A continental-scale hydro-economic model for integrating water-energy-land nexus solutions

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Key Points:

- A new large-scale hydro-economic model (ECHO) is developed
- ECHO is used to evaluate the water management adaptation pathways in Africa under various socio-economic and climate futures
- Future scenario simulations highlight the capacity of ECHO to address challenging research questions related to water-energy-land nexus

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Abstract

This study presents the development of a new bottom-up large-scale hydro-economic model, Extended Continental-scale Hydro-economic Optimization (ECHO), that works at a sub-basin scale over a continent. The strength of ECHO stems from the integration of a detailed representation of local hydrological and technological constraints with regional and global policies, while accounting for the feedbacks between water, energy and agricultural sectors. In this study, ECHO has been applied over Africa as a case study with the aim of demonstrating the benefits of this integrated hydro-economic modeling framework. Results of this framework are overall consistent with previous findings evaluating the cost of water supply and adaptation to global changes in Africa. Moreover, results provide critical assessments of future investment needs in both supply and demand side water management options, economic implications of contrasting future socio-economic and climate change scenarios, and the potential tradeoffs among economic and environmental objectives. Overall, this study demonstrates the capacity of ECHO to address challenging research questions examining the sustainability of water supply, and the impacts of water management on energy and food sectors and vice versa. As such, we propose ECHO as useful tool for water-related scenario analysis and management options evaluation.

Keywords. Hydro-economic model**;** large-scale modeling**;** scenario analysis; water management options; economic cost; water-energy-land nexus

1. Introduction

Global water withdrawals have been increasing rapidly during the last decades in order to sustain growing food and energy demands and increasing standards of living (Kummu et al., 2010; Liu et al., 2017; Mekonnen & Hoekstra, 2016). As a result, many basins around the world have experienced pervasive water scarcity conditions and related water management challenges (Kahil et al., 2015a; Veldkamp et al., 2017; Wada et al., 2013). These challenges are expected to become more critical in the coming decades as countries attempt to sustain a larger and more prosperous human population and economy under changing climate conditions (Hanasaki et al., 2013a; Kim et al., 2016). As such, policymakers in vulnerable basins need to anticipate on how to adapt management practices to secure reliable future water supply that can meet the demands from different sectors. However, the choice of water management options is often associated with tradeoffs across multiple water-related systems such as food production, energy supply, and ecosystem services, as well as across space and time (Banzhaf, 2009; Hurford et al., 2014). An appropriate choice of these options calls for the development of a systematic approach, depicting the biophysical and socio-economic factors that determine the future dynamics of river basins, including the key interactions among water, energy and agricultural systems (Brown et al., 2015; Rogers & Fiering, 1986; Wada et al., 2017).

In recent decades, hydro-economic (HE) models have emerged as an important tool for informing basin-scale water resources planning because they include an integrated biophysical-technological-economic representation of the water resources systems (Bekchanov et al., 2017; Harou et al., 2009). These features are usually represented using a set of physical and technology choice equations (or core model). Numerical optimization algorithms are then applied to the core model to back-calculate a set of primary decisions that collectively result in the best feasible outcome from the perspective of specific objectives important to decision-making (Booker et al., 2012). For example, an economic objective that focuses on minimizing costs or maximizing benefits is typical in HE models because it facilitates valuation of resource and policy constraints (Ward, 2009). Similarly, simulation algorithms can be used in HE models to more realistically represent complex water systems with nonlinear physical or institutional processes. Traditionally, HE models have been used to evaluate the efficiency of alternative water allocation mechanisms under existing infrastructure (Booker et al., 2005; Booker & Young, 1994; Cai et al., 2003; Kahil et al., 2015a; Noel & Howitt, 1982; Ward & Lynch, 1997), and to identify bottlenecks in the water system, where investments in new infrastructure would be most beneficial (Acquah & Ward, 2017; Gohar et al., 2013; Qureshi et al., 2010). Recently, HE models have also been used to assess how effectively the water system can adapt to future climatic and socio-economic changes and explore the value of various options for doing this (Connor et al., 2009; Escriva-Bou et al., 2017; Kahil et al., 2016; Medellín-Azuara et al., 2008; Tanaka et al., 2006).

In the literature, HE modeling is rarely used across large spatial scales. More typically, HE models have been designed at basin scales (Harou et al., 2009), with a few designed to model systems ranging from household or utility scales (Alcubilla & Lund, 2006; Jenkins & Lund, 2000; Rosenberg et al., 2007) to transboundary basin scales (Fisher et al., 2002; Nigatu &

Dinar, 2016; Ringler et al., 2004). The few large spatial scale models include national scale examples, such as the statewide HE model of California (CALVIN) (Draper et al., 2003), and global scale examples, such as the IMPACT-WATER (Cai & Rosegrant, 2002) and IGSM-WRS (Strzepek et al., 2013) models. Advantageously, these large-scale HE models provide the opportunity to integrate a detailed representation of local biophysical and technological constraints with farther-reaching regional and global policies. This feature is particularly relevant because the availability of water, energy and land resources varies significantly at local scales, whereas the linkage to regional and international markets for energy and food commodities and transboundary treaties for water resources results in global influences (Dalin et al., 2017; Holland et al., 2015; Zawahri et al., 2016). However, existing large-scale HE models use a reduced number of spatial units in order to minimize the computational burden, which limits their potential for integrating properly local-level constraints. Moreover, these large-scale HE models have been designed to identify bottlenecks in the water system, but they have not been designed to identify the least-cost optimal combination of water management options for meeting growing and changing water demands. Likewise, many omit the implications of management options in the energy and agricultural sectors such as investments into thermal power plant cooling technologies, irrigation systems, and trade opportunities.

To meet this specific need and consistently address water-energy-land nexus management solutions, we develop the Extended Continental-scale Hydro-economic Optimization (ECHO) model: a new large-scale HE model for long-term water management planning. ECHO is an extended HE model because it includes both capacity expansion and operational decisions for a wide range of water management options in the water system, as well as in energy and agricultural systems, with the choice among these options is always economically evaluated to reveal opportunities for efficiency gains. This feature is particularly relevant, given that adaptation to future water scarcity is a challenging task, especially for regions with limited economic capacity to invest in capital-intensive water infrastructure and management options. In these regions, a better alignment of policies across water-related domains and regions is needed in order to reduce overall investment costs. Moreover, ECHO covers an extensive number of sub-basin units within a reduced-form transboundary river network. This feature enables identifying the spatial differences in supply and demand patterns and the choice of adaptation pathways. Lastly, the ability of ECHO to combine various components, including hydrology, agriculture and energy uses, and economics into a holistic large-scale modeling framework, which is solved in its entirety where information between components is transferred endogenously, facilitates a more effective integrated optimization of water-energy-land nexus management solutions. Therefore, ECHO could identify a broader solution space, achieving overall efficiency of water-energy-land resources utilization and producing synergistic benefits across large spatial domains (Cai et al., 2018). In this paper, we apply ECHO to Africa as a case study in order to assess important interactions between the region's future water demand and availability under various socio-economic and climatic scenarios. However, ECHO is currently designed to operate at different spatial scales and in different regions or continents, given the data availability, and its application to Africa aims only to highlight the benefits of ECHO model development, rather than to recommend definitive policy actions.

This paper is organized as follows. Section 2 presents the modeling framework, including an overview of the model structure and mathematical formulation. Section 3 introduces the scenario analysis implemented to demonstrate the benefits of the approach, including an overview of the assumptions used in the African case study. Section 4 describes results of the case study scenario analysis and Section 5 discusses the main findings and possible future developments. Finally, Section 6 summarizes the main conclusions.

2. Modeling framework

2.1 Model structure

Figure 1 depicts the main features of the ECHO model including input data and outputs. ECHO is a bottom-up linear optimization model, which includes an economic objective function and a representation of the most relevant biophysical and technological constraints. The objective function of ECHO minimizes the total investment and operating costs of a wide variety of water management options over a long-term planning horizon (e.g., a decade or more), to satisfy sectoral water demands across sub-basins within river basins at a continental scale. ECHO optimization approach can be classified as a normative optimization because it goes beyond improvements in the management of existing facilities, towards projections of the capacity and activity levels of various water management options, based on the assumption that water users seek to minimize the cost of water supply and demand management subject to constraints. The optimization procedure in ECHO uses a perfect foresight formulation, which provides the most optimal transition for the water system across the studied spatial and temporal ranges under anticipated future climate, socio-economic and policy changes. Most sectoral planning models in the literature assume perfect foresight, although limited foresight in different forms has been applied to some of these models (Keppo & Strubegger, 2010).

The sub-basin units are created by intersecting river basin and country administrative boundaries (hereafter *Basin-Country Units* or BCUs), and are linked within a reduced-form transboundary river network. This spatial delineation seeks to cover both the political boundaries of management policies and hydrological domains. Figure 2 shows the spatial delineation used in ECHO for the African case study, which covers 150 BCUs across Africa. However, ECHO is designed to operate at different spatial scales and in different regions or continents, given the data availability. Each BCU is treated as a single unit, meaning that water flows between spatial locations within a BCU are not considered (i.e., water availability is aggregated over a BCU). However, water can be transferred between BCUs pertaining to the same river basin, and each BCU can have inflow from upstream BCUs as well as discharge into downstream BCUs and/or a natural sink.

ECHO also includes reasonable representations of essential biophysical and technological features at the BCU level. These include representations of various water supply sources (surface water, groundwater, and non-conventional water such as desalinated water), sectoral demands (irrigation, domestic, manufacturing, and electricity), and infrastructure (surface water reservoirs, desalination plants, wastewater treatment plants, irrigation systems, and hydropower plants). Moreover, ECHO incorporates a continental-scale electricity market for electricity trade between BCUs, which enables the explicit representation of feedbacks between local water constraints and regional electricity development. The GAMS optimization software is used for ECHO development and scenario simulations (Brooke et al., 1988). The optimal solution generated by ECHO provides spatially explicit information on a least-cost combination of water management options that can satisfy sectoral water demands looking at water, energy, and land sectors.

