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Document Sheet

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The purpose of the technical report series is to support informed stakeholder dialogue and decision making in order to achieve sustainable socio-economic development through equitable utilization of, and benefit from, the shared Nile Basin water resources.

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Front matter

This report was produced as one input to a Strategic Water Resources Assessment of the Nile Basin water resources, a process undertaken by the Nile Basin Initiative to guide development and coordination efforts across countries sharing these resources. The publication is a knowledge product and the discussions and results that are stated in the report do not represent the views of the NBI or specific riparian countries, and therefore should not be used on their own and in isolation of other inputs and considerations to advocate for specific policies or negotiations over water sharing and infrastructure development. This is particularly the case when considering specifics of how to implement benefit sharing agreements – for example, while the paper sheds light on the most efficient uses of water and energy generated from hydroelectric facilities in the basin, such allocations should not be interpreted to imply that there should not also be sharing of benefits via compensation for the alternative uses that are forgone when those uses are less efficient. Furthermore, the report makes no judgment on what is a *fair* sharing of benefits, in light of such considerations.

The analyses presented were also subject to data constraints and conducted within a limited scope that did not allow generation of new data. The presentation of data should not be interpreted as suggesting that the countries participating in the analytical framework development officially endorse specific parameter values, which are subject to change as the situation in the basin evolves. Moreover, the report leaves out of the quantitative analysis a range of impacts that cannot be easily quantified and valued at this time, due to lack of data and insufficient scope to explore those measures and their economic values, in this particular assignment. Discussion of such aspects is limited to qualitative comments in the report, where they apply.

The report benefited from the thoughtful review of the Nile country teams participating in the SWRA, as well as a team of Nile Basin economists who comprise the Nile Basin Economic Forum. Their comments are included in the annex to the report, along with author responses. All remaining errors are solely attributable to the authors.

Contents

A. Introduction: The purpose of this report ... 4

B. Brief review of objectives of the assignment ... 5

1. Background: Key Nile-related challenges on which HEMs could provide insight ... 5
2. Scope of the assignment and work plan ... 7

C. Organizing framework for the assessment, and summary of scenarios ... 9

1. Introduction: Reminder of main policy questions to be tackled through the analysis ... 9
2. Framework for scenario analysis ... 10
3. Review of scenario assumptions: Parameters and system configuration ... 13
4. Irrigation efficiency improvements ... 29
5. Additional sensitivity analyses ... 30

D. Results ... 32

1. Current and mostly unilateral development (DL-C0 scenario) ... 33
2. The baseline without the GERD ... 40
3. Exploring the effects of increasing development ... 44
4. Adding the effects of different cooperative institutions ... 50
5. Sensitivity to hydrological flows ... 55
6. The value of irrigation efficiency improvements ... 64
7. The cost of maintaining environmental flows in critical locations ... 66

E. Discussion ... 67

F. References ... 72

A. Introduction: The purpose of this report

The NBI Secretariat (Nile-Sec) launched and conducted the first phase of a strategic water resources analysis in 2015-2016. The strategic water resources analysis is aimed at developing options of measures (water resources infrastructure and management options) for meeting the growing water demand in the Nile Basin sustainably, reducing the stress on the river system and minimizing water allocation related tensions among the riparian countries. Following a first phase of analysis focused on water supply and demand assessment through 2050 that highlighted important water availability constraints relative to riparians' plans, the second phase was launched to identify and better characterize viable solutions to basin challenges. One of the tools being applied for this assessment is hydro-economic modeling.

This report, the fourth deliverable related to the hydro-economic modeling activity, follows three reports: 1) an inception report; 2) a methodology report; and 3) a scenarios report. Herein, we present results according to the description of the study and analytical framework presented in those prior reports, incorporating feedback on the draft results report obtained from the NBI Secretariat as well as comments from the country teams reviewing the draft report. Modest changes were made to the original analytical framework to conform to data availability, but much of the structure was retained.

In the remainder of this report, we briefly review the scope of the hydro-economic model (HEM) assignment in Section B, discussing the key Nile challenges about which an HEM can provide insight, and describing the place of this report within the work plan envisioned for the activity. Section C reviews the HEM analytical framework and scenario assumptions. Section D then presents the main results from the analysis. Section E examines the sensitivity of those results to various important factors and assumptions, and Section F summarizes and concludes.

B. Brief review of objectives of the assignment

1. Background: Key Nile-related challenges on which HEMs could provide insight

Though the HEM developed in this activity cannot reasonably consider all issues facing the Nile Basin riparians today, this section provides an overview of the potential applications of the Nile Hydro-Economic Optimization Model (NHEOM) that was developed. This overview has been adapted from that presented in the prior reports to reflect the latest construction of the model and provide a sense of the potential for modifications to it. The purpose is to provide the NBI and other stakeholders of the strategic water resources assessment with a sense of what might be possible using this tool, even if some of those identified possibilities have not been explored in the current assignment.

In theory, HEMs can be applied to study a wide range of economic questions related to issues including:

- economic development potentials and robustness (Whittington et al. 2005, Jeuland 2009, Jeuland and Whittington 2014),
- benefit-sharing (Tilmant and Kinzelbach 2012, Jeuland et al. 2014),
- tradeoffs (Wu and Whittington 2006, Wu et al. 2013),
- the importance of unpriced resource values (Kragt et al. 2011, Dinar and Nigatu 2013), and
- water-energy system interactions (Bekchanov et al. 2017, Jeuland 2017).

Using such tools, solutions such as infrastructure investments (storage (Strzepek et al. 2008, Nigatu and Dinar 2016), flood protection (Jeuland 2010), irrigation network expansion or efficiency-improving technology (Bekchanov et al. 2016), watershed protection, and supply augmentation (Pulido-Velazquez et al. 2008)) and institutional or management (operating rules for control infrastructure (Goor et al. 2010), allocation institutions, power trade arrangements, and environmental regulations) options can be explored. However, it is also important to highlight that the extent of such analyses will always be inherently constrained by existing data, and the extent to which it can be usefully translated into either physical or economic water constraints and valuation equations. The NHEOM is subject to many such limitations; among the issues flagged as important by country teams reviewing this work were valuation related to flood control benefits, watershed protection via reforestation and vegetation enhancement, environmental values associated with specific minimum flow regimes, and improved understanding of the potential for groundwater and conjunctive water use to meet the existing and future demand for water.

A concise summary of issues worthy of additional analytical work using HEMs appears in Table B1, which is divided into general themes that are not solution-dependent (Panel A) and into solution (or "building block") types (Panel B). This list emerged from the Nile Economist Forum meetings held in Entebbe in May 2017 and was modified based on subsequent analysis and discussions with other Nile stakeholders, Rows colored in gray have been partially addressed in the current work. Table 1 also highlights the specific contributions that HEMs can make regarding these issues and building blocks (additional details which were generated as outputs of the Nile Economist Forum are available upon request). Comments received in that forum and subsequent scoping meetings informed the development of the framework and scenarios that we review in Section C.

Table B1. Grouping of major planning issues to which HEM analysis could provide valuable input, synthesized from the Nile Economists Forum and subsequent discussions

Panel A: General themes worthy of study using a Nile HEM		
#	**General theme(s)**	**Question(s) of interest**
1	Benefit-sharing	What can we say about the comparative advantages of different countries, and the value of specialization and trade vs. diversification of water resources benefits generation? (Trade, geography of water productivity, food vs. energy, value of water in different uses)
2	Tradeoffs	What are the important economic tradeoffs in the basin? What is the current economic value of water in different uses? (cost of meeting limited objectives (e.g., food, energy), existing institutions, shadow values)
3	Robustness	What are the most important drivers of change or of the economic value proposition of different solutions? (Climate, hydrological variability, politics, macroeconomic conditions, population growth, tastes)
4	Nonmarket values and scarcity pricing	How can we think about ecosystem values in the Nile, and also the value of environmental services? (salinity control in Egypt's delta, upstream watershed management, sediment flows, pollution control, flood control, fisheries) How should tariffs for water and power be set?
5	Water-energy nexus	How should we compare hydropower with other alternative (conventional or renewable) energy sources (diversification, interdependencies, comparative advantage)
Panel B: Specific solutions or interventions worthy of study using a Nile HEM		
#	**Solution**	**Question(s) of interest**
1	New water storage / run-of-river projects	What is the optimal portfolio of investment in new dams (size, portfolios of projects, multipurpose vs. single purpose)? What are the economic benefits and distributional implications of that configuration relative to other combinations? How are benefits divided across projects and uses (irrigation supply augmentation, power generation, flood / sediment control, etc.)?
2	Large-scale irrigation expansion	What is the optimal configuration of irrigation in the basin? What are the economic benefits and distributional implications of that configuration relative to other combinations? What are the economic benefits of specific projects?
3	Irrigation efficiency technology	What is the economic and cooperative case for technical efficiency improvements (i.e., making water work harder via physical improvements)?
4	Sediment and watershed protection	What are the economic costs of erosion, in terms of reduced benefits from dams, irrigation, or other schemes? How would watershed protection reduce those costs, and is it economically attractive on such grounds?
5	Non-storage water supply augmentation	What is the economic role of groundwater management and exploitation in the Basin? Is there a role for conjunctive use of sources for irrigation? Wastewater reuse? Interbasin transfers?
6	Non-storage flood protection	What is the value of flood protection infrastructure (levies, etc.) other than dams? What is the cost of operational strategies at control infrastructure for enhanced protection against extreme events?
7	Coordinated operations of control infrastructure	How should filling and coordination strategies be developed for maximizing benefits? What are the costs of strategies that achieve other objectives (downstream protection, upstream development, faster filling, etc.)?

8	Water allocation rules / trading / pricing	How can water allocations for consumptive use be improved to maximize benefits? What are the costs of specific water requirements (with and without trading, and subject to demand management institutions such as pricing)?
9	Power trade	What is the optimal power distribution from hydropower facilities in the Basin, and how can power trade enhance the value of this production? What are the costs of power supply requirements (subject to power tariff institutions)
10	Environmental flow regulations	What are the costs of environmental flow constraints?

2. Scope of the assignment and work plan

Table B2 summarizes the structure of the work plan for this activity, updated to reflect the current status. Data collection with the assistance of Nile Regional Expert Group (NREG) liaisons from each country or through other phase 2 activities proved somewhat challenging for some aspects, but the modeling was heavily informed by support from the NBI regarding hydrology and infrastructure details, and by the irrigation valuation work conducted by the International Water Management Institute (IWMI) team as part of the broader activities of the NBI.

Table B2. Work plan for HEM activity

Step	**Description**	**Target Dates**	**Associated deliverable** (if applicable)
1. Inception ***(Complete)***	*Review of NBI phase I strategic water resources analysis; refinement of key research questions; review of Nile DSS capabilities; draft of initial methodological considerations*	*Delivered end of July** **Date adjusted to accommodate initial mission to NBI in early July 2018*	Inception report
*2. Discussion of valuation approach, development of model framework (**Complete**)*	*Construct modeling framework; specify water users and valuation approach; parameterize system baseline; write up draft*	*Draft end of July, revised October 2018*	Technical report with detailed description of methodology
3. Development of scenarios (***Complete***)	Define consistent scenarios for the basin according to the following types of considerations (population, economy, water/food/energy demand, economic integration, technology); define and begin to adapt/project parameters consistent with these scenarios	*Draft end of September, revised October 2018*	Technical report with detailed description of scenarios to be considered for analysis
4. Specification of policy / management options; analysis (***Complete***)	Assess system condition and tradeoffs under scenarios defined in step 3 (relative to baseline); describe policy/intervention options in detail; discuss with NBI regional expert group; analyze efficiency and distributional implications, including tradeoffs and key sensitivities; write up draft results	15 May 2020	Technical report with draft results

5. Presentation and discussion of results	Refine write up, present results,;	31 December 2020	Draft report
6. Finalization (***This report, policy brief pending approval)***	Discuss outcomes with NBI, Regional Expert Group, Nile Economists Forum; revise and finalize report; develop a policy brief w/ NBI	30 June 2022	Final report and policy brief

C. Organizing framework for the assessment, and summary of scenarios

This section closely follows the framework proposed in deliverables 2 and 3, in laying out the organizational structure for the scenario assessment of the HEM activity. The overall goal of this framework was to guide an analysis that would shed light on the potential production of economic value from the Nile Basin system, and to show the relative importance of coordination between riparians in achieving that value. A more specific goal was to begin to identify the types of infrastructures and policy strategies that might be robust to what is a highly uncertain and evolving basin situation. It was expected that the analysis would support recommendations that decision-makers in the basin could use to improve water resources management and development outcomes.

1. Introduction: Reminder of main policy questions to be tackled through the analysis

The main questions that were meant to be addressed in the HEM exercise were:

1. How can we characterize potential institutional and economic development-related futures for the Nile Basin? What are some key policy implications and perspectives on these potential futures?
2. Given these potential futures, what are the most economically attractive and robust policy options (infrastructural; demand management instruments, institutional solutions) for enhancing water-dependent outcomes in the Nile Basin?
3. What are the most salient economic characteristics of these attractive options? In other words, are they attractive based on their high expected marginal value, their distributional/equity features, or due to their properties in enhancing risk management and system robustness?
4. Is the attractiveness of different policy options highly correlated with future uncertainties in the basin, and are the relevant uncertainties issues that the riparians can control (e.g., extent of cooperation across countries, trading, land use/development policy) or not (e.g., climate/hydrological change, global economic conditions)? Given these dependencies, what are the implications for policy-making?

Q1 and Q2 suggested a need for a framework that would accommodate institutional and technological solutions as well as combinations of these, both of which may influence economics development outcomes in the basin. Q3 is about the efficiency and equity implications of those solutions, which requires a sectoral and country disaggregation of benefits. Q4 finally requires attention to the dependence of these economic outcomes on future conditions, and highlights notable institutional / economic aspects such as the extent of cooperation, trade and general macroeconomic conditions, as well as primarily physical drivers of change such as climate or land use change in the basin. Although land use change can arguably also be influenced by policies and institutions, consideration of such levers is beyond the scope of this HEM analysis due to lack of reliable data on its impacts on basin hydrology, an issue that is discussed further in the limitations section of this report.

2. Framework for scenario analysis

A workshop was held in Entebbe in July 2018 helped to elicit opinions from the Nile Regional Expert Group on the types of analyses that would be most useful to decision-makers in the basin. A first important point in the discussions was that national priorities and civil society perspectives would need to be represented in the analysis, covering agriculture, energy, and other water-dependent income generation sectors, balanced also with social and environmental needs. Second, NREG members noted that the analysis would be most useful if it informed collective planning over a meaningful time horizon, dealt with trade and coordination of infrastructure operations, addressed potential gains from specialization and leveraging of comparative advantage, but also explicitly thought about equity, and especially food security. Group work further highlighted that various plausible institutional and development futures could be anticipated, necessitating an approach that would consider the rationale for decisions along those lines.

These points pointed to scenario analysis that would encompass the following:

- Development pathways that included **more and less** infrastructure development, given that infrastructure tends to be particularly disruptive for some types of livelihoods;
- Various elements of cooperation along a continuum from low to full cooperation: At one end of this spectrum is a condition with country-specific optimization and limited power trade, and at the other end is an approach without borders that allows for full interconnection to maximize economic efficiency;
- Testing of the sensitivity of these dimensions to assumptions about population and economic growth; specialization, and hydrology/climate change.

On those grounds, a scenario analysis was structured according to Table C1. In Table C1, the two key dimensions are based around different types of cooperative institutions, on the one hand, and infrastructure development, on the other. The various features of these are presented in more detail below and in the subsequent sections, which describe baseline and future assumptions.

<u>Defining the cooperation continuum</u>. This continuum comprises three institutional elements: a) Extent of coordination in planning and operations of infrastructure or management institutions; b) Trading of benefits across borders; and c) Information sharing. The final assumptions and HEM operationalization for each of these are described below in Table C2, for current, *mostly* unilateral development (C0), a cooperation regime that would prioritize existing uses (C1), and a different cooperation regime that would prioritize economic efficiency (C2). In considering these alternative institutions, one should consider that C0 and C1 represent two management extremes. On the one hand, C0 prioritizes upstream uses above all other uses for any given infrastructure development level, regardless of whether they represent existing demands and claims on Nile water. On the other hand, C1 prioritizes uses that are documented as existing at this time, regardless of where they occur. This prioritization is achieved by placing large weights on the corresponding uses to make them take precedence over the others, as highlighted in the notes to Table C2. C2 is agnostic

about where the uses occur or whether they represent existing uses; in this scenario, water is simply allocated to where it generates the most economic value.[1]

We also note here the implications of each of these institutions for coordination of infrastructure, which is implicit in every model analysis. That is, the model tries to collectively operate infrastructures according to the institutional objectives of each scenario. In practice, this measns that in the unilateral development case, infrastructure operations are coordinated, but only within each country to maximize benefits, starting the value of coordination furthest upstream. In contrast, in the existing uses prioritization (C1), coordination op operations seeks to best meet existing uses. Finally, in the efficiency-maximizing case, coordination is aimed at achieving the highest overall basin-wide benefits.

Table C1. Overall proposed structure for the analysis, where scenarios are constructed to shed light on infrastructure development and institutional dimensions

Cooperation / **Infrastructure Development**	**Cooperation type 0 (C0): Unilateral development** (Current info sharing, mostly unilateral development w/limited power trade)	**Cooperation type 1 (C1): Cooperation to maintain existing uses and power trade** (Full info sharing, increased power/ag trade, limited joint infrastructure)	**Cooperation type 2 (C2): Cooperation to maximize economic efficiency** (Full info sharing, full trading, full joint infrastructure)
Current (No new control infrastructure)	Low dev-unilateral development (DL-C0)	Low dev-prioritize existing demands (DL-C1)	Low dev-efficiency maximizing cooperation (DL-C2)
Medium (Limited new control infrastructure)	Med dev-unilateral development (DM-C0)	Med dev- prioritize existing demands (DM-C1)	Med dev- efficiency maximizing cooperation (DM-C2)
High (Major new control infrastructure)	High dev-unilateral development (DH-C0)	High dev- prioritize existing demands (DH-C1)	High dev- efficiency maximizing cooperation (DH-C2)

[1] Note also that the institutional scenarios do not consider existing agreements or treaties in the basin, which are contested.

Table C2. Final assumptions for the cooperation dimension undergirding the scenario analysis

Assumption	**C0: Unilateral development**	**C1: Maintain existing uses and power trade**	**C2: Maximize economic efficiency**
HEM objective function weights	Weight upstream country benefits, to encourage allocation upstream (this mimics sequential optimization)[1]	Weight existing irrigation demands only[2]	No weights
Implied information sharing	No information sharing assumed	Implies full sharing of flow information to guide meeting existing demands	Implies full sharing of inflows to guide basin optimization
Reservoir coordination across countries	Not considered	Automatically included in objective function	Automatically included in objective function
Energy trade[3]	Satisfy internal demands first (even if lower in value all the way to zero), then trade excess only up to existing capacities	Satisfy internal demands first (even if lower in value), trade only excess power	Full trade to optimize value of power demanded
Trade of irrigation benefits	Not considered	Not considered	Not considered
Valuation of spillover benefits: Carbon offsets[4]	Side calculation	Side calculation	Included in objective function
Coordination of infrastructure selection	None	None	None assumed; but could be explored further
Joint financing of new storage infrastructure (dams)	None	Compare incremental power production relative to CL; determine implication for proportional financing	Compare incremental power production relative to CL; determine implication for proportional financing

Notes:

[1] Prior to reporting the results, we rescale the weighted results to convert them back to actual values (US$). The weighting scheme we implement is to include a weight for the Equatorial Lakes of 1000, for South Sudan/ Ethiopia of 100, and for Sudan of 10. Benefits in the furthest downstream country in this parameterization, Egypt, are unweighted. This weighting system is arbitrary, but was tested to ensure that water would be prioritized as implied by the desired institutions. Results were insensitive to the specific weighting until the weights dropped substantially, at which point it was apparent that the upstream prioritization of water uses was no longer working as desired.

[2] Prior to reporting the results, we rescale the weighted results to convert them back to actual values (US$). The weighting scheme we implement is to include a weight for existing agricultural demands of 10; all new agriculture demands are unweighted. This weighting system is again arbitrary, but was tested to ensure that water would be prioritized as implied by the desired institutions. Results were insensitive to the specific weighting until the weights dropped substantially, at which point it was apparent that the existing claims prioritization of water uses was no longer working as desired.

[3] Below we explain the approach used for valuing power benefits, based on projected future demand in the modeled regions. For energy trade, we assume internal transmission losses to be 15%, which is in line with losses estimated in Egypt and Sudan under the Eastern Nile Power Trade study; for long-range transmission across markets, an additional loss of 5% is included.

[4] Details of the valuation approach are provided further below.

Defining the development continuum. This continuum similarly includes three settings, one containing major current infrastructure and irrigation water uses (as detailed below), the second with limited new infrastructure encompassing a subset of expanded irrigation and new hydropower installations, and the third with the full set of major new control infrastructures specified by the countries during scenario development, which correspond to the most important storage dams and expanded irrigation projects in the basin. These we call DL, DM, DH in shorthand.[2] The specific assumptions of the development scenario infrastructures are described in more detail below.

Also, to maintain tractability (i.e., a manageable set of scenarios), the full set of possibilities in this report have only been examined without demand management and irrigation efficiency improvements. That is, the three development configurations were analyzed under each cooperation scenario (DL, DM and DH were assessed with C0, C1, and C2, yielding 9 combinations). The additional benefits of two levels of irrigation improvements (medium and high) was then considered in the C2 efficiency-maximizing variant only (for all three levels of development DL, DM and DH). The motivation for this was that many of the benefits of increased efficiency flow downstream, and that there is therefore limited incentive for such improvements – except within Egypt where such benefits can be reallocated to other irrigators in that country – in the absence of cooperation. In future work, we could further study the role of demand management and irrigation efficiency improvements for a larger subset of relevant development and cooperative institution options.

3. Review of scenario assumptions: Parameters and system configuration

The Nile Hydro-Economic Optimization Model (NHEOM) schematic. We refer to the representation of the final Nile Hydro-Economic Optimization Model (NHEOM), as represented by the schematic shown in Figure C1 (a more complete description of the model set-up is included in the appendix). For a more complete description of the model development and current infrastructure assumptions, the reader can consult deliverables 2 and 3: *Hydro-economic analysis for the Nile Basin Collaborative Water Resources Assessment: Draft Methodology (Model Setup) Report* and *Hydro-economic analysis for the Nile Basin Collaborative Water Resources Assessment: Draft Economic Scenarios Report*. Differences with the schematics and assumptions presented in those reports are due to final availability and updating of data.

In the sections below, we describe the current (uses and infrastructures) assumptions as they pertain to a) hydrology and climate; b) characteristics of existing and planned water infrastructure; c) current and expanded irrigation demands; d) current and future anticipated municipal and industrial demands; and e) other important assumptions.

[2] Here again, the analytical framework passes no judgment on whether existing uses in DL are fair or not; rather, these are taken to represent low relatively low development because that is the current situation. The DH scenario is the contrasting case where all development plans specified by the riparians during the scenario development phase are included. Again, whether or not these plans represent a fair distribution across countries is not discussed.

