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## LETTERS

**PAPER**

# Operational planning of WEF infrastructure: quantifying the value of information sharing and cooperation in the Eastern Nile basin

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## Abstract

Integrating the planning of a multi-reservoir system in nexus with agricultural and electricity infrastructure could alleviate security concerns for these resources in regions where demand is growing while water and land scarcity are exacerbated by climate change and anthropogenic pressures. This study focuses on the benefits of resource integration and cooperation in the Eastern Nile basin. To overcome common limitations of equilibrium and soft-linked partial equilibrium models (e.g. high levels of spatial aggregation, non-insightful cooperation scenarios and a lack of heterogeneity), we propose a regional hard-linked WEF-nexus model that explicitly represents resource connectivity networks for water and electricity, and describes heterogeneity in resource availability, production potentials and physical constraints. Using a non-linear operational process, we optimise reservoir operations, water allocations, cropping patterns, electricity mixes and trade quantities on a monthly time-step over multiple years in a receding horizon fashion to maximize economic benefits for each country and regionally. This iterative implementation allows the modelling of operational changes as feedback against exogenous climate disturbances and enables information exchange between upstream-downstream countries. Thus, we describe four different levels of transboundary cooperation with their corresponding constraints and policy objectives. Compared to the reference scenario of unilateral planning, our results indicate an increase in regional economic returns for scenarios in which river flow information is shared between countries (+9%), river flow and trade information are shared (+10%) and WEF resources are coordinated regionally (+15%). These increased returns successively come from an increase in the effectiveness of agricultural water consumption, especially in Sudan, a change in trade patterns for agricultural products and a shift in cropping patterns. These findings underscore the importance of adequate representations of spatial and temporal heterogeneity of resources and their connectivity, as well as the need for a more diverse set of collaboration scenarios to facilitate planning in transboundary river systems.

## 1. Introduction

Under the pressure of population growth, socio-economic and cultural changes, the demand for freshwater, energy and food has grown sharply over the past fifty years and is expected to further increase in the next decades [1]. Because these resources have many shared attributes [2], countries will experience increasing competition between different sectors as demand grows and resources become scarce. This competition increases the risk of conflict and ultimately undermines water, energy and food security. The upstream-downstream connectivity of water in transboundary river basins makes downstream communities dependent on upstream management [3], further complicating resource management [4] and calling for policies not only between sectors, but also across boundaries [5].

In this letter we analyse the WEF resource management in the Eastern Nile basin (ENB) shared between Ethiopia, (former) Sudan and Egypt; a basin characterised by a strong connectivity in water resources as a result of spatial and temporal climate variability. While the population and energy consumption in the region have already increased significantly in the last few decades, further economic development and similar population growth rates are expected in the next few decades [6]. Compared to the situation in 1990, a population growth to 400 million in 2040 (+209%) [7] is expected to be accompanied by a 22 fold increase in annual demand for electricity (890 TWH) [8, 9] and an increase in the daily caloric supply (including supply chain losses) of 3400 TJ (+271%) [10, 11]. To meet these growing demands, countries need to boost their agricultural production [12, 13] and expand their energy portfolio; a significant number of multi-purpose reservoirs have therefore been built, are under construction or planned. Given that the basin is already practically closed [14], prior to filling the Grand Ethiopian Renaissance Dam (GERD), the accompanying increase in water consumption through evaporation and transpiration, which could be aggravated by climate driven reductions in yield potentials [15] and increases in evapotranspiration rates [16], makes cooperation and integration between WEF sectors and among riparian states crucial [13]. However, although the importance of integration and the shortcomings of existing approaches were already emphasized by [17] in 2004, recent literature [18] highlights the lack of progress in the Eastern Nile, posing WEF security risks for downstream states and resulting in suboptimal water utilization and weaker resilience for the whole basin.

To promote cooperation, the Nile basin countries launched the Nile Basin Initiative in 1999 [19]. However, due to political changes in the region and foreign interference, the countries have once again started to develop their plans for (water) resource management unilaterally [20]. To reverse this trend, a clear understanding of the potential benefits and costs for the different users to engage in cooperative management is required.

A number of works have studied the value of cooperation in the (Eastern) Nile basin. The first economic (nonlinear) optimization model of hydropower generation and irrigation in the Nile basin, The Nile Economic Optimization Model (NEOM), developed by Whittington *et al* [21] indicates basin-wide annual economic benefits of cooperation around US$5 billion. Goor *et al* [22] uses a stochastic dynamic program to study the impact of river infrastructure development in Ethiopia and irrigation expansion in Sudan and Ethiopia on downstream operating strategies and the economic benefits. Scenarios indicate a huge increase in basin-wide benefits (on average US$3.5 billion annually), with

Sudan and Ethiopia being the main beneficiaries, and positive externalities for hydropower generation in Sudan and Egypt. Similar positive externalities of cooperative management of the GERD are illustrated by Digna *et al* [23], making use of a genetic algorithm. Additionally, this work illustrates the basin-wide trade-offs between agricultural water consumption and hydropower generation in a non-cooperative scenario. Dinar and Nigatu [24] include distributional aspects of economic benefits in the post-processing of the optimization. With the inclusion of water consumption rights, water trade and sediment externalities, this work illustrates the existence of a stable cooperation scenario with annual basin-wide benefits of US$0.5 billion.