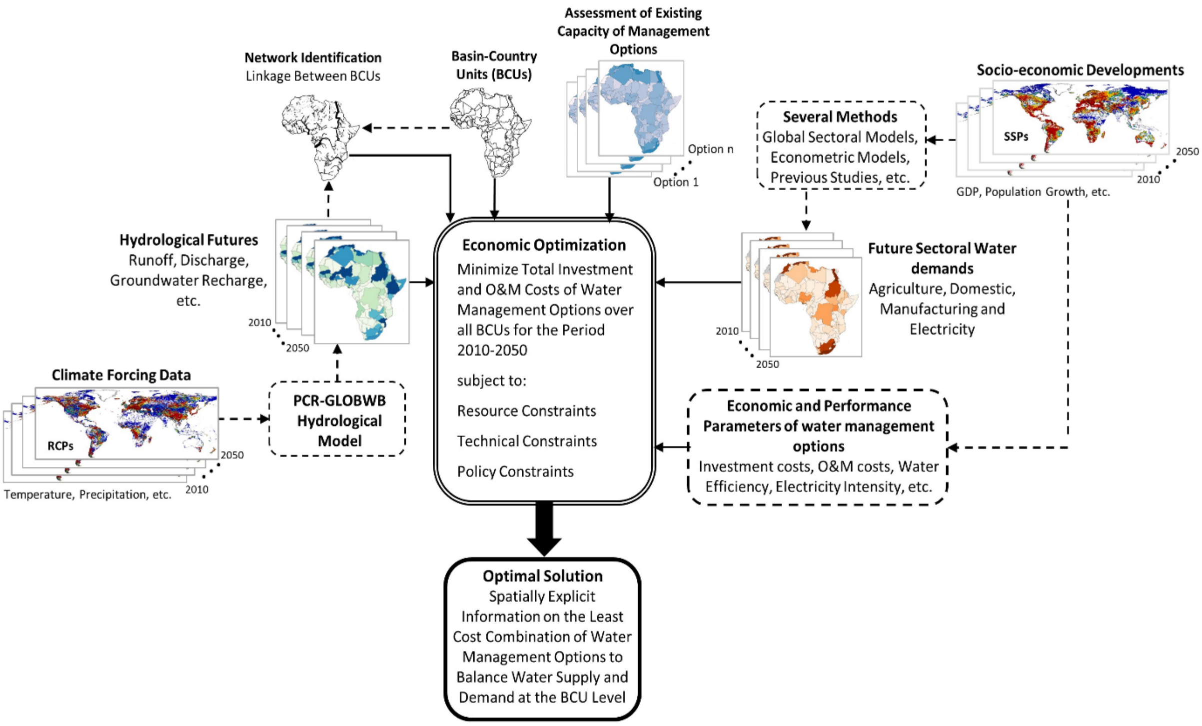

Figure 1. Schematic overview of ECHO modeling framework. Dashed-lined boxes denote intermediate models or processes used to generate input data, double-lined box represents the optimization module, and the solid box indicates the results. Dashed arrows denote intermediate input data, and solid arrows indicate main input data needed for the optimization.

2.2 Water management options

A diverse range of water management options are represented in ECHO, including supply and demand options that span over the water, energy and agricultural systems (Table 1). The supply-side management options are surface water diversion, groundwater pumping, desalination, wastewater recycling, and surface water reservoirs. Surface water diversion, groundwater pumping, and desalination all transform raw water resources (surface water, groundwater, and seawater) into freshwater suitable for consumption within the different sectors (irrigation, domestic, manufacturing, and electricity uses). Wastewater recycling enables upgrading of wastewater originating from domestic and manufacturing sources to suitable quality for different purposes. Surface water reservoirs store water across several months for later multipurpose uses. The demand-side management options include different irrigation systems (flood, sprinkler, and drip), and various options to improve crop water management in irrigation and water use efficiency in the domestic and manufacturing sectors. The electricity consumption of these water management options is accounted for, explicitly linking water and electricity systems.

Moreover, several electricity generation technologies are included in ECHO which convert different forms of primary energy resources into electricity. These technologies consist of a combination of different fuel and turbine types. Thermal power plants are distinguished in particular by types of cooling technology, to enable feedbacks to the water supply system, including once-through and closed-loop cooling systems utilizing freshwater, as well as air-cooled and seawater-cooled once-through systems. Hydropower plants are also included in ECHO and their production depend on the BCU level hydropower generation potential.

A significant amount of cost and performance data associated with the water management options considered are required to parametrize ECHO. This information is often available in the literature for only a few regions, and can be highly variable depending on factors that include water quality, technology capacity, and political and environmental conditions. Here, best estimates of these parameters have been collected by reviewing much of the available literature. These estimates have been scaled for BCUs using information on biophysical (e.g., groundwater table depth) and economic (e.g., energy and labor costs) conditions. The cost and performance parameters of the water management options are provided in Table 1. The full list of the electricity supply technologies implemented in ECHO is provided in Table S1 in the Supporting Information (SI). ECHO also has the capacity for additional water management options, which can be added when the corresponding cost and performance parameters become available.

Table 1. Cost and performance of water management options.

Options	Electricity intensity (KWh/m^3)	Water efficiency (%)[*]	Investment cost[**]		O&M cost[***]		Lifetime (Years)	References
			Unit	Value[†]	Unit	Value[†]		
Supply-side options								
Surface water diversion[††]	0.03	90	\$/m^3-day	57 (34-135)	\$/m^3	0.01 (0-0.05)	10	Albiac et al. (2003); Plappally and Lienhard (2012); Stillwell et al. (2010)
Groundwater pumping[††]	0.1	80	\$/m^3-day	8.5 (7-15)	\$/m^3	0.01 (0-0.05)	10	Fan et al. (2013); Fischer et al. (2007); Kirshen et al. (2005)
Desalination	3.5	50	\$/m^3-day	1700 (900-2500)	\$/m^3	0.25 (0.15-0.35)	30	Ghaffour et al. (2013)
Recycling	1	70	\$/m^3-day	1300 (600-1700)	\$/m^3	0.15 (0.05-0.25)	30	Iglesias et al. (2010); Rodriguez-Garcia et al. (2011)
Surface water reservoirs	0		1000\$/Mm^3	450 (150-2500)	\$/m^3	0.05 (0.01-0.3)	60	Keller et al. (2000); Wiberg and Strzepek (2005)
Demand-side options								
Flood irrigation[ǂ]	0	60	\$/ha	460 (80-1200)	\$/ha	23 (4-60)	30	Ignaciuk and Mason-D'Croz (2014); Kahil et al. (2015b); Phocaides (2000); Sauer et al. (2010)
Sprinkler irrigation[ǂ]	0.24	75	\$/ha	650 (200-2800)	\$/ha	33 (10-140)	20	
Drip irrigation[ǂ]	0.18	90	\$/ha	1400 (700-4000)	\$/ha	70 (35-200)	20	
Improved irrigation management[ǂǂ]	0	+10% relative to regular management	\$/ha	0	\$/ha	200 (-600-1400)	0	Evans and Sadler (2008); Fischer et al. (2007); Sanchez et al. (2016); Wada et al. (2014b)
Improved domestic and manufacturing management	0	+10% relative to regular management	\$/m^3	0.4 (0.05-1.5)	\$/m^3	0.1 (0.01-0.4)	10	Escriva-Bou et al. (2015); Rosenberg et al. (2008)

Note:

[*] Water efficiency measures the relationship between input water (raw water such as seawater or wastewater) and output water (feed water such desalinated water or treated wastewater) for each technology. Estimates of water efficiency by option are taken from Dubreuil et al. (2012).

[**] The investment cost for the supply-side options is expressed in terms of the supply capacity of each option (not in terms of the activity). The investment cost of surface water diversion is estimated based on the cost of different inter-basin water transfer projects.

[***] O&M cost does not include the energy cost.

[†] The values of both the investment and O&M costs shown are the best estimates with the possible ranges shown in parentheses.

[††] The O&M cost (not including the energy cost) is assumed to be the same for both surface water diversion and groundwater pumping.

[ǂ] For all irrigation systems, the O&M cost is assumed to be equivalent to 5% of the investment cost.

[ǂǂ] A negative O&M cost indicates that some irrigation management options might be able to concurrently save water and generate additional economic benefits to farmers (i.e. win-win options).

2.3 Mathematical formulation

An overview of the main equations in ECHO is presented in this sub-section. In all equations, parameters are represented by lower case letters and variables are represented by capital letters. A reduced-form water mass-balance equation is used in ECHO to ensure water conservation in each BCU $i \in I$ and time-step $t \in T$. This equation enables the hydrological connectivity between BCUs in the transboundary river network and can be represented as follows:

$$S_{i,t} - S_{i,t-1} = R_{i,t} + I_{i,t} - Q_{i,t} + RF_{i,t} - D_{i,t} - L_{i,t} \quad (1)$$

where $R_{i,t}$ is the local runoff and $I_{i,t}$ is the inflow from upstream BCUs in each BCU i during time period t. $Q_{i,t}$ is the water release to demand sectors, $RF_{i,t}$ is the return flow to the river system, $D_{i,t}$ is the discharge to downstream BCUs and sinks, and $L_{i,t}$ are the evaporation and seepage losses, in each BCU during the same time period. $S_{i,t}$ and $S_{i,t-1}$ represent the storage level of surface water reservoirs at the end of period t and $t-1$, respectively, in each BCU.

The total inflow from upstream BCUs, $I_{i,t}$, in each BCU and time-step is calculated as follows:

$$I_{i,t} = \sum_j b_{j,i} \cdot D_{j,t} \quad (2)$$

where $D_{j,t}$ is the discharge from each upstream BCU $j \in J$ (with J as a subset of I), and $b_{j,i}$ is a vector of coefficients that links each BCU i to all upstream BCUs j. The coefficients that comprise this vector take on values of +1 if a BCU is linked to an upstream BCU, and 0 otherwise. This linkage between BCUs is defined based on historical discharge data.

The downstream discharge, $D_{i,t}$, in each BCU and time-step must be greater than or equal to the minimum environmental flow requirements needed for healthy aquatic ecosystems, $e_{i,t}$, as follows:

$$D_{i,t} \geq e_{i,t} \quad (3)$$

For each BCU, ECHO incorporates a supply-demand balance equation, which is tracked for each demand sector $d \in D$ in each time step, so that water withdrawal of each sector must be less than or equal to the total sum of water originating from suitable supply options $s \in S$ (i.e., surface water, groundwater, desalination, and recycling):

$$W_{i,t}^{d} \leq \sum_{s} \gamma_{s,d} \cdot Q_{i,t}^{s} \tag{4}$$

where $W_{i,t}^{d}$ is the water withdrawal of each sector, and $Q_{i,t}^{s}$ is the outflow from each supply option. $\gamma_{s,d}$ is a vector that links supply options to demand sectors. The coefficients that comprise this vector take on values of +1 if a demand sector is using a certain supply option, and 0 otherwise. Here, we assume that irrigation, domestic and manufacturing sectors can use all available water supply options, while the electricity sector can only use diverted surface water.

