agenda of economic development and natural resource management, adequate and sustainable power supply holds a central place in the Nile basin. There is a need to provide renewable, clean and affordable energy matching the economic development plans of all the riparian states. The power supply asymmetry currently observed in the basin can be addressed by joint investments in renewable energy projects in countries with abundant potential. Ethiopia has a relatively low cost of hydropower production with a promising prospect of exporting electricity to neighboring countries in addition to meeting domestic demand for power. To exploit the huge hydropower potential in the upstream countries and address existing power shortage in several countries of the basin, regional power trade and integration of the electricity sector is a crucial course of action. Detailed analysis and projection on the economic implication of regional power trade need to be conducted in the future.

In addition to electricity trade, there are viable opportunities to pursue trade in agricultural commodities between the riparian nations if the profound infrastructure problem in the basin is alleviated and agricultural productivity is enhanced (diversified) creating a surplus (sufficient product mix) for trade. Increased regional economic links will create a favorable environment for cross-broader investments and ultimately have implications on the overall economy of the basin countries, reflected by key macroeconomic indicators of employment and economic growth. Regional economic integration will also magnify the positive impacts of cross-border investments in WEF sectors by strengthening backward and forward linkages, and widening the scope of consumption-induced changes due to the investments. In general, the WEF nexus in the Eastern Nile basin is complex and dynamic requiring a package of cooperation mechanisms from technical, economic and institutional domains.

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Appendices

Appendix A: Existing and Proposed Water Infrastructures included in ENMOS

Table A.1: Existing irrigation schemes in the Eastern Nile basin

Model Symbol	Name of command area	Sub-basin	Area (1000ha)
	Ethiopia		**140**
D1	Lake Tana	BN	22 [117]
D2	Lake Tana to Karadobi	BN	43 [69]
D3	Fincha-Neshe	BN	11 [16]
D20	Small scale/traditional irrigation-Tekeze	TSA	63.5 [142]
	Sudan		**1359**
D11	Abu Nama (Jute)	BN	13
D12	Blue Nile Pump schemes	BN	105
D13	El-Suki	BN	37
D14	North West Sennar Sugar	BN	22
D15	Gezira and Managil	BN	579
D16	Rahad I	BN	95
D17	Hurga and Nour Edin	BN	13
D18	Guneid Sugar	BN	29
D19	Seleit pump schemes	BN	30
D25	New Halfa	TSA	155
D41	Kenana Sugar Estate	BASW	37
D42	Hagar Assalaya (Sugar)	BASW	18
D43	White Nile pump schemes	BASW	151
D44	Khartoum-Tamaniat irrigation	MN	23.1
D45	Tamaniat-Hassanab irrigation	MN	28.6
D46	Hassanab-Dongola irrigation	MN	23
	South Sudan		**13**
D40	Melut Sugar	BASW	13
	Egypt		**3345**
D48	Upper Egypt	MN	1143
	- El Ibrahimiya		645
	- Naga hamadi El sharkia		43
	- Naga hamadi El Gharbia		179
	- El Kalabia		72

	- Asfun		29
	- Direct intakes		174
D49	Middle Egypt	MN	371
	- Ismailiya canal		244
	- Direct intakes		127
D50	East Delta	MN	495
	- El Raiyah Al Tawfiki		282
	- El Mansoria		136
	- Direct intakes		77
D51	Middle Delta	MN	638
	- El Raiyah El Monofi		309
	- El Raiyah El Abasi		329
D52	West Delta irrigation	MN	699
	- El Raiyah El Bihiri		502
	- Mahmoudia (pumping)		120
	- El Raiyah Al Nasri		32
	- Direct intakes		45

Source: ENTRO (2014a)

Note: Values in brackets for irrigation sites in Ethiopia represent irrigated areas at full potential (or with expansion plans) which are considered under S6 and S7 in the model.

Table A.2: Under construction and proposed irrigation schemes in the Eastern Nile basin

Model Symbol	Name of command area	Sub-basin	Area (1000ha)	Status
	Ethiopia		**915**	
D4	Didessa-Negesso-Nekemet- Anger	BN	101	*FS conducted*
D6	Dinder	BN	59	*Master plan*
D7	Rahad (Ethiopia)	BN	55	*Master plan*
D21	Humera	TSA	43	*FS conducted*
D23	Metema	TSA	12	*Reconnaissance*
D22	Angereb	TSA	16.5	*Master plan*
D26	Baro R.B from Gambella Dam	BASW	68	*Master plan*
D27	Baro L.B from Gambella Dam	BASW	57	*Master plan*
D28	Baro R.B from Itang Dam	BASW	129	*Master plan*
D29	Baro L.B from Itang Dam	BASW	168	*Master plan*
D31	US Alwero demand	BASW	16	*Master plan*
D32	Alewero L.B	BASW	13.5	*Master plan*
D33	Gilo1 R.B from Gilo 1 Dam	BASW	47	*Master plan*
D34	Gilo1 L.B from Gilo 1 Dam	BASW	34	*Master plan*
D35	Gilo 2 R.B from Gilo 2 Dam	BASW	61	*Master plan*

D36	Gilo2 L.B from Gilo 2 Dam	BASW	34	*Master plan*
	Sudan		**1088**	
D8	Great Kenana	BN	252	*PFS conducted*
D9	Roseries and Dinder South	BN	311	*FS conducted*
D10	Rahad II	BN	357	*FS conducted*
D24	Upper Atbara	TSA	168	*FS conducted*
	South Sudan		**210**	
D37	Pibor	BASW	126	*Reconnaissance*
D39	Sobat	BASW	84	*Reconnaissance*
	Egypt		**250**	
D47	Toshka	MN	250	*Under construction*

Source: ENTRO (2014a)
Note: FS= Feasibility study; PFS= Pre-feasibility study

Table A.3: Existing dams in the Eastern Nile basin

Model symbol	Reservoir/HP Name	Sub-basin	Main Purpose	HP Capacity (MW)	Average Energy (GWh/yr)
	Ethiopia			**760**	
TB	Tana-Beles	BN	RRHP	460	2,050
R10	Tekeze I	TSA	HP & IRR	300	1,069
R20	Abobo	BASW	IRR**		
	Sudan			**1924**	
R8	Roseires	BN	HP***	280	2125
R9	Sennar	BN	HP & IRR	26	95
R11	Rumela and Burdana	TSA	HP***	320	502
R12	Kashm El Girba	TSA	HP & IRR	18	110
R23	Jebel Aulia	BASW	HP	30	143
R27	Merowe	MN	HP & IRR	1250	5500
	Egypt			**2100**	
R30	HAD	MN	HP & IRR	2100	11,500

Source: EEPCO (2011); ENTRO (2014a)
Note: RRHP = run-of-river hydropower plant, HP = hydropower, IRR = Irrigation, ** currently not in use for irrigation, ***to be used for irrigation

Table A.4: Under construction and proposed dams in the Eastern Nile basin (included in the model)