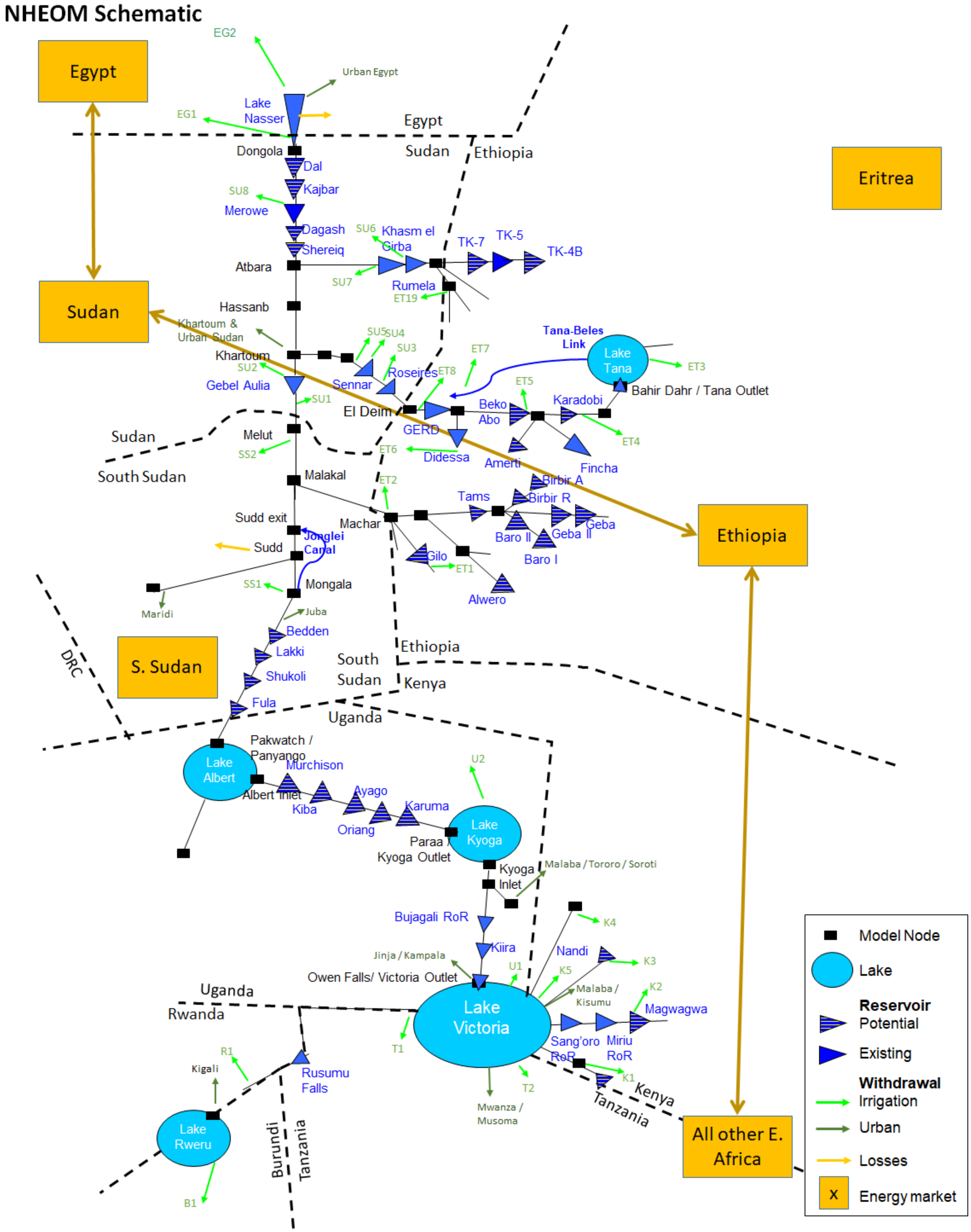


Figure C1. Final NHEOM Schematic

System hydrology and climate. Inflows were used based on the historical runoff from different catchments in the Nile DSS. These inflows are natural virgin inflows and do not indicate channel losses as the tributaries and main river flow towards the downstream. Thus, reach-specific losses were parameterized to adequately account for channel losses and yield a range of flows that are consistent with that observed at Aswan over the same historical period. Three 5-year sequences were selected for the analysis, representing dry, median, and wet conditions as measured by overall runoff, but note that these sequences may not represent dry, median, or wet conditions within specific sub-catchments as a result, especially for smaller sub-catchments.

Table C3. Sequences used for assessment of results sensitivity to hydrological variation

Hydrological scenario	Years of runoff used	5-year runoff percentile
Dry	04/1969-03/1974	10^{th}
Median	04/1971-03/1976	50^{th}
Wet	04/1953-03/1958	90^{th}

Characteristics of current and potential water control infrastructure. Table C4 provides details on the hydropower facilities in the current situation, low and high development infrastructure configurations. Each of these projects are modeled as separate nodes in the system, since aggregating hydropower projects together can lead to considerable loss of accuracy. As with all other similar existing system characteristics that follow, any errors in these estimates would come from the underlying data provided by each country, or from omission of relatively minor projects for which such data have not been shared.

Description of current and potential irrigation demands. Table C5 provides details on the irrigation demands in the system, with some additional explanation, when relevant, on how smaller projects have been aggregated together. The current amounts at each point were initially specified based on the final 5 years of data included in the Nile DSS (2010-2014), as applied in the baseline phase I analysis. Future irrigation demands were similarly drawn from the potential identified in the Nile DSS and other documents. Following submission of the draft report and based on complete details provided by the NBI Secretariat, these assumptions were then checked and updated to ensure consistency with the analyses in the rest of the second phase of the strategic basin assessment, for the **no water saving intervention case**. This can be considered to be the case of irrigation water use under the country-specified levels of existing technology; we relax this assumption of existing technology in the analysis of the implications of enhanced irrigation technology investments that are described further below.

Table C4. Hydropower projects included in the model for the current situation, and further added for low and high development scenarios

Hydropower facility	River	Node	Installed capacity (MW)	Max gross storage (bcm)	Dead storage (bcm)	Tailwater level (masl)	Operating range (masl)
Current							
Rusumu Falls RoR	Kagera River	5	80	n.a.	n.a.	1290	1325
San'goro RoR	Sondu River	27	20.2	n.a.	n.a.	1170	1205
Owen Falls[1]	Lake Victoria	34	388	n.a.	n.a.	1113	n.a.
Kiira RoR	Victoria Nile	45	200	n.a.	n.a.	1090	1111-1113
Bujagali	Victoria Nile	46	250	0.054	0.041	1071	1088-1090
Gebel Aulia	White Nile	155	28.8	3.4	0.1	372	372.1-377.2
Tana-Beles	Blue Nile	175	470	n.a.	n.a.	1543	Above 1780
Finchaa	Finchaa River	193	134	0.65	0.20	2290	2310-2327
Lower Didessa	Didessa River	203	300	8.5	4.5	639	770-810
GERD	Blue Nile	211	6000	64.7	21.1	494	590-640
Roseires	Blue Nile	213	280	5.5	1.1	443	469-489
Sennar	Blue Nile	215	15	0.83	0.02	403.7	415-421.7
TK-5	Tekeze River	249	300	4.3	1.7	970	1065-1100
Khasm el Girba	Tekeze River	265	13	0.54	0.05	433	462-473
Merowe	Main Nile	283	1250	12.1	4.3	243	289-303
HAD	Main Nile	286	2100	183	31	98	147-175
OAD	Main Nile	287	626	n.a.	n.a.	83	n.a.
Low development							
Magwagwa	Sondu River	26	100	0.66	0.40	1490	1582.6-1586.4
Sondu Miriu	Sondu River	27	60	0.003	0.000	1208.1	1405-1410
Nandi	Yalas River	29	60	0.28	0.1	1770	1811-1831
Karuma	Victoria Nile	62	600	0.080	0.034	960	1028-1030
Ayago RoR	Victoria Nile	64	612	0.003	n.a.	776	857-860
Fula	White Nile	82	890	0.82	0.19	570	600-620
Shukoli	White Nile	83	235	0.11	0.01	537	540-560
Birbir I (A)	Birbir River	106	95	1.10	0.22	1220	1410-1430
Geba I	Geba River	103	105	0.86	0.35	1840	2160-2170
Baro I	Baro River	111	180	1.34	0.33	1320	1485-1520
Tams	Baro River	113	1060	10.0	3.6	486	680-760
Alwero (Chiru)	Alwero River	120	?	0.136	0.046	428	450.6-460
Amerti	Finchaa River	195	97	0.13	0.036	1950	2230-2235

Beko Abo	Blue Nile	198	2000	38.2	8.4	789	960-1080
TK-4B	Tekeze River	248	85	2.52	1.53	1114	1222-1260
Rumela	Tekeze River	262	120	3.0	1.32	480	508.4-517.5
Dal	Main Nile	285	620	2.47	0.46	180	190-201
High development							
Murchison RoR	Victoria Nile	44	648	n.a.	n.a.	625	718-758
Oriang RoR	Victoria Nile	63	392	n.a.	n.a.	852	923-980.1
Kiba RoR	Victoria Nile	65	288	n.a.	n.a.	718	765-770
Lakki	White Nile	84	410	0.22	0.05	513	523-535
Bedden	White Nile	85	570	1.83	0.23	473	490-510
Birbir II (R)	Birbir River	107	465	2.70	0.18	766	1056-1158
Geba II	Geba River	109	310	3.95	1.0	861	1030-1115
Baro II	Baro River	112	500	0.073	0.041	810	1318-1320
Gilo	Gilo River	127	80	3.6	0.90	530	578.5-610
Karadobi	Blue Nile	190	1600	40	22.8	910	1100-1146
TK-7	Tekeze River	251	220	10.1	1.85	840	881-998
Shereiq	Main Nile	280	350	2.20	0.32	324	330-343
Dagash RoR	Main Nile	281	284.8	0.1	n.a.	300	322-323
Kajbar	Main Nile	284	250	0.3	0.1	202.6	207.9-213

Notes: Project data was reviewed for accuracy; the data above come from various sources including the Nile-DSS and published papers, as well as online sources.
[1] Owen Falls hydropower is modeled based on a turbine efficiency relationship as described in Jeuland (2009), which is based on the rating curve established in the Nile-DST developed by Georgakakos. This efficiency is a function of releases, height of the water in Lake Victoria, and the tailwater level.

Table C5. Irrigation demand locations to be included in the model in the current situation, and medium and high development scenarios

Location	Withdrawal node #	Relevant projects (if named)	Current demand (bcm/yr)	Low development (bcm/yr)	High development (bcm/yr)
Rwanda	7	Ruvubu, Nyabarongo, Rwagitugusa, Kagera, Lakes George and Edward	0.05	0.06	0.06
Burundi	2		0.08	0.1	0.13
Magogo, Tanzania	11		-	0.1	0.2
Other Tanzania	34		-	0.4	0.8
Kuja, Kenya	25		-	0.01	0.02
Sondu, Kenya	27		-	0.01	0.1
Yalas, Kenya	29		-	0.1	0.3
Nzoia, Kenya	33	Various projects included in Nile-DSS	0.01	0.02	0.02
Other Kenya	34	Nyando, Itare, Sare, Awach, Lake Victoria, Mamwe, Isanga, Simiyu, Rubana, Mara	0.2	0.2	0.5
Victoria, Uganda	34		0.17	0.2	0.2
Kyoga, Uganda	50	Lake Kyoga, Malaba, Olweny	0.2	0.2	0.2
Bahr el Ghazal, S. Sudan	86		0.15	0.3	0.55
Other S. Sudan	91		-	0.01	0.01
Alwero, Ethiopia	120	Alwero	0.2	0.2	0.2
Baro-Akobo, Ethiopia	138	Abobo, various other projects	0.2	5.0	10.5
U/S Gebel Aulia, Sudan	155	Kenana and Asalaya	1.4	2.4	3.4
D/S Gebel Aulia, Sudan	156	Pump schemes	0.2	0.2	0.2
Tana, Ethiopia	175	Lake Tana, Tis Abbay, Koga	1.6	1.8	2.0
U/S Beko, Ethiopia	188	Kessie	0.4	0.9	1.4
Finchaa River, Ethiopia	194	Finchaa, Amerti	0.4	0.4	0.4
Didessa River, Ethiopia	205	Arjo-Didessa	0.3	0.3	0.6
Tana-Beles, Ethiopia	208		0.4	0.4	0.4
U/S GERD, Ethiopia	211		-	0.3	0.6
U/S Sennar, Sudan	214	Suki, Hurga, Private pumps, Seleit, Waha, Guneid	1.1	1.1	1.1
Sennar, Sudan	215	Gezira, Sennar	7.4	7.4	7.4
D/S Sennar, Sudan	215	Rahad	2.9	4.0	4.5
U/S Tekeze, Ethiopia	262		0.3	0.8	1.3
D/S Girba, Sudan	263	New Halfa	1.2	1.2	1.2
North Sudan	282	Hasanb, Merowe, Tamaniat	1.1	1.1	1.1
New Valley, Egypt	285	New Valley	3	3	3
D/S HAD, Egypt	286	Nile Delta	64	69	69

Table C6. Urban demand locations to be included in the current situation, and medium and high development scenarios

Location[1]	Withdrawal node	Demand at baseline	Population at baseline	% increase population (2015-2040)	% increase urbanized (2015-2040)	Implied demand in future (2040)
Gitega, Burundi	2	0.001 bcm/yr	72,600	99.8%	10.2%	0.002 bcm/yr
Kigali, Rwanda	4	0.01 bcm/yr	860,000	63.9%	6.9%	0.02 bcm/yr
Mwanza/Musoma, Tanzania	34	0.02 bcm/yr	840,000	102.4%	17.5%	0.05 bcm/yr
Bungoma, Kenya	34					0.08 bcm/yr
Malaba/Kisumu, Kenya	34	0.01 bcm/yr	510,000	72.1%	14.0%	0.02 bcm/yr
Jinja/Kampala/Tororo, Uganda	34	0.06 bcm/yr	1,710,000	108.3%	15.6%	0.14 bcm/yr
Soroti, Uganda	47	0.001 bcm/yr	62,000	108.3%	15.6%	0.002 bcm/yr
Rutshuru, DRC	68	0.001 bcm/yr	62,000	106.2%	15.2%	0.002 bcm/yr
Juba, S. Sudan	85	0.01 bcm/yr	370,000	78.3%	10.8%	0.02 bcm/yr
Gondar, Ethiopia	175	0.005 bcm/yr	324,000	66.4%	13.3%	0.009 bcm/yr
Khartoum, Sudan	233	0.3 bcm/yr	5,000,000	74.3%	12.1%	0.6 bcm/yr
Cairo and Egypt cities	287	12.5 bcm/yr	41,000,000	46.2%	6.6%	19.5 bcm/yr

Notes: Data was reviewed for accuracy; the original data above come from the Nile-DSS, cross-checked with the municipal and industrial demands reports of the SWRA. Projections from baseline pertain to the median UN-variant of projected increases in population in 2040 due to population growth and urbanization (UN) (https://population.un.org/wup/Download/), assuming similar consumption levels.

[1] These locations are not the only urban water use locations in the basin. They are those that rely in some way on surface water resources from the Nile Basin, rather than groundwater sources or surface water from outside the basin.

Description of current and potential municipal demands. Table C6 lists the urban demands across development futures. It is important to note that these demands represent only those that are met using surface water, and that the majority of urban demands in the basin rely on groundwater. The baseline amounts for municipal withdrawals were specified based on the final 5 years included in the Nile DSS (2010-2014), as applied in the baseline phase I analysis. Future demands were based on population and urbanization projections, as described below. This is admittedly a relatively simplistic projection that does not allow for changes in water demand due to other factors such as economic growth, but development of a more sophisticated model was beyond the scope of this work. Following submission of the draft report and based on complete details provided by the NBI Secretariat, these assumptions were then checked and updated to ensure consistency with the analyses in the municipal demand analysis of the second phase of the strategic assessment.

Other baseline scenario assumptions. Other important assumptions for the current analysis are shown in Table C7. These pertain mostly to valuation parameters for the economic analysis.

Table C7. Other model parameter assumptions for the scenario analysis

Location	Description	Assumption	Source
Social discount rate	Parameter for consistently aggregating consumption benefits over time, and for annualization of capital costs	4%	n.a.
Shadow value of investment	Represents the opportunity cost of investment in capital-constrained economies	1.5	n.a.
Real economic growth	Determines increase in water and energy value over time	1%/yr	IMF
Value of irrigation water	Parameter for valuing irrigation water delivered	Varies by location; see description in text	Jeuland & Whittington (2014)
Return flows	Based on irrigation efficiency	Varies by location according to irrigation efficiency; see text	n.a.
E-flows	Minimum flow constraints	None imposed	n.a.
Value of baseload hydropower	Parameter for valuing baseload power generated at hydropower facilities	Varies by location and generation amount; see text	Jeuland & Whittington (2014)
Fraction of peaking power	Dams with re-regulating infrastructure downstream can generate peaking power, which is more valuable	Only for upstream dams within cascades: 33%	Jeuland & Whittington (2014)
Value of peaking hydropower	Parameter for valuing peaking power generated at hydropower facilities	2 times the value of baseload	Jeuland & Whittington (2014)
Transmission losses	Parameter that accounts for loss of energy being generation site and final demand site	15% within market, 20% across markets	Eastern Nile Power Trade study
Value of carbon offsets	Value of mitigating climate-forcing emissions with hydropower generation, depends on carbon intensity of alternative generation	Time-consistent social cost of carbon derived from the discount rate, applied to country-specific offset factor	EPA, IEA (2017)
Flood damage reduction	Not included	n.a.	n.a.

Social discount rate. The social discount rate reflects the lower value of costs and benefits deferred in time relative to the present. In this analysis, it is set on the basis of the relative social preference for increased consumption across generations. Following Ramsey (1928), we specify this parameter to be a function of the pure rate of time preference and the product of the elasticity of marginal utility with respect to consumption and the growth in consumption over time:

$$d = \delta + \eta \cdot c(t) \tag{1}$$

Here, the pure rate of time preference is set to 0 on the basis that it is not ethically reasonable to weight current consumption preferences more heavily than future consumption preferences simply because they occur in the future. Dasgupta (2008) defines η as "the index of the aversion society ought to display toward consumption inequality among people – be they in the same period or in different periods." For typical long-term growth rates of 2-3% and reasonable values of η (in the range of 1-2), the implied social discount rates range from 2-6%, we use 4% in our main analysis.

Shadow value of capital. These social discount rates do not account for the shadow cost of capital investment, which must be considered prior to annualizing investment costs (Dasgupta et al. 1972). For infrastructure costs (which are applied as side calculations), we use a shadow value of investment of 1.5 in the main analysis. A value of 1 would imply that only consumption is displaced, while a value of 2 would be consistent with a situation in which the rate of return on capital is 10%, the social discount rate is 4%, and the two thirds of the investment resources come from taxes on investment. These are reasonable assumptions for capital-constrained countries that are raising significant financial resources using a limited tax base.

Real rate of economic growth. The real rate of economic growth contributes to a higher relative value of benefits produced by the system, via increased demand for water, energy, and other outputs. This parameter is highly uncertain; in the main analysis, we set it based on the median growth rate among all Nile countries over the 1998-2018 period. Thus, for each development future (current, medium, and high development), our comparison starts from a 2050 model year – this is deemed necessary to realistically allow for the expanded infrastructure and irrigation development represented in the medium and high development scenario variants – such that values are inflated by a factor of $(1 + g)^{30} = 1.01^{30} = 1.35$ relative to current demand. In subsequent years, benefits continue to rise at a real rate of 1.01 per year, but are discounted such that all benefit estimates are in 2050US$.

An additional point that is important to highlight for interpretation of results is that all values are according to these projected 2050US$, and are not adjusted for purchasing power parity differences across countries. There are several reasons for this. First and most importantly, the PPP adjustment is best used when analyzing final consumption, but the location of that consumption could vary substantially, depending on whether energy is being exported via power trade or food is being grown for domestic consumption or the export market. Second, while the projection of growth according to the real rate of growth that is described is tractable and empirically based, the projected evolution of PPP-adjustments over time and across countries is more challenging.

Irrigation water valuation and benefits. One of the aims of this work was to update the value of energy and irrigation water or crop output, to be spatially heterogeneous based on water productivity assessments being conducted as part of the NBI's second phase of strategic assessment. The assumptions for valuing irrigation water were set based on the recent value of water work done by the International Water Management Institute (IWMI). As this deviates from the set-up proposed in the scenarios report which proposed to use a prior uniform value for the entire basin, we describe the more complex and nuanced approach that was adopted in more detail below.

The IWMI valuation work produced a set of country-specific water productivity values for major crops being grown, assuming provision of the full water requirement and based on netting out of production costs. The team derived estimates based on world and farm gate prices; in most cases we use the estimates based on world prices to account for market distortions that would lead to overestimates of these valuations in particular locations due to hidden subsidies or price supports that benefit producers.

It is important to note that our model set-up does not allow for adjustments in cropping patterns, since such an approach typically leads to selection of odd crop mixes by an HEM due to lack of inclusion of the demand and market structure for agricultural commodities, which would limit corner solutions dominated by specific high value crops, such as fruit orchards. Instead, we started from the crop typologies identified by IWMI to determine and fix the pattern of irrigated crops in four locations and five seasons: 1) Egypt – summer; 2) Egypt – winter; 3) Ethiopia; 4) Sudan; and 5) the Equatorial Lakes region. These typologies and the corresponding values in each site /season for full irrigation were then derived based on areal weighting by crop and crop-water requirement. The cropping patterns are summarized in Table C8 below.