The amount of water withdrawn by each sector is calculated based on the exogenous consumptive water demand of that sector combined with the efficiency of its corresponding demand-side management options (irrigation systems, irrigation management practices, domestic and manufacturing management practices, and cooling technologies) (Hanasaki et al., 2018) as follows:

$$c_{i,t}^{d} = E_{i,t}^{d} \cdot W_{i,t}^{d} \tag{5}$$

where the parameter $c_{i,t}^{d}$ is the exogenous consumptive water demand of each sector, and the variable $E_{i,t}^{d}$ describes the efficiency of the demand-side management options suitable for each sector. For example, the agricultural sector can invest in flood, sprinkler or drip irrigation systems or different irrigation management practices (as shown in Table 1) with varying levels of efficiency, which affect the quantity of water withdrawn for irrigation and return flows. The volume of return flows from each demand sector, $RF_{i,t}^{d}$, is computed as follows:

$$RF_{i,t}^{d} = \left(1 - E_{i,t}^{d}\right) \cdot W_{i,t}^{d} \tag{6}$$

The total amount of return flows to the river system, $RF_{i,t}$, which can be reused by downstream BCUs, is assumed to equal the sum of the return flows from all sectors, excluding domestic and manufacturing return flows that can be recycled and reused within the BCU where they are produced.

A capacity constraint is used to limit the activity of both the supply and demand side management option $o \in O$ according to the available physical capacity of the options:

$$Q_{i,t}^{o} \leq Z_{i,t}^{o} \tag{7}$$

where $Q_{i,t}^{o}$ is the activity level of each management option in each time step, which represents the volume of water supplied by that option. $Z_{i,t}^{o}$ is the installed capacity of each option in the same time step. The capacity constraint therefore works, for instance, to ensure the volume of desalinated water produced does not exceed the installed desalination capacity or so that the volume of irrigation water supplied via an irrigation system does not exceed the installed capacity of that system.

Moreover, ECHO incorporates capacity expansion decisions $Z_{i,t}^{o,new}$ that alleviate capacity constraints for the different management options. Capacity retirements $Z_{i,t}^{o,ret}$ are further decision variables that allow options to have finite lifecycles. The installed capacity of a particular option is thus given by:

$$Z_{i,t+1}^{o} = Z_{i,t}^{o} + Z_{i,t}^{o,new} - Z_{i,t}^{o,ret} \tag{8}$$

ECHO calculates the total annual cost of supplying water $C_{i,t}^{o,tot}$ by each water management option o. This is equal to the sum of the annual cost of investment in new capacity, the activity operating cost, and the maintenance cost associated with the installed capacity, for each option in each BCU and time-step:

$$C_{i,t}^{o,tot} = \sum_{o} c_{i,t}^{o,inv} \cdot Z_{i,t}^{o,new} + \sum_{o} c_{i,t}^{o,Op} \cdot Q_{i,t}^{o} + \sum_{o} c_{i,t}^{o,Mc} \cdot Z_{i,t}^{o} \tag{9}$$

where parameters $c_{i,t}^{o,inv}$, $c_{i,t}^{o,Op}$, and $c_{i,t}^{o,Mc}$ are, per unit, investment cost, activity operating costs, and installed capacity maintenance costs, for each option, respectively.

To determine the optimal solution and the associated decision variables, ECHO minimizes the net present value of the total cost of supplying water in all BCUs at a continental scale over the planning horizon subject to the constraints (1) to (9). Other additional constraints are used, and these are outlined in the following sections describing ECHO's application to Africa. The length of the planning horizon depends upon both the specific problem under consideration and the target objective. The objective function of ECHO takes the following form:

$$Min\ C^{npv} = \sum_{o,i,t} \frac{C_{i,t}^{o,tot}}{(1+\delta)^{t}} \tag{10}$$

where C^{npv} is the net present value of total cost, and δ is the discount rate.

3. ECHO model application to Africa

The description of ECHO has focused so far on the core modeling framework applicable to different regions or continents. Since we apply ECHO over Africa as a case study, this version of ECHO is hereafter referred to as ECHO–Africa. Africa is a challenging but important region because of its rapidly growing demands and lack of water infrastructure (Cervigni et al., 2015). To highlight the capacity of ECHO model, we examine different scenarios representing alternative socio-economic and climate futures for Africa towards the year 2050. ECHO-Africa has been solved monthly over the 2010–2050 period in ten-year increments (i.e. five time steps: 2010, 2020, 2030, 2040 and 2050). In this section, we provide an overview of the input data and assumptions used in ECHO–Africa, and we introduce the scenario analysis.

3.1 Spatial delineation and river network

Balancing spatial details with computational requirements is critical in ECHO because the size of the optimization problem, as described in the previous section, can increase exponentially with the number of spatial units. Thus, to minimize the computational burden, ECHO–Africa uses the hierarchical spatial delineation depicted in Figure 2. ECHO–Africa runs at the level of BCUs representing the intersection between river basin and country administrative boundaries (Figure 2d). The HydroBASINS dataset is used to define the river basin delineation in ECHO–Africa (Figure 2a) (Lehner & Grill, 2013). HydroBASINS incorporates sub-basins of higher order (Figure 2b), which have a single outlet, but as opposed to river basins, can have inflow from upstream sub-basins. ECHO–Africa taps into this feature to track hydrological connectivity between BCUs. Sub-basins corresponding to each river basin are initially intersected with national boundary polygons from the Global Administrative Areas Database (GADM, 2012) (Figure 2c) to generate 1622 *sub-basin country units* (sub-BCUs) (Figure 2e). These sub-BCUs are then dissolved in a subsequent step according to their corresponding basin classification obtaining a consistent set of BCUs (150 BCUs) (Figure 2d). Table S2 in the SI provides the list of river basins and countries included in ECHO-Africa.

In the next step, each sub-BCU is overlaid with the gridded flow accumulation data from HydroBASINS at 15 arc-seconds to identify the main outlet, which is the grid-cell within the sub-BCU with the maximum flow accumulation (Figure 2g). Neighboring grid-cells located in other sub-BCUs are then checked to see if there exists greater flow accumulation, as this may indicate an overland flow of runoff downstream to that neighboring sub-BCU. Where this is possible, the connection and direction are noted so that the outflow from the upstream sub-BCU can be tracked and accounted for in the analysis of water availability in the downstream sub-BCU. If no downstream grid-cell can be identified, the sub-BCU is treated as a sink, where outflow goes to the sea or other inland sink. This process is repeated for all sub-BCUs, resulting in a reduced-form transboundary river network that distinguishes sub-basins by country. An example of the network generated for the Nile River Basin is depicted in Figure 2g. For the spatial delineation of Africa, the continental network has 1622 nodes and 1031 links (Figure 2f).

The total average monthly runoff in each sub-BCU is estimated using the rainfall-runoff component from the global hydrological model PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2014a). These monthly runoff estimates act as nodal inputs to the network. The sub-BCU network database is linked with a network analysis tool to enable efficient identification of upstream nodes from any point in the network (Csardi & Nepusz, 2011). This facilitates tracking of natural flows in the network, where any unmanaged nodal inputs are assumed to accumulate in downstream nodes. The network between sub-BCUs is further simplified for the optimization procedure in ECHO to represent a network between BCUs. In order to account for environmental flow requirements in the model simulations (as shown in equation 3), we assume a minimum outflow of 30% of monthly runoff in each BCU, following the study by Cai & Rosegrant (2002).

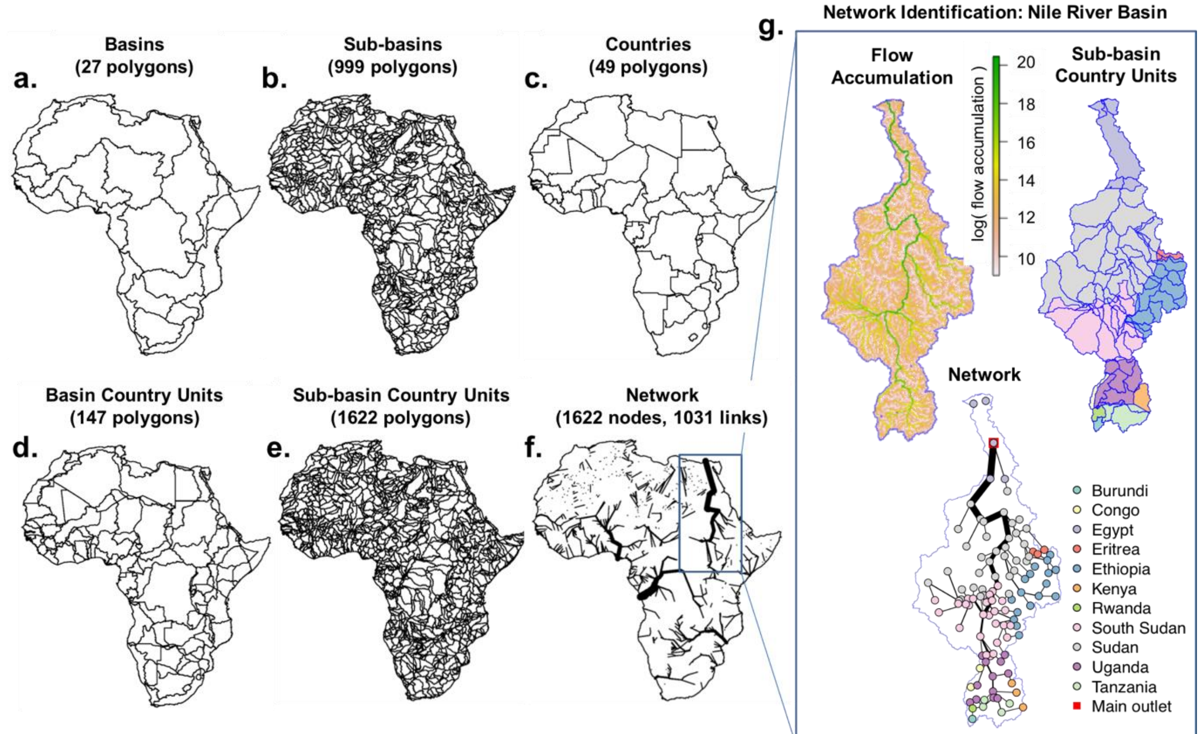

Figure 2. Delineation of Africa into spatial units and networks in ECHO: a. Basins; b. Sub-basins; c. Countries; d. Basin-Country Units (BCUs); e. Sub-Basin-Country Units (sub-BCUs); and f. Sub-BCU network. g. Example identification of the sub-BCU network for the Nile River Basin: the flow accumulation and sub-BCUs are combined to generate a network between sub-BCUs. Network line widths are plotted proportionally to the identified flow accumulation at the outlet and for the example shown connect centroids of the sub-BCUs as opposed to the outlets. Madagascar, Comoros, and Sao Tome and Principe are also included in the analysis but are not depicted here.