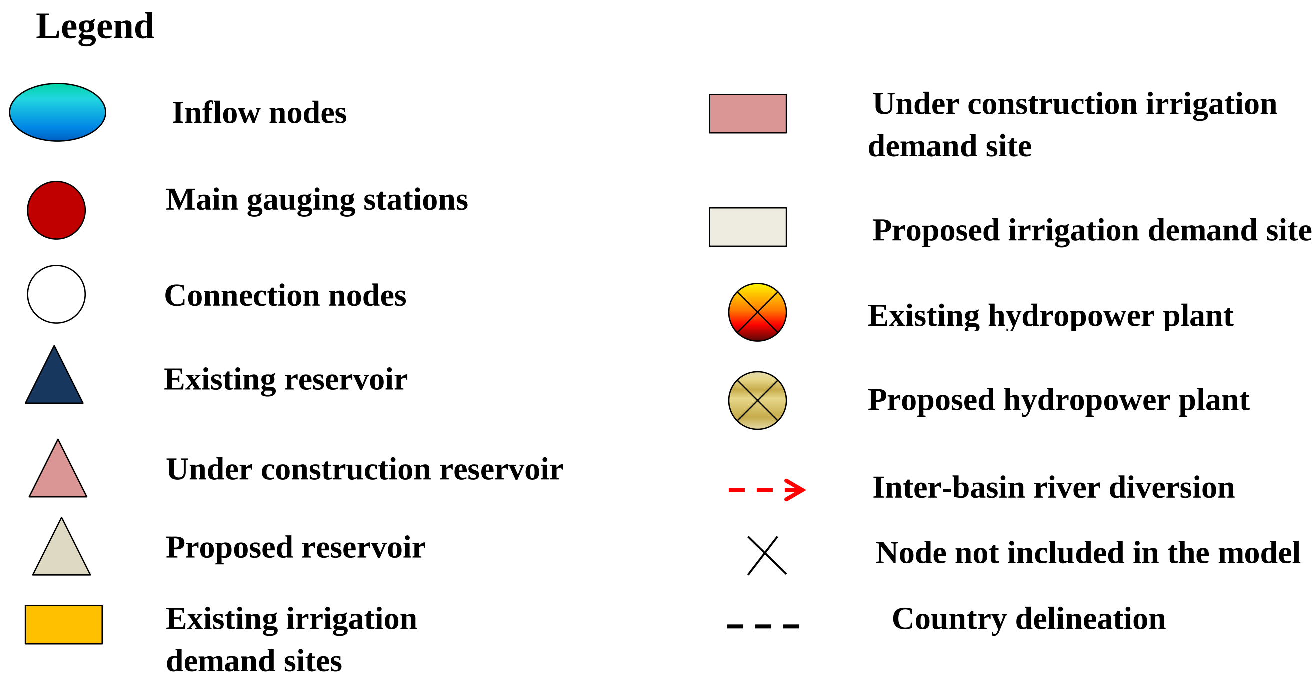
Model Symbol	Project Name	Sub Basin	Main Purpose	HP Capacity (MW)	Status
	Ethiopia			**12721**	
R2	Karadobi	BN	HP	1600	*PFS conducted*
R3	Beko Abo	BN	HP	935	*PFS conducted*
R4	Upper Mandaya	BN	HP	1700	*PFS conducted*
R5	Lower Didessa	BN	HP	550	*FS conducted*
R7	GERD	BN	HP	6450	*Under construction*
R14	Baro I	BAS	HP	166	*FS conducted*
R15	Baro II	BAS	HP	479	*FS conducted*
R16	Genji	BAS	HP	216	*FS conducted*
R17	Gambella	BAS	HP & IRR	258	*Master plan*
R18	Itang	BAS	IRR		*Master plan*
R19	Dombong	BAS	IRR		*Master plan*
R21	Gilo 1	BAS	HP & IRR	80	*Master plan*
R22	Gilo 2	BAS	IRR		*Master plan*
R25	TK7	TSA	HP	275	*Master plan*
R13	TK21	TSA	HP	11.6	*Master plan*
	Sudan			**1300**	
R24	Sabaloka	MN	HP	120	*Reconnaissance*
R28	Kajbar	MN	HP	360	FS *conducted*
R29	Dal	MN	HP	400	FS *conducted*
R58	Shereik	MN	HP	420	FS *conducted*

Source: ENTRO (2014a)
Note: FS= Feasibility study; PFS= Pre-feasibility study

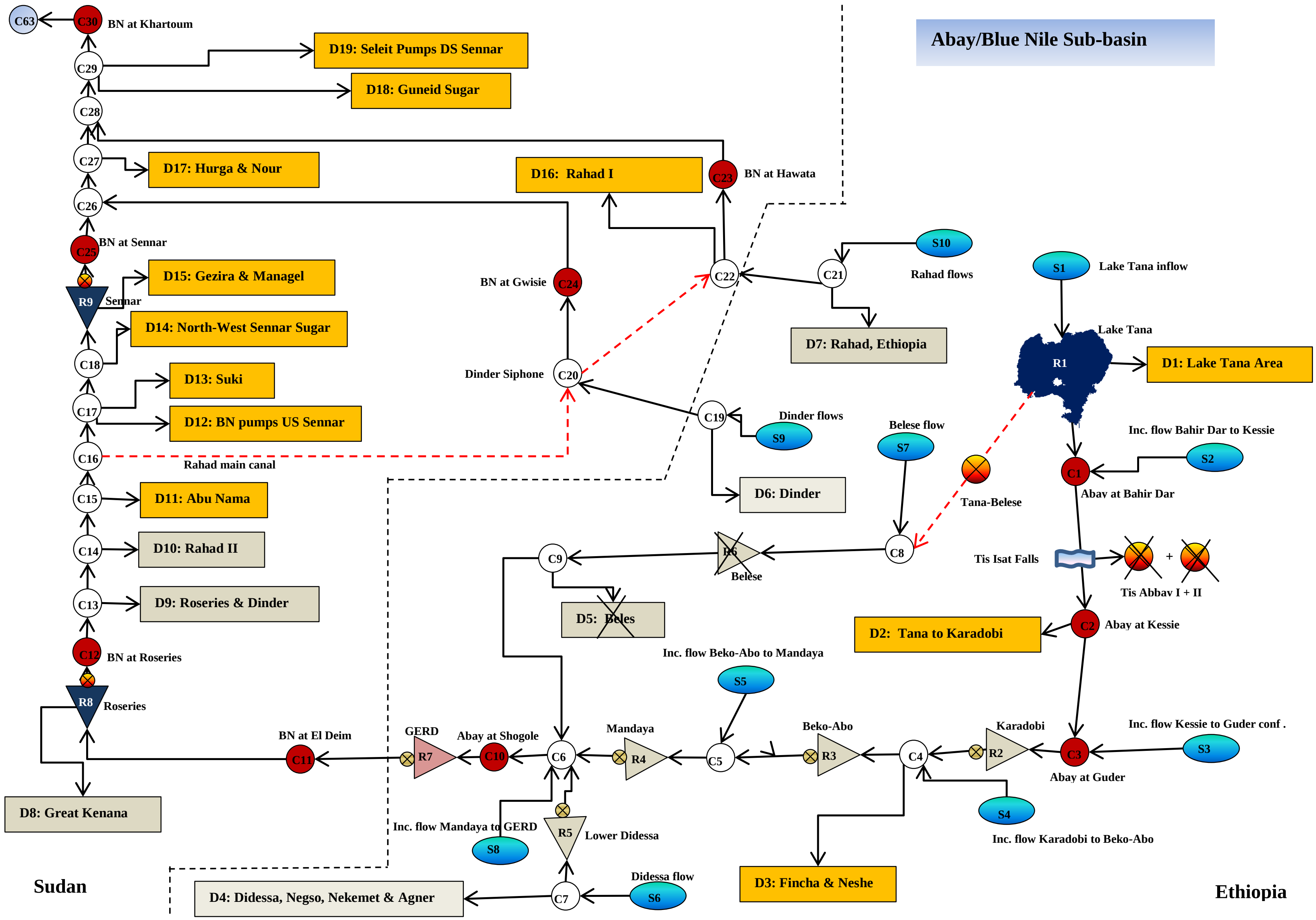
Table A. 5: List of crops included in the model

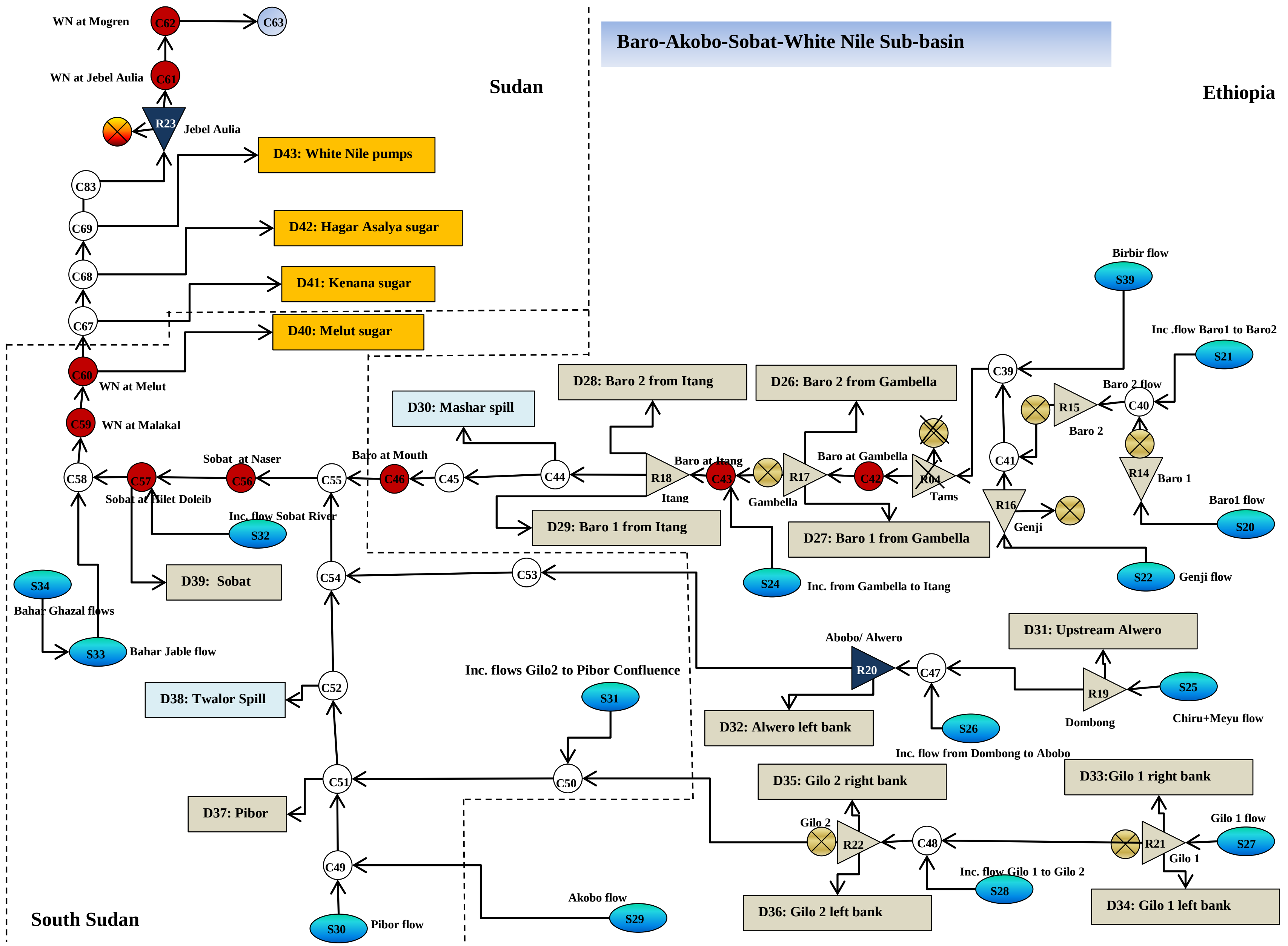
Ethiopia	Sudan and South Sudan	Egypt
Cotton	Cotton	Apple
Maize	Sugarcane	Banana
Teff	Wheat	Barley
Wheat	Groundnut	Bean
Barley	Sorghum	Cabbage
Groundnut	Vegetables	Cotton
Sesame	Rice	Maize
Noug	Sunflower	Orange
Sunflower	Sesame	Peanuts
Field peas	Fodder	Potato
Soybean		Rice
Castor bean		Sesame
Potato		Sorghum
Lentil		Sugarcane
Sugarcane		Sugar beet
Grape		Wheat
Fruits		
Red-peeper		
Ginger		
Coffee		
Tobacco		
Onion		
Rice		
Fodder		