Next, we used yield curves from the Nile DSS, provided by the NBI, to determine how these values would be affected by deficit irrigation, which provides the basis for determination of the two key decision variables in the model:
1) the extensive margin of site-specific irrigation, whereby the total land irrigated can be adjusted up and down according to water availability and its optimal use; and
2) the intensive margin of site-specific irrigation, whereby the proportion of the total water requirement on the cultivated land can be adjusted to allow deficit irrigation, if that maximizes value overall due to higher value uses elsewhere.[3]

[3] Note that allowing for deficit irrigation does not impose this solution *a priori* on any user in the basin. In other words, the model does not make a judgment that deficit irrigation should be allowed in one country but not another; rather it allows for deficit irrigation according to the institutional characterization of the objective function previously described. Thus, in the unilateral development institutional arrangement (C0), deficit irrigation will only occur in an upstream country if that is beneficial from the perspective of that set if countries, owing to greater hydropower production or other irrigation uses in the same country but further downstream. On the other hand, when existing

To do this, we took the full irrigation water demand (in m^3/hectare) specified by the IWMI team to set the upper bound for water allocation to each crop grown in the typology, along with the location-specific yield gain from irrigation associated with that full allocation. These yields vary by location due to differences such as growing conditions, rainfall contribution to the water requirement, sunlight, soil quality, farmer know-how, seeds, and technology, and other factors. From the set of yield curves provided by the NBI, we specified relationships between yield and water allocation for crops that had such relationships, and multiplied the implied production at 10% intervals based on the world price of the output (in US$/ton). For crops not included in the Nile DSS or with strange relationships, we assumed a linear water-yield function.[4]

Table C8. Irrigated proportion, by crop, in each irrigated site / season

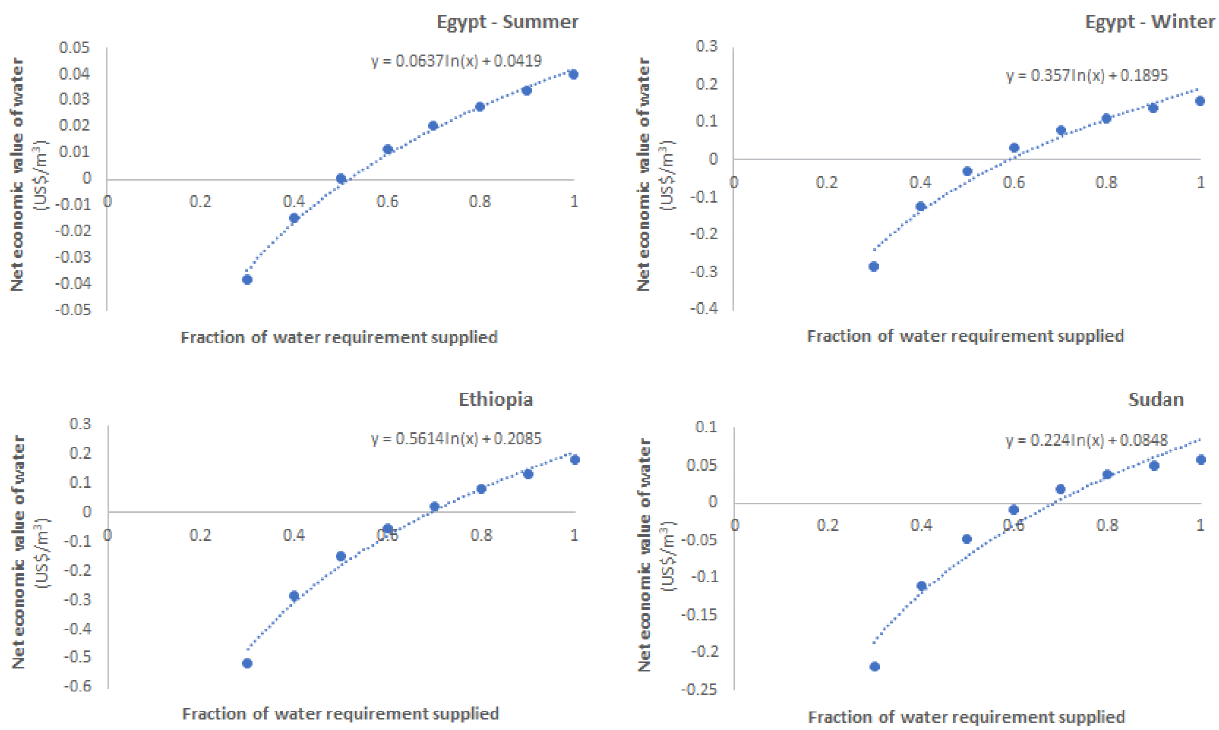
Crop	Egypt – summer (intensive)	Egypt – winter (intensive)	Ethiopia (extensive highland)	Sudan (semi-intensive)	Equatorial Lakes (extensive low land)
Maize	9.6		0.01		3.6
Wheat	13.2		0.01	5.0	
Sorghum	1.2		9.7	15.2	3.3
Potato	0.7		0.01		
Banana		10.2	15.0	10.1	23.3
Vegetables		15.0	31.9	8.9	4.9
Cotton		2.8	24.8	8.9	1.2
Rice		6.7			7.0
Apple		2.3			
Sweet Potato			6.0		5.3
Sugar cane			7.4		38.6
Millet				37.6	
Groundnut					0.03
Cassava					0.05
Total accounted for	**24.7**	**37.0**	**94.9**	**85.8**	**87.3**

Notes: Source is IWMI (2019). In all sites, the IWMI typology captures the majority of the cropped area, but note that area in Egypt is summed over two seasons, such that the total area represented by the typology there is 61.7%, which is relatively smaller than in the other locations, where the typology represents 85.8-94.9% of all irrigated area. Due to rather sparse data for some countries, a single Equatorial Lakes typology was constructed by weighting each of Kenya, Rwanda, Burundi, Tanzania and Uganda's irrigated area in the extensive low land typology.

claims are prioritized (C1), deficit irrigation may exist upstream of those uses in order to enable those existing claims to be better satisfied.

[4] Crops without such information for which we assumed a linear relationship include: a) potato, banana, apple, and vegetables in Egypt; b) potato, banana, and vegetables in Ethiopia; c) banana, vegetables, and millet in Sudan; and d) banana, vegetables, cotton, groundnuts and cassava in the Equatorial Lakes region.

Finally, in cases for which world prices yielded unbelievably high implied valuations, we substituted farm gate prices in their place. This adjustment was made for the following crops in locations as specified: Potato, rice and banana in Egypt; potato, sweet potato and banana in Ethiopia; banana in Sudan; and sweet potato and banana in the Equatorial Lakes region. For banana, the difference between farm gate and world prices likely reflects spoilage and therefore accounts for the loss of production value; for potato and sweet potato spoilage may also be a factor, but it is somewhat unclear what drives the divergence. Cost (in US$/hA) was then netted out, as this was implied to not vary with water allocation. This allowed for determination of the value of water in 10% increments of the water allocation. We then fit a log function to these data for use in the models, since this function performs well in nonlinear optimization and approximates the value fairly well. The functions slightly overestimate value at high water allocations and underestimate value for irrigation under substantial deficit.[5] The valuation curves at each site are presented below (Figure C2), and their parameters are summarized in Table C9.



[5] It should be noted, however, that the underestimation of water value for irrigation under major deficit is somewhat exaggerated since the yield curve for most crops drops more rapidly then the linear yield curves imply, somewhat offsetting this error.

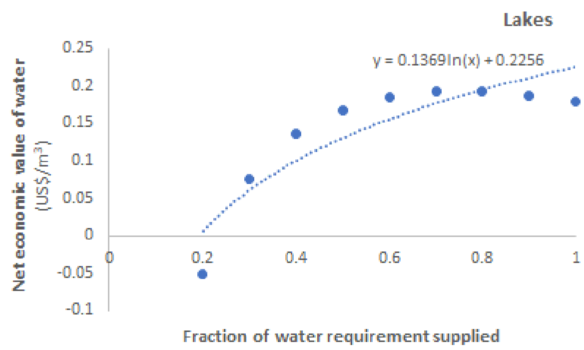


Figure C2. Value of water as a function of irrigation water supplied, in the five model location and season combinations: a) Egypt – Summer; b) Egypt – Winter; c) Sudan; d) Ethiopia; and e) Equatorial Lakes.

Table C9. Parameters of the irrigation water value function (v = slope*ln(irrfraction)+ constant)

Parameter	Egypt – summer (intensive)	Egypt – winter (intensive)	Ethiopia (extensive highland)	Sudan (semi-intensive)	Equatorial Lakes (extensive low land)
Slope	0.0637	0.357	0.561	0.224	0.1369
Constant	0.0419	0.1895	0.2085	0.0848	0.2256
Max water requirement (m^3/hA)	6136	7431	4621	3339	3911

Notes: Source of underlying data is IWMI (2019). Authors' analysis of yield and water requirement data. Irrfraction is the fraction of full crop water requirement that is supplied.

Return flows. The table below (Table C10) shows irrigation efficiencies across country irrigation schemes, both initially and under maximum improvement conditions. We model return flows to be dependent on overall efficiency (accounting for conveyance and application loss). Specifically, we assume the return flow to be 40% of the water that is not productively used by crops. This implies that in most locations at baseline, about 30% of diverted water is lost from the system, to non-productive evaporation or groundwater recharge, while 20% is return flow. In Egypt, return flows are somewhat lower, at 17.6%, due to higher application efficiency from some use of drip irrigation.

Table C10. Return flows by country

Location	Current technology application efficiency	Current technology conveyance efficiency	Current technology overall efficiency	Current technology return flow	Best technology efficiency (drip + lining)	Best technology return flow
Sudan	70%	70%	49%	20.4%	81%	7.6%
Ethiopia	70%	70%	49%	20.4%	81%	7.6%
Egypt	80%	70%	56%	17.6%	81%	7.6%
Kenya	70%	70%	49%	20.4%	81%	7.6%
Tanzania	70%	70%	49%	20.4%	81%	7.6%
Rwanda	70%	70%	49%	20.4%	81%	7.6%
Uganda	70%	70%	49%	20.4%	81%	7.6%
South Sudan	70%	70%	49%	20.4%	81%	7.6%
Burundi	70%	70%	49%	20.4%	81%	7.6%
DRC	70%	70%	49%	20.4%	81%	7.6%

In the irrigation improvement scenarios (detailed further below), return flow fractions are adjusted to account for the reduced natural recharge that is entailed by such technology. In all cases, the proportion of flow returning to the river is assumed to be 40% of the water that is not used productively by crops.

Energy production valuation and benefits. For hydropower, we similarly deviated from prior modeling that has assumed a constant value for baseload and peak energy produced throughout the basin. Specifically, we consulted energy demand projections to specify demand curves according to each of six mostly separate energy markets: The Equatorial Lakes Region, South Sudan, Ethiopia, Sudan, Eritrea, and Egypt.

To parameterize these demand curves, we further considered a) IEA and other estimations of current energy demand and b) literature on the price elasticity of demand for electricity in economic studies (Howitt et al. 1980, Espey and Espey 2004, Reiss and White 2005, Scheierling et al. 2006, Schoengold et al. 2006, Andreyeva et al. 2010, Alberini and Filippini 2011, Labandeira et al. 2017).[6]

For convenience and tractability reasons (facilitating optimization), we assume that energy demand follows an exponential demand function, where:

$$q_i = A * e^{-p/b}.$$

[6] We summarize relevant literature here. The literature finds that the demand for irrigation water is generally inelastic in the short run (ranging from 0.48 to 0.79 in meta-analyses), especially for high value crops. Electricity is more inelastic, ranging from below 0.3 in the short run to 0.4-0.8 in the long run. Thus, a parameter of b=0.25 implies a demand elasticity of 0.1/0.25 = 0.4 at a typical electricity tariff rate of US$0.1. For food, demand is somewhat inelastic (0.6 for cereals and vegetables, for example) and varies considerably according to the availability of close substitutes.

In this formulation, the constant term *A* indicates maximum annual quantity demanded in market *i*. The marginal value of additional electricity is then derived by solving this equation for p, and the value of non-marginal changes in electricity produced are assumed to be equal to this marginal value multiplied by the quantity added to the energy mix in each country. Values of A (set based on recent IEA data (IEA 2019) and assuming a 4% growth in energy demand year on year, except in Egypt, where energy demand growth is assumed to be 2%/yr owing to that country's more advanced state of industrialization) and b (based on inelastic short run demand for electricity at typical electricity tariff rates of US$0.1, as indicated by the literature in footnote 3) in each market are shown in Table C11 below. Here we note that projections of energy demand are often much higher than 4%/yr in existing analyses such as the IEA's Global Energy Outlook and the Eastern Nile Power Trade Study, but these tend to be optimistic about economic growth and industrialization in LDCs, and were generally found to exceed historical growth rates.

Given the data and parameters shown in Table C11, we further value energy generation as follows. For regions where demand can be fully met by alternative sources (e.g., namely Egypt and Other East Africa), we value all hydropower consumed in the market at the levelized cost of energy (LCOE) of the alternative generation source, since the hydropower in such cases is displacing that alternative generation. This value was obtained from the 2014 EAPP Master Plan (EAPP 2014). For regions where electricity demand cannot be fully met by alternatives, we instead value hydropower production using the method described above for all generation between the amount generated from alternatives and the total demand, and then value any excess power allocated in the market at the alternative LCOE cost. Alternative sources vary across countries, from a lower value in Ethiopia, which has other hydropower options (costed at US$0.08/kW-hr), to higher values in Eritrea and South Sudan, where the alternative is oil-based electricity generation (with an LCOE of US$0.21/kW-hr).

Table C11. Energy demand assumptions and parameters

Energy market	2019 Non-Nile generation (GW-hr)[1]	2019 demand (GW-hr)	A (projected demand for 2050)	b	Planned additional non-Nile generation (GW-hr)[1]	Alternative cost (US$/kW-hr)[1]
Egypt	175,170	199,699	361,727	0.25	190,057	$0.12
Sudan	1,830	15,542	50,409	0.25	13,902	$0.09
Ethiopia	10,680	20,009	64,897	0.25	21,261	$0.08
Eritrea	423	423	1,372	0.25	0	$0.21
South Sudan	542	542	1,758	0.25	2,742	$0.21
Other East Africa	31,850	38,676	125,441	0.25	134,834	$0.093

Notes:

[1] Based on information in the EAPP Master Plan (2014). Alternative cost is for gas in Egypt, coal in Sudan, non-Nile hydro in Ethiopia, oil in South Sudan and Eritrea, and a weighted mix of coal, non-Nile hydro, geothermal, and gas in other East Africa, based on the balance of investments in the EAPP Master Plan.

[2] Projected demand assumes a 4%/annum rate of growth from 2019 in all regions except Egypt, for which a growth rate of 2%/annum is assumed.

Peaking power. Finally, hydropower dams located just upstream of another re-regulating dam were assumed to feasibly generate about 33% of peaking, and 67% of non-peak power, with peaking power having a value 2 times that of baseload power. This yield a value of power generated from such projects that is equivalent to 1.33 times the average value of baseload-only generation plants. The facilities capable of peaking generation are the following (where the downstream re-regulating infrastructure is listed in parentheses): Kiira (Murchison), Karuma (Oriang), Fula, Lakki, Shukoli (all upstream of Bedden), Birbir A (Birbir R), Baro 1 (Baro 2), GERD (Roseires) and Rumela (Girba).

Electricity transmission. Electricity transmission loss within a market is assumed to be 15%, based on estimates for several countries in the Eastern Nile Power Trade study. This is increased to 20% for transmission across markets. As noted above in the assumptions for different cooperation variants, transmission capacity in the current, unilateral development scenario is limited by existing connections that link Ethiopia to Sudan (300 MW), Sudan to Egypt (300 MW), and Ethiopia (2000 MW) to the Equatorial Lakes region via Kenya, with the transmission capacities as indicated in parentheses.

Value of carbon offsets. The value of climate mitigation offsets is pegged to the discount rate through the social cost of carbon (SCC), which consistently aggregates the economic cost of climate change over time. We follow the Interagency Working Group on the Social Cost of Carbon in the US in specifying this SCC to vary according to the differences across climate change and integrated assessment models, and set the base value to $13.3 per ton avoided, based on the mean of the distribution of estimated SCCs for a 4% discount rates (Interagency Working Group on Social Cost of Carbon 2015). The approach is described in more detail in Jeuland et al. (2018). Offsets are then determined based on the country-specific offset factors in the countries where power is consumed, as published by the IEA (IEA 2018), and presented below in Table C12.

Table C12. Emissions intensity of energy generation in each market

Energy market	**Grid intensity (ton/GW-hr)**
Egypt	472.1
Sudan	306.3
Ethiopia	0
Eritrea	758.9
South Sudan	632.2
Other East Africa	207.2

Flood damage reductions. We ultimately decided not to include flood benefits functions since data were missing for valuing this benefit for most locations in the basin, and we did not want to bias the analysis for Blue Nile infrastructure – where such a function has previously been estimated, though it is likely now outdated – relative to other infrastructure. Specifying flood protection benefits is therefore left to future work.

Sensitivity analysis. Finally, we note here the main sensitivity analysis conducted on the HEM results.

Hydrological variation. Dry, median and wet sequences of five years were identified based on median, atypically high, and atypically low amounts of total system runoff, for use in sensitivity analysis (Table C13). Note that these may not be the driest or wettest sequences from the perspective of the downstream system, owing to the channel losses along the way, but they are abnormal sequences of total runoff across all catchments in the system. Further analysis could be conducted for sequences in which particular tributaries are abnormally wet and dry.

Table C13. Years used for hydrological scenario analysis

Hydrological scenario	Years of runoff used	5-year runoff percentile
Dry	04/1969-03/1974	10^{th}
Median	04/1971-03/1976	50^{th}
Wet	04/1953-03/1958	90^{th}

4. Irrigation efficiency improvements

To understand the benefits of irrigation efficiency improvements, we consider two levels of improvements beyond the current efficiency presented in Table C10. The first is for improvement from flood to sprinkler irrigation (0.7 to 0.8 application efficiency improvement), coupled with moving from mostly unlined to lined canals (0.7 to 0.8 conveyance improvement). The second level of improvement then moves to drop irrigation (0.9 application efficiency) and fully lined and covered canals (0.9 conveyance efficiency). We consider such investments only in the context of efficiency-maximizing cooperation, since most of the benefits (with the exception of large potential benefits within Egypt due to the high water use there) of irrigation efficiency improvements come from spillovers of downstream water savings that would become most valuable in the context of such cooperation. Unfortunately, we lack data to also incorporate the costs of such efficiency improvements, which are likely to vary substantially with the layout of irrigation systems and their location relative to the surface waters of the Nile. Full economic analysis ought to compare the benefits associated with efficiency improvements to their costs, to determine their net value. This is left for future extensions of the current study, to the extent that the gains prove potentially significant.

5. Additional sensitivity analyses

Finally, we also discuss how results are sensitive to two other features of the Nile system. The first of these considers the baseline situation without the Grand Ethiopian Renaissance Dam, given the questions about this project and the fact that it is only just beginning filling and operations. This analysis maintains all baseline infrastructure except for the GERD, and allows isolation of the incremental impacts of the GERD under optimal management as specified in the no, partial, and full cooperation scenarios.

The second layers several levels of environmental flow constraints onto the system, at 9 locations in the basin, as also considered in the e-flows component of the phase 2 basin analysis. Table C14 describes the locations of these e-flows; we impose Classes A, B and C to explore sensitivity to various requirements for maintaining downstream flow, and comment on when violations of these constraints preclude the finding of an optimal solution.[7]

Table C14. Locations and magnitude of e-flows in the NHEOM model, for three class levels (mcm/month)

E-flow location	**Model Node**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total** mcm/yr
Class A														
Kyaki (Kagera)	9	146.9	153.1	163.2	181.6	211.6	179.1	156.4	119.5	101.8	97.3	119.6	124.5	1754.6
Jinja (Vict. Nile)	45	722.2	728.5	732.1	771.6	847.2	838.5	762.2	720	698.4	712.9	729.3	728.6	8991.5
Mongalla (Bahr el Jebel)	87	1316	1265	1226	1228	1280	1310	1305	1573	1527	1491	1501	1403	16427
Gambella (Baro)	115	55.7	35.6	38.5	34.8	51.8	234.3	528	679.5	858.3	489.4	202.9	109.2	3318
Hillet Dolieb (Sobat)	136	118.7	62	37.4	36.3	84.9	229.9	418.7	534.6	602.7	645.1	648.5	306.7	3725.5
Malakal (W.Nile)	151	731.8	636.5	592.6	571.2	575.5	713.1	874.1	996.1	1083	1127	1144	980.3	10026
El Deim (B.Nile)	212	209.2	129.4	96.1	81.6	114.4	431.8	1797	4577	3448	1545	666.7	363.4	13459
Kubor (Atbara)	265	6.2	4.2	6	8	14	60.2	506.4	1057	516.4	95.6	27.4	12.2	2313.2
Dongola (M.Nile)	284	768.6	628.2	599.9	816	683.2	601.9	1367	4816	4122	2170	1244	886.4	18703
Class B														
Kyaki (Kagera)	9	53.9	60	56.6	62	64.7	65	61.1	68.9	81	90.5	102	100	865.7
Jinja (Vict. Nile)	45	477.8	454.5	494.6	566.3	555.7	574.3	556.7	554.8	558.9	535.1	554.2	549.6	6432.5
Mongalla (Bahr el Jebel)	87	480	514.2	518.8	536.8	568.7	689.3	663.2	712	635	833.9	766.3	735	7653.2
Gambella (Baro)	115	43	33	31.4	30	40.7	93.5	170.6	227.8	226.8	205.4	119.7	69.7	1291.6
Hillet Dolieb (Sobat)	136	87.7	45.7	33.6	37.4	76.6	120.8	141.5	181	186.8	201.8	221.8	200.3	1535
Malakal (W.Nile)	151	429.3	405.3	377.9	370	380.4	454.9	477.6	567	551.9	548.7	575.8	550.2	5689
El Deim (B.Nile)	212	153.4	106.5	90.9	80.7	105	232.2	599.5	1137	862.5	561.8	342.1	227.1	4498.6
Kubor (Atbara)	265	3	2.3	3.5	4.4	5.7	20	147	304.6	124.9	42.7	14.4	5.1	677.6
Dongola (M.Nile)	284	374.8	337.6	345.3	362.9	343.2	419.5	645.2	1721	1855	1395	1181	855.8	9836.7
Class C														
Kyaki (Kagera)	9	37.4	41.4	39	42.5	45.2	44.9	42.4	48.3	61.7	78.3	88.1	85.8	655
Jinja (Vict. Nile)	45	337.2	363.1	368.1	519.9	509.7	526.3	509.8	508.6	520.6	503	428	505.2	5599.5

[7] Note that the e-flows estimates come from a parallel building blocks study on the SWRA, which specified that three classes of e-flows shown in Table C14. The values from that study were taken as given.

Mongalla (Bahr el Jebel)	87	353.7	378.4	363.3	375.9	398.6	464.3	441.8	474.2	442	564.6	534	511.6	5302.4
Gambella (Baro)	115	36.9	27	23.4	21.2	29	57.3	90.5	116.1	121.6	106.5	65.7	49.9	745.1
Hillet Dolieb (Sobat)	136	52.7	35.7	22.1	32.6	38.8	53.3	63.3	82.5	84.8	92	101.5	92.2	751.5
Malakal (W.Nile)	151	327.2	319.3	299.1	292.4	299.3	363	387.4	536.9	541.4	538.9	562.3	541.4	5008.6
El Deim (B.Nile)	212	129.7	88.5	67.1	59.6	76.9	136.2	345.4	672.6	549	354.3	225.3	164.9	2869.5
Kubor (Atbara)	265	2.8	2.1	3.2	4.1	5.5	19.9	124.9	254.6	107.8	39.4	14.2	4.9	583.4
Dongola (M.Nile)	284	319.3	300	288.7	305.5	291.5	335.9	455.1	1109	1197	888.3	737.8	557.8	6785.9

D. Results

This section summarizes the main results of this analysis. To provide a reference point, we begin by presenting the outcomes corresponding to the current development and mostly unilateral development (DL-C0) scenario, under median hydrological conditions, since this is the situation that most closely resembles the current state of affairs. ***We emphasize here that this is not a pure "baseline" because it is an artefactual situation that optimizes outcomes given a specific hydrological sequence that occurred in the past when the current level of infrastructure was not in place in the basin***. As such, the model outcomes should not be compared to recent levels of production in the basin, which may diverge from these "optimal" outcomes for numerous reasons.

In our presentation of the results from the DL-C0 scenario, we offer a detailed discussion of the following outcomes:

- Total system benefits, disaggregated into energy consumption benefits, carbon offsets, agricultural consumption benefits, and disaggregated by the country of production of those benefits
- Hydropower metrics:
    - Power generation overall, by country, and by energy production site
    - Peaking power generation overall, by country, and by energy production site
    - Power traded (before losses), overall, and across markets
    - Power consumption (after losses), overall, and within each energy market, accounting for contributions from alternative generation sources
    - Energy demand shortfalls (e.g., consumption minus maximum demand at p=0), overall, and within each energy market
- Irrigation metrics:
    - Water diverted to irrigation overall, by country, and by agricultural production site
    - Irrigation demand shortfalls relative to targets overall, by country, and by agricultural production site
- Water diverted to urban demands overall, monthly by country, and monthly by surface node
- Other relevant hydrological outcomes:
    - Node flows at critical locations in the system, by month (flow out of Lake Victoria, diversion through Tana-Beles, Blue Nile and White Nile flow at Khartoum prior to their confluence, flow into Egypt)
    - Reservoir storage and evaporation losses (in mcm) overall, by country, and by energy production site.