3.2 Existing capacity of water management options

In order to estimate future investment needs, first the existing capacity of the different water management options implemented in ECHO is assessed at the BCU level. Here, we gather information on existing capacities from various databases. The capacities of existing surface water reservoirs are estimated by aggregating facility-level data from the GRanD database (Lehner et al., 2011). Evaporative losses due to increased surface area during reservoir storage are incorporated into the water mass-balance equation defined in section 2.3 using a linearized area-volume relationship (Lele, 1987). New future investments in surface water reservoir capacity are constrained within each BCU where reservoir exclusion zones were distinguished (Liu et al., 2018). The existing capacities of surface water diversion and groundwater pumping infrastructure are identified using historical gridded water withdrawals and groundwater extraction rates from Wada et al. (2010, 2011). These withdrawals are aggregated to the level of the BCUs, and the maximum monthly withdrawal in the historical time-series plus a 10% reserve margin is used to define the capacity in each BCU. Moreover, the global hydrological model PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2014a) includes groundwater recharge as well as baseflow component in the groundwater balance and connects baseflow discharge from groundwater to the river systems. In this paper, estimates of monthly groundwater recharge at grid scale are used to compute the availability of renewable groundwater resources in each BCU. Therefore, ECHO calculates a groundwater budget in each time step and BCU, and provides the level of depletion of groundwater resources, as the difference between pumping and renewable groundwater resources.

Existing desalination capacities are identified using a refined version of the global desalination database (DESALDATA) (GWI, 2017). Wastewater treatment capacities are defined using estimates of return flows from the domestic and manufacturing sectors and national data on water treatment access rates from Baum et al. (2013). For countries without historical data, the water treatment access rate is estimated by matching each country to another with similar GDP per capita. The existing water treatment capacity is estimated in each BCU by multiplying the estimated water treatment access rate for 2010 by the maximum volume of domestic and manufacturing return flows. Figure S2 in the SI depicts the estimated capacities of selected water management options in 2010.

3.3 Sectoral water demands

Monthly sectoral water demands for the period 2010-2050 at BCU level are estimated to be included as inputs into ECHO-Africa. This section provides an overview of the estimation procedures and data sources. Monthly domestic water demands are estimated following the approach used in several previous studies (Hanasaki et al., 2013b; Hejazi et al., 2014; Wada et al., 2016), which use harmonized projections of population, GDP, and technological change from the Shared Socio-economic Pathways (SSPs) database (O'Neill et al., 2014). Manufacturing water demands are estimated following an approach similar to one reported in Hejazi et al. (2014). To estimate the historical water demand of the manufacturing sector at the country-level, data on the historical water demands of the industrial sector (manufacturing plus electricity) are taken from AQUASTAT database (FAO, 2016), and reduced by the 2010 water demand of the electricity sector, as calculated in ECHO-Africa (following the approach described in section 3.4). Future changes in manufacturing demands are then projected using a statistical log-linear model fit to the historical GDP and manufacturing data (Parkinson et al., 2016b). National manufacturing water demand projections are then downscaled to BCU level using the gridded urban population projections aligned with the SSPs from Jones and O'Neill (2016). The volume of return flows from both the domestic and manufacturing sectors is determined by recycling ratios developed per country taken from Wada et al. (2011; 2014a).

Monthly irrigation water demands for the period 2010-2050 are estimated at BCU level using irrigated crop area and monthly gross water requirements per unit area. In order to estimate irrigated crop area in each BCU for the period 2010-2050, data on historical (year 2000) cropping patterns for major irrigated crops at the global scale with a spatial resolution of 5 min are obtained from the MIRCA2000 data set (Portmann et al., 2010). This gridded crop area is aggregated across each BCU, and crop distributions (i.e., the fraction of each crop area relative to total irrigated area) are calculated. These historical crop distributions are combined with country-specific projections of future change in irrigated area from 2000 to 2050 according to SSP scenarios originating from the GAEZ model (Fischer et al., 2012). This provides a first-order estimate of future irrigated area at BCU level. This method is unable to reproduce changes in crop distribution within BCUs, but adequately reflects the large-scale dynamics of the expanding irrigated areas over the coming decades (Wisser et al., 2010).

Net water requirements for irrigation per unit crop area (i.e., consumptive demands) are estimated using the crop coefficient method (Allen et al., 1998). Monthly crop evapotranspiration is calculated by combining a crop coefficient per crop development stage with a monthly reference (potential) evapotranspiration for the period 2010-2050. Net monthly irrigation requirements are calculated at BCU level, so as to ensure the optimum growth of each crop. These net requirements are the difference between crop evapotranspiration and actual evapotranspiration. Crop-specific calendars and growing season lengths are obtained from the MIRCA2000 dataset, while crop coefficients and potential and actual evapotranspiration are taken from the PCR-GLOBWB model (van Beek et al., 2011; Wada et al., 2014a). Lastly, irrigation gross water requirements are calculated per unit crop area and at BCU level as the ratio between net irrigation requirements and irrigation efficiency. This efficiency factor measures the overall effectiveness of irrigation, which takes into account losses during water conveyance as well as application efficiency of irrigation systems (flood, sprinkler, and drip) at plot level, and management practices (regular or improved).

3.4 Agriculture and energy system linkages

To integrate the agricultural and water systems, ECHO includes investments in irrigation systems and management practices as decision variables. These investment decisions have impacts on the volume of irrigation water withdrawn from the water system and the cost of water supply to the agricultural system. The current irrigation efficiency level and irrigation system distribution in each BCU for the model base year (2010) are assumed to be similar to the corresponding country-level data as reported by the AQUASTAT database (FAO, 2016). The maximum theoretical efficiency of irrigation systems at plot level are taken from Phocaides (2000), and further adjusted in order to match with the current overall irrigation efficiency in each BCU. Because not all crop types can be irrigated using all irrigation systems (for instance, paddy rice needs flood irrigation and some crops cannot use sprinklers), ECHO-Africa includes a constraint that defines the suitability between irrigation systems and crop types following Sauer et al. (2010). Moreover, the inclusion of irrigated crop area for each BCU enables additional water management options and interactions between the agricultural and water systems to be integrated into ECHO-Africa in future model developments. These might include the possibility of virtual water trade.

To account for feedbacks between local water constraints and regional electricity development, ECHO-Africa includes a reduced-form electricity sector planning module following an approach similar to one reported in Loulou and Labriet (2008) and Loulou (2008). The objective of the module is to satisfy the monthly electricity demand (including non-water and water-related demands) in each BCU during the model's planning horizon at a minimum supply cost (including investment and operating costs) subject to various technical and resource constraints, by simultaneously making decisions on investment and operation of various electricity supply technologies (as shown in Table S1 in the SI). The main constraints included in the electricity module are the availability of primary energy resources, the availability of physical capacity of technologies (which accounts for existing, new, and retired capacities in a similar way as equation (8) in section 2.3), supply-demand balance, and peak load constraint (which is used to insure against unexpected events such as unplanned technology down time or random peak demand that exceeds the average demand).

BCUs that pertain to the same power pools can trade electricity, as delineated and parameterized in Taliotis et al. (2016). This links electricity generation in the BCUs at the continental-scale. Electricity transmission is modeled using a simple transport representation between power pools and does not address voltage and power flow constraints. Table S3 in the SI depicts the list of countries for each of the five major African power pools. The electricity demand of non-water activities are taken from the study by Bauer et al. (2017), which projects the future of the energy sector using an ensemble of integrated assessment models and harmonized projections of population, GDP, and technological change from the SSPs database. The electricity demand of water-related activities is calculated endogenously in ECHO-Africa using the electricity intensity of each water management option and its optimized activity level, which links water and electricity systems. The electricity module is calibrated using data on electricity production and technology mix at country level from UN (2017).

Moreover, ECHO-Africa includes additional relevant connections between water and electricity systems. Hydropower is one such connection, and is assessed in each BCU following the approach described by Cuya et al. (2013). The approach tracks water inflows in conjunction with elevation changes between the inlets and outlets at the BCU level to estimate total hydropower potential. Hydropower generation is then calculated using a linear model that is fitted between historical total inflow and hydropower production in each BCU, and constrained by estimated hydropower potential following the approach described by Khan et al. (2017). Thermal power plant cooling technologies also represent an important electricity-water linkage, and are modeled explicitly in ECHO-Africa. Each thermal power plant type is defined in terms of its cooling technology type (once through and closed-loop cooling systems utilizing freshwater, air-cooled system, and seawater-cooled once-through systems). Existing cooling technology capacities for 2010 are estimated using cooling technology shares compiled for each BCU from a facility-level dataset described by Raptis and Pfister (2016). The water demand of the electricity sector is thus calculated endogenously in ECHO-Africa using the volume of water withdrawn by each cooling technology and its optimized activity level following the approach described by Fricko et al. (2016).

3.5 Socio-economic and climatic scenarios

A set of global water scenarios based on combinations of the Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) have been developed by Wada et al. (2016), in order to represent the full range of plausible and anticipated future climatic and socio-economic changes. These scenarios have been used to assess future water scarcity conditions using hydrological models at both the global (Wada et al., 2016) and the regional (Satoh et al., 2017) scales. In this paper, we use these scenarios in order to explore strategies aimed at balancing future water demand and availability in Africa using ECHO-Africa for the period 2010-2050. Three alternative scenarios are used here, which encompass a higher, middle, and lower range of plausible future changes in climate and society towards 2050 (Table 2). Our objective is thus to demonstrate ECHO's potential across contrasting scenarios, rather than to recommend definitive policy actions (i.e., a sensitivity analysis).

The middle range scenario (hereafter referred to as *Middle of the Road* (*MoR*)) represents a combination of SSP2 and RCP6.0, assuming relatively moderate changes in socio-economic and climatic drivers. All assumptions (e.g., GDP and population growth rates, technological changes) used in this scenario vary among BCUs. For the other two scenarios, the assumptions concerning relative changes to water demand and availability compared to *MoR* scenario are applied uniformly for all BCUs, but they are still consistent with possible overall changes in Africa. The higher range scenario (hereafter referred to as *Regional Rivalry* (*RR*)) represents a scenario with slow economic growth, large population growth, and negative climate change impacts on water availability (corresponding to SSP3). The lower range scenario (hereafter referred to as *Sustainability (Sust)*) represents a scenario with medium-high economic growth, low population growth, and positive climate change impacts on water availability (corresponding to SSP1).