Appendix B: Detailed Model Schematics by Sub-basin

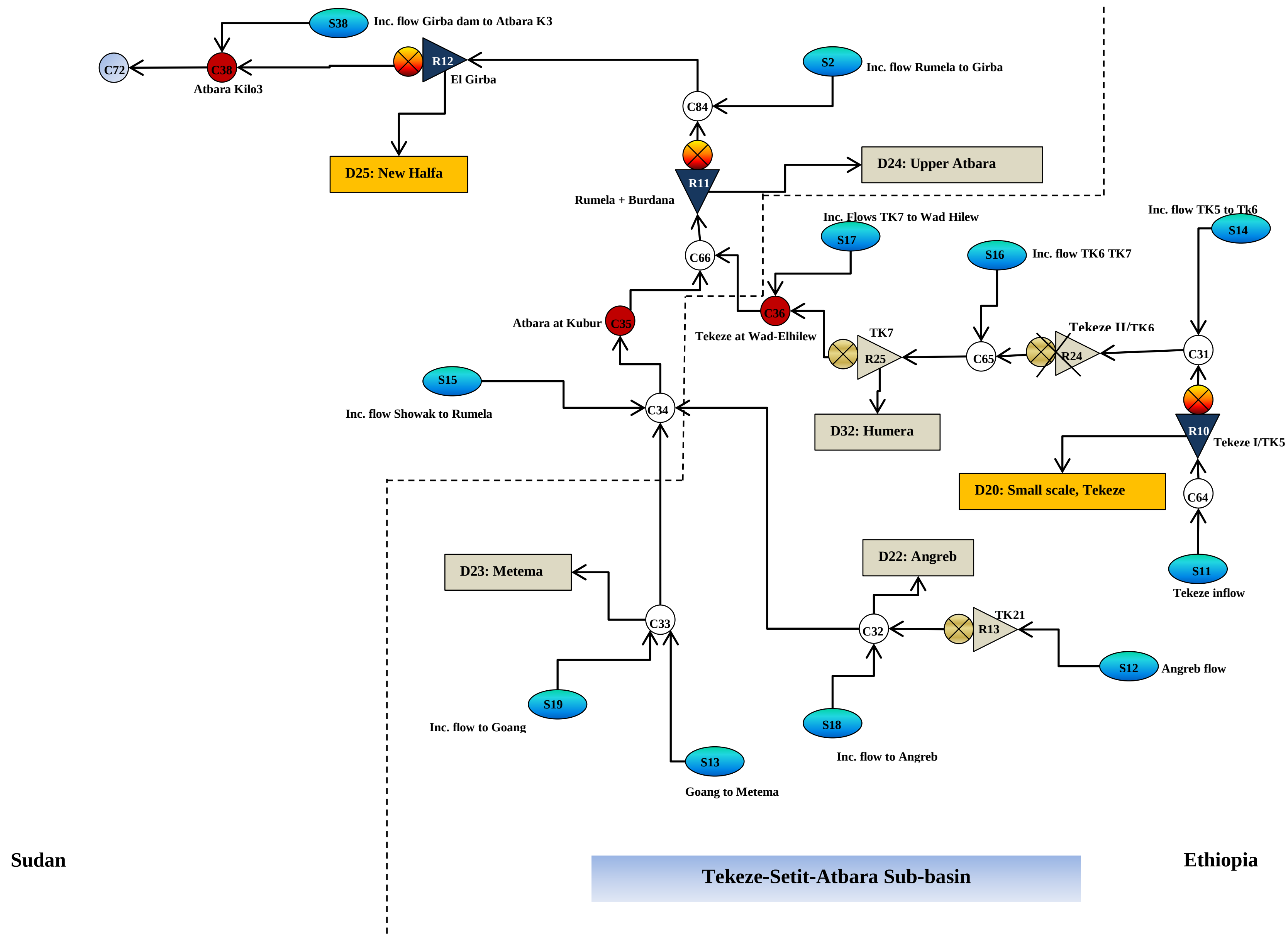


Source: Based on ENTRO (2014c)