Following presentation and description of this DL-C0 scenario, we briefly discuss changes when the GERD is omitted from the system. Then, we turn to the other combinations of development and cooperation, where we present a somewhat less detailed description. Finally, we consider the sensitivity of results to and wet hydrological flow conditions, and the effects of adding environmental flow constraints. The full set of results that correspond to each of the sensitivity analyses appears in the Appendix to this report, for comparison purposes. In the main report, rather than presenting such exhaustive results, we aim to provide a comparative perspective on how outcomes change across both the development and cooperation continuums, and across sensitivity analyses. The latter also leads in to discussions about implications for equitable financing of new projects in the development scenarios. We also offer a discussion on model performance (tracking runtime, the number of model iterations, and GAMS success in finding a global optimum) which is useful for considering whether adding more complexity to the model by extending the hydrological period or adding more energy or food market specificity is likely to be feasible in the future.

1. Current and mostly unilateral development (DL-C0 scenario)

Under current development and mostly unilateral development, the system generates about US$5.7 billion of economic benefits per year under the median hydrology sequence (all reported economic metrics are in real US$2020). As shown in Table D1, the majority of these benefits (about 61%) are from use of water for irrigated agriculture, with energy consumption representing 37%, and a small portion (about 2%) from carbon offset value.

Table D1. Overall optimized economic benefits under the current and unilateral development (DL-C0) scenario

Benefit category	**Average amount**	**Net economic value per year (present value)**
Energy consumption	62,712 GW-hr/yr	US$3.1 billion
Carbon offsets	14.0 million tons of CO_2-eq	US$0.17 billion
Agricultural water consumption	61.2 bcm/yr	US$2.4 billion
Municipal diversions	13.5 bcm/yr	n.a.
Total		US$5.7 billion

Notes: Municipal water consumption is not valued, owing to lack of demand information.

The value of offset carbon is a relatively minor fraction of the economic benefits, mainly because these benefits primarily accrue in Egypt, Sudan, and to a lesser extent in the other East Africa grouping (Table D2). Despite high energy production in Ethiopia, Nile hydropower there is offsetting alternative hydropower investments from other resources, and therefore does not deliver carbon mitigation benefits. Meanwhile, due to constraints on transmission and cooperation in this scenario, there is no generation and transmission to the most carbon intensive energy production areas in the basin, namely South Sudan and Eritrea, under this scenario.

The country breakdown provided in Table D2 further shows that most of the irrigation benefits (72%) are produced in Egypt, where the implicit unit value of water diversions at US\$0.04/m^3, once we account for losses in irrigation and the reuse of irrigation multiple times downstream of Aswan. The modeled net economic value of irrigation water in Sudan and South Sudan are much lower, at US\$0.01/m^3 and US\$0.02/m^3, respectively (this indicates that increasing water use in these countries would imply tradeoffs with existing Egyptian production), while it is somewhat higher in Ethiopia (at US\$0.06/m^3) and in the Equatorial Lakes region (at US\$0.08/m^3). These somewhat higher values are due to the crops being produced in irrigated areas there, and the relatively lower water requirements (which thus increase yields and profits relatively faster). It is however important to note that water diversions for downstream demands in the basin remain optimal nonetheless, because water kept in the river system generates other values (in hydropower production) at multiple points while flowing downstream.

The net energy consumption values (about US\$0.054/kW-hr) are considerably lower than the gross values of (US\$0.091/kW-hr), because these account for transmission and distribution costs of about \$0.037/kW-hr, once distribution losses are included. All final consumption values account for these distribution losses.

Table D2. Optimized economic benefits under the DL-C0 scenario, by country

<table>
<tr><th>Country</th><th>Gross energy consumption[1]</th><th>Net energy consumption[1]</th><th>Carbon offsets[1]</th><th>Agricultural water consumption</th><th>Total[2]</th></tr>
<tr><td>Egypt</td><td>1.85</td><td>1.08</td><td>0.11</td><td>1.93</td><td>3.13</td></tr>
<tr><td>Eritrea</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>Ethiopia</td><td>1.93</td><td>1.13</td><td>0.00</td><td>0.10</td><td>1.24</td></tr>
<tr><td>Burundi</td><td rowspan="6">0.47</td><td rowspan="6">0.28</td><td rowspan="6">0.02</td><td>0.00</td><td>0.00</td></tr>
<tr><td>DRC</td><td>0.00</td><td>0.08</td></tr>
<tr><td>Kenya</td><td>0.02</td><td>0.12</td></tr>
<tr><td>Rwanda</td><td>0.00</td><td>0.01</td></tr>
<tr><td>Tanzania</td><td>0.00</td><td>0.08</td></tr>
<tr><td>Uganda</td><td>0.02</td><td>0.04</td></tr>
<tr><td>South Sudan</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>Sudan</td><td>1.03</td><td>0.60</td><td>0.04</td><td>0.35</td><td>1.00</td></tr>
<tr><td>Total</td><td>5.29</td><td>3.10</td><td>0.17</td><td>2.44</td><td>5.71</td></tr>
</table>

Notes: Economic benefits (all in billions of 2020US\$) are in discounted annualized values. Energy production is based on the location of the hydropower plant (border plants are assumed to be shared 50-50); while energy consumption assumes that energy consumed in a market is allocated in direct proportion to total demand in each country.

[1] Energy consumption is by market, and Burundi, the DRC, Kenya, Rwanda, Tanzania, and Uganda are modeled as a single market. We account for transmission losses and in the net calculation, transmission costs.

[2] Total benefits are based on country of production for agriculture, and of consumption for energy, where consumption is divided proportionally to energy demand.

Table D3. Optimized hydropower generation (GW-hr/yr) under the DL-C0 scenario, by country and generation site

Energy production site	Average (GW-hr/yr)	Range (GW-hr/yr)		Proportion that is peaking	Power kept in local markets	Power traded to other markets
		Min	Max			
Egypt						
High Aswan Dam	16,947	13,840	18,364	0%	80%	20%
Old Aswan Dam	5,484	5,484	5,484	0%		
Total Egypt	22,431	19,324	23,848			
Ethiopia						
Tana-Beles	2,172	2,172	2,172	0%		
Finchaa	1,013	820	1,152	0%		
Lower Didessa	2,070	1,606	2,386	0%	100%	0%
GERD	20,146	14,147	25,822	25%		
TK-5	2,098	1,341	2,628	0%		
Total Ethiopia	27,499	20,086	34,160			
South Sudan	nil	nil	nil	n.a.	n.a.	n.a.
Sudan						
Gebel Aulia	122	48	237	0%		
Roseires	2,453	2,453	2,453	0%		
Sennar	131	131	131	0%	79%	21%
Khasm el Girba	114	114	114	0%		
Merowe	10,105	8,142	10,950	0%		
Total Sudan	12,925	10,888	13,885			
Kenya						
San'goro	177	177	177	0%		
Rwanda						
Rusumu Falls	350	350	350	0%		
Tanzania						
Rusumu Falls	350	350	350	0%	79%	21%
Uganda						
Owen Falls	3,399	3,399	3,399	0%		
Kiira	1,752	1,752	1,752	0%		
Bujagali	1,407	1,391	1,420	0%		
Total Uganda	6,558	6,541	6,570			
Basin total	70,291	57,717	79,340	7.17%	88%	12%

Notes: Average amount, in GW-hr, produced over five years at each energy production site. Generation at border (shared) plants is shared evenly across countries.

Table D3 next provides a breakdown of the optimal power generation across plants in the basin, and reveals that the optimization routine tries to maintain high power generation relative to installed generation capacity, at many plants. Merowe, the Aswan Dam complex, Finchaa, Rusumu Falls, San'goro, Owen Falls, Girba, Roseires and Sennar all operate near their generation capacity throughout the model period. A notable exception is the GERD, which is unable to utilize much of its installed capacity of 6000 MW for most of the year, although it is the largest electricity generation facility in the basin (but notably lower than the full complex at Aswan that includes the Old Aswan Dam) (Figure D1). TK-5, Tana-Beles, Lower Didessa, Gebel Aulia and Bujagali also fall somewhat short of maximum generation relative to their installed capacities, though less so than the GERD. These fluctuations serve to highlight the importance of natural hydrological variability, which influences some infrastructures more than others, as well as the fact that a median set of years for the basin may not correspond to a median sequence of years in a particular sub-basin (for example, in this sequence, the Blue Nile is somewhat wet). A modest amount of power generation is exported in this current infrastructure scenario, but projected local demand far outstrips the power produced in most markets. A final observation in this optimized setup is the substantial benefit that Sudan experiences from regulated Blue Nile flow due to the GERD, which enables relatively high levels of power generation at Roseires, Sennar, and finally Merowe.

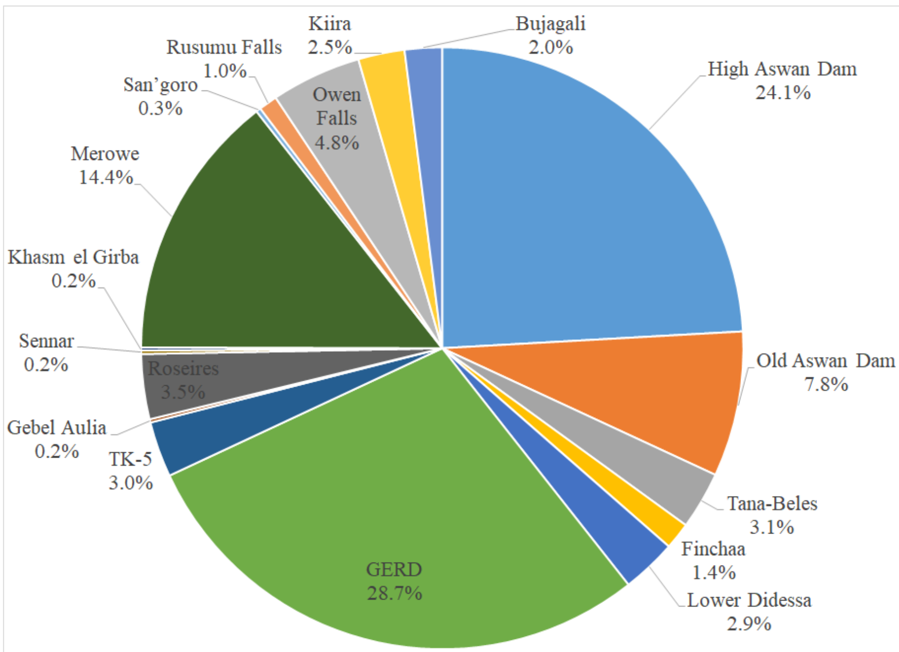


Figure D1. Distribution of optimal hydropower generation across facilities included in the DL-C0 scenario

As shown in Table D4, the power that is generated is fairly stable across years in this scenario, but only satisfies a small proportion of the total demand in each market. Most Egyptian electricity needs are met from alternative sources (mainly natural gas), while both Ethiopia and Sudan experience substantial electricity deficits in this scenario, even accounting for alternative investments planned over the coming decade. As such, there appears to be substantial room and need for additional energy investments in the basin, an issue that we return to further below, when analyzing scenarios with additional investments. Other countries without hydropower generation or transmission options (Eritrea and South Sudan) rely entirely on alternative sources, with Eritrea experiencing significant electricity deficits.

Table D4. Optimized energy consumed in each market in the DL-C0 scenario, from Nile hydropower and alternative sources

Energy market	Consumption from Nile hydropower (GW-hr/yr)			Consumption from alternatives (GW-hr/yr)			Average shortfall (GW-hr/yr)
	Average	Range		Average	Range		
Egypt	17,853	15,601	18,880	343,874	346,126	342,847	0
Eritrea	0	0	0	423	423	423	949
Ethiopia	28,851	22,176	34,854	31,941	31,941	30,043	4,105
Sudan	10,129	8,518	10,887	15,732	15,732	15,732	24,548
South Sudan	0	0	0	1,758	1,758	1,758	0
Other East Africa	5,879	0	0	119,562	125,441	125,441	0
Basin total	**62,712**	**46,295**	**64,622**	**513,291**	**521,422**	**516,244**	**29,601**

Notes: Average amount, in GW-hr, consumed over five years in each market.

Table D5. Optimized water allocation to irrigation (mcm/yr) under the DL-C0 scenario, by country and site

Irrigation site	Water allocation (mcm/yr)			Demand shortfall (mcm/yr)
	Average	Min	Max	Average
Egypt				
New Valley	2,365	2,056	2,828	638
D/s Aswan	44,313	44,313	44,313	12,977
Total Egypt	46,677	46,369	47,140	13,615
Ethiopia				
Alwero	-	-	-	200
Tana	713	713	713	-
U/s Beko Abo	230	-	399	170
Finchaa	225	209	238	75
Didessa	92	86	99	8
Tana-Beles	364	340	396	36
Total Ethiopia	1,623	1,349	1,845	489
Sudan				
U/s Gebel Aulia	1,023	889	1,224	276
D/s Gebel Aulia	236	205	282	64
U/s Sennar	2,236	1,984	2,728	661
Sennar	5,258	4,656	6,403	1,542
D/s Sennar	616	547	753	183
D/s Girba	1,730	1,675	1,802	72
North Sudan	1,141	1,095	1,200	59
Total Sudan	12,240	11,052	14,391	2,857
Kenya				
Nzoia	96	96	96	4
All other (near Lake Victoria)	191	191	191	9
Total Kenya	287	287	287	13
Total Rwanda	48	48	48	2
Total Uganda	191	190	191	9
Total South Sudan	118	103	141	32
Basin total	61,185	59,397	64,044	17,017

Notes: Average amount, in mcm/yr, diverted over five years to each irrigation site. The shortfall in Egypt accounts for water recycling, which leads to net use of 52,023 mcm/yr for irrigation in Egypt.

Table D5 next summarizes the optimal allocation of water across irrigation sites in this current development scenario, and reveals that it is optimal to meet most (specifically, an average of 83% of target allocations across sites), but not all, current demands in the system (Figure D2 also shows the distribution by country). One site in Ethiopia in the Baro-Akobo basin – Alwero – appears to suffer from highly variable flow that prevents the model from allocating water to it, and a number of other demands in Ethiopia and Sudan are only partially satisfied, in lieu of passing this water downstream through the GERD and other dam turbines. The Alwero site would require seasonal water storage investment or conjunctive use of groundwater, which is not included in the optimization model. Finally, deficits in Egypt similarly occur internally due to a tradeoff between irrigation and urban or minimum flow requirements (see Table D6). The no-cooperation scenario also does not allow additional allocation to Egyptian irrigation beyond the limit of 55,500 mcm/yr.

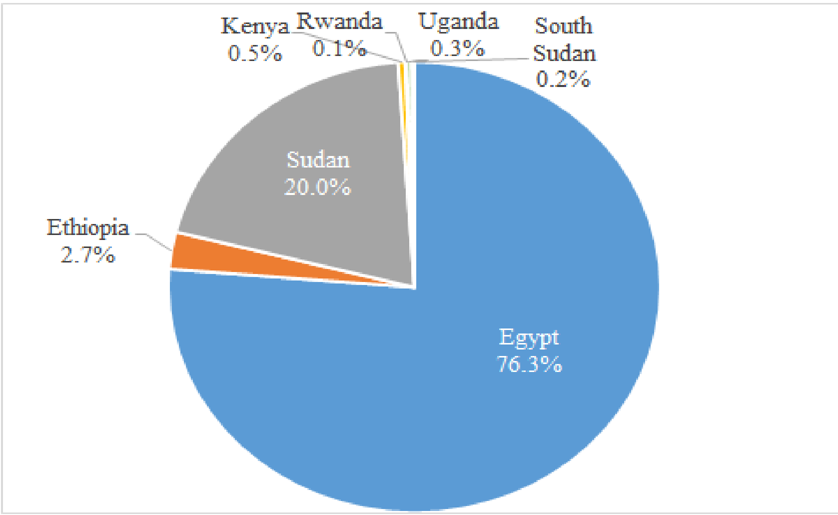


Figure D2. Distribution of optimal irrigation diversions by country in the DL-C0 scenario

Table D6. Water allocated to urban uses (mcm/yr) in the DL-C0 scenario, by demand location

Municipal site (country)	**Water allocation (mcm/yr)**
Gitega (Burundi)	2.0
Rutshuru (DRC)	2.0
Egyptian cities (Egypt)	12,500
Gondar (Ethiopia)	9.0
Bungoma (Kenya)	81
Malaba/Kisumu (Kenya)	23.6
Kigali (Rwanda)	25.0
Juba (South Sudan)	20
Khartoum (Sudan)	600
Mwanza/Musoma (Tanzania)	47
Jinja/Kampala/Tororo (Uganda)	141
Soroti (Uganda)	2.0
Basin total	13,454

Notes: Average amount, in mcm/yr, diverted over five years to each urban demand location.

We finally consider several other aspects related to the water balance in this current and unilateral development scenario. Tables D7 and D8 summarize the key results, and indicate that basin-wide evaporation from man-made reservoirs averages about 25.0 bcm/yr, with more than half of this (16.0 bcm/yr, or 64%) occurring in Lake Nasser in Southern Egypt (Figure D3). The other reservoirs contributing substantially to basin evaporation are the GERD (2.6 bcm/yr), Gebel Aulia (1.9 bcm/yr), and Merowe (1.9 bcm/yr). Natural lakes also contribute substantial evaporation, but their overall contribution is slightly less than that of the man-made reservoirs, despite their much larger total size. An important observation is that the dams in Ethiopia and Sudan experience high fluctuations in optimal storage, which points to their important collective role in regulating optimal flows and benefits in the basin. This function also helps to keep levels in Lake Nasser fairly stable, at least under normal hydrological conditions.

Table D7. Optimized storage and evaporative loss (mcm/yr) under the DL-C0 scenario, by country and generation site

	Storage (mcm)			Evaporative loss (mcm/yr)		
Storage dam	**Average**	**Range**		**Average**	**Range**	
		Min	**Max**		**Min**	**Max**
Egypt						
High Aswan Dam	141,480	127,500	159,491	16,021	15,692	16,576
Total Egypt	141,480	127,500	159,491	16,021	15,692	16,576
Ethiopia						
Finchaa	377	5	550	586	586	586
Lower Didessa	6,820	5,674	8,014	266	266	266
GERD	55,506	43,590	64,700	2,628	2,595	2,652
TK-7	6,784	2,168	8,889	284	266	295
Total Ethiopia	69,488	51,437	82,153	3,764	3,714	3,800
Sudan						
Gebel Aulia	1,318	115	3,400	1,885	1,285	2,899
Roseires	1,547	0	5,500	428	318	535
Sennar	404	186	830	280	258	309
Khasm el Girba	722	364	1,400	577	542	602
Merowe	10,215	5,864	12,100	1,857	1,682	1,954
Total Sudan	14,206	6,529	23,230	5,028	4,085	6,300
Uganda						
Bujagali	53	43	54	208	208	208
Total Uganda	53	43	54	208	208	208
Major system lakes						
Lake Victoria	2,968,493	2,941,864	2,987,889	15,184	15,184	15,184
Lake Kyoga	13,413	11,220	15,865	2,937	2,902	3,003
Lake Albert	160,158	157,947	163,800	2,638	2,638	2,638
Lake Tana	26,971	24,241	31,884	2,958	2,938	2,975
Basin total	3,394,262	3,320,781	3,464,366	48,739	47,361	50,683

Notes: Average amount, in mcm over years, at each lake or reservoir.

Turning to hydrology, it is important to note that the optimal flows at Khartoum in this scenario are roughly equally obtained from the Blue and White Niles, under median hydrological conditions. The Blue Nile carries significantly more water than both the White Nile exiting the Sudd and the Sobat system combined, but a large amount of this water is utilized in irrigation in Sudan. By the time the Nile flows into Lake Nasser (and after diversion to the New Valley irrigation schemes in Southern Egypt), there is about 79.6 bcm/yr of water entering the lake under normal hydrological conditions, and fully meeting demands in Egypt therefore implies that the lake must be drawn down slightly, once we account for evaporative losses there (16.0 bcm/yr). Wet years, which are not included in this hydrological sequence, would be necessary to replenish that reservoir if all demands were to be met.

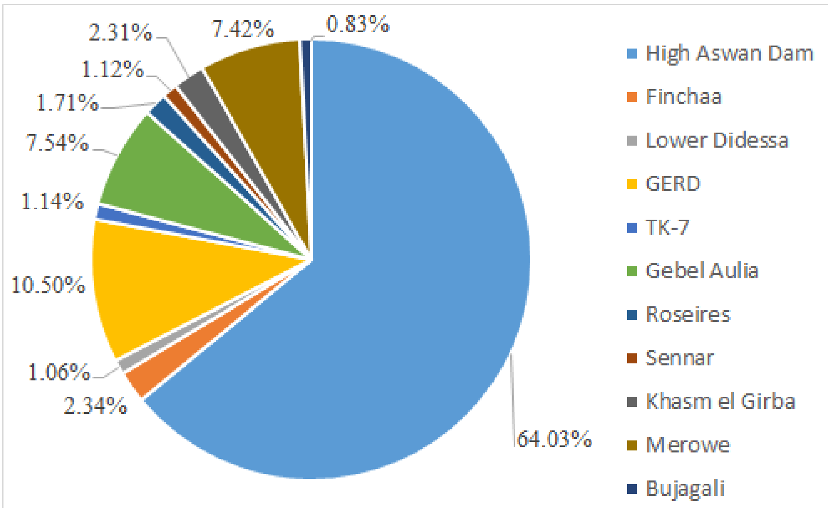


Figure D3. Distribution of evaporative losses by reservoir in the DL-C0 scenario

Table D8. Optimized flows at key nodes in the Nile system in the DL-C0 scenario

	Flows (mcm/yr)		
Node	**Average**	**Min**	**Max**
Owen Falls	28659	28282	28928
Kyoga	29161	27741	31280
Albert	36814	36376	37322
Sudd outflow	26456	24736	29400
Sobat junction	40174	33385	45363
WN-Khartoum	35743	32046	41090
Tana-Beles release	3744	3744	3744
BN Deim	55769	39603	62643
BN Khartoum	34617	18982	48941
Merowe	64594	52272	97620
Dongola	71308	49459	93306

2. The baseline without the GERD

This section considers how these optimal results would be different if the GERD were not included in the baseline system configuration. We primarily focus on the reduction in total economic benefits and power generation, and on changes in the distribution of the latter as well as the optimal irrigation allocations across countries, to clarify the incremental value and potential tradeoffs associated with this infrastructure. Table D9 presents the country-wise energy and irrigation benefits (analogous to Table D2). Interestingly, under these low demand and median hydrological conditions, energy generation benefits in Sudan and Egypt are slightly higher with the GERD than without it, but the most significant change is in the energy consumption benefit for Ethiopia, which decreases by about US$0.8 billion per year. There are minor changes to agricultural benefits in Sudan and Ethiopia; for the latter, the optimal solution is to use slightly more water upstream without the GERD (since this has lower costs in terms of reduced power production), while the former uses slightly less water without the GERD, which helps to steady flows in the Blue Nile and therefore allows for additional abstractions. The net effect on agricultural benefits is that the GERD increases these slightly (by about 2%).