To assure that ECHO-Africa is producing robust future projections, estimated water withdrawals of all sectors at country level for the base year 2010 have been validated against the data available in AQUASTAT and calibrated, if needed, to correct data imperfections and get the baseline solution close to the observed values. The calibration procedure involved adjustments in some model parameters such as gross crop water requirements or irrigation efficiency. Per capita water use for drinking water has been already taken from the reported country statistics from AQUASTAT. Moreover, some variables in ECHO including the installed capacity of all water management options and the share of the different supply sources (surface water, groundwater, desalination, recycling) relative to total withdrawals are all fixed at observed levels for the base year 2010. For the rest of the planning horizon (from 2020 to 2050), a constraint that assures a minimum use of existing capacity of the water management options is implemented in order to force the optimal solution to be within the physical and logical system boundaries. Additional constraints are also used such as prioritizing the use of desalinated water over recycled wastewater or groundwater for the domestic and manufacturing sectors in coastal BCUs, and the definition of the share of hydropower in the electricity technology mix in each BCU. This approach is widely used in large-scale modeling, given the lack of detailed local level information for calibration (Hanasaki et al., 2018). The results of the validation procedure are provided in Table S4 in the SI.

Table 2. Summary of the socio-economic and climatic scenarios.

<table>
<tr><th rowspan="2">Scenario</th><th rowspan="2">Water availability</th><th colspan="3">Water Demand</th><th rowspan="2">Constraints</th><th rowspan="2">References</th></tr>
<tr><th>Domestic</th><th>Industrial</th><th>Irrigation</th></tr>
<tr><td>MoR</td><td>Runoff for the period 2010-2050 is projected using the global hydrological model PCR-GLOBWB, with the climate forcing data based on RCP 6.0 scenario.</td><td colspan="3">Water demand of the different sectors are projected for the period 2010-2050 based on assumptions about GDP growth, population growth and technological development, for the SSP2 scenario.</td><td rowspan="3">Groundwater pumping can increase by up to 50% compared to historical maximum pumping in all BCUs for the period 2020-2050.

A minimum outflow constraint of 30% of runoff in each BCU for the period 2010-2050 is implemented.

A minimum use constraint for existing expensive water options such as desalination, recycling or efficient irrigation system is implemented.

A constraint prioritizing the use of desalinated water over other sources (that are less expensive) for the domestic and manufacturing sectors in coastal basins is implemented.

A constraint defining the share of hydropower in the electricity technology mix for the period 2010-2050 is implemented.</td><td rowspan="3">Wada et al. (2016); Nasta et al. (2016); Cai & Rosegrant (2002); Hanasaki et al. (2018); UN (2017)</td></tr>
<tr><td>RR</td><td>Runoff decreases by 10% in each decade compared to MoR for all BCUs in the period 2020-2050.</td><td>Increases by 100% in 2050, +25% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td><td>Increase by 80% in 2050, +20% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td><td>Increases by 20% in 2050, +5% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td></tr>
<tr><td>Sust</td><td>Runoff increases by 10% in each decade compared to MoR for all BCUs in the period 2020-2050.</td><td>Decreases by 50% in 2050, -12.5% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td><td>Decrease by 40% in 2050, -10% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td><td>Decrease by 20% in 2050, -5% per decade, compared to MoR, for all BCUs in the period 2020-2050.</td></tr>
</table>

4. Results

In this section, we present the results of ECHO-Africa simulations for the three alternative scenarios. To keep the scope of the result sub-sections within reasonable limits, we focus on results aggregated to the continental-scale and some relevant regional findings. We also focus on the end of the simulation period (the year 2050) and compare it to the base year (2010).

4.1 Least-cost combination of water management options

Figure 3 depicts total water demand, sectoral water withdrawals, and the sources of water, aggregated to the continental-scale for 2010 and 2050, and the ten countries and basins with the highest changes in withdrawals over the simulation period, across the three alternative scenarios. Figures 4 and 5 provide results of water withdrawals at the BCU level by sector and source, respectively. Figures S3 to S6 in the SI provide the same results aggregated to basin and country scales. Results from Figure 3 show that total water withdrawals in Africa amount to 460 km^3 yr^{-1} in 2010, and are projected to reach between 560 and 820 km^3 yr^{-1} by 2050 depending on the scenario, an increase of 20–80% compared to current withdrawals. As expected, the *RR* scenario has the largest increase in withdrawals driven by the highest population growth. This is followed by the *MoR* scenario and the *Sust* scenario, respectively. The largest increases in water withdrawals between 2010 and 2050 in all scenarios are expected to take place in areas with already large withdrawals in 2010 such as in Egypt by country, followed by Ethiopia and Nigeria, and in the Nile by basin, followed by Niger and Congo. However, some areas with marginal water withdrawals in 2010 may increase significantly their withdrawals by 2050 such as the Democratic Republic of the Congo, Tanzania and Burundi by country, and Africa West Coast, Orange, and Lake Chad by basin.

The increase in total water withdrawals is primarily driven by growing manufacturing and domestic withdrawals, which are projected to rise substantially from 38 km^3 yr^{-1} in 2010 to 90–279 km^3 yr^{-1} in 2050. Moreover, the growth in electricity generation in Africa will be considerable, with water withdrawals for cooling of thermal power plants projected to increase significantly, from 1 km^3 yr^{-1} in 2010 to 18–30 km^3 yr^{-1} in 2050. Most increases in non-irrigation withdrawals are found in the Congo, Lake Chad and Niger by basin, and in the Democratic Republic of the Congo, Tanzania and Burundi by country (Figure 4, and Figures S3 and S5 in the SI). At the same time, irrigation withdrawals are expected to continue increasing between 2010 and 2050, but at a slower pace, induced by both climate change impacts and growing food demand, from 420 km^3 yr^{-1} in 2010 to 473-576 km^3 yr^{-1} in 2050. Irrigation will remain the largest water user in Africa, but its relative share is projected to decrease by 2050. Major increases in irrigation withdrawals are mostly found in the Niger, Nile and Volta by basin, and in Uganda, Nigeria and Mozambique by country (Figure 4, and Figures S3 and S5 in the SI). It is important to note that the assumptions related to the changes in irrigated areas and cropping patterns used in ECHO may overstate the gains from improved irrigation efficiency, and therefore estimated irrigation withdrawals should be considered as part of scenario assessments, which could be further improved subject to improved spatial datasets in irrigation area and distribution.

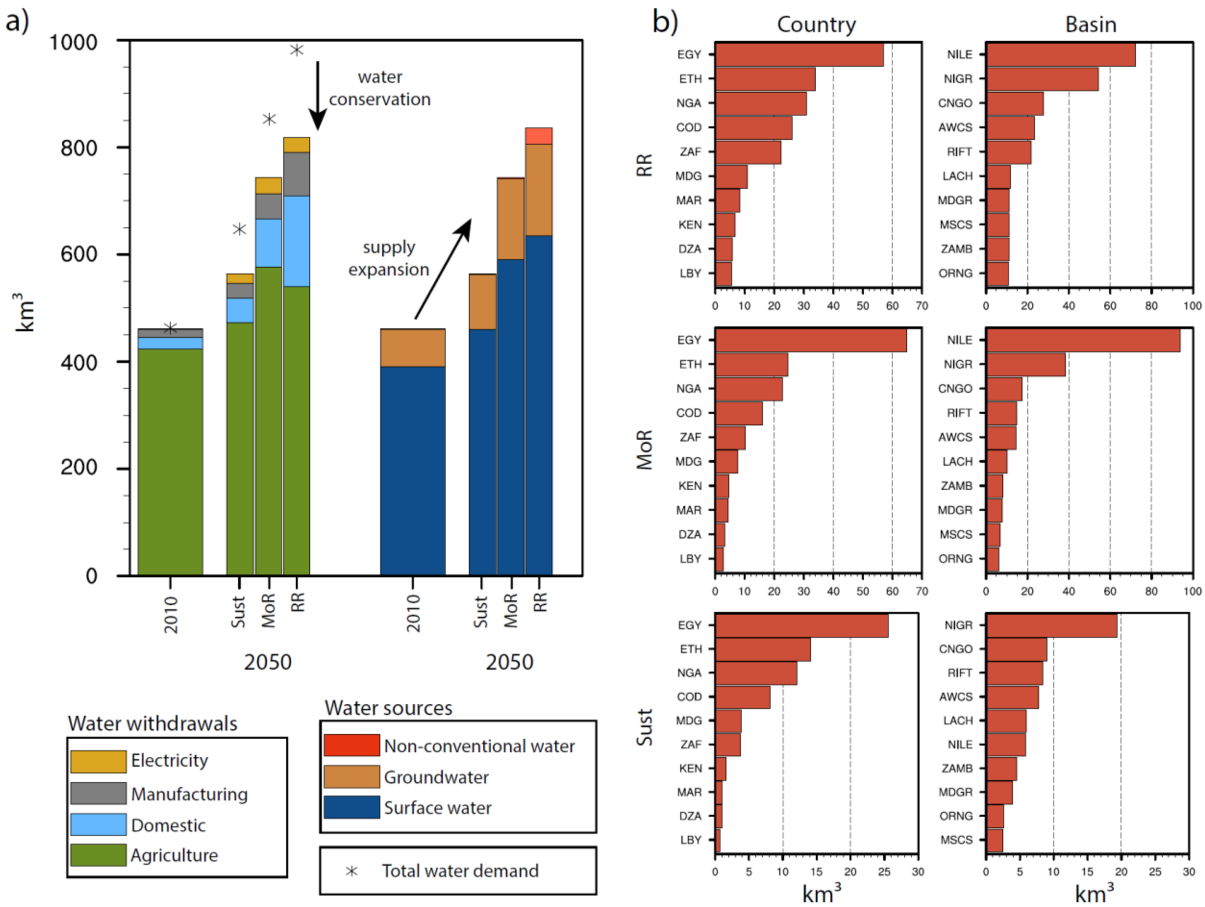

Figure 3. (a) Total water demand, actual sectoral water withdrawals, and water sources in the African continent for each scenario. (b) Ten countries (left) and basins (right) with highest change in withdrawals between 2010 and 2050 in Africa for each scenario. Total water demand is estimated for 2050 by assuming no change in baseline efficiency across all sectors. This highlights water conservation originating from the implementation of demand-side management options. Non-conventional water includes both desalinated water and recycled wastewater. Full names for countries and basins are provided in Table S2 in the SI.