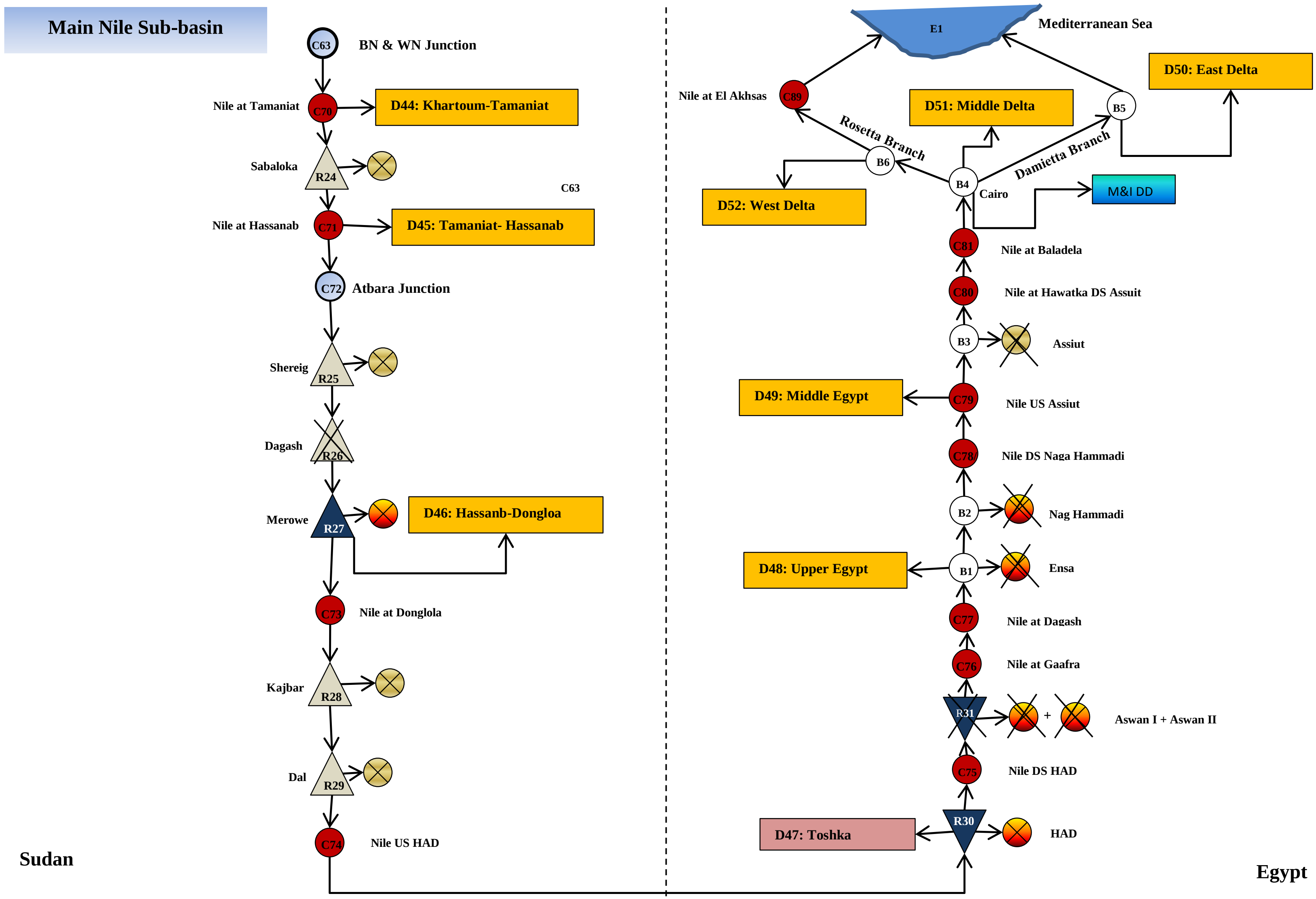

Abay/Blue Nile Sub-basin
C63
C30
BN at Khartoum
D19: Seleit Pumps DS Sennar
C29
D18: Guneid Sugar
C28
C27
D17: Hurga & Nour
D16: Rahad I
C23
BN at Hawata
C26
BN at Sennar
C25
D15: Gezira & Managel
R9
Sennar
D14: North-West Sennar Sugar
BN at Gwisie
C24
C22
C21
S10
Rahad flows
S1
Lake Tana inflow
D7: Rahad, Ethiopia
Lake Tana
R1
D1: Lake Tana Area
C18
D13: Suki
Dinder Siphone
C20
C17
D12: BN pumps US Sennar
C19
Dinder flows
S9
Belese flow
S7
Inc. flow Bahir Dar to Kessie
S2
C16
Rahad main canal
C1
Abay at Bahir Dar
Tana-Belese
C15
D11: Abu Nama
D6: Dinder
C14
D10: Rahad II
C9
R6
Belese
C8
Tis Isat Falls
Tis Abbay I + II
C13
D9: Roseries & Dinder
D5: Beles
D2: Tana to Karadobi
C2
Abay at Kessie
C12
BN at Roseries
Inc. flow Beko-Abo to Mandaya
S5
R8
Roseries
BN at El Deim
GERD
Abay at Shogole
Mandaya
Beko-Abo
Karadobi
Inc. flow Kessie to Guder conf .
C11
R7
C10
C6
R4
C5
R3
C4
R2
C3
S3
Abay at Guder
S4
Inc. flow Karadobi to Beko-Abo
D8: Great Kenana
Inc. flow Mandaya to GERD
S8
R5
Lower Didessa
Didessa flow
S6
C7
D3: Fincha & Neshe
Sudan
D4: Didessa, Negso, Nekemet & Agner
Ethiopia



Baro-Akobo-Sobat-White Nile Sub-basin
Sudan
Ethiopia
South Sudan
WN at Mogren
C62
C63
WN at Jebel Aulia
C61
R23
Jebel Aulia
D43: White Nile pumps
C83
C69
D42: Hagar Asalya sugar
C68
D41: Kenana sugar
C67
D40: Melut sugar
C60
WN at Melut
C59
WN at Malakal
C58
C57
Sobat at Hilet Doleib
Sobat at Naser
C56
C55
Baro at Mouth
C46
C45
C44
D30: Mashar spill
D28: Baro 2 from Itang
D26: Baro 2 from Gambella
R18
Baro at Itang
Itang
C43
Gambella
R17
Baro at Gambella
C42
R04
Tams
D29: Baro 1 from Itang
D27: Baro 1 from Gambella
Inc. flow Sobat River
S32
D39: Sobat
S34
Bahar Ghazal flows
S33
Bahar Jable flow
C54
C53
S24
Inc. from Gambella to Itang
Birbir flow
S39
Inc .flow Baro1 to Baro2
S21
C39
Baro 2 flow
R15
Baro 2
C40
C41
R14
Baro 1
R16
Genji
Baro1 flow
S20
S22
Genji flow
D31: Upstream Alwero
Abobo/ Alwero
R20
C47
R19
Dombong
S25
Chiru+Meyu flow
D32: Alwero left bank
S26
Inc. flow from Dombong to Abobo
Inc. flows Gilo2 to Pibor Confluence
C52
D38: Twalor Spill
S31
C51
C50
D37: Pibor
D35: Gilo 2 right bank
D33:Gilo 1 right bank
Gilo 2
R22
C48
R21
Gilo 1
Gilo 1 flow
S27
Inc. flow Gilo 1 to Gilo 2
S28
D36: Gilo 2 left bank
D34: Gilo 1 left bank
C49
Akobo flow
S29
S30
Pibor flow



Tekeze-Setit-Atbara Sub-basin


Main Nile Sub-basin
C63
BN & WN Junction
Nile at Tamaniat
C70
D44: Khartoum-Tamaniat
Sabaloka
R24
C63
Nile at Hassanab
C71
D45: Tamaniat- Hassanab
C72
Atbara Junction
Shereig
R25
Dagash
R26
Merowe
R27
D46: Hassanb-Dongloa
C73
Nile at Donglola
Kajbar
R28
Dal
R29
C74
Nile US HAD
Sudan
E1
Mediterranean Sea
Nile at El Akhsas
C89
D50: East Delta
D51: Middle Delta
B5
Rosetta Branch
B6
Damietta Branch
B4
Cairo
M&I DD
D52: West Delta
C81
Nile at Baladela
C80
Nile at Hawatka DS Assuit
B3
Assiut
D49: Middle Egypt
C79
Nile US Assiut
C78
Nile DS Naga Hammadi
B2
Nag Hammadi
D48: Upper Egypt
B1
Ensa
C77
Nile at Dagash
C76
Nile at Gaafra
R31
+
Aswan I + Aswan II
C75
Nile DS HAD
D47: Toshka
R30
HAD
Egypt

Appendix C: Model Structure and Formulation

C.1: Model Structure

SETS

n,n1	nodes	
Subset nodes		
	sn	start nodes
	cn	confluence or connection nodes
	dn	demand nodes
	rn	reservoir nodes
	rhp	run-of-river hydropower nodes
	br	barrage nodes
	sp	spills to wetlands
	rsp	reservoir spillway nodes
	en	end node

d	system demand type
c	crop type
t	months
y	year (1900-2002)

country	countries in the basin
region	sub-basins in the basin

PARAMETERS

Identifying parameters and the node-link network

NODETYPE(n)	type of node
NCOUNTRY(n)	node by country
NREGION(n)	node by sub-basin
CONNECT(n,n1)	node to node connection matrix for defining network
RFSCON(n,n1)	connection for return flow from node n to n1

Source Data

QINFLOW(y,t,n)	inflow at start node n at time t in year y (MCM)

Reservoir Data

RCAP(n)	live capacity of reservoir (MCM)
SRDEAD(n)	dead storage of reservoir (MCM)
ANOT(n)	area at dead storage of reservoir(km2)
HNOT(n)	reference minimum elevation for storage-elevation relationship (masl)
MAXELEVATION	maximum water surface elevation (masl)
MAXAREA	maximum water surface area (km2)

ECOEFF(n,t)	evaporation at node reservoir node n (mm)
c, d, e, f, g, h, i, j	reservoir area/storage/elevation relationship parameters

Hydropower Data

TAILWATERLEVLE(n)	tail water level (m)
RMINHEAD(n)	minimum head for hydropower generation (m)
MAXHEAD(n)	maximum available head for hydropower generation (m)
HPCAP(n)	maximum hydropower generation installed capacity at n (MW)
HPEFF(n)	hydropower generation efficiency (fraction)
LF(n)	load factor for HP generation in reservoir n (fraction)
FU(n)	factor of utilization for HP generation in reservoir n (fraction)

Irrigation (Crop) Data

AMAX(n)	maximum irrigable area at n (Km2)
CROPCAL(c,t)	crop calendar matrix
CRPLOCS(c,n)	crop location matrix for crop c at n
CPOBS(c,n)	observed cropping pattern in system (%)
CPMIN(c,n)	min cropping constraint for system (%)
CPMAX(c,n)	max cropping area constraint for system (%)
FRFS (n,n1,t)	fraction of return flow from n to n1 in t
EFFDIV (n)	overall irrigation efficiency
CRPYIELD(n,c)	observed crop yield (tonne per ha)
YLDPOT(n,c)	maximum or potential crop yield (tonne per ha)
ETM(n,c,t)	maximum crop evapotranspiration (mm)
Ky(c)	total growing period FAO yield response coefficient
Kym(c)	monthly FAO yield response coefficients

Domestic (municipal) water use data

QDDOM(n)	domestic water demand at node n (MCM)

Economic Data

HPBEN (n)	hydropower selling price at node n (USD per KWh)
HPCOST (n)	cost of hydropower production at node n (USD per KWh)
CROPPRICE (c)	price of crop c (USD per ton)
CROPCOST (c)	cost of producing crop c (USD per ton)