Table D9. Optimized economic benefits under the DL-C0 (no GERD) scenario, by country

Country	Gross energy consumption[1]	Net energy consumption[1]	Carbon offsets[1]	Agricultural water consumption	Total[2]
Egypt	1.81	1.14	0.11	1.93	3.18
Eritrea	0.00	0.00	0.00	0.00	0.00
Ethiopia	0.40	0.29	0.00	0.12	0.41
Burundi	0.47	0.30	0.02	0.00	0.00
DRC				0.00	0.09
Kenya				0.02	0.13
Rwanda				0.00	0.01
Tanzania				0.00	0.09
Uganda				0.02	0.04
South Sudan	0.00	0.00	0.00	0.00	0.00
Sudan	0.98	0.62	0.04	0.30	0.96
Total	**3.66**	**2.35**	**0.17**	**2.40**	**4.91**

Notes: Economic benefits (all in billions of US$) are in discounted annualized values. Energy production is based on the location of the hydropower plant (border plants are assumed to be shared 50-50); while energy consumption assumes that energy consumed in a market is allocated in direct proportion to total demand in each country.
[1] Energy consumption is by market, and Burundi, the DRC, Kenya, Rwanda, Tanzania, and Uganda are modeled as a single market. We account for transmission losses and in the net calculation, transmission costs.
[2] Total benefits are based on country of production for agriculture, and of consumption for energy, where consumption is divided proportionally to energy demand.

Table D10 disaggregates these energy generation benefits by site, and Table D11 presents the agricultural diversions and shortfalls across sites. We observe that the uplift in power production occurs mainly at Merowe (by nearly 6%), and slightly less at the High Aswan Dam (by 2%). Most other sites are unchanged, though there are very small increases at Roseires (<1%) with the GERD. The agricultural diversions without the GERD are somewhat higher in Ethiopia in the Blue Nile catchment upstream of the Beko Abo site, but the GERD allows an increase at several locations in

Sudan: at several points along the Blue Nile between Roseires and Khartoum, and along the Main Nile. The increases in optimized irrigation with the GERD do not come at the expense of irrigation in Egypt, however, given the modest demands in this scenario. As shown in Tables D11 and D5, steady state demands met in Egypt are identical given the median hydrology.

Table D10. Optimized hydropower generation (GW-hr/yr) under the DL-C0 (no GERD) scenario, by country and generation site

Energy production site	Average (GW-hr/yr)	Range (GW-hr/yr)		Proportion that is peaking	Power kept in local markets	Power traded to other markets
		Min	**Max**			
Egypt						
High Aswan Dam	16,576	13,401	18,396	0%	79%	21%
Old Aswan Dam	5,484	5,484	5,484	0%		
Total Egypt	22,059	18,884	23,880			
Ethiopia						
Tana-Beles	2,172	2,172	2,172	0%	100%	0%
Finchaa	1,013	820	1,152	0%		
Lower Didessa	2,072	1,617	2,385	0%		
TK-5	2,093	1,328	2,628	0%		
Total Ethiopia	7,349	5,936	8,336			
South Sudan	nil	nil	nil	n.a.	n.a.	n.a.
Sudan						
Gebel Aulia	123	56	190	0%	82%	18%
Roseires	2,443	2,406	2,453	0%		
Sennar	131	131	131	0%		
Khasm el Girba	114	114	114	0%		
Merowe	9,511	7,522	10,860	0%		
Total Sudan	12,323	10,230	13,748			
Kenya						
San'goro	177	177	177	0%	79%	21%
Rwanda						
Rusumu Falls	350	350	350	0%		
Tanzania						
Rusumu Falls	350	350	350	0%		
Uganda						
Owen Falls	3,399	3,399	3,399	0%		
Kiira	1,752	1,752	1,752	0%		
Bujagali	1,407	1,391	1,420	0%		
Total Uganda	6,558	6,541	6,570			
Basin total	**49,167**	**42,470**	**53,413**	**0%**	**82%**	**18%**

Notes: Average amount, in GW-hr, produced over five years at each energy production site. Generation at border (shared) plants is shared evenly across countries.

Table D11. Optimized water allocation to irrigation (mcm/yr) under the DL-C0 (no GERD) scenario, by country and site

Irrigation site	**Water allocation (mcm/yr)**			**Demand shortfall (mcm/yr)**
	Average	**Min**	**Max**	**Average**
Egypt				
New Valley	2,365	2,056	2,828	638
D/s Aswan	44,313	44,313	44,313	12,977
Total Egypt	46,677	46,369	47,140	13,615
Ethiopia				
Alwero	-	-	-	200
Tana	713	713	713	-
U/s Beko Abo	398	391	400	2
Finchaa	-	-	-	300
Didessa	99	97	100	1
Tana-Beles	397	387	400	3
Total Ethiopia	1,607	1,588	1,613	505
Sudan				
U/s Gebel Aulia	1,012	889	1,223	286
D/s Gebel Aulia	233	205	282	66
U/s Sennar	1,984	1,984	1,984	913
Sennar	4,656	4,656	4,656	2,144
D/s Sennar	547	547	547	252
D/s Girba	1,777	1,752	1,802	25
North Sudan	1,175	1,154	1,200	25
Total Sudan	11,384	11,188	11,694	3,712
Kenya				
Nzoia	96	96	96	4
All other (near Lake Victoria)	191	191	191	9
Total Kenya	287	287	287	13
Total Rwanda	48	48	48	2
Total Uganda	191	191	191	9
Total South Sudan	95	-	140	55
Basin total	60,290	59,670	61,113	17,912

Notes: Average amount, in mcm/yr, diverted over five years to each irrigation site. The shortfall in Egypt accounts for water recycling, which leads to net use of 52,023 mcm/yr for irrigation in Egypt.

Figure D4 presents a concise graphical summary of the GERD-no GERD results, given these baseline demands.

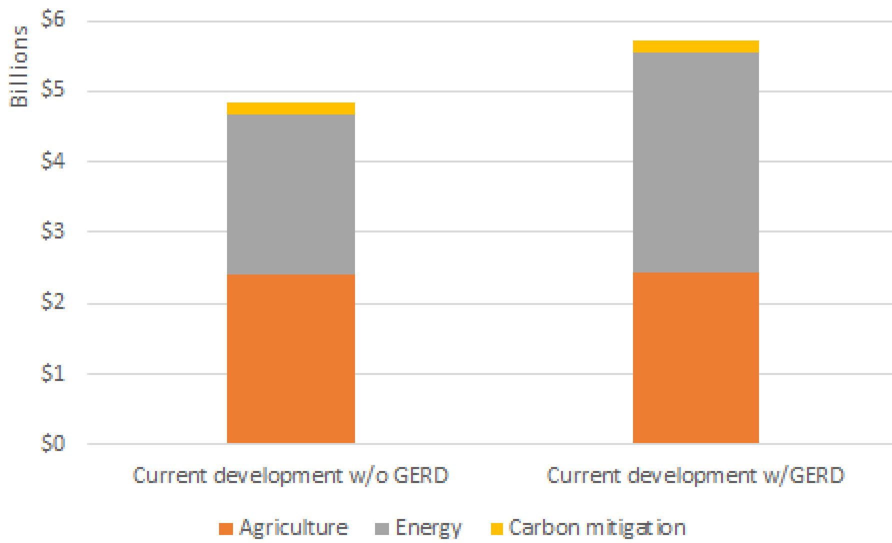


Figure D4. Distribution of benefits by type in the DL-C0 case, with and without the GERD

3. Exploring the effects of increasing development

Having explored the system with current infrastructure and irrigation demands, we next consider changes to the optimal allocation that occur with increasing levels of infrastructure development under unilateral development. Here we do not present the full detailed tables shown above, which appear in the appendix. Instead, we focus on how key results change, using a set of comparative tables and figures.

Figure D5 displays the annual net economic benefits as development increases and highlights several interesting points. First, despite inclusion of substantial new irrigated area in the medium development scenario (which increases diversion requirements outside of Egypt by about 65% under existing irrigation technology), the economic net benefits of irrigation actually decrease by about 5% in this scenario, in part because of competing water uses, as well as insufficient storage to support and render productive newly irrigated areas. As a result, moderate development increases the net economic benefits in the basin overall by only 45%, despite a doubling of energy benefits. Full cooperation does deliver somewhat more benefit, but competing water uses still affect the irrigation sector. Further development then increases irrigation benefits by a minor amount over baseline irrigation (by 2%), with more significant increases again in energy consumption (where benefits are 71% higher than under the current development situation). Full results detailing these adjustments appear in the appendix.

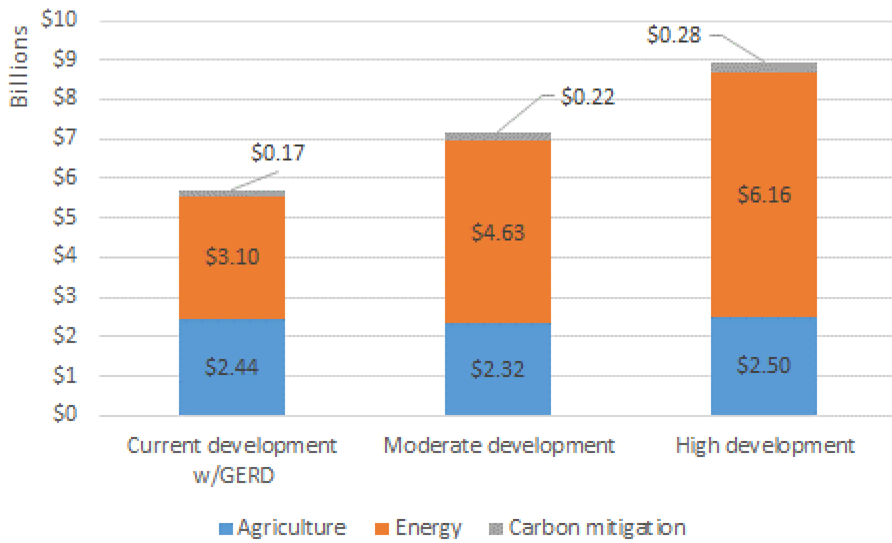


Figure D5. Total economic net benefits and its components across the development scenarios, for median hydrological conditions and unilateral development institutions (C0)

To illustrate distributional outcomes, we provide information on the country distribution of irrigation and hydropower benefits under these scenarios in Figures D6 and D7, and the hydropower project-specific distributions in Figure D8. As shown, the value of irrigation in Egypt declines as upstream development proceeds (Figure D6). Meanwhile, benefits in Sudan increase slightly, but generally remain relatively stable. Irrigation increases most significantly in Ethiopia, while increases in the Equatorial Lakes region are relatively modest.

The majority of irrigation water continues to be allocated to Egypt across scenarios (Figure D7), though the share declines substantially with development, especially at high levels (Panel B). This decline in allocations to Egypt is almost entirely the result of increasing diversions in Ethiopia, but Ethiopia, Sudan and Egypt all experience increasing deficits relative to their ambitions under the higher development scenario, due to increasing water scarcity (Figure D8). Modest deficits also appear in Kenya and South Sudan under high development, but remain very low in other countries. For Ethiopia, deficits are also somewhat larger under moderate development due to lack of storage to support irrigation expansion in several areas, but deficits remain significant in all scenarios, suggesting that the potential of many considered sites is limited, at least with respect to surface water availability.

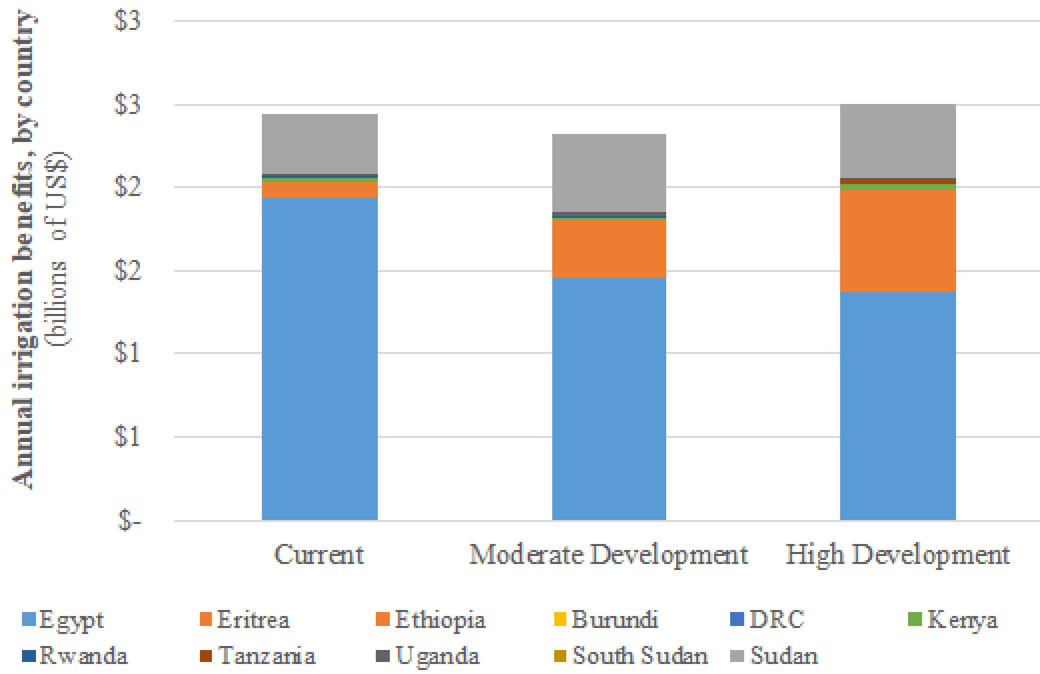
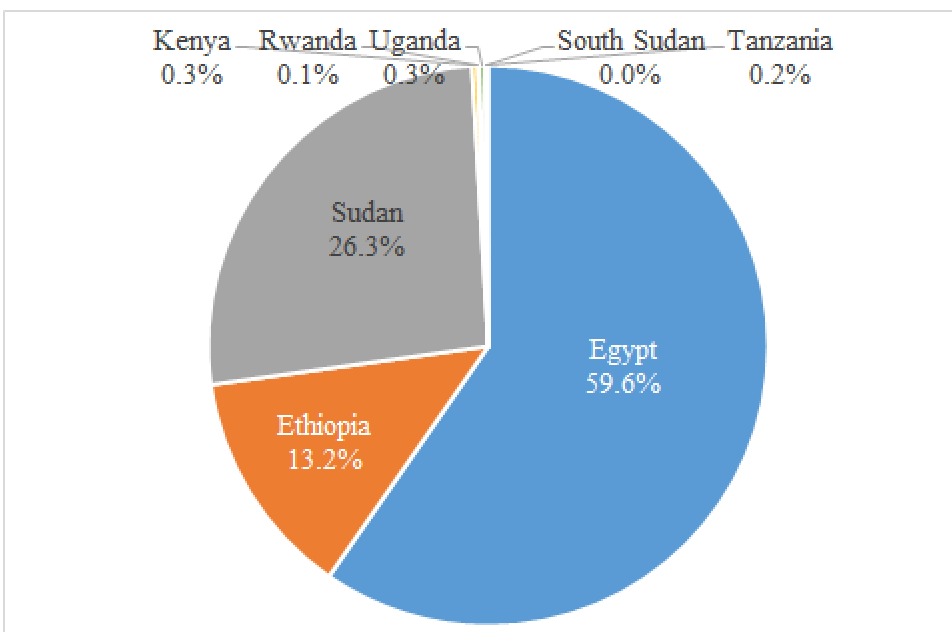
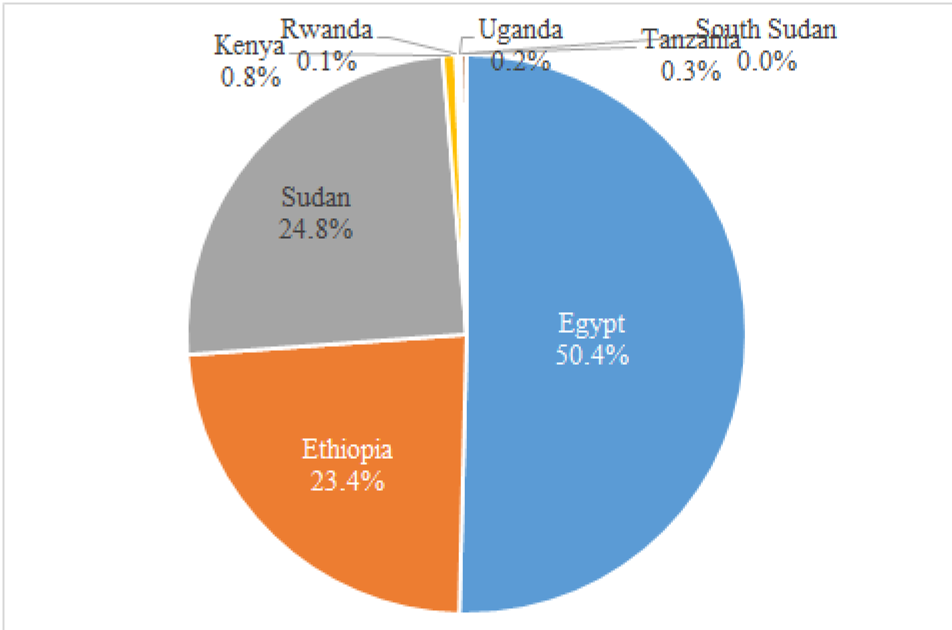


Figure D6. Total net value of irrigation allocations across the development scenarios, for median hydrological conditions and unilateral development institutions (C0)



Panel A



Panel B

Figure D7. Distribution of irrigation diversions by country in the A) moderate and B) high development infrastructure scenarios, under unilateral development institutions (C0)

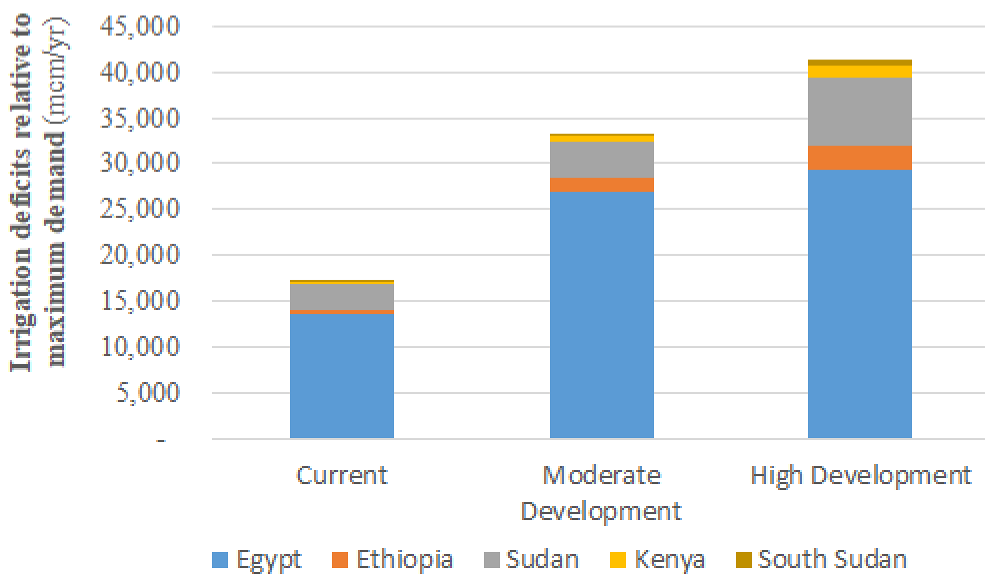


Figure D8. Total allocation deficits relative to maximum irrigation demand across the development scenarios, for median hydrological conditions and unilateral development institutions (C0)

Turning to energy generation and consumption, we note large increases in consumption in Ethiopia under each development scenario (Figure D9). The East Africa power grouping of Uganda, Kenya, Tanzania, Rwanda, Burundi and the DRC also experiences large increases, while Sudan's power generation mostly increases in the high development scenario due to large potentials that are exploited on the Main Nile between Khartoum and Dongola. Egyptian power consumption declines slightly in the high development scenario, as flows through the Aswan power complex decrease.

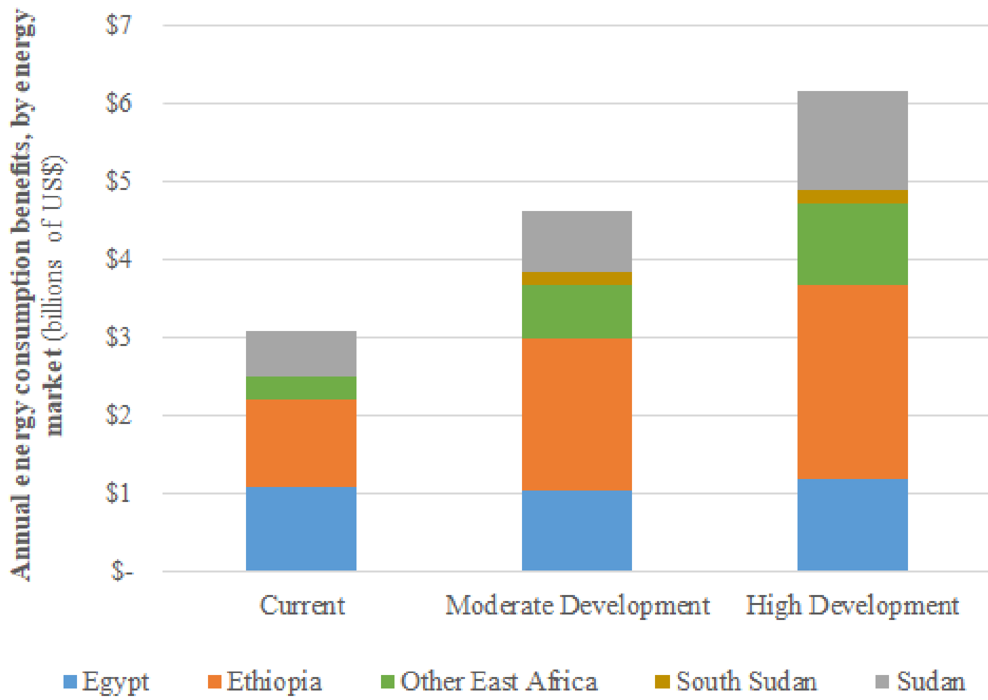
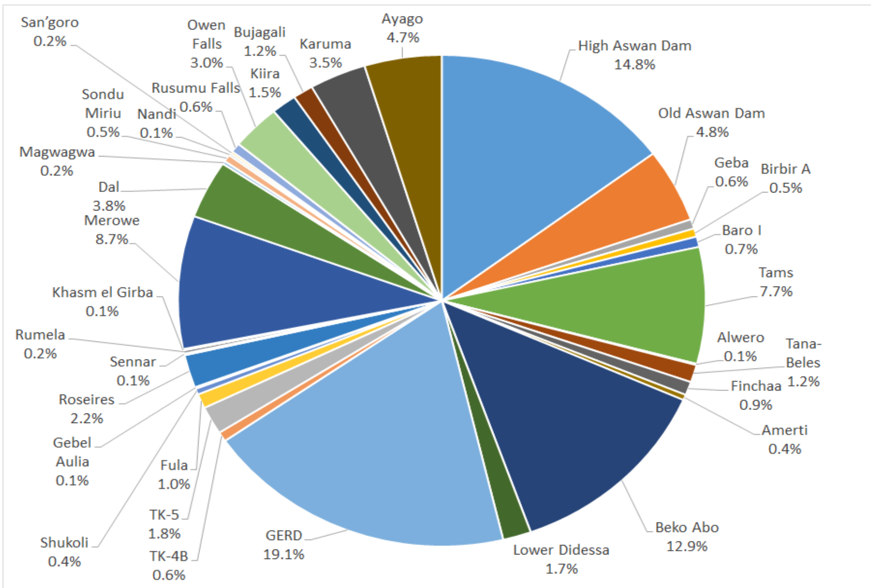


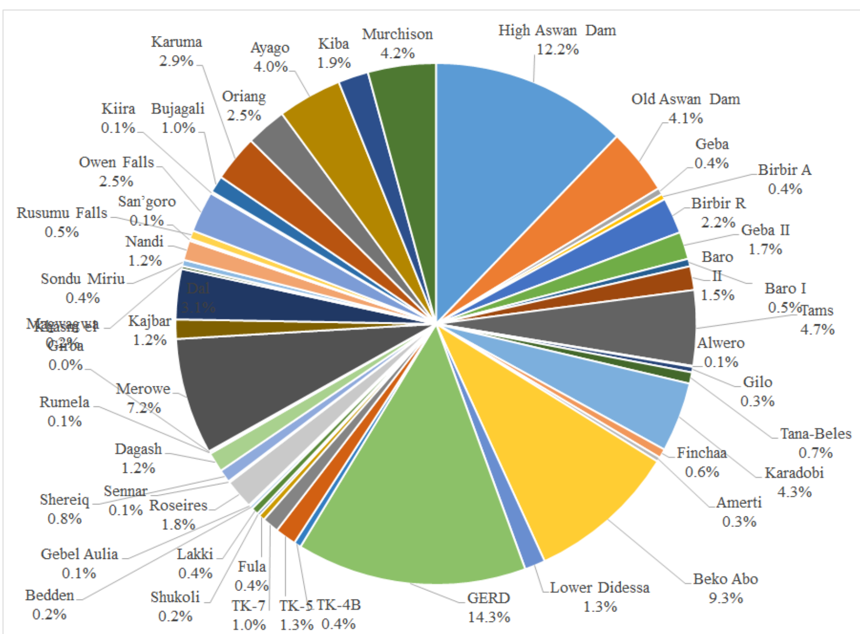
Figure D9. Total net value of energy consumption across the development scenarios, for median hydrological conditions and unilateral development institutions (C0)

These energy consumption increases are supported by a large set of projects (Figure D10). Panel A provides the distribution across infrastructures in the moderate development scenario, and Panel B further shows the high development situation. Under moderate development, several new projects are especially notable for their significant contributions to the optimal basin power generation mix: Tams and Beko Abo in Ethiopia (which contribute 21% of power generation in this scenario, which exceeds the generation from the GERD), Ayago and Karuma in Uganda (which represent nearly 8% of basin power generation), and Dal in Sudan (3.8% of basin generation). For high development, additional significant contributions come from Murchison Falls and Oriang in Uganda, and especially Karadobi in Ethiopia.