Results from Figure 3 show that various water sources are used to satisfy the water withdrawals. Surface water is the major source of water in all scenarios. Surface water diversion increases from 390 km^3 yr^{-1} in 2010 to 460–590 km^3 yr^{-1} in 2050 (an increase of 18–50%), driven by an increase in surface runoff in some basins or a better allocation of water over time and space. The largest increases in surface water withdrawals across all scenarios are found in the Congo basin, followed by the Lake Chad and the upstream part of the Nile basin, and in several countries in sub-Saharan and Southern Africa (Figure 5, and Figures S4 and S6 in the SI). Groundwater pumping also increases from 70 km^3 yr^{-1} in 2010 to 100–150 km^3 yr^{-1} in 2050 (an increase of 43–114%). These increases are projected to take place in all scenarios mostly in Northern Africa including the Mediterranean South Coast, Africa North West Coast and Africa North Interior by basin and Egypt, Algeria and Tunisia by country, and in Southern Africa including the Orange, Africa South Interior and South Africa South Coast by basin and South Africa, Namibia and Botswana by country (Figure 5, and Figures S4 and S6 in the SI). The use of non-conventional water (including both desalination and recycling) in Africa stood at about 1 km^3 yr^{-1} in 2010, or less than 0.3% of the 2010 supply mix. For the *MoR* and *Sust* scenarios, the quantity and share of non-conventional water remain almost unchanged. However, the use of non-conventional water grows considerably to support accelerated demand growth in the *RR* scenario, reaching 30 km^3 yr^{-1} in 2050, or 4% of the 2050 supply mix. An expansion of desalination capacity under the *RR* scenario is projected in several coastal areas including Africa West Coast, Gulf of Guinea, Namibia Coast and Mediterranean South Coast by basin, and Egypt, Namibia and Angola by country. Similarly, an expansion of recycling capacity under the same scenario is projected in many areas such as the Congo, Mediterranean South Coast and Volta by basin, and Mali, South Africa and Sudan by country (Figure 5, and Figures S4 and S6 in the SI).

Results from Figure 3 show also the benefit of using demand-side management options, which allow for the conservation of water resources. These include improving irrigation efficiency by adopting efficient irrigation systems such as sprinkler and drip systems. Domestic and industrial water may also be better managed through the adoption of water-saving equipment in industrial plants and households, the reduction of leakage in water distribution networks, and switching to more water-efficient cooling technologies in thermal power plants. Indeed, without implementing the demand-side management options, total water demand in Africa would reach 650-980 km^3 yr^{-1} by 2050, an increase of 15-20% compared to actual withdrawals expected in 2050. The rate of adoption of the different demand-side management options varies among BCUs and scenarios, but a higher adoption rate is necessarily found in the *RR* scenario. A more detailed description of the adoption of the demand-side management options is provided in the SI.

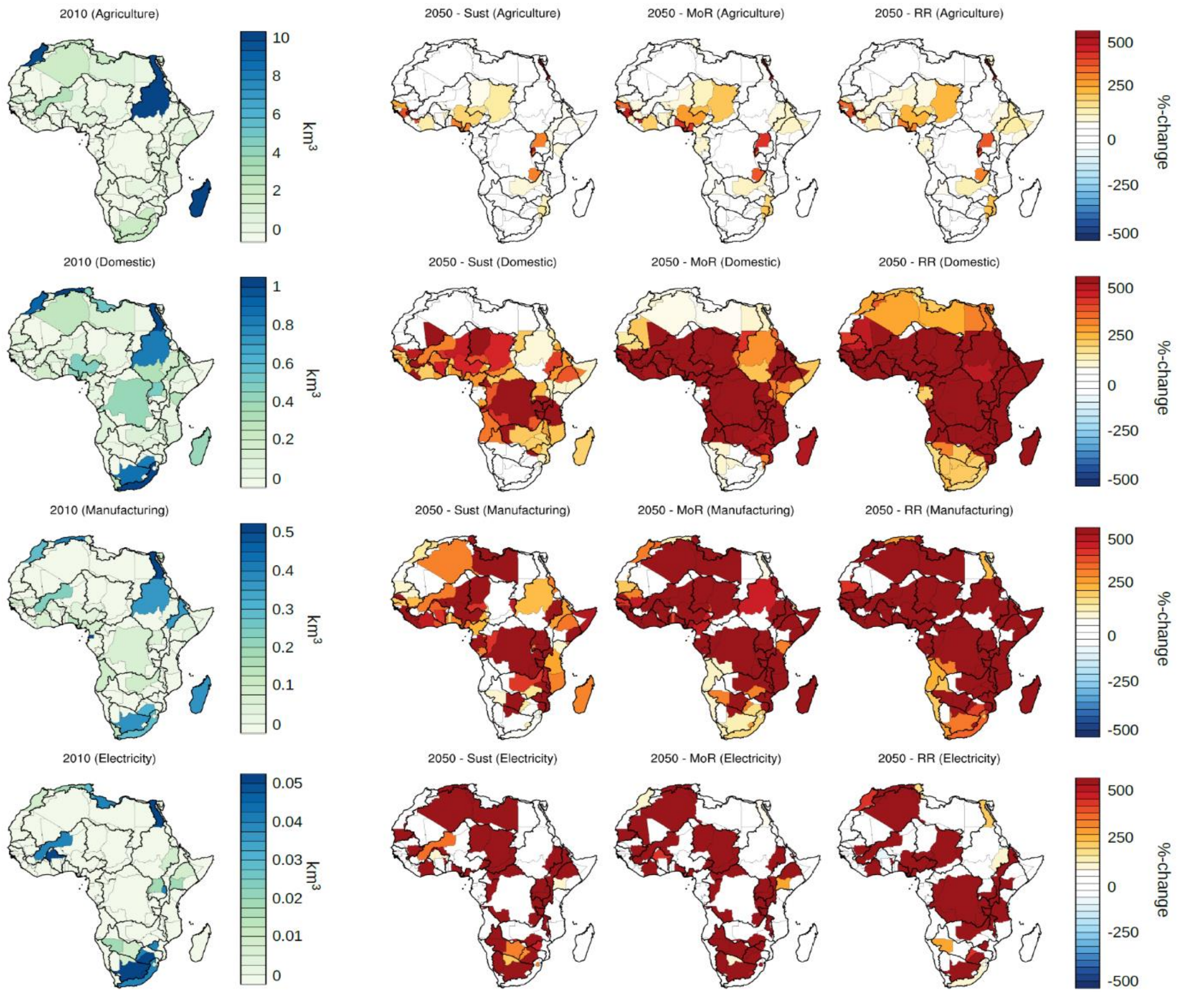

Figure 4. Sectoral water withdrawals at the BCU level in 2010 and percentage change of withdrawals in 2050 compared with 2010 for each scenario. The boundaries of the BCUs are highlighted with thin grey lines while the boundaries of the 28 major basins in Africa are highlighted with thick black lines. The list of BCUs and major basins is provided in Table S2 in the SI.

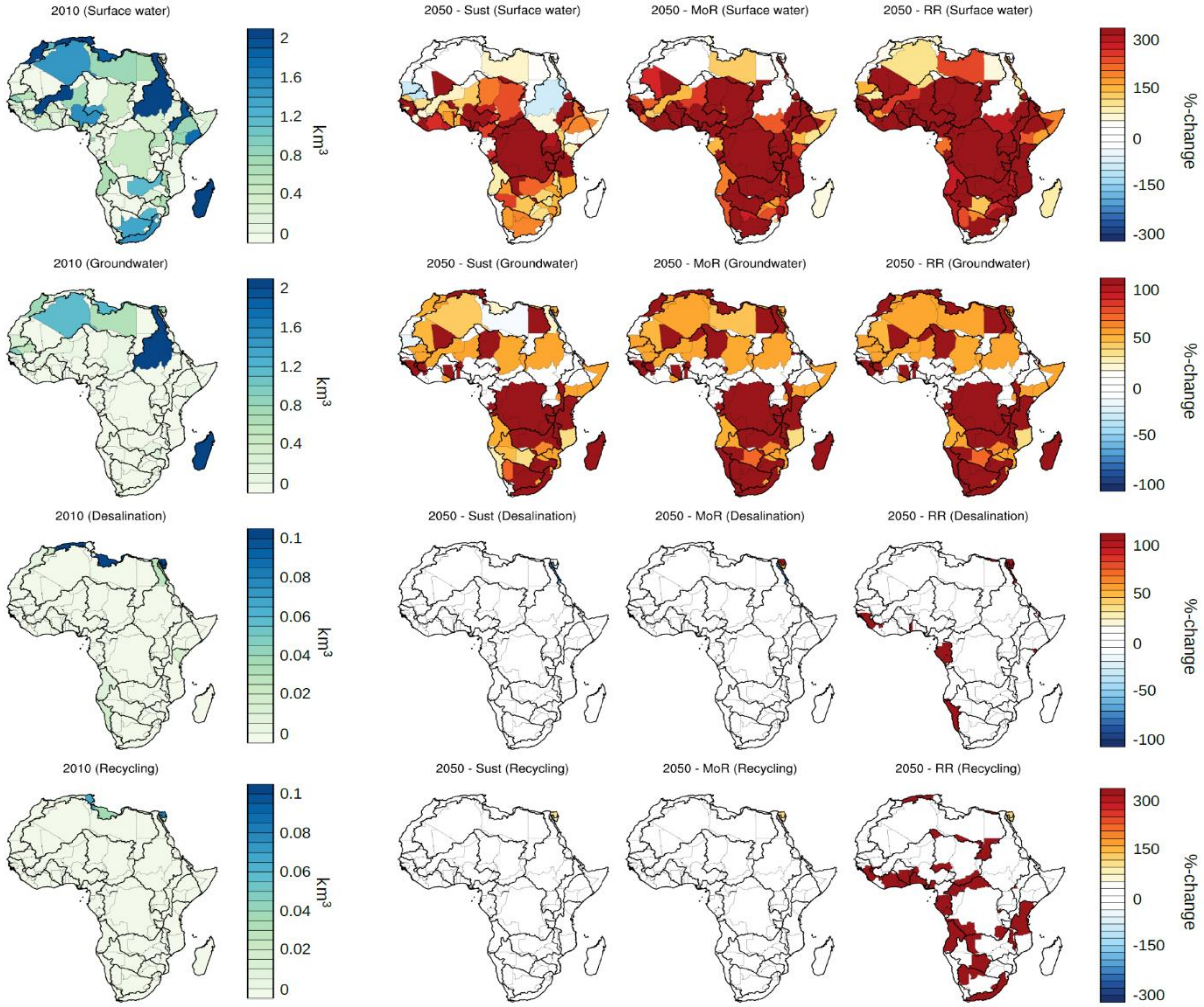

Figure 5. Water withdrawals by source of water at the BCU level in 2010 and percentage change of withdrawals in 2050 compared with 2010 for each scenario. The boundaries of the BCUs are highlighted with thin grey lines while the boundaries of the 28 major basins in Africa are highlighted with thick black lines. The list of BCUs and major basins is provided in Table S2 in the SI.