Decision Variables

Z	net basin-wide economic benefit (million USD)
HPGEN(n,t)	hydropower generation at n in time t (GWh)
Crop production (n,t)	crop production at n in time t (thousands of tonnes)
NETHB (n)	net hydropower benefit at n (million USD)
NETIB (n)	net irrigation benefit at n (million USD)
Q (n,n1,t)	flow from n to n1 at time t (MCM/month)
QD (n,d,t)	amount of water withdrawn for irrigation at n at time t (MCM)
AREAS (c,n)	irrigated area at n with crop c (ha)

State or Intermediate Variables

SR(n,t)	live storage in reservoir n at time t (MCM)
SRT(n,t)	total storage at reservoir n at time t (MCM)
RFS(n,n1,t)	return flow from sys use at n to n1 at time t (MCM)
HEAD(n,t)	head at reservoir n in time t (m)
WSELEVATION(n,t)	reservoir water surface elevation (m)
RESSUAREA(n,t)	reservoir surface area (Km2)
RELEASE(n,t)	release or discharge from n in time t (MCM)
EVAP(n,t)	evaporation at n in time t (MCM)

C.2: Model Formulation

Objective function

$$Z = \sum_{\mathrm{n}} NETIB(n) + \sum_{\mathrm{n}} NETHB(n)$$

Profit function for irrigation demand site

$$NETIB(n) = \sum_{\mathrm{c}} \mathrm{AREAS}_{\mathrm{c,dn}} * \mathrm{YIELD}_{\mathrm{c,dn}} * (\mathrm{CROPPRICE}_{\mathrm{c}} - \mathrm{CROPCOST}_{\mathrm{c}})$$

Profit function for hydropower generation

$$NETHB(n) = \sum_{t} \mathrm{HPGEN}_{\mathrm{rn}\&rhp,\mathrm{t}} * (\mathrm{HPBEN}_{\mathrm{rn}\&rhp} - \mathrm{HPCOST}_{\mathrm{rn}\&rhp})$$

Water balance (continuity constraints)

Water balance at start nodes

$$\sum_{\boldsymbol{n1}} Q_{sn,n1,t} = QINFLOW_{sn,t} \ldots \forall(sn,t)$$

Water balance at confluence nodes

$$\sum_{n1} Q_{n1,cn,t} + RFS_{n1,cn,t} = \sum_{n1} Q_{cn,n1,t} \ldots \forall(cn,t)$$

Water balance at reservoir nodes

$$\sum_{\boldsymbol{n1}} Q_{n1,rn,t} + \; +SR_{rn,t-1} + RFS_{n1,rn,t}$$
$$= \sum_{\boldsymbol{n1}} Q_{rn,n1,t} + SR_{rn,t} + ECOFF_{n,t} * RESSURAREA_{n.t} \ldots \forall(rn,t)$$

Water balance at run-of-river hydropower nodes

$$\sum_{n1} Q_{n1,rhp,t} + RFS_{n1,rhp,t} = \sum_{n1} Q_{rhp,n1,t} \dots \forall(rhp,t)$$

Water balance at irrigation demand nodes

$$\sum_{n1} Q_{n1,dn,t} + RFS_{n1,dn,t} = \sum_{n1} Q_{dn,n1,t} + \sum_{dn} QD_{dn,t} \dots \forall(dn,t)$$

Water balance at end node (minimum flow to the Mediterranean Sea)

$$\sum_{n1} Q_{n1,ed,t} \geq 10000$$

Reservoir/hydropower related equations

Total reservoir volume

$$SRT_{n,t} = SR(n,t) + SRDEAD(n)$$

Release (volume of water passing through hydropower)

$$RELEASE(n,t) = \sum_{n1} Q_{cn,n1,t}$$

Net head

$$HEAD(n,t) = WSELEVATION_{n,t} - TAILWATER_n$$

Hydropower generation (monthly power production)

$$HPGEN(n,t) = (2.725) * HPEFF_n * HEAD_{n,t} * RELEASE_{n,t} * LF_n$$

Maximum hydropower that can be generated

$$HPGEN(n,t) = (2.725) * HPEFF_n * (MAXELEVATION_n - TAILWATER_n) * RELEASE_{n,t}$$

Head-storage relationship for reservoirs (reservoir morphological characteristics**)**

$$WSELEVATION_{n,t} = c * SR_{rn,t}{}^2 + e * SR_{rn,t} + f$$

Area-storage relationship for reservoirs

$$\text{RESSUAREA}_{n,t} = g * SR_{rn,t}{}^2 + i * SR_{rn,t} + j$$

Water level constraint at run-of-river reservoirs

$$WSELEVATION_{n,t} = HNOT(n)$$

Irrigation related equations

Irrigated area constraints (allowing for multiple crops in a year where possible)

$$AREAS_{c,dn} * CROPCAL \leq AMAX_n \dots \forall(dn,t)$$

Minimum cropping constraints
$AREAS_{c,dn} \geq CPMIN_{n,c}$ ... $\forall(c, dn)$

Maximum cropping constraints
$AREAS_{c,dn} \leq CPMAX_{n,c}$ ... $\forall(c, dn)$

Monthly gross water requirement at irrigation nodes

$$\sum_{c} eta_{dn,c,t} = QD_{dn,t} * EFFDIV\ (dn), \ldots \forall(dn, t)$$

FAO's crop yield response function

$$YLDACT_{(dn,c)} = YLDPOT_{(dn,c)} * \left[1 - max_t \left(kym_{c,t} * \left(1 - \frac{eta_{dn,c,t}}{10^{-5} * area_{dn,c} * etm_{dn,c,t}}\right)\right)\right]$$

Where, $YLDACT_{dn,c}$ is actual crop yield

M&I water demand equation
$EDOM_{dom(n),t} = QDDOM_n / 12$
Where, $EDOM_{dom(n),t}$ is M&I water use equation with equally distributed demand over months

Other equations (spill to wetlands)

Twalor spill loss
$Q_{cn52,dn38,t} = 0.4029 * Q_{cn51,cn52,t} + 14.682$

Machar spill loss
$Q_{cn42,dn30,t} = 0.00006 * Q_{cn43,cn44,t} + 2.1029$

Appendix D: Additional Results

Figure D.1: Observed flow vs flow with optimal water allocation (model) at major gauging stations