One might expect that increasing irrigation under the development scenarios would come at the cost of reduced generation. The optimization model reveals that this is not necessarily the case, however, because releases through power turbines can remain steady, and indeed, greater water storage and regulation can offset the effect of lower flows. There are exceptions for some projects, however. Moving from low to moderate development, power generation at Tana-Beles becomes less beneficial, because water is diverted away from the Blue Nile and the new dam at Beko Abo, which is highly productive. Power generation at Girba drops very modestly due to greater irrigation withdrawals in the upstream Atbara. All other power stations existing in the baseline either produce the same or additional power in this scenario. Moving from moderate to high development, a larger number of power stations see reduced production, however, with the greatest decreases at Geba (Ethiopia, -22%), Birbir A (Ethiopia, -23%), Tams (Ethiopia, -28%), Finchaa (Ethiopia, -25%), Beko Abo (Ethiopia, -14%), Fula (South Sudan, -52%), Shukoli (South Sudan, -51%), Rumela (Sudan, -32%), and Girba (Sudan, -37%).



Panel A



Panel B

Figure D10. Distribution of hydropower generation across facilities included in the A) moderate and B) high development infrastructure scenarios, with unilateral development institutions (C0)

4. Adding the effects of different cooperative institutions

Finally, we turn to the effects of increased cooperation as considered in the scenario typology previously described. Figure D11 displays the annual net economic benefits across the full development and institutional continuum. As shown, new development projects deliver significant new benefits in the basin, especially the high development that includes several large dams that generate large amounts of hydropower. More striking, however, is the fact that efficiency-maximizing cooperation also increases the relative value of these investments, and the added benefits generated could thus help to mitigate somewhat the tradeoffs shown previously. This is due to both of more agricultural value, and generation of revenues that could be used to compensate those negatively affected by the tradeoffs induced by greater development. Interestingly, efficiency-maximizing cooperation adds relatively less to benefits in the current and moderate development scenarios (+23% for current vs. +41% under high development). In addition, cooperation that prioritizes existing claims only barely increases benefits over the unilateral development institutions. We dissect these patterns further below.

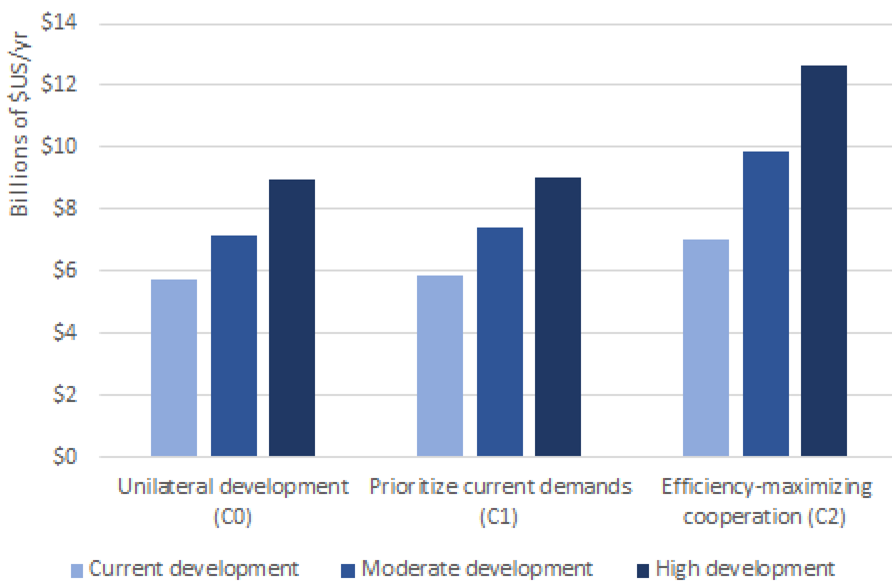


Figure D11. Total economic net benefits across the 9 development and institutional scenarios, for median hydrological conditions

The benefits breakdown – energy. irrigation, and carbon offsets – across institutional scenarios is shown in Figure D12. As shown, the components of benefits are very nearly the same under unilateral and existing claims prioritizations, due to limited trading opportunities, and only marginal shifts in water allocations. The largest difference is in the high development scenario, where existing claims prioritizations better preserves downstream irrigation value. Efficiency-maximizing cooperation similarly only marginally affects irrigation benefits (which are largely traded over space with competing demands immediately apparent), but strongly increases energy consumption benefits, since power can be traded freely to locations where it is especially valuable.

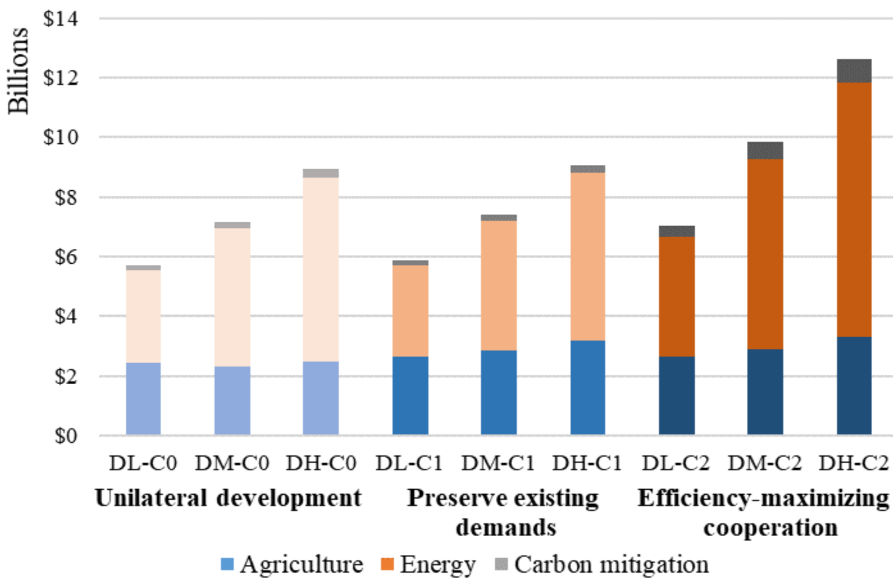
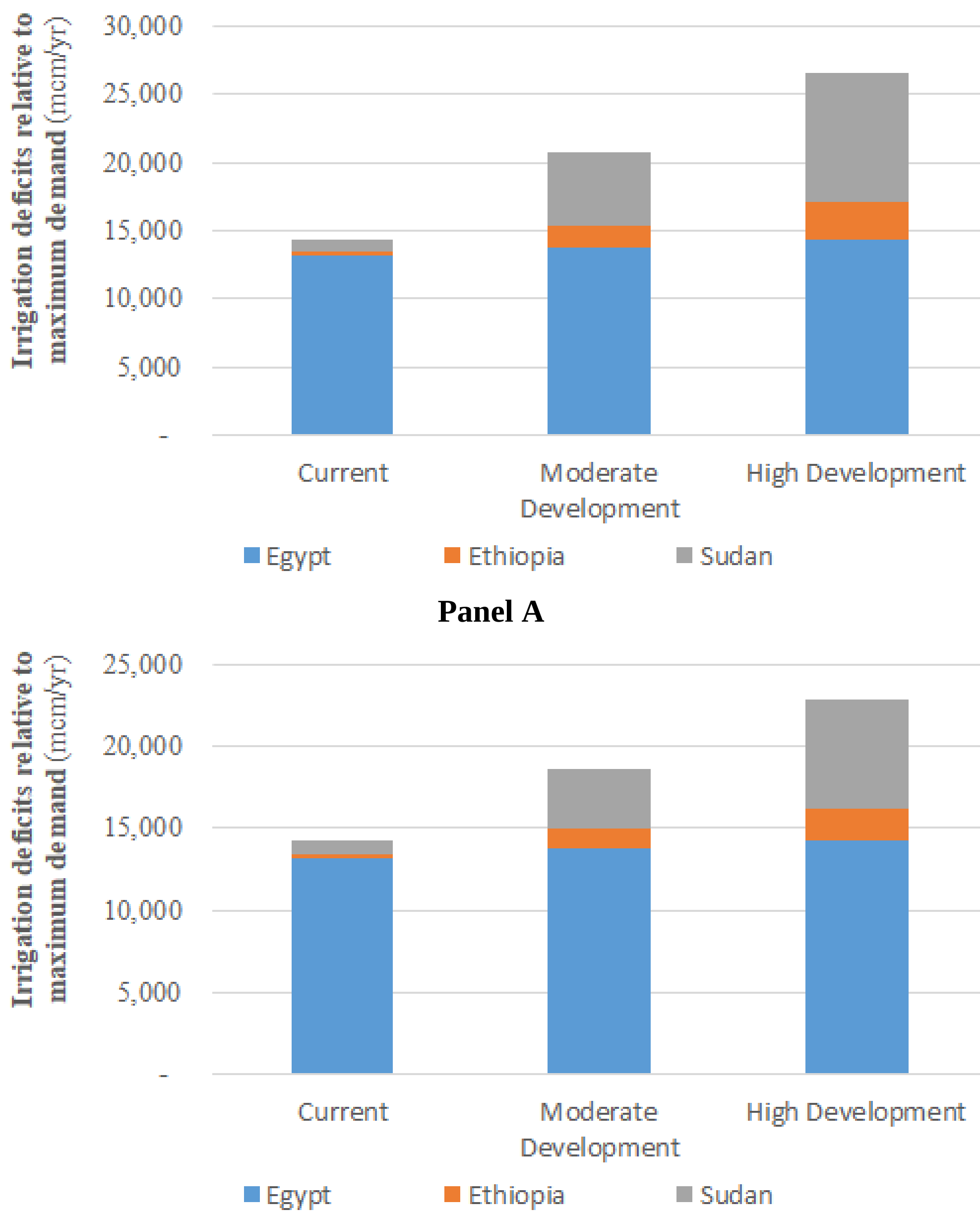


Figure D12. Total net benefits across the 9 development and institutional scenarios, for median hydrological conditions

To further explain this result, it is important to remember that most irrigation demands can be met without inducing significant tradeoffs across locations in the lower development scenarios, as previously shown in Figure D7, at least under normal hydrological conditions. What irrigation demand shortfalls exist under such conditions are typically not due to lack of coordination across demand sites, but rather to demand that exceeds supply overall (in Egypt), or a lack of storage and seasonality of flow (upstream in Sudan and Ethiopia). Thus, deficits under current development are similar across institutional scenarios.

As development increases, however, irrigation deficits increasingly reflect tradeoffs across locations in the basin, increasing in Egypt and Sudan downstream due to lack of water that is now consumed in greater amounts upstream (especially in Ethiopia). Efficiency-maximizing cooperation helps to protect more of these existing downstream demands, because there is benefit to keeping water in the river longer, rather than abstracting it further upstream and removing it from downstream consumptive uses as well as the locations of many instream power generation facilities. Cooperation according to either existing allocations protection or efficiency-maximizing allocations preserves higher value irrigation in Egypt somewhat more. This can be seen in Figure D13, which shows that deficits are somewhat lower in Egypt and in the basin overall under efficiency-maximizing cooperation relative to unilateral development, when development is much high. To further clarify the shifts in the irrigation benefits distribution across countries with high development, we illustrate the outcomes for this development scenario as a function of institutions in Figure D14.



Panel B

Figure D13. Distribution of irrigation deficits by country across infrastructure development scenarios, with A) existing claims prioritization (C1) and B) efficiency-maximizing cooperation (C2)

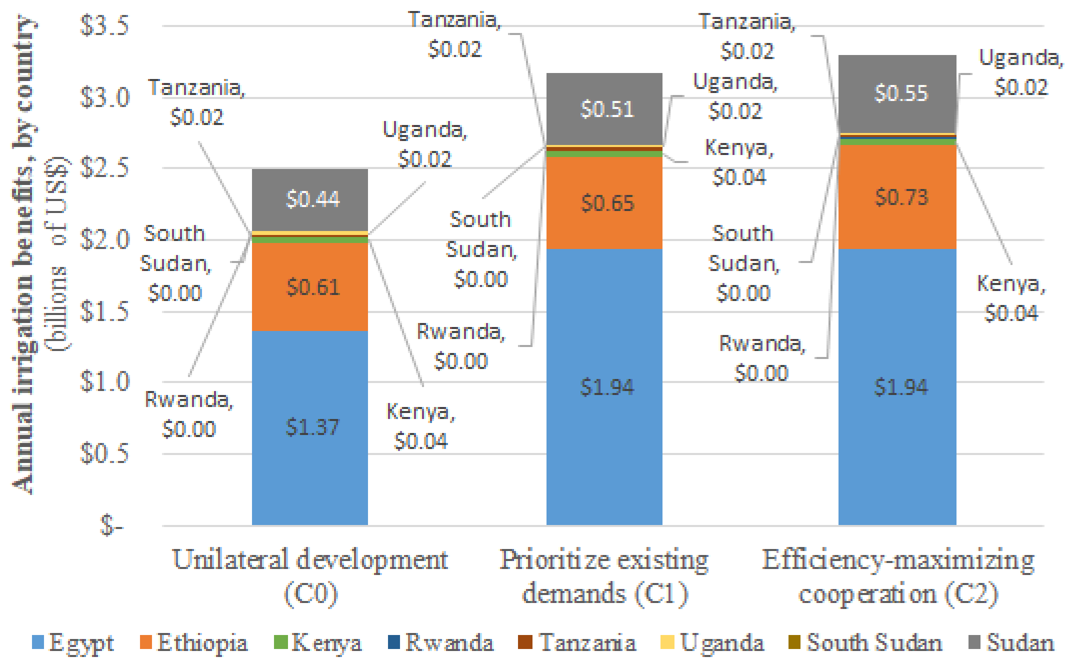
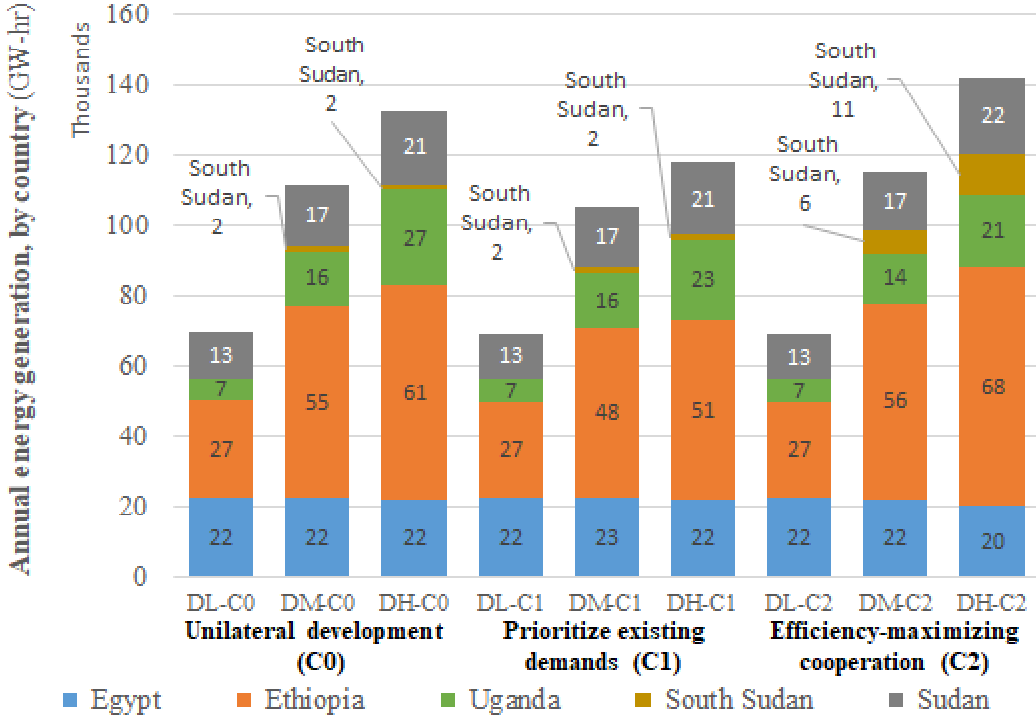
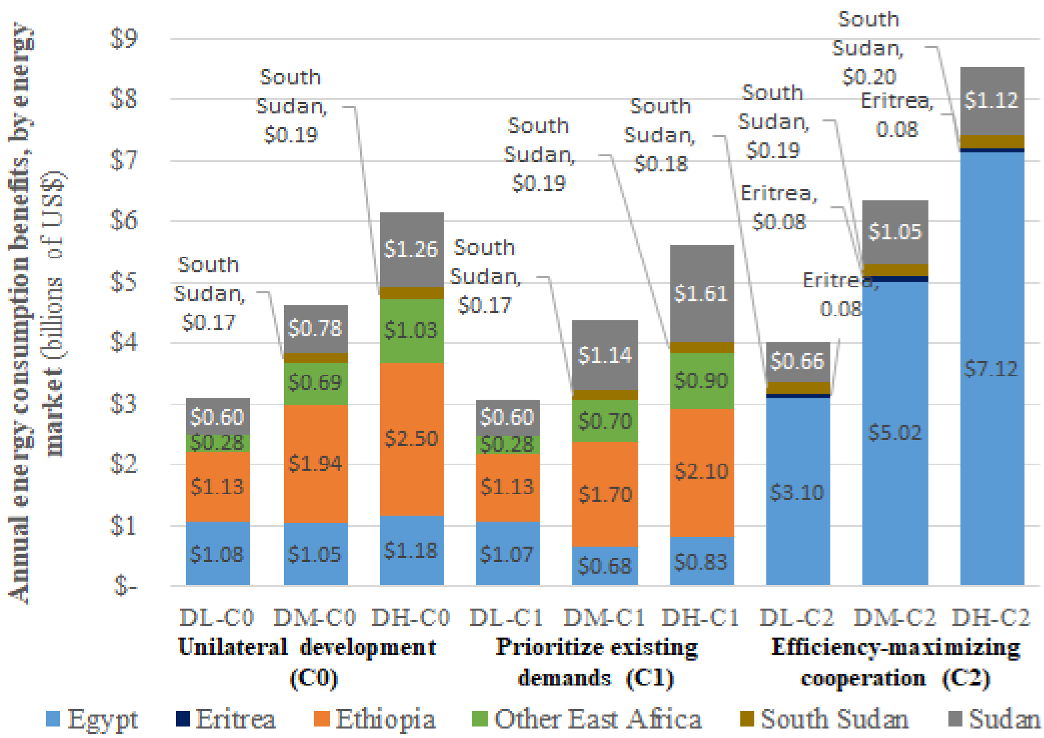


Figure D14. Total net value of irrigation allocations across the institutional scenarios, for median hydrological conditions and high development

These irrigation results notwithstanding, efficiency-maximizing cooperation could especially increase the potential for value to be derived from energy trade: As transmission constraints loosen, the model moves energy between Ethiopia and Sudan, on the one hand, to Eritrea and Egypt, as well as between South Sudan, Ethiopia and the Equatorial Lakes region. This leads to a very different distribution of energy consumption relative to the balance of generation, as shown in Figure D15 (Panel A shows the breakdown of generation across countries, and Panel B shows where that power would be optimally consumed). Thus, while Ethiopia becomes a major source of energy generation, that power is optimally traded to Egypt because of higher costs of alternative generation there, as well as the carbon offset value from displacing natural gas with hydropower. The value of displaced power is also high in South Sudan and Eritrea (which both depend on expensive oil-fired generation). The Other East Africa region also exports power to these valuable locations, owing to its lower alternative generation costs. Power generated in Sudan mainly remains in Sudan, since the value of displaced generation there is relatively high, rendering longer-range transmission less economically viable.