4.2 The cost of water management options

Figure 6 depicts the annual discounted total cost (including both investment and operating costs) of water supply aggregated to the continental-scale (hereafter referred to as the water supply cost) from 2010 to 2050, and the ten countries and basins with the highest changes in the water supply cost over the simulation period, for the three alternative scenarios. This water supply cost comprises the costs of supplying water from different water sources (including surface water diversion, groundwater pumping, non-conventional water production, and reservoirs), the cost of demand-side management options in irrigation, domestic and manufacturing sectors, and the cost of cooling in thermal power plants.

Nevertheless, it is important to note that our cost assessment does not account for all the potential costs associated with the water management options implemented in ECHO (e.g. transaction and environmental costs).

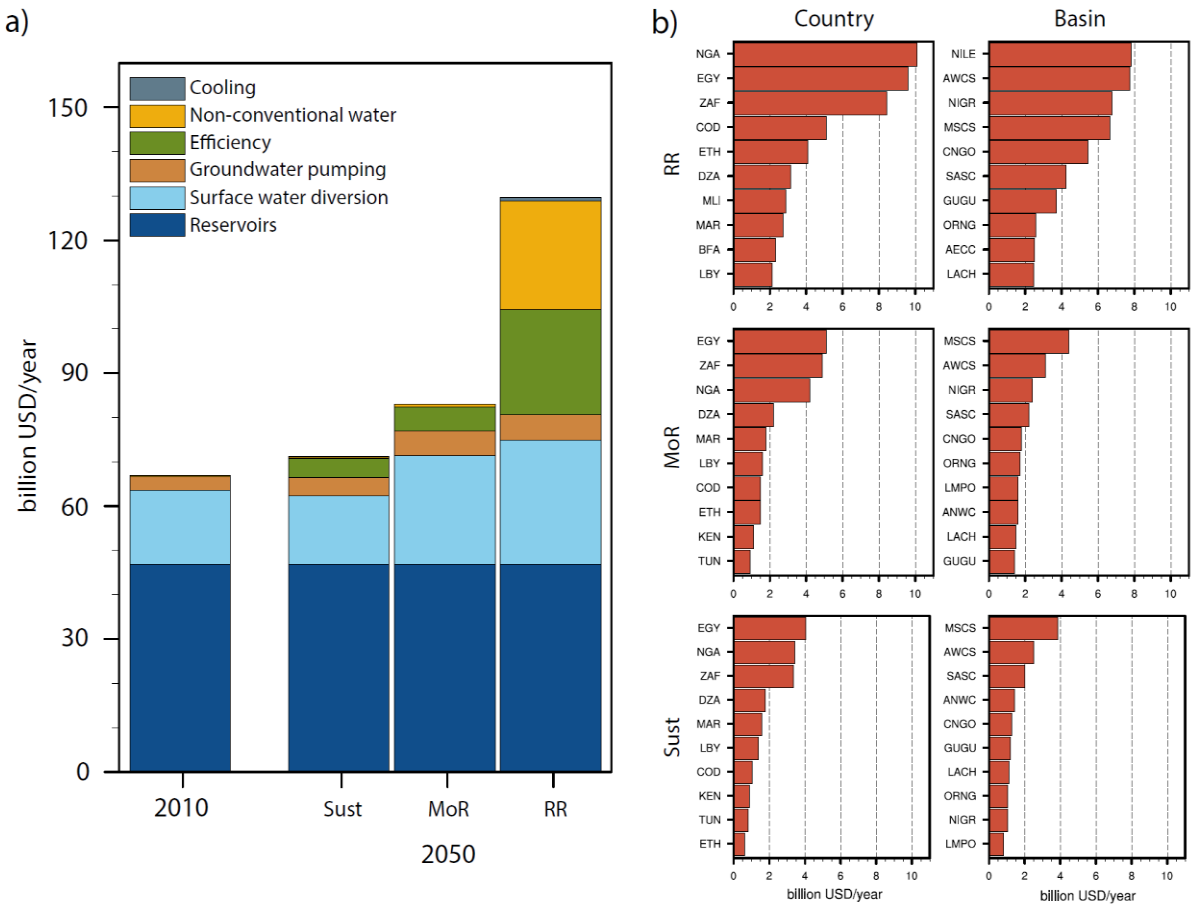

Figure 6. (a) Annual water sector cost in 2010 and 2050 by scenario and management option for the African continent. (b) Ten countries (left) and basins (right) with highest change in annual cost between 2010 and 2050 by scenario. Full names for countries and basins are provided in Table S2 in the SI.

Results from Figure 6 indicate that the water supply cost in 2010 amounts to 67 billion USD yr^{-1} (roughly 3% of the continent's current GDP), and will increase over the coming decades, regardless of the scenario. This cost is projected to increase by 25% in 2050 compared to the present condition in the *MoR* scenario, reaching 83 billion USD yr^{-1}. Following a sustainable pathway (*Sust* scenario) would likely reduce the cost by 15% (or 12 billion USD) in 2050 compared to the *MoR* scenario. However, following a less sustainable pathway (*RR* scenario) could result in a significant increase of the cost by 60% (or 50 billion USD) in 2050 compared to the *MoR* scenario. Interestingly, these results suggest that the cost increase under the *RR* scenario exceeds the savings made under the *Sust* scenario. This arises when the low-cost options such as surface water diversion and groundwater pumping reach full capacity as water demand continues to increase, and therefore ECHO starts expanding existing capacities and investing gradually in more expensive options such as efficiency measures and non-conventional water production.

Figure 6 shows that a major part of the water supply cost originates from the operation and expansion of surface water diversion, groundwater pumping, and surface water reservoirs (66 billion USD or 99% of the total cost in 2010, and 66-80 billion USD or 60-90% of the total cost in 2050, depending on scenario). The cost of demand-side management options (or efficiency measures) increases over time in all scenarios, representing 6% (4-5 billion USD) of the total cost in 2050 under both the *MoR* and *Sust* scenarios, and 18% (24 billion USD) of the total cost in 2050 under the *RR* scenario. The cost of non-conventional water increases moderately over time under the *MoR* and *Sust* scenarios to amount to 0.4-0.7 billion USD in 2050 (less than 1% of the total cost), respectively. However, it increases considerably under the *RR* scenario, reaching 25 billion USD in 2050 (19% of the total cost). The cost of cooling thermal power plants is negligible under both the *MoR* and *Sust* scenarios (2-4 million USD by 2050), while it rises sharply under the *RR* scenario, reaching about 1 billion USD by 2050 (although its share remains less than 1% of the total cost). Results from Figure 6 also indicate that potential future socio-economic and climatic changes will likely have different implications on the water supply cost in different areas. The highest increases in the water supply cost between 2010 and 2050 for all scenarios are found by country in Nigeria, Egypt, South Africa, Algeria, Morocco and Democratic Republic of the Congo, and by basin in the Nile, Mediterranean South Coast, Africa West Coast, Niger, and South Africa South Coast. The different cost implications are obviously driven by the different changes in total water withdrawals, but also by the different choices of water management options. For instance, the change in the cost of water supply between 2010 and 2050 in the Mediterranean South Coast basin is higher than that of the Congo basin, despite the much larger change in total water withdrawals in the latter. This is mainly because more expensive management options, such as supply expansion with non-conventional water sources and use of pressurized irrigation systems, need to be implemented in the Mediterranean South Coast basin to address the growing water demand.

Table 3. Existing estimates of the cost of water supply and adaptation to future scenarios.

Study	Objective of the study	Spatial scale	Methodology	Cost estimate
Briscoe (1999)	Estimating 1990 spending on water infrastructure	All developing countries worldwide	Literature review	65 billion USD yr^{-1}
Woetzel et al. (2016)	Estimating current and future (year 2030) spending on water infrastructure	Global	Literature review	200 billion USD yr^{-1} in 2016 500 billion USD yr^{-1} in 2030
Kirshen (2007)	Estimating adaptation costs for two scenarios of socio-economic and climatic changes (IPCC scenarios B1 and A1b)	200 countries around the world including many African countries	Simple unit cost estimates	Additional 130-140 billion USD yr^{-1} by 2030 compared to 2000 for Africa
Ward et al. (2010)	Estimating the cost of adaptation to climate change for the industrial and municipal water supply sectors	Global including Africa	Intervention-based needs assessment	19 billion USD yr^{-1} for developing countries (3-6 billion USD yr^{-1} for Africa) for the period up to 2050
Schmidt-Traub (2015)	Estimating the investment cost for ensuring access to safe water and improved sanitation including the incremental costs for dam construction and flood protection	Global	Literature review	49 billion USD yr^{-1} for the period 2015-2030, with major investments needed in low and lower-middle income countries

Our cost estimates can be benchmarked against various existing estimates from previous studies of the cost of adaptation to the impacts of future socio-economic and climatic changes on water resources at the global scale including some estimates for Africa, as shown in Table 3. However, it is important to note that the methodological approaches, input data, spatial and temporal resolutions, and scenario assumptions differ between these studies, and therefore direct comparison of results is not straightforward. Despite the differences between our study and those in Table 3, it appears that our cost estimates are broadly consistent with previous estimates. For example, our 2010 water supply cost in Africa is comparable with the overall spending on water-related infrastructure provided by Briscoe (1999) for developing countries, and stands within the same order of magnitude as the global spending estimates provided by Woetzel et al. (2016). Our 2050 water supply cost in Africa aligns with the estimates of Ward et al. (2010) for Africa, but is lower than the investment range calculated for Africa by Kirshen (2007), whose study was conducted at country level and using only supply-side management options. Lastly, our cost estimates are consistent with estimates to achieve water-related Sustainable Development Goals (SDG6) globally (Schmidt-Traub, 2015), which could be considered an upper bound cost.

Despite the cost implications, adaptation of the water resources system to future socio-economic and climatic changes may involve tradeoffs among various environmental and economic objectives. For instance, some of the identified adaptation options in this study may be inconsistent with climate change mitigation targets because they involve high levels of energy consumption, such as desalination, recycling, pumping, and pressurized irrigation systems. Indeed, in the *RR* scenario, we find that electricity use in the water sector could increase five-fold (or by 125 TWh) by 2050 compared to 2010. The largest increase originates from the development of non-conventional resources, which accounts for more than 40% of water-related electricity use in 2050 (only 14% in 2010) (Figure 7). Major increases in electricity use between 2010 and 2050 in all scenarios are found by country in Sudan, Egypt, Nigeria, Burkina Faso, Ethiopia and Madagascar, and by basin in the Nile, Volta, Madagascar, Africa West Coast, Gulf of Guinea and Mediterranean South Coast. However, significant potential for energy savings in the water sector of these basins remains, for example by tapping the energy embedded in wastewater, and reducing water losses along the supply chain (IEA, 2016).