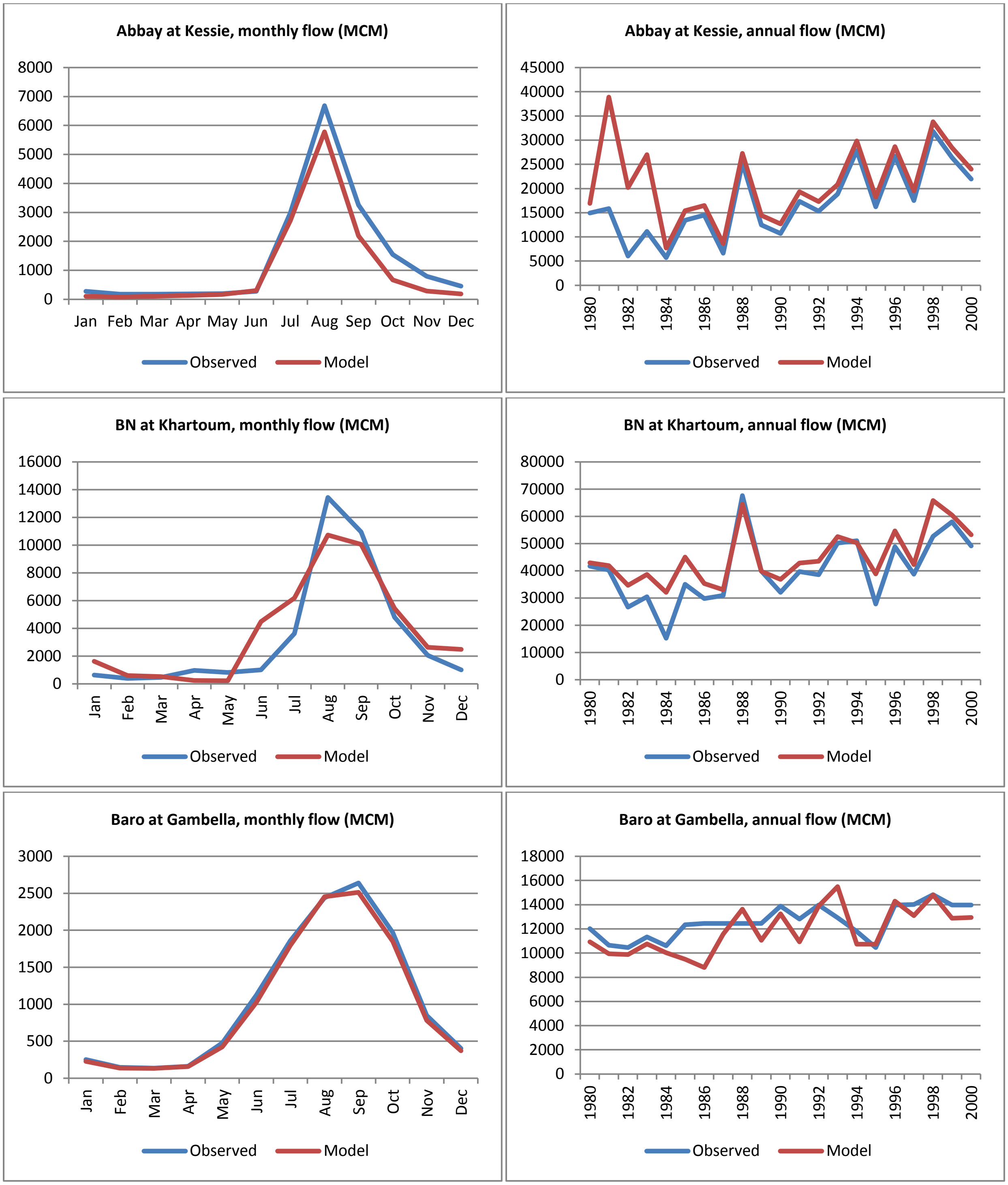


Figure D.1 continued…

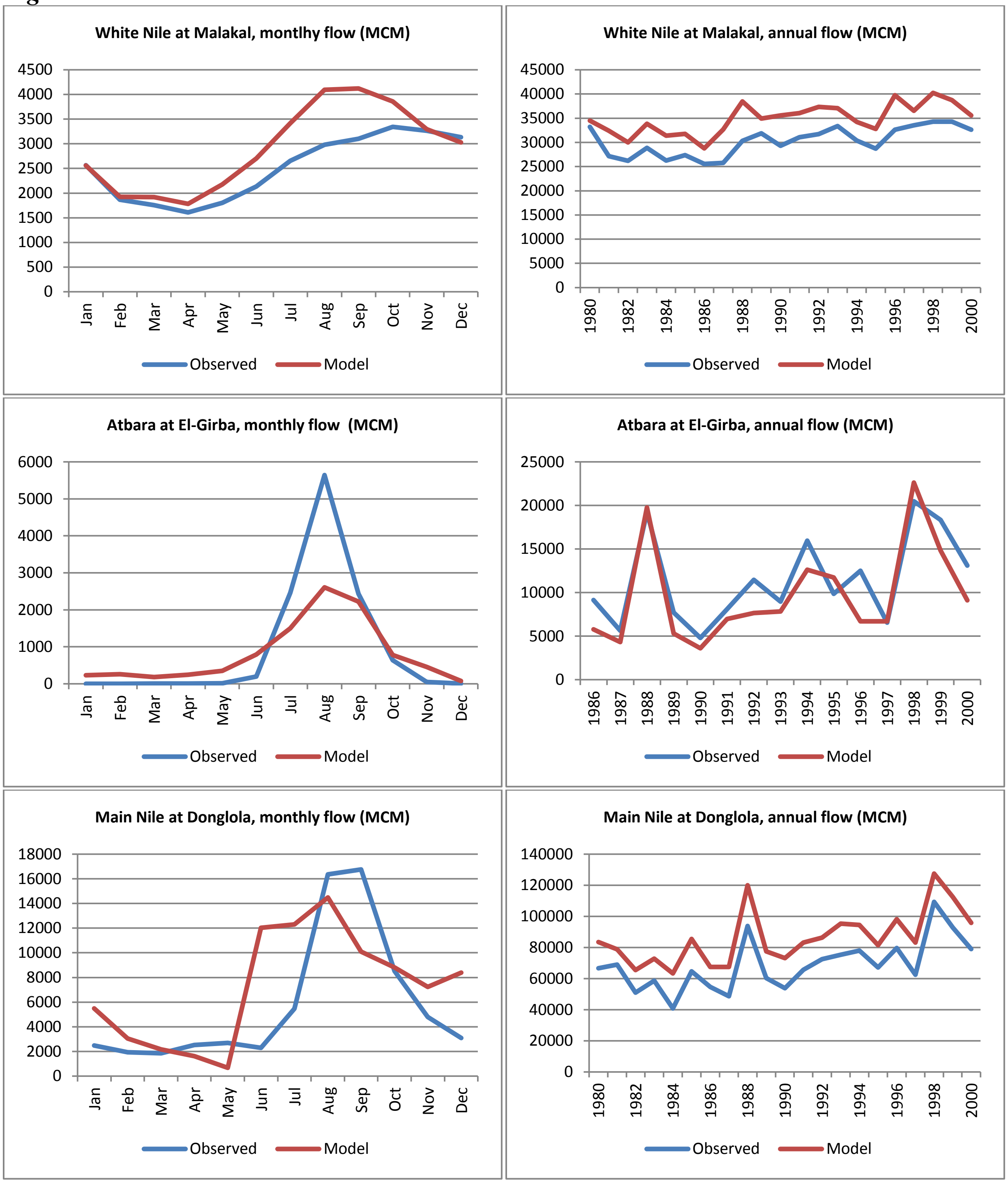
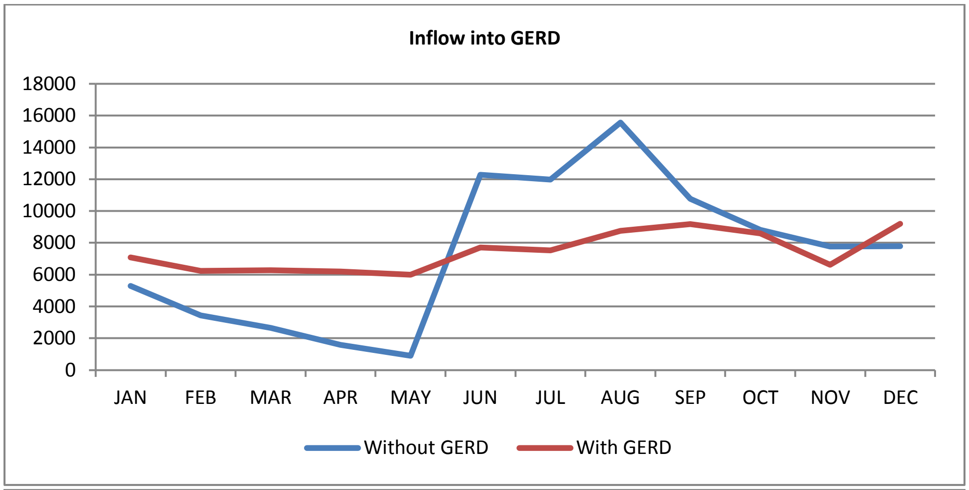


Figure D.2: Flow into and release from HAD without and with GERD



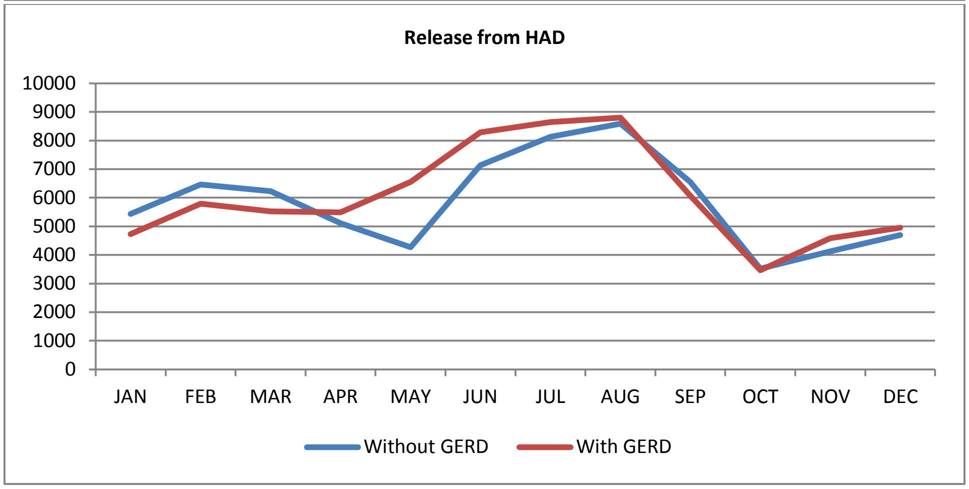


Figure D.3: Flow to Mediterranean Sea under different scenarios (average 1900-2001)