Panel A



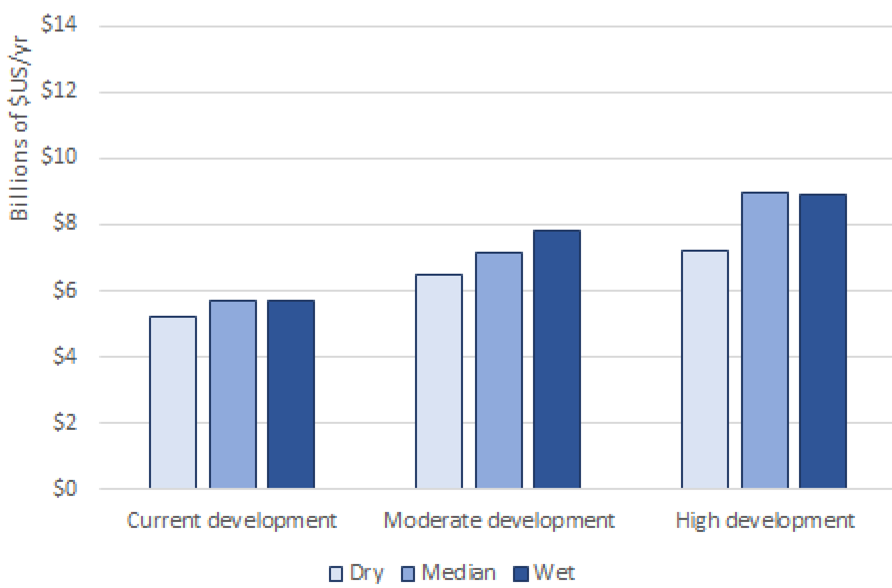
Panel B

Figure D15. Total A) generation and B) net value of energy consumption across the institutional and development scenarios, for median hydrological conditions

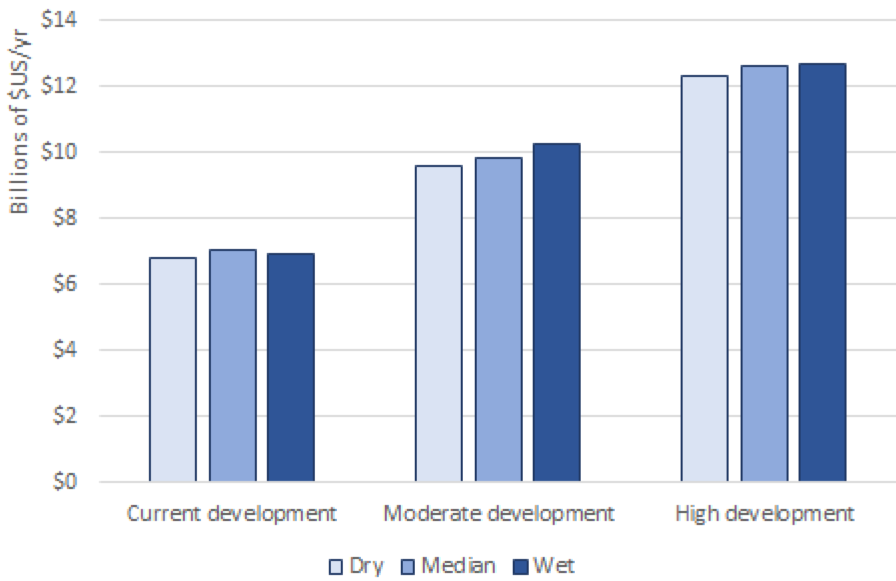
5. Sensitivity to hydrological flows

We next consider the sensitivity of these main results to hydrological conditions in the Nile, based on the framework outlined in Table C13, considering both prolonged (5-year) dry and wet sequences of flows. It is worth highlighting at the onset that these hydrological conditions are for the basin as a whole, measured based on accumulated naturalized flows arriving at Dongola (upstream of Lake Nasser). As such, they may not be "dry" or "wet" for particular tributaries or river reaches, and do not account for the differential demand pressures that exist in different sub-basins. Nonetheless, they provide a global picture of how economic benefits vary according to hydrological conditions, and can be imagined to represent how long-term outcomes would change in considerably drier or wetter futures.

We begin by presenting the overall picture (Figure D16). As shown, hydrological variation does affect outcomes, but moving from the 10th to the 90th percentile makes less of a difference than do either of the two policy dimensions of development intensity and institutions. Panel A displays the results for the unilateral development institutions scenario, while Panel B shows those for the efficiency-maximizing cooperation scenario. Thus, we see in a first observation that wet hydrology delivers approximately 8-18% higher benefits than dry hydrology across development scenarios, with unilateral development. With efficiency-maximizing cooperation, the effects of variable hydrology are somewhat reduced due to the gains from trade and optimization across wet and dry portions of the basin, with the wet conditions delivering only 3-8% higher benefits compared to the dry hydrology.



Panel A

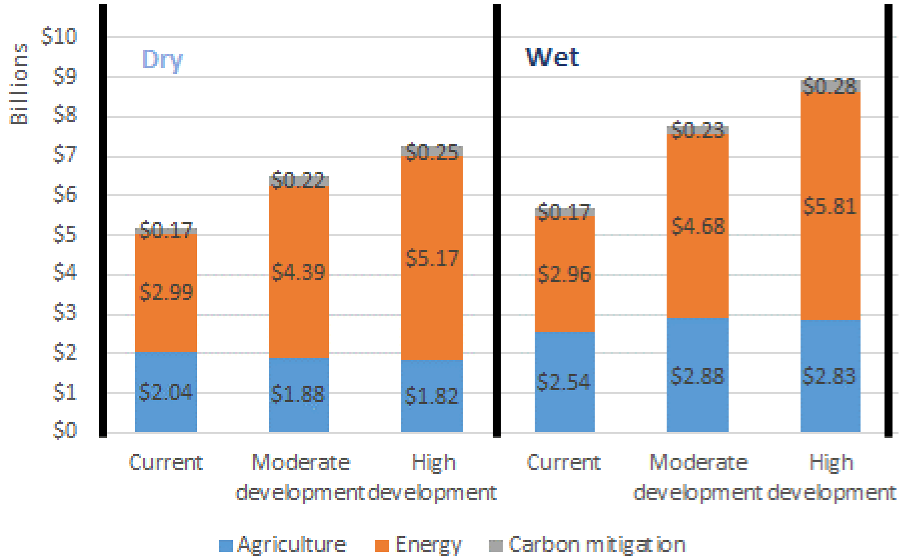


Panel B

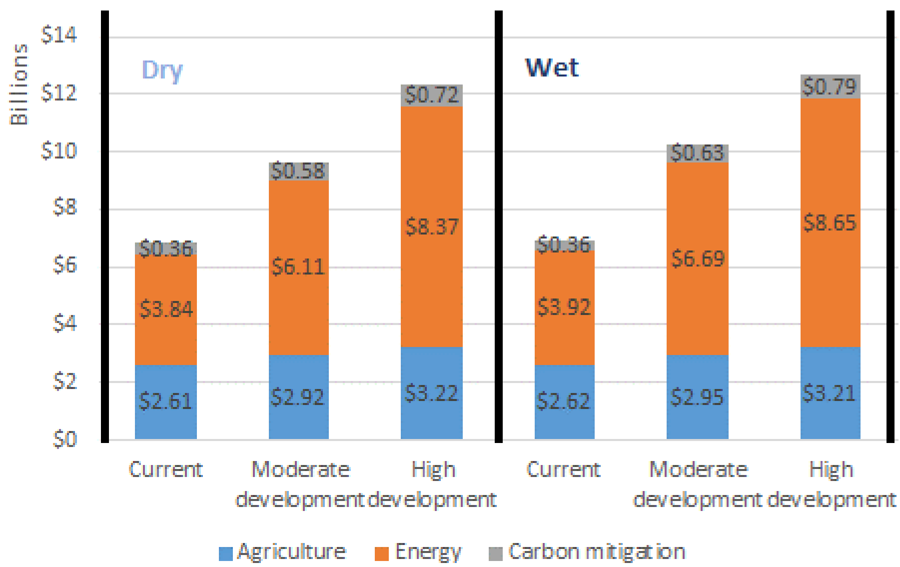
Figure D15. Total benefits under different hydrological conditions, for A) unilateral development and B) efficiency-maximizing cooperation scenarios

A second interesting observation is that wet conditions only provide higher benefits when development increases somewhat to moderate development, but then revert back towards those for the median under high development. This nonlinear response may seem counterintuitive, but stems from existing institutional constraints that bind in the current development situation and prevent much greater water use, on the one hand. At the other end of the development spectrum, there is significant water scarcity in the basin regardless of hydrology, such that tradeoffs emerge that render many sites infeasible even with some increase in flows, such that a wetter hydrology provides only marginal benefits. Of course, these varying responses also relate to the specific geography of infrastructure development projects relative to the locations of water uses.

Figure D16 helps to clarify some of these patterns further based on their sectoral breakdown. In particular, wetter conditions consistently deliver more hydropower consumption benefits than dry conditions when development increases and more dams in a larger set of locations can exploit tributary-specific advantages. In the current development situation, however, wet conditions deliver very little additional benefit in terms of optimal power generation. The response for agriculture as a function of hydrology is less consistent due to water use constraints increasing with development. If anything, the benefits from a wet hydrology are greatest for agriculture under current development, when allocations can be better optimized with some loosening of water scarcity. When development proceeds, scarcity again binds, regardless of the hydrological condition in the basin.



Panel A



Panel B

Figure D16. Breakdown of benefits under different dry and wet hydrological conditions, for A) unilateral development and B) efficiency-maximizing cooperation scenarios

Figure D17 provides a similar comparison as Figure D16 Panel A (no cooperation) for the GERD and no GERD breakdown of benefits. We focus on dry and median hydrologies and unilateral development, given that these combinations of changes might be of most concern to those worried about adverse effects from the GERD. This analysis shows, however, that under both dry and median hydrologies, the GERD has little effect on optimal irrigation abstractions, and that hydropower production gains from the GERD display a similar sensitivity to hydrological conditions as that of other power facilities in the basin.

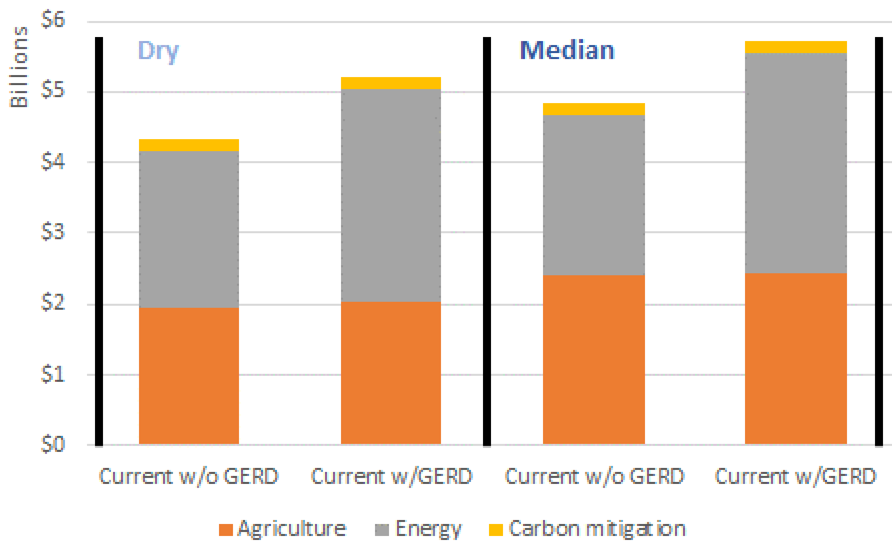


Figure D17. Breakdown of benefits under different dry and median hydrological conditions, for the unilateral development scenario

We next investigated where hydropower production was most sensitive to the difference between dry and wet conditions, in the unilateral development scenario that tries to maximize power moving from upstream to downstream. We also then further explored how the efficiency-maximizing cooperation would lead to deviation (either reduction or increase) in these sensitivities. These most sensitive dams are ranked according to the power reduction seen in the unilateral development scenario in Table D12, and according to contributions in the high development case, because this one includes all projects. This analysis shows that power losses are generally greatest at the largest facilities. This makes sense given their higher dependence on large flows to maximize output from their large higher installed turbine capacity. Losses are also somewhat concentrated downstream and in the Blue Nile system which is more heavily responsible for the overall flow of the Blue Nile. Still, we also see substantial power generation reductions at several facilities in the White Nile system starting from the Victoria Nile and flowing through the region leading into South Sudan.

Moreover, efficiency-maximizing cooperation has mixed effects on these losses. Some dams do better, i.e. have reduced hydrological sensitivity, in the efficiency-maximizing cooperative scenario, but this condition better optimizes power generation basin-wide, since full trading then allows that electricity to be reallocated anywhere in the basin (subject of course to transmission losses). This means that there is less need for power generation at Aswan, which correspondingly produces less. In general, the efficiency-maximizing scenario allows for more flexibility in releases from dams to meet needed irrigation requirements, given the benefits from trading.

Table D12. Loss of power production under dry hydrological conditions, relative to wet (Percentages in parentheses are relative to median hydrology production under each institutional scenario)

Dam	**Unilateral development**: Reduction in power generation [wet-dry] GW-hr/yr	**Efficiency-maximizing cooperation**: Reduction in power generation [wet-dry] GW-hr/yr
High Aswan Dam	-2,376 (14%)	-4,237 (27%)
Merowe	-1,644 (17%)	-579 (7%)
GERD	-1,643 (9%)	-4,402 (20%)
Beko Abo	-1,523 (12%)	-2,019 (17%)
Karadobi	-1,377 (24%)	-2,449 (32%)
Dal	-1,180 (28%)	-1,335 (35%)
Owen Falls	-901 (27%)	-680 (25%)
Murchison	-858 (15%)	-1,135 (23%)
Karuma	-833 (22%)	-473 (13%)
Ayago	-734 (14%)	-620 (17%)

Overall country-wise generation is shown in Figure D18, for dry and wet conditions (the analogue for median hydrology is shown in Figure D15 Panel A). This figure shows the differing hydrological sensitivity across countries, with South Sudan hardly affected due to the regulating effects of the Equatorial Lakes, relative to Ethiopia, which sees more variation across dry and wet conditions. Other hydropower producing Nile riparians lose roughly 3-4 GW-hr.

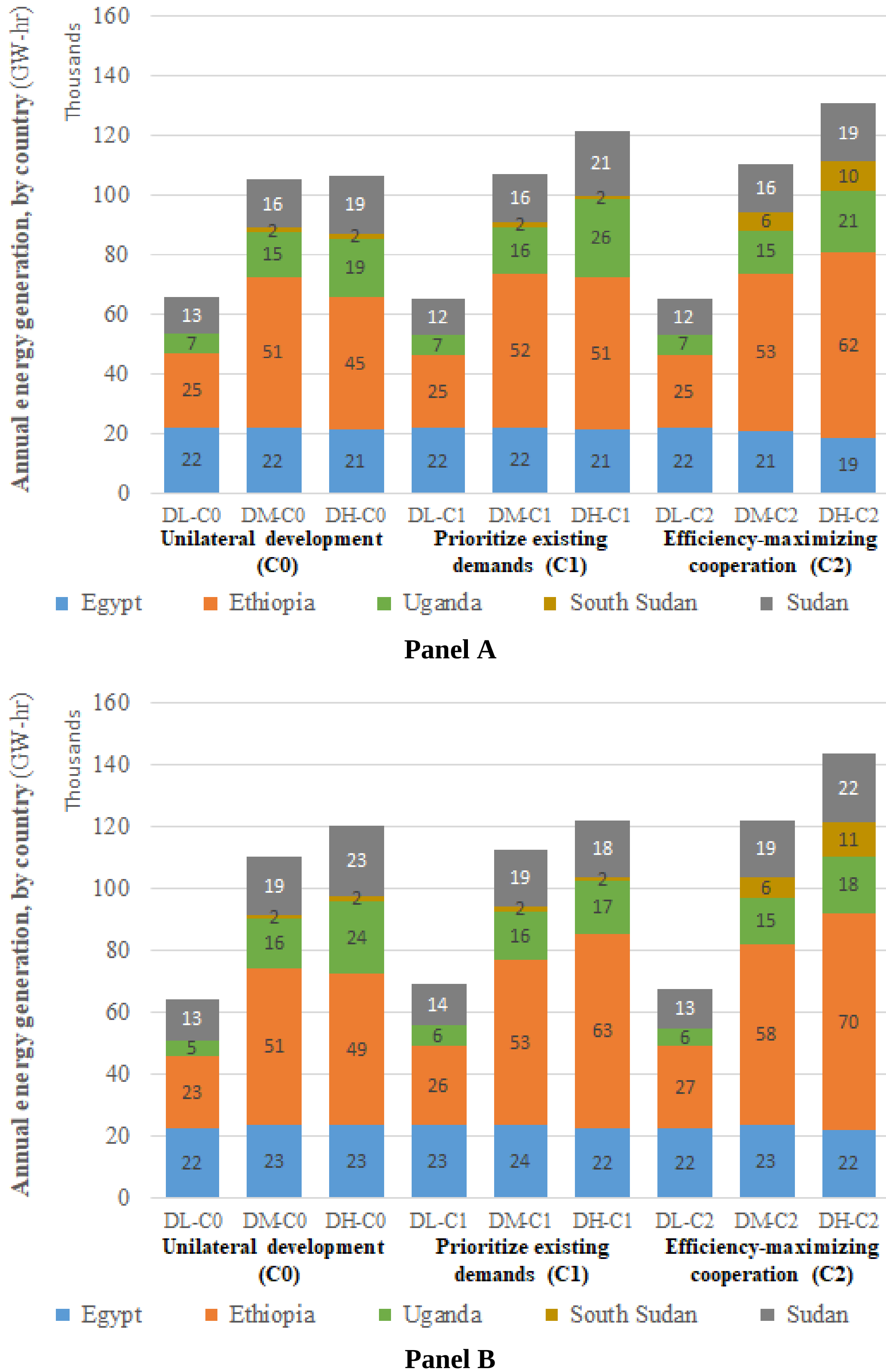
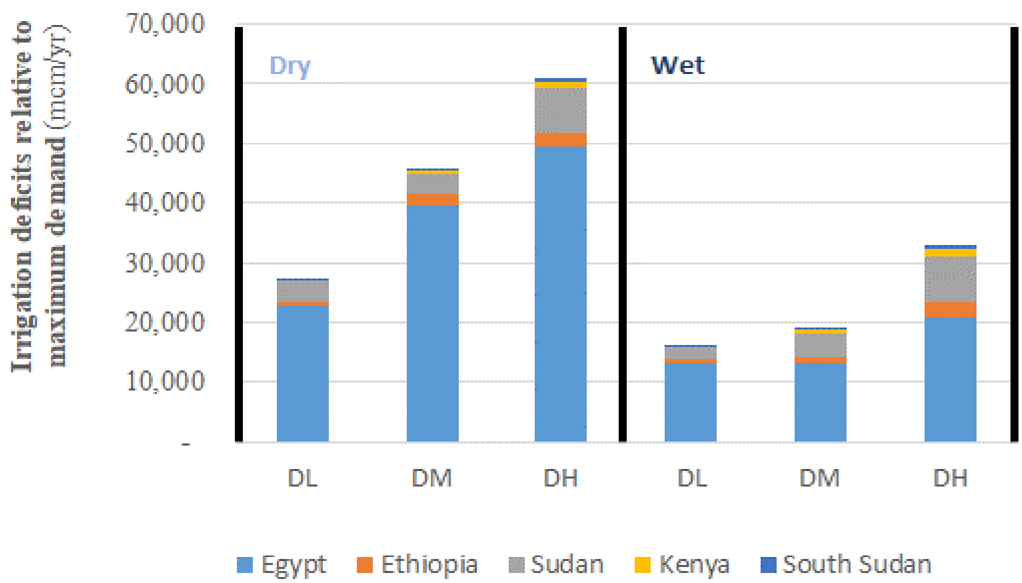


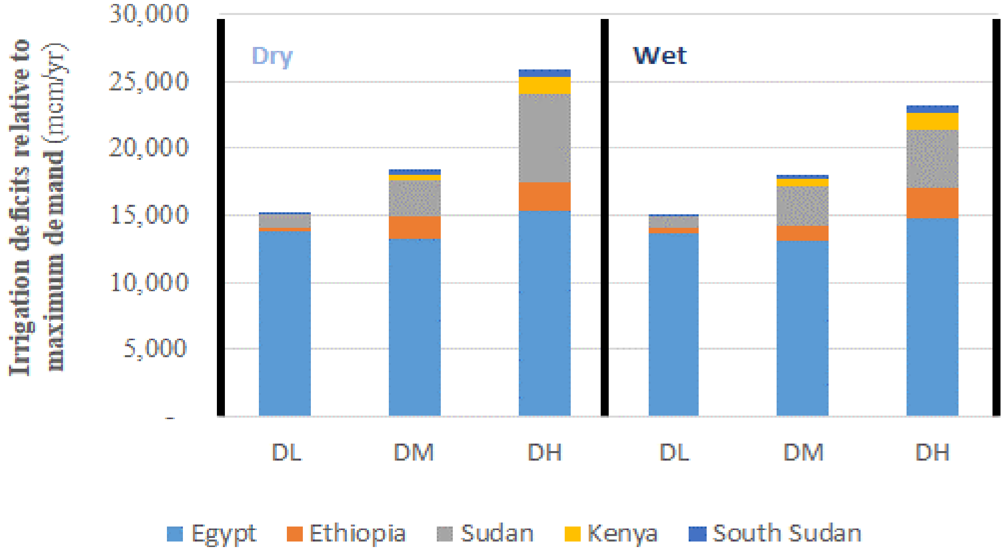
Figure D18. Total generation of energy for A) dry and B) wet conditions

We conclude this section by turning to the country-wise irrigation outcomes as a function of hydrology, we present key results in Figures D19 and D20. In Figure D19 Panel A (non-cooperation), we see what was already apparent in the sector-wise breakdown of Figure D16. Namely, deficits increase sharply under dry conditions even in the moderate development scenario, and become extremely high in the high development scenario (due to acute water scarcity and low downstream flow overall). The possibility of drier conditions and irrigation development and these acute deficits should be a cause for considerable caution among Nile riparians. Under wet conditions, it takes a much higher level of development to begin to see such tradeoffs emerging, but even a wet future would not suffice if development were consistent with all countries' plans and ambitions.

In Panel B, we see that efficiency-maximizing cooperation does help to alleviate shortfalls by ensuring that more water flows downstream to Egypt where it is most valuable for irrigation. Nonetheless, increased development places significant strain on irrigation water availability, and shortfalls increase substantially under the full development scenario, even with efficiency-maximizing releases and coordination of demands. Even more telling however, is the fact that though deficits increase much less under wet conditions, economic benefits from irrigation are quite similar (Figure D20 Panel B). At first glance, this result is counterintuitive, but it reflects the fact that greater water availability is not sufficient to generate higher profits even under wet conditions, because irrigation sites optimally supply water to only generate breakeven values in additional sites, rather than simply not exploiting them. In other words, the model allocates water in additional sites under deficit irrigation to just achieve zero values as more water becomes available, but the optimum is still to pass as much downstream towards Egypt as possible. In the unilateral development scenario (Figure 20 Panel A), then, though water allocations increase with development, *less* economic value is produced overall, because of the loss of productive agriculture especially in Egypt.