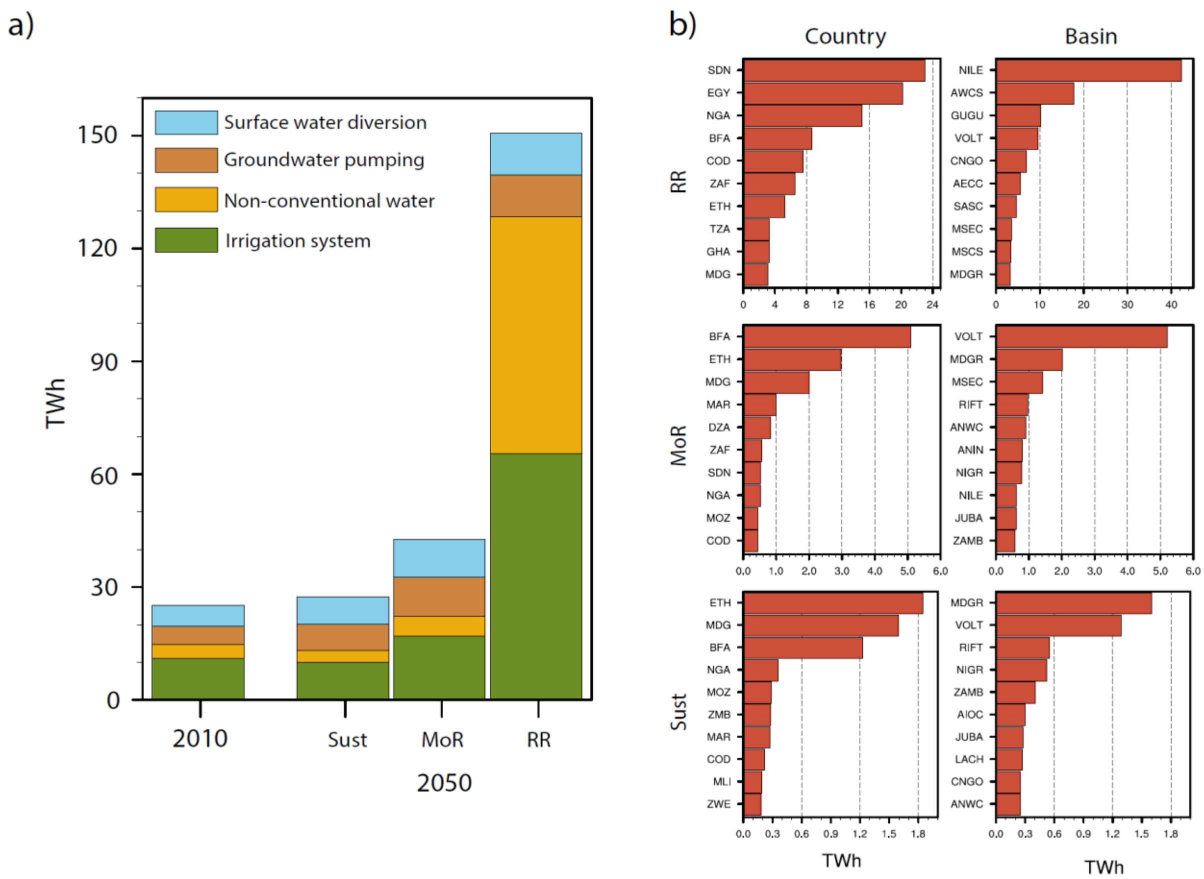

Figure 7. (a) Electricity use of the water sector in the African continent in 2010 and 2050 by scenario and management option. (b) Ten countries (left) and basins (right) with highest change in electricity use of the water sector between 2010 and 2050 by scenario. Full names for countries and basins are provided in Table S2 in the SI.

5. Discussion

In this paper, we present the development of the Extended Continental-scale Hydro-economic Optimization (ECHO) model. ECHO was applied to the challenging continent of Africa in order to assess the scope of possibilities to adapt to various scenarios of socio-economic and climatic changes, while at the same time considering the interactions between water, energy and agricultural systems. The results of this study highlight the importance of water resources in Africa for future human and economic developments. These developments are projected to heighten water withdrawals across the continent, with potential consequences on available freshwater resources and economic costs, especially in the current water scarcity hotspots such as northern Africa basins, the downstream part of the Nile basin and several basins in southern Africa. Importantly, results show that the varying scenario assumptions lead to different combinations of supply and demand side management options in different areas, which demonstrate ECHO's sensitivity to changes in parameters, and therefore make ECHO eligible for providing more effective policy support.

Furthermore, this study also provides important insights on the spatial differences in water supply and demand patterns among the different African countries and basins and highlights opportunities for more strategic and efficient water management options. Such information could be useful for global donors and policymakers in order to make more informed and impactful investments in water-related sectors across the whole Africa. As an illustration of the benefit of this large-scale hydro-economic modeling analysis, our results show that different basins in Africa choose different options for reducing water scarcity, which are appropriate and cost-effective for each basin. For example, the growing water demand in the coastal basins of North Africa (e.g. Mediterranean South Coast, Africa North West Coast) throughout the simulation period in all scenarios will likely be covered by expanding the supply of groundwater resources and non-conventional water resources (i.e. desalination and recycling) (Figure 5). Increased groundwater withdrawal in these basins is mostly unsustainable (as shown in Figure S7 in the SI), which can have adverse economic and environmental consequences. Further expansion of irrigation for food production in those basins appears to be unfeasible from a water resources perspective, and more sustainable management options need to be implemented to reduce groundwater depletion in these basins. These include for example improving irrigation efficiency and growing more drought-resistant crops, together with targeted measures, such as metering and regulation of groundwater pumping. Alternative food trade strategies may also be needed, given that most unsustainable groundwater withdrawal in these basins is used to irrigate export crops (Dalin et al., 2017). In contrast, in the Congo basin in Sub-Saharan Africa, most demand increase will be covered by the plentiful surface water resources. Irrigation withdrawal in the Congo basin remains relatively small compared to available freshwater resources and could be potentially further expanded in the future. This example of spatial differences in water supply and demand patterns among different African basins indicates the existence of considerable opportunities to improve the sustainability of water use in the whole continent through the implementation of more strategic and efficient management options such as the possibilities for food trade (or virtual water transfer), enhanced electricity trade, or water transfers between basins across the continent.

A certain number of simplifying assumptions were used in defining the structure of ECHO model. ECHO is a linear optimization model incorporating a simplified representation of complex water resources systems. In ECHO, we assume that the objective of water resources systems is to minimize the cost of water supply, given a set of constraints. However, real water resources systems are managed according to broader criteria, including reliability, environmental performance, and energy use. Other important assumptions used in ECHO are associated with the aggregation of spatial units. While these assumptions are reasonable for modeling at large scale, it may not be suitable for detailed basin studies, in which the spatial distribution of water supply and demand may need to be represented explicitly. Moreover, given the lack of reliable biophysical and economic information, this study does not thoroughly consider important local processes including environmental flow requirements (i.e., simple representation in the current version of ECHO), impacts on water quality, impacts of groundwater overexploitation, and the potential increase of water supply costs over time. These processes need detailed local information to capture the impacts at a large scale and the inherent uncertainty in existing large-scale calculations may need further consideration to incorporate in this type of large-scale hydro-economic models. For example, groundwater overexploitation can have considerable negative impacts at local scale, such as increased pumping costs, reduced base flow, saltwater intrusion, and land subsidence.

Another limitation of this study is related to our findings on the water saving potentials of improving irrigation efficiency, which differ from those of several previous studies indicating that improved irrigation efficiency does not necessarily save water at basin scale, but it could rather foster increased water use and depletion driven by the expansion and intensification of irrigation activities. This could lead to the reduction of return flows, which could be essential for downstream consumptive and environmental uses subject to water quality issues (Ward & Pulido-Velazquez, 2008; Perry & Steduto, 2017). The reason for these different findings is that our study assumes improvements in irrigation efficiency with current spatial crop area and distribution (Berbel et al., 2018). More dynamic land use optimization module will be included in a next version of ECHO to be able to identify such effects. Lastly, the optimization procedure in ECHO uses a perfect foresight formulation, which might lead to unjustified optimism about the efficiency of water management options (e.g. unrealistic reservoir operation with large (little) carryover storage prior to drought (wet) years or an overvaluation (underestimation) of the value of existing (new) investments), given that in reality decision makers do not have full information about future changes.

Despite all these limitations, ECHO currently serves well for a comparative analysis of the effects of different scenarios and management options, since the errors and limitations are applied uniformly across model runs. Future work will aim to improve the model structure, incorporating additional important biophysical processes such as groundwater dynamics and environmental flow requirements, using more disaggregated spatial representations and local-level data, improving model calibration and validation, and using different optimization procedures. Additional water management options and local practices such as controlling water demand with for example the possibility to adjust crop patterns and deficit irrigation, virtual water trade, water transfers, and green infrastructure will be also investigated and included in future works. To provide further insight into robust water management strategies, future work should also consider representations of uncertainties underlying the key model parameters.

6. Conclusions

In this study, we present the development of a new large-scale HE model (ECHO), which fully integrates biophysical, technological, and economic features of water resources systems. ECHO covers multiple sub-basin units interacting at continental-scale within a reduced-form transboundary river network, and involves the main water users at sub-basin level. The embedded linkages between sub-basin units and sectors at continental scale in ECHO provide a unique opportunity to model water management options at multiple spatial scales and account for their impacts on energy and agricultural sectors. ECHO was applied over Africa with the aim of demonstrating the benefits of this integrated hydro-economic modeling framework. Results of this application were found to be consistent with previous studies assessing the cost of water supply and adaptation to future socio-economic and climatic changes in Africa. Moreover, the results provide insight into several critical areas related to future investments in both supply and demand-side management options, the varying implications of contrasting future scenarios, and the potential tradeoffs among economic and environmental objectives. Overall, results highlight the capacity of ECHO to address challenging research questions related to the sustainable supply of water, and the impacts of water management on energy and food sectors and vice versa. As such, we propose ECHO as useful tool for water-related scenario analysis and policy options evaluation.

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