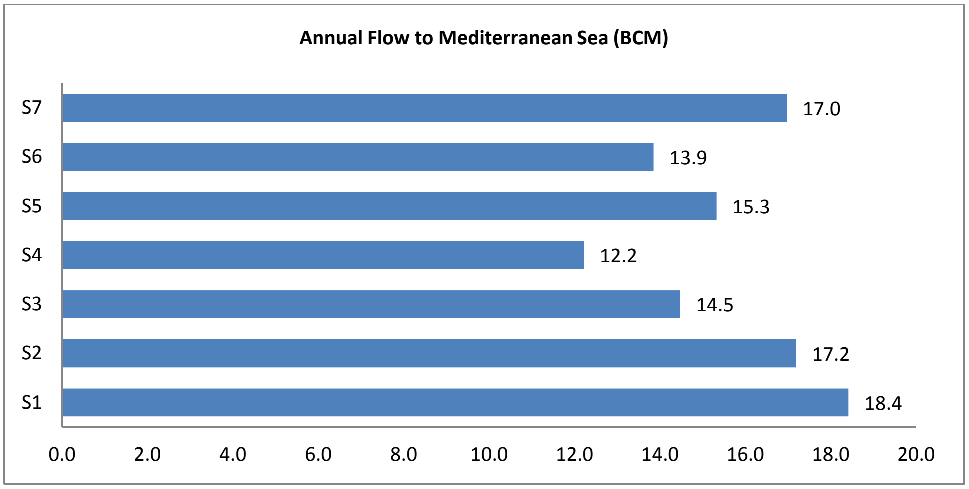


Table D.1: Sectoral tradeoff analysis scenario results for S2 to S7 (% changes from system optimization)

	S2				S3				S4			
	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total
Total benefit												
HPP	-21.2	-72.6	-0.7	-10.4	-16.6	-71.3	-2.2	-10.3	-5.6	-73.4	-0.7	-9.5
IRRP	-13.0	-2.2	4.9	3.2	-14.4	5.1	-0.8	-0.8	-19.4	-0.8	-1.2	-3.1
Hydropower benefit												
HPP	0.5	12.1	9.8	5.0	0.3	14.5	8.6	5.3	0.0	19.0	5.0	3.6
IRRP	-18.1	-16.6	-2.9	-14.9	-18.3	-15.8	-2.9	-14.8	-21.9	-20.9	-3.2	-20.3
Irrigation benefit												
HPP	-91.8	-85.1	-0.9	-11.5	-89.5	-84.7	-2.3	-11.3	-88.8	-95.3	-0.8	-11.5
IRRP	3.4	-0.1	5.0	4.4	2.5	8.4	-0.8	0.2	16.2	3.9	-1.2	-0.5
Total water use												
HPP	-20.3	-62.2	-0.1	-7.9	-18.5	-59.0	-3.3	-9.5	-9.4	-19.2	-1.0	-4.4
IRRP	5.3	2.8	2.5	2.6	5.4	6.8	-1.3	-0.3	7.0	3.9	-0.8	0.2
Irrigation water use												
HPP	-97.2	-92.8	-1.0	-7.7	-96.8	-92.3	-4.9	-13.9	-95.8	-99.3	-2.5	-13.0
IRRP	17.5	8.1	3.4	3.0	21.8	12.3	-1.3	1.0	83.7	17.0	-0.6	1.6
Evaporation loss from reservoir												
HPP	-3.2	18.1	3.3	4.9	-3.8	25.1	3.7	6.0	-3.4	47.4	4.9	17.6
IRRP	2.6	-11.0	-1.1	-2.2	2.3	-7.0	-1.1	-1.6	1.6	-7.0	-1.9	-3.1
Irrigated area												
HPP	-41.5	-70.4	1.5	-6.3	-44.5	-63.3	0.3	-5.4	-43.5	-74.5	-2.7	-9.9
IRRP	9.2	5.2	-0.3	0.4	4.0	12.9	1.5	2.4	9.9	11.6	0.0	1.2
Flow to Mediterranean Sea (MCM)*												
HPP				23125.9				21660.9				14820.5
IRRP				15253.4				14824.5				11921.3

Table D.1 Continued…

	S5				S6				S7			
	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total
Total benefit												
HPP	-5.4	-74.5	0.0	-11.8	-11.1	-69.8	4.0	-12.4	-16.3	-69.4	9.1	-12.1
IRRP	-9.6	-3.1	5.3	2.1	-13.1	-4.2	4.4	-0.4	-11.0	0.1	6.7	-2.3
Hydropower benefit												
HPP	0.4	13.1	10.2	3.4	1.2	18.2	11.9	4.8	2.0	17.5	20.5	5.9
IRRP	-10.9	-10.7	-1.6	-10.2	-19.7	-20.4	-1.6	-18.6	-12.1	-17.2	-2.3	-12.4
Irrigation benefit												
HPP	-89.5	-94.8	-0.1	-14.7	-65.9	-82.1	3.8	-15.3	-57.3	-81.7	8.9	-15.4
IRRP	9.1	-1.4	5.4	4.4	16.6	-1.9	4.5	3.6	-8.6	2.5	6.8	4.9
Total water use												
HPP	-9.4	-33.3	-3.8	-4.6	-23.6	-36.3	5.6	-5.1	-50.1	-44.1	11.9	-8.2
IRRP	8.0	0.1	1.4	1.3	8.0	-3.5	3.1	1.8	-1.8	2.5	7.1	5.1
Irrigation water use												
HPP	-96.7	-99.4	-6.1	-21.3	-98.4	-99.7	6.3	-13.3	-93.5	-99.4	15.4	-17.0
IRRP	87.0	8.2	2.2	3.6	27.9	2.6	4.6	4.6	-5.4	18.8	10.9	11.6
Evaporation loss from reservoir												
HPP	-1.9	26.8	4.0	11.6	-2.0	36.5	2.8	13.9	-1.5	24.3	1.9	9.7
IRRP	1.1	-7.3	-1.5	-3.3	2.3	-10.6	-2.1	-4.5	2.2	-17.7	-3.4	-8.0
Irrigated area												
HPP	-33.5	-60.3	-3.9	-11.3	-30.7	-58.0	3.5	-9.9	-34.9	-65.2	8.1	-12.7
IRRP	16.3	-0.8	4.1	3.8	7.5	-1.0	1.1	1.3	-3.7	11.0	6.1	5.0
Flow to Mediterranean Sea (MCM)*												
HPP				22371.6				17073.9				21860.2
IRRP				14490.5				12703.2				13456.5

*Level value (not percentage change)

Table D.2: Transboundary tradeoff analysis scenario results for S3 to S7 (% changes from system optimization)

	S3				S4				S5			
	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total
Total benefit												
ETHP	2.8	-0.5	-0.1	0.0	4.8	3.1	-3.0	-1.5	1.0	-25.8	0.9	-3.1
SUDP	-5.6	19.4	-7.2	-4.3	-2.6	19.4	-13.5	-8.7	-3.6	0.3	-1.9	-1.8
EGYP	-26.1	-67.2	4.7	-4.5	-20.4	-70.5	5.9	-5.6	-10.5	-59.1	8.6	-4.0
Hydropower benefit												
ETHP	0.2	-2.9	0.0	-0.6	-0.3	-2.5	-1.6	-0.8	0.3	-3.5	0.7	-0.3
SUDP	-1.6	6.5	-8.3	-1.0	-1.8	12.8	-21.1	-0.9	-1.9	7.7	-17.1	-1.2
EGYP	-18.4	-36.7	10.3	-17.2	-18.5	-39.1	18.9	-19.0	-8.7	-40.9	27.6	-11.9
Irrigation benefit												
ETHP	13.9	-0.1	-0.1	0.0	80.0	4.5	-3.0	-1.6	10.5	-30.9	0.9	-3.6
SUDP	-22.6	21.4	-7.2	-4.5	-15.0	20.9	-13.4	-9.8	-27.9	-1.4	-1.7	-1.9
EGYP	-59.0	-72.0	4.6	-3.6	-49.6	-78.0	5.7	-3.6	-36.0	-63.3	8.3	-2.5
Total water use												
ETHP	8.4	-0.2	-1.1	-0.8	12.0	3.0	-2.3	-0.9	8.9	-7.5	-1.4	-2.3
SUDP	-12.3	73.0	-9.2	-0.6	-9.3	93.5	-18.9	0.2	-9.4	51.3	-10.4	3.5
EGYP	-18.8	-66.4	6.6	-1.7	-12.2	-59.9	8.1	-4.0	-15.4	-62.8	8.8	-8.3
Irrigation water use												
ETHP	88.7	-1.6	-1.7	-1.3	156.1	4.9	-2.6	-1.3	68.2	-16.7	-1.2	-3.3
SUDP	-63.4	91.4	-11.3	-1.7	-53.8	87.8	-23.6	-12.0	-69.4	29.3	-13.1	-6.6
EGYP	-82.4	-64.0	6.8	-2.0	-74.1	-77.6	7.4	-2.8	-72.8	-75.1	6.3	-7.6
Evaporation loss from reservoir												
ETHP	-6.7	3.4	1.6	1.1	1.8	1.4	-1.0	0.1	3.8	0.8	-2.0	-0.3
SUDP	-2.7	26.6	-0.1	3.4	-6.1	98.3	0.7	31.3	-4.2	71.4	-1.5	24.7
EGYP	-6.8	-30.1	6.0	-0.3	-7.9	-37.3	10.7	-7.1	-10.5	-48.1	17.0	-9.9
Irrigated area												
ETHP	17.4	5.2	0.9	1.7	14.1	0.0	0.1	0.5	16.3	-5.3	1.6	1.1
SUDP	-21.5	61.6	-1.4	2.5	-34.9	50.2	-11.4	-6.8	-29.9	12.0	-3.4	-2.2
EGYP	-32.8	-66.7	2.9	-3.0	-32.4	-59.6	0.2	-6.1	-26.7	-53.0	2.5	-4.7
Flow to Mediterranean Sea (MCM)*												
ETHP				14730.4				12860.8				17040.3
SUDP				14719.2				10593.8				11477.6
EGYP				15485.7				15683.2				22169.7