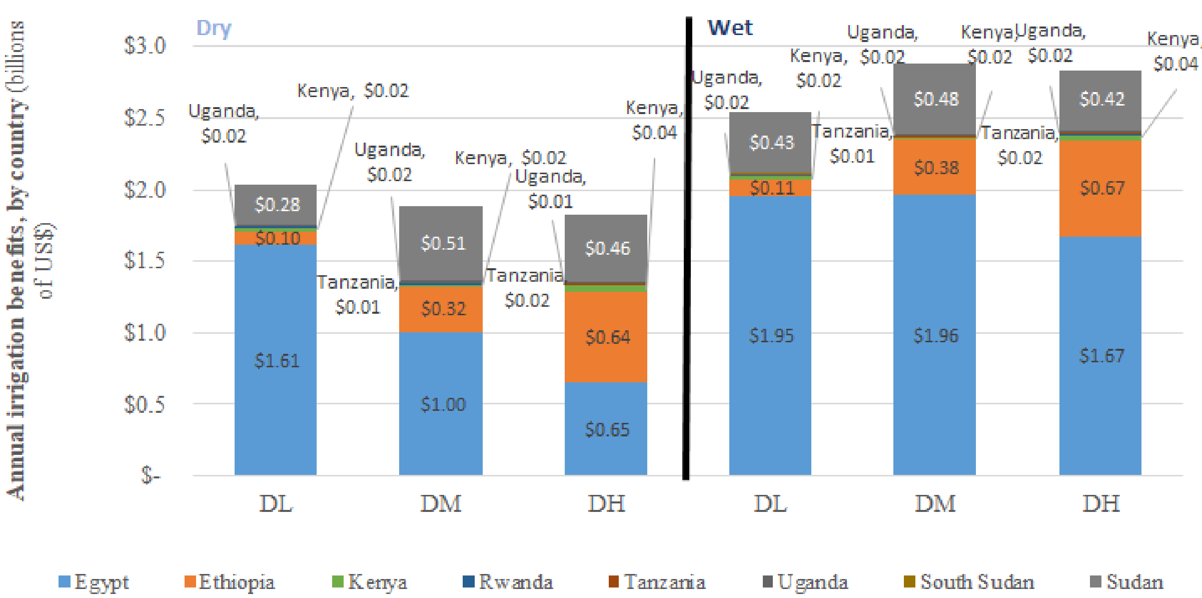


Panel A

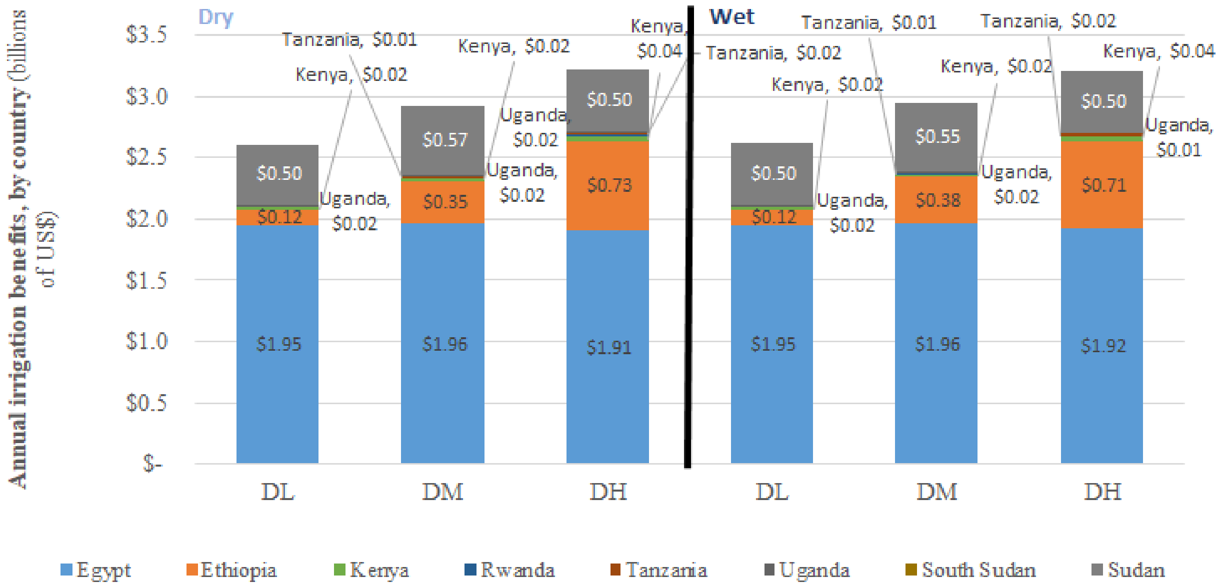


Panel B

Figure D19. Demand deficits relative to country targets under dry and wet hydrological conditions, for A) unilateral development and B) efficiency-maximizing cooperation



Panel A



Panel B

Figure D20. Agriculture benefits by country under dry and wet hydrological conditions, for A) unilateral development and B) efficiency-maximizing cooperation

6. The value of irrigation efficiency improvements

We next draw attention to analyses that aim to assess the value of additional irrigation efficiency improvements, which on the one hand may help reduce the magnitude of diversions needed to satisfy existing agricultural water demands, but on the other would also reduce return flows and the ability to reuse water multiple times in the basin. The latter issue has been dubbed the "irrigation efficiency paradox", whereby such improvements can be observed in practice to not do much to relieve water scarcity (Grafton et al. 2018). It is also important to highlight at the outset that this analysis only discusses the economic benefits from irrigation efficiency investments and their effects on deficits in the basin, owing to the lack of cost data needed to parameterize the model correctly to account for these. As such, one can think of the change in agricultural benefits and in the value of water as a gross value that would need to be compared against the investment cost required to achieve the higher efficiency levels. As discussed in the prior section, we consider a movement to full sprinkler and lined canal irrigation as an intermediate technology improvement, and then the high level of irrigation improvement corresponds to full lining and covering of conveyance plus drip irrigation delivery. This moves the irrigation efficiency from about 0.5 in most basin sites (and 0.56 in Egypt) up to 0.64 overall (intermediate), and 0.81 overall (high). We analyze the outcomes only for full cooperation, given the fact that most of the benefits would flow downstream, and consider the median hydrology case for the sake of parsimony in the results presentation.

Figures D21 and D22 summarize the main results. Figure D21 shows how deficits are substantially reduced by these improvements. Still, irrigation efficiency has diminishing value as one proceeds downstream due to the decline in return flows, as shown by the fact that these improvements are unable to fully remove deficits especially in Egypt, and, when development increases upstream, in Sudan. When development is low, the impacts on deficits in the latter two countries are larger, especially in Sudan.

Turning to the valuation of these changes, the intermediate efficiency improvement increases agricultural benefits by about US$0.5 billion per year over current technology (Figure D22), and the high efficiency improvement increases benefits an additional US$0.8-1.2 billion per year. [These benefits would need to be compared to the annualized capital cost of the improvements]. The paradox is most apparent in the high demand – intermediate efficiency scenario, where Ethiopian benefits gains are largely offset by reduced water use downstream in Sudan, though Egypt benefits consistently in all cases due to its high value agriculture. Overall, the net value of a unit of water diverted for agriculture increases from about US$0.045/$m^3$ with current irrigation technology to US$0.055/$m^3$ and US$0.068/$m^3$, with each level, respectively.

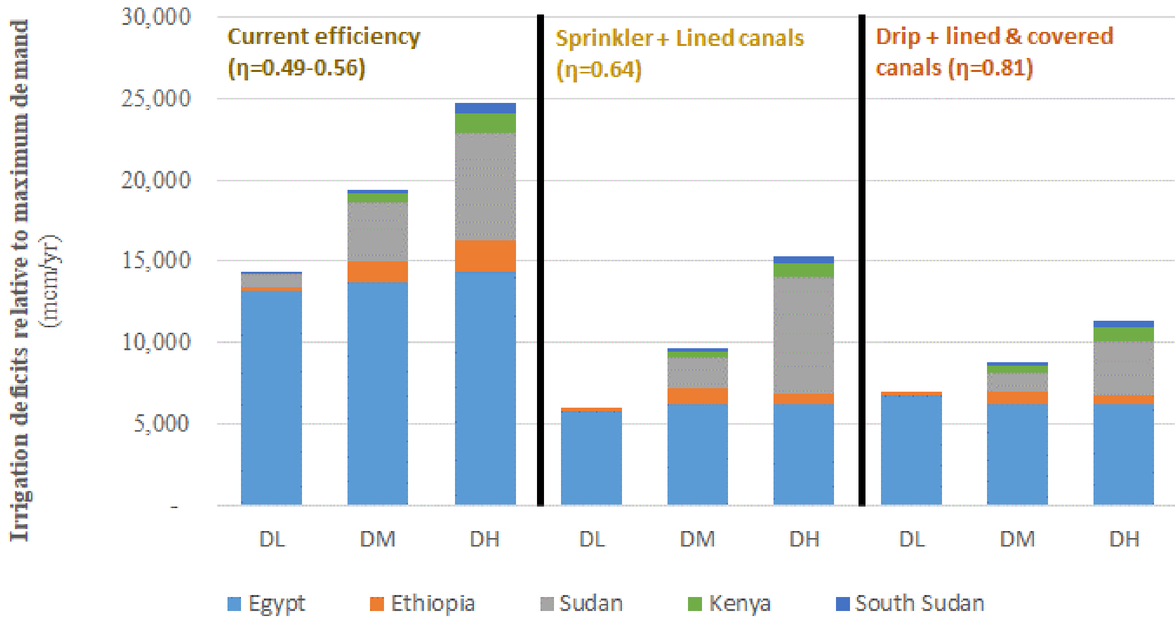


Figure D21. Irrigation deficits by country under various irrigation improvement scenarios, assuming efficiency-maximizing cooperation

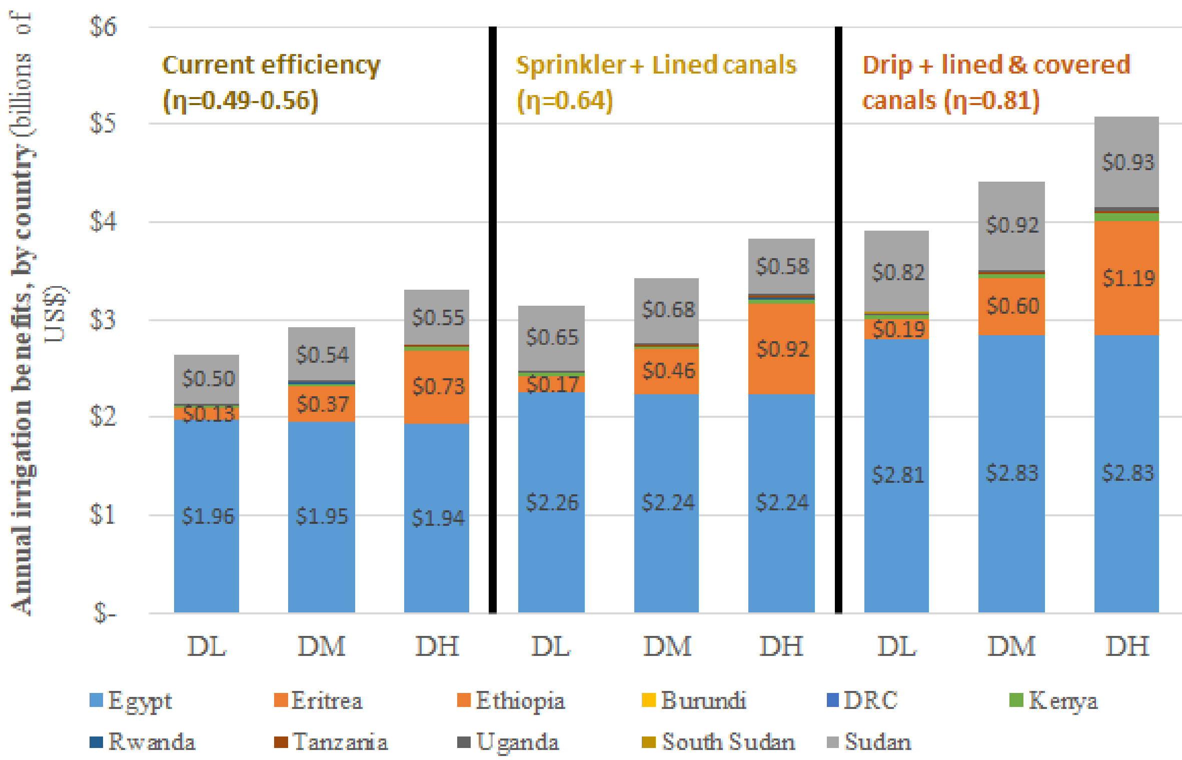


Figure D22. Agriculture benefits by country under various irrigation improvement scenarios, assuming efficiency-maximizing cooperation

7. The cost of maintaining environmental flows in critical locations

We conclude this section by considering the tradeoffs induced by tighter e-flow restrictions (Yang 2011, Sharma et al. 2020). Here, it is important to highlight that the NHEOM does not solve in several hydrological years owing to the specific flows entailed in those years and the e-flows specified according to average hydrological conditions, shown in Table C14. The discussion here is therefore primarily qualitative, and aimed at clarifying what sorts of tradeoffs appear most significant once e-flows are included. More work would need to be done to better characterize what an e-flow regime should look like over time and how it could be supported by conjunctive groundwater use rather than shutting off irrigation completely at affected sites, prior to trying a more robust optimization for this system.

Moving from no e-flows to the least restrictive, class c condition leads to reduced viability of several agricultural sites. For the current development condition, the following locations are affected: Local irrigation in the Blue Nile catchment between Lake Tana and upstream of the Beko Abo site, and e-flow restrictions lead to minor reductions in withdrawals in Sudan along the Blue Nile, and in Uganda along the Victoria Nile. Total reductions amount to about 112 mcm/yr. Effects are somewhat more significant for moderate and high development cases. In the former, we see reduced irrigation in the Baro-Akobo basin, by nearly 900 mcm/yr, reduced irrigation development around Lake Tana (about 400 mcm/yr reduction), as well as Didessa (60 mcm/yr), Tana-Beles (80 mcm/yr) and Blue Nile irrigation in the catchments between the Beko Abo and GERD sites (60 mcm/yr). Withdrawals are similarly reduced in new Kenya and Uganda irrigation development sites, by about 157 mcm/yr, and numerous problems emerge along the Blue and White Niles in Sudan (where deficits increase by nearly 3 bcm/yr). Importantly, the required e-flows are much lower than these reductions, but due to their timing, they reduce cropped area considerably in specific months, which leads to the larger reductions overall. With high development, additional problems emerge throughout the basin at both new and established irrigation sites, and make solving the model difficult.

The same trends can be seen with class b and class a e-flows, and they become much worse. With the most restrictive e-flows, there are few years that solve optimally while requiring agriculture to deliver net production. On the other hand, e-flow tradeoffs with hydropower are much less significant. All in all, additional work is needed to better characterize the necessity for specific e-flows, and to perhaps move to an optimization approach that would impose fuzzy penalties (perhaps based on the cost of groundwater pumping to make up for irrigation shortfalls) for violating these constraints.

E. Discussion

This report has aimed to synthesize a large number of results from an optimization model developed to explore development and institutional cooperation trajectories in the Nile Basin. The model was developed through a careful study of documents and country data provided by the Nile Basin Initiative, and was applied to consider a number of questions of special interest to policy-makers from the riparian countries. To the best of our knowledge, it is the first such basin-wide model applied since the NEOM was developed roughly 20 years ago, a model which had very little of the specificity that current countries are considering for their Nile-based development activities (Whittington et al. 2005, Wu and Whittington 2006).

There are a number of inherent limitations to the current NHEOM structure. Among the issues flagged as important by country teams reviewing this work were valuation related to flood control benefits, watershed protection via reforestation and vegetation enhancement, environmental values associated with specific minimum flow regimes, improved understanding of the potential for groundwater and conjunctive water use to meet the existing and future demand for water, water quality aspects, and sensitivity to climate change or extreme events. In considering each of these issues, the analytical team producing the results in this report had to grapple with, and balance, the limited or insufficient data that disallowed a credible representation of relatively complex dynamics. Their omission certainly limits the extent to which benefit sharing is possible and can result from more coordinated planning activities, and as such, the cooperative institutions analyzed in the report would likely be even more beneficial than has been shown.

To be sure, considering first the potential of groundwater, there is very likely substantial potential to leverage this resource to meet the demand shortfalls that would appear with exclusive reliance on surface water resources from the Nile. Unfortunately, there has yet to be a comprehensive mapping of groundwater resources and availability, which is essential for understanding the amount of water available in different locations, how it has evolved over time as a function of climate and population pressures, and the costs of exploiting those resources (which is a function of the depth to groundwater and available technology and energy resources needed for pumping). We recommend such a detailed and comprehensive analysis in the next phase of planning, as expanded groundwater use could help mitigate projected future water scarcity. **Among all the model omissions, it is the view of the economists working on this report that this one has the most potential for altering conclusions about the tradeoffs that have been identified, given that groundwater use may substantially alleviate irrigation demand shortfalls.**

Next, with more infrastructure in the basin would come enhanced ability to control flooding, which is damaging to economic activities and livelihoods in many locations. However, two important data-related problems, and one behavioral one, precluded our inclusion of flood control benefits in the current work. The first is the challenge of attributing damages and losses to enhanced management of Nile Basin surface waters. Prior studies have noted the difficulty of such attribution in the context of frequent flash and localized flooding from non-river sources in even the most flood-prone locations (e.g., Khartoum) (Walsh et al. 1994, Davies and Walsh 1997), where infrastructure would seemingly, but not always, do much to reduce damages (Jeuland 2009). The second issue concerns valuation of damages, which can include loss of life and property that is hard enough to quantify in physical terms, much less value, in the context of imperfect and distorted property markets as well as mortality and morbidity risk valuation. In the future, the riparian countries should work with environmental economists to conduct detailed and rigorous flood damage assessments as have been done in other parts of the world, e.g., in Bangkok, Thailand (Nabangchang et al. 2015). They should also partner with socio-hydrologists, who have advanced understanding of the behavioral responses to infrastructure that often negate flood control benefits, specifically the propensity of populations in areas that are protected to take on more risk by moving to previously overly risky settlement sites (Viglione et al. 2014). **Regarding this HEM model omission, the economists working on this report feel that inclusion of flood control benefits would not substantially alter the major conclusion that storage-backed hydropower facilities remain attractive investments for the basin riparians; indeed, including flood control benefits would only strengthen this conclusion.**

A related issue that is challenging for HEM analysis to incorporate, is the role of watershed protection and vegetation enhancement. It is widely believed and argued that population pressures to convert land for agricultural and settlement purposes in upland areas, and forest loss and degradation from intensive household biomass use throughout the basin have led to accelerated erosion, stronger short-term pulses of flood waters, and weaker base flow. Yet, scientific research highlights the complexity in such processes, noting that forests usually evaporate more water than farmland crops due to trees' rough surface and deeper root systems which allow maintaining of transpiration during dry periods (Calder et al. 1995). Forests that are large also induce their own microclimates. Thus, while short-term runoff typically decreases with forested area, what happens to overall water flow downstream is less clear (Bewket and Sterk 2005, Hurni et al. 2005). Net effects are likely highly location-specific. Given the lack of understanding of the processes that would result from different afforestation interventions in the basin, it was deemed unwise to include speculative predictions on such aspects in the NHEOM. **The impacts of their omission from the HEM are difficult to predict with any certainty at this time.**

Next, while we did consider tradeoffs with environmental flows to some extent, it is clear that the NHEOM in its current iteration is not ideal for exploring such tradeoffs, due to a lack of understanding of the economic values associated with the different flow e-flow regimes included in the SWRA. In reality, environmental flows could also be managed by better modeling options for conjunctive water use, and working more carefully on calibration over longer term hydrological sequences. An additional alternative approach that should be attempted is to impose penalties in the model objective function for reducing e-flows at critical locations in the basin, based on realistic valuations that represent actual environmental costs in each location, rather than imposing these as binding constraints that otherwise render many basin infrastructure configurations infeasible. Other issues that could be considered with additional data include water quality, to the extent that such problems stem from existing uses and management strategies in the basin. **Regarding this HEM model omission, the economists working on this report feel that inclusion of environmental benefits could only strengthen conclusions about the existence of tradeoffs induced by increased upstream consumptive use of surface water.**

Concerning climate change and extreme events, meanwhile, prior work with HEMs has highlighted that different approaches, relying on simulation or robust optimization techniques, are generally warranted to deal with the substantial uncertainty and lack of foresight in predicting and responding to such events (Harou et al. 2009). Future work should consider such aspects, building on similar work conducted in the Blue Nile (Jeuland and Whittington 2014).

A final (non-structural) limitation of the analysis is that the NHEOM objective function is purely limited to demonstrating the *efficiency* implications of water management of the Nile Basin surface water resources. As such, the report makes no judgment on whether the efficient allocations recommended here under each institutional arrangement, are in fact fair, and many riparians will likely find that they are not, at least absent significant compensation for forgone development (among currently less developed sectors or countries with lower existing uses) or losses of current exploitations (among more highly developed sectors or countries with higher current uses). An *equity* analysis that sheds light on efficiency-equity tradeoffs, if they exist, would also be interesting, but would require a very different process for analytical development. Such a process would need to focus on one or more concept(s) of equity that would be agreeable to the Nile riparians, as well as a practical operationalization of that concept. This was beyond the scope of the present analysis, but we recommend that the countries engage in such a process along with economists working with an HEM when the time is right.

In spite of these limitations, the analysis provided a number of important results that go beyond those previously established for this basin. First, while there remains significant development potential in the basin today, most of that development would immediately induce large tradeoffs. This is especially true of irrigation development, which is difficult to support further without significantly elevating the risk of water deficits downstream in Sudan and Egypt. The greatest tradeoffs appear to be associated with further irrigation development in Sudan, and with potentials in the Blue Nile and Baro-Akobo sub-catchments located in Ethiopia. While irrigation development in the Equatorial Lakes region also comes at a cost, it is considerably lower due to the damping effects of the lake region’s hydrology and most notably the Sudd. Still, at a more local or national level, there are large tradeoffs across irrigation sites (e.g., within Uganda or Kenya), or between hydropower generation and irrigation (e.g., in Ethiopia).

Second, hydropower tradeoffs are less pronounced. Countries have an incentive to release water through dam turbines, allowing it to flow downstream to irrigators. While dams upstream do increase evaporative losses, such losses can be reduced by optimal management that does not store excessive amounts of water, especially in dams located in arid and hot reaches of the river. The evaporative benefits of upstream storage should not be assumed however. These depend on the extent to which evaporation can be lowered downstream as a result of that increase upstream storage capacity.

A third important result concerns the value of cooperation. Partial cooperation that safeguards existing demands and allows for some enhanced trading of benefits yields fairly minimal benefits, while full cooperation with extensive trading of energy delivers large benefits. This is because of the wedge in alternative costs of producing energy in different locations, and in the extent of the gap between demand and energy generation capacity. Simply put, energy is not equally valuable in all parts of the basin, and full cooperation allows for large gains from trade as this energy can move to more valuable markets. As the countries consider to grow economically and pursue energy access and electrification goals associated with Sustainable Development Goal 7, the logic in favor of energy trading and deregulation of the regional market will only grown stronger. The Basin's plentiful hydropower potential could literally transform the Nile into a large battery, if properly managed.

Fourth, our analysis is consistent with other recent modeling studies that suggest that under normal hydrological conditions, the Grand Ethiopian Renaissance Dam will increase electricity generation and hydropower benefits, while having only minor effects – mostly positive – on the stability of water supplies and energy production downstream (Wheeler et al. 2020). Even under relatively dry conditions, this result appears stable. This analysis did not explore extreme drought conditions, as optimization models aiming to maximize efficiency are not really appropriate for considering such circumstances and rarely accurately reflect real world behavior by dam operators.

Fifth, we showed that irrigation efficiency can lead to substantial reductions in the potential for future water deficits. For such investments carried out in Egypt, the benefits are somewhat modest, because additional efficiency improvements decrease return flows that eventually make their way downstream when they can be used by farmers in the same system. In contrast, irrigation efficiency improvements made upstream tend to have spillovers outside their own countries; these investments thus allow for expansion of irrigated land without at a lower opportunity cost for farmers in countries downstream of them. Efficiency improvements increase the net value of diversions by 20-50%, depending on the extent of the improvements, and relieve some, but not all, of the pressure that would come from further irrigation expansion upstream.

Sixth, benefits remain sensitive to hydrological conditions in the basin, which is a well-known dimension of managing water in the Nile. This sensitivity is greatest for Ethiopia, relative to other countries, due to the greater flow and lack of natural phenomena that smooth out water system variability, such as the Sudd swamps and large lakes located upstream in the White Nile sub-basin. Somewhat ironically, dams allow for more management of variability, yet the benefits they produce (especially power production) are also sensitive to that variability. As a result, Ethiopia bears the costs of variability disproportionately and will continue to do so, relative to other countries in the basin. Ethiopia should consider carefully strategies for managing the associated risks, which vary across projects and basins. For example, development in different basins may help hedge risks if drought conditions are relatively uncorrelated across basins. Alternatively, coordinated infrastructure operations across multiple infrastructures rather than independent operations may allow buffering and smoothing of extreme conditions.

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