Table D.2 Continued…

	S6				S7			
	ETH	SUD+S.SUD	EGY	Grand Total	ETH	SUD+S.SUD	EGY	Grand Total
Total benefit								
ETHP	1.7	-6.8	3.9	1.5	5.5	-6.4	-0.6	-0.8
SUDP	-6.8	8.8	-11.7	-7.0	-11.6	20.4	-2.7	-8.1
EGYP	-18.8	-65.3	17.1	-3.7	-24.6	-65.9	20.6	-5.7
Hydropower benefit								
ETHP	-0.4	-3.2	1.5	-0.7	0.6	-5.9	-1.7	-0.7
SUDP	-0.7	9.8	-19.0	-0.2	-0.4	10.5	-13.1	0.7
EGYP	-13.0	-39.6	29.1	-14.5	-8.5	-38.9	40.5	-10.7
Irrigation benefit								
ETHP	10.9	-7.3	4.0	1.9	16.3	-6.4	-0.5	-0.8
SUDP	-34.2	8.7	-11.6	-8.1	-36.8	24.8	-2.6	-9.6
EGYP	-44.9	-68.8	16.9	-1.9	-60.4	-69.7	20.3	-4.8
Total water use								
ETHP	17.8	-9.7	1.2	-0.5	38.2	-6.2	-0.2	1.3
SUDP	-22.7	59.5	-15.6	0.9	-48.4	37.3	-6.1	2.2
EGYP	-26.8	-68.0	18.2	-3.1	-54.5	-71.7	26.1	-6.7
Irrigation water use								
ETHP	68.9	-18.6	1.7	-0.8	68.8	-11.5	0.5	2.2
SUDP	-84.2	40.6	-20.0	-10.5	-87.8	7.0	-7.7	-9.5
EGYP	-89.2	-84.6	19.7	-0.5	-94.3	-88.2	30.2	-4.4
Evaporation loss from reservoir								
ETHP	3.1	0.4	-0.4	0.3	3.8	0.4	-2.2	-0.6
SUDP	-5.0	81.2	-0.2	27.4	-4.2	74.6	-1.6	25.9
EGYP	-8.9	-43.5	12.9	-9.1	-9.8	-48.5	14.4	-11.3
Irrigated area								
ETHP	17.0	-17.3	-2.3	-3.0	18.7	-10.0	0.6	2.3
SUDP	-25.1	18.8	-9.3	-6.1	-31.6	3.2	-3.8	-9.1
EGYP	-27.8	-54.2	6.7	-6.6	-35.5	-68.3	12.3	-10.6
Flow to Mediterranean Sea (MCM)*								
ETHP				14206.9				16452.2
SUDP				11520.8				13113.8
EGYP				16905.1				22166.0

*Level value (not percentage change)

Table D.3: Irrigation water requirement for irrigated crops with climate change (% changes by 2050 from historical period, averaged over irrigation nodes)

Crops by country	GFDL_ 4.5	GFDL_ 8.5	HGEM _4.5	HGEM _8.5	IPSL_ 4.5	IPSL_ 8.5	MIRC_ 4.5	MIRC_ 8.5	NESM _4.5	NESM _8.5
Ethiopia										
Barley	0.5	4.9	2.7	1.9	-4.4	-4.7	1.1	3.7	-3.8	3.2
Castor bean	-0.4	3.8	3.0	2.0	-4.3	-4.5	-1.3	1.5	-2.8	3.0
Coffee	-6.1	-1.0	2.6	0.4	-15.4	-19.2	2.6	1.7	-3.2	2.8
Field peas	0.4	4.8	2.2	1.7	-3.4	-3.7	0.4	2.4	-4.0	1.6
Fodder	-5.3	-0.3	3.1	1.2	-14.9	-19.4	3.2	1.9	-2.7	2.6
Fruits	-6.5	-1.4	2.2	-0.2	-15.0	-18.7	1.7	1.2	-3.9	3.1
Ginger	-16.0	-7.1	0.5	-4.3	-24.9	-33.8	-0.9	-3.4	-5.5	6.0
Grape	-5.6	0.7	1.7	-0.7	-14.2	-17.3	-3.5	-1.7	-6.2	2.0
Groundnut	-1.6	2.6	3.0	2.0	-8.5	-11.1	1.6	4.8	-3.9	4.7
Lentils	0.4	4.8	2.2	1.7	-3.4	-3.7	0.4	2.4	-4.0	1.6
Maize	-0.9	4.5	3.0	1.6	-6.5	-6.8	-1.1	2.0	-4.3	3.3
Onion	-1.8	1.7	3.0	2.2	-8.0	-10.9	1.7	4.5	-3.1	4.4
Potato	-1.4	1.9	3.0	2.3	-6.8	-9.1	1.8	4.3	-2.8	4.2
Red pepper	-12.5	-0.5	2.9	0.0	-15.2	-23.6	-6.2	-11.7	-6.7	-3.4
Rice	-3.7	-0.6	3.7	1.9	-13.4	-17.3	4.5	7.5	-2.7	6.2
Soybean	-1.2	1.7	3.5	2.9	-7.8	-11.3	2.4	5.5	-2.9	4.3
Sugarcane	-6.2	-1.1	2.5	0.1	-16.6	-20.4	2.5	1.4	-3.8	2.8
Sunflower	-4.6	0.5	3.1	1.6	-15.5	-18.1	2.2	2.4	-5.2	1.7
Tobacco	0.2	4.7	2.9	2.0	-6.9	-6.9	1.3	4.6	-5.1	3.7
Wheat	0.6	4.4	2.7	2.1	-4.2	-3.5	1.4	3.6	-3.4	3.1
Sudan**										
Cotton	0.7	2.8	4.4	4.4	-3.2	-3.1	-1.2	-2.9	-1.2	-1.1
Groundnut	1.8	6.3	9.5	8.6	-15.0	-15.4	-4.8	-11.1	-5.6	-6.0
Fodder	0.8	2.0	3.4	3.4	-2.1	-2.0	0.5	-0.5	-0.5	0.1
Rice	0.9	1.2	1.7	2.4	1.3	1.9	1.6	2.0	0.8	1.6
Sesame	1.8	6.3	9.5	8.6	-15.0	-15.4	-4.8	-11.1	-5.6	-6.0
Sorghum	0.4	5.4	10.3	9.4	-18.2	-17.4	-7.2	-14.9	-6.8	-7.6
Sugarcane	0.9	2.2	3.3	3.5	-1.9	-1.6	0.6	-0.4	-0.4	0.2
Sunflower	0.8	1.5	1.9	2.3	1.2	1.7	1.5	1.9	1.0	1.6
Vegetables	0.5	1.7	3.2	3.5	-1.4	-1.8	0.1	-0.7	-0.5	0.1
Wheat	0.7	1.5	1.8	2.1	1.1	1.6	1.4	1.8	1.0	1.6
Egypt										
Fruits (apple, banana, orange)	1.4	2.1	2.0	3.2	1.9	2.7	2.4	3.3	1.7	2.4
Barley	1.2	2.2	2.0	3.0	1.9	3.1	2.6	3.2	1.6	2.4
Bean	1.5	2.2	2.2	3.2	1.9	2.6	2.3	3.4	1.9	2.6
Cabbage	1.5	2.2	2.1	3.2	1.8	2.5	2.3	3.3	1.8	2.5
Cotton	1.3	2.1	2.0	3.2	1.8	2.6	2.4	3.2	1.8	2.3
Maize	1.5	2.2	2.1	3.2	1.8	2.6	2.3	3.3	1.8	2.5
Peanuts	1.4	2.1	2.2	3.3	1.8	2.5	2.3	3.2	1.9	2.4
Potato	1.4	2.2	2.0	3.1	1.9	2.7	2.3	3.2	1.7	2.3
Rice	1.2	2.0	2.2	3.2	1.8	2.5	2.3	3.2	1.7	2.3
Sesame	1.6	2.2	2.1	3.2	1.9	2.6	2.3	3.4	1.9	2.6
Sorghum	1.4	2.1	2.2	3.3	1.8	2.6	2.2	3.3	1.9	2.5
Sugarcane	1.4	2.1	2.0	3.2	1.9	2.7	2.4	3.3	1.7	2.3
Sugar beet	1.3	2.2	1.8	3.2	2.0	3.2	2.8	3.2	1.7	2.4
Wheat	1.1	2.2	2.1	2.9	1.9	2.9	2.3	3.1	1.6	2.3

Note: ** including South Sudan