Roughly, this literature makes use of partial equilibrium hydro-economic optimization models [18, 21, 22, 24–26], general equilibrium models [27], or a soft linked combination of both [28]. While equilibrium models suffer from a lack of hydrological detail due to high levels of aggregation [29], the strong water resource centered focus in partial equilibrium models and soft linked combinations, wherein the unit value of water allocated towards agriculture (US$0.05 m$^{-2}$) or electricity generation (US$0.08 kWh$^{-1}$) is described with uniform values in space and time, falls short in considering the possibilities and limitations that origin from heterogeneity, physical constraints and mutual interdependency of WEF resources and infrastructures. In addition, the non-operational optimization approach used in these studies, which only allows the formulation of two extreme cooperation scenarios (unilateral and regional coordination), provides little insight into the structure of economic benefits. Hence, we propose two new cooperation scenarios between these extremes to study the value of sharing information about expected river flow and product trade. Sharing hydrological data is argued to improve the water use efficiency and soften the negative externalities of droughts and floods on people's livelihood [4, 30, 31]. Sharing trade data is a critical step towards a functional implementation of a free trade market [32] and regional power pool [33]. Both form a basis for full regional coordinated management.

We therefore present a novel method that, by expanding the set of cooperation scenarios and explicitly representing resource connectivity networks and heterogeneity in supply (e.g. availability, potentials and constraints) and demand in a hard-linked (holistic integration of processes, fluxes, objectives and constraints in a single mathematical optimisation model as opposed to soft-link approach where individual models are solved in isolation and information is exchanged between them [34]) WEF-nexus optimisation, makes the composition of economic benefits more transparent, acknowledges the spatial and temporal variation in resources valuation, provides insight into the underlying spatial shifts

in resource consumption patterns and explores the impact of policy objectives (e.g. desired levels of self-sufficiency in food production). Following the notion of [35], a deterministic historic simulation period ranging from 1990 to 2009 is used to minimize the modellers' bias and to improve understanding of the policy narrative by providing tangible results using high quality datasets. In this historic context, Sudan refers to the union of the current countries of Sudan and South-Sudan.

## 2. Methodology

### 2.1. Eastern Nile in WEF nexus terms
The basin is characterised by extreme hydroclimatic variability in space and time, with droughts predominantly in the northern semi-arid and arid zones and a distinct wet season in the southern subtropical zones [36]. Consequently, the tributaries in the Ethiopian highlands (Blue Nile, Baro Akobba Sobat and Tekeze Atbara) contribute most (85%) to the annual Nile flow in Egypt [16], but their contribution is, in contrast with the White Nile flow, highly seasonal (figure 1). With claimed rights on the Nile waters of 55.5 BCM (Billion Cubic Meter) per year as per the 1959 Nile agreements [37], Egypt's consumption is strongly asymmetrical with its internal renewable resources and dependent on upstream run-off. To achieve all year round river control, Egypt therefore built the Aswan High Dam (AHD) [38]. Development in Sudan started with the aim to supply water to the Blue Nile irrigation schemes. Over the following decades, reservoirs have also been built in other river basins for hydropower generation. Historically, Ethiopia made little use of the Nile resources, except for some river regulation for small-scale irrigated agriculture since the beginning of the 21st century [39].

Our analysis of the energy balance focuses on the electricity system. Egypt had the largest consumption in the region with an average per capita consumption of 1 MWh yr$^{-1}$ [9] over the simulated historic period between 1990 and 2009 and a grid coverage in the 90% [40]. Whereas the percentage of hydropower capacity increased in most other riparian states, in Egypt the percentage gradually decreased because the majority of the potential has already been exploited [41]. Thermal power plants therefore accounted for the bulk of capacity [9]. Sudan's and Ethiopia's power systems were both underdeveloped and characterized by low coverage (< 50%) [40], low per capita consumption (< 100 kWh yr$^{-1}$) [9] and high transmission and distribution losses (up to 30%) [40, 42]. Hydropower accounted for 85%–95% [42] of the installed capacity over the historic period in Ethiopia and approximately 50% in Sudan [43, 44]. The installed capacity of renewables wind, solar, biomass and geothermal plants was small in all countries. International transmission capacity was

constructed between Egypt and neighboring Arab countries [45] during the study period. For the other states, this development only started in the decade following.

In Egypt, food production takes place almost exclusively in irrigated agriculture. Between 1990 and 2009, the irrigated area expanded from approximately 2.6–3.6 million hectares [10]; our simulation period explicitly incorporates these resource dynamics. In Sudan, approximately 1.8 million hectares [10, 46] was equipped for irrigation, mainly located in the lower Blue Nile basin. In addition, agriculture took place in rainfed areas in the southern regions. In Ethiopia most agriculture was rain-dependent with only 0.6 million hectares [10] equipped for irrigation realized by 2009 and largely located outside the Nile basin [47].

### 2.2. WEF system: boundaries and decision variables
Closed hard-linked balances for water, electricity and food resources make up the core of this mathematical approach (supplementary information G (available online at stacks.iop.org/ERL/16/085006/mmedia), hereafter: SI-G). The operational characteristics and physical constraints for WEF infrastructures, spatial heterogeneity in water availability and agricultural production potentials, and national energy and food demands are respectively described using high-quality node-specific, gridded (0.5° resolution) and national data sources (SI-E). Because of the national character of economics, trade and policies [48], this study is conducted with national boundaries.

The water balance is, however, only represented in detail in the ENB by a dynamic network model describing river connectivity along with associated delays, seepage and evapotranspiration losses, and representing the storage, losses, manipulation and consumption by operational and over-time newly commissioned reservoirs, hydropower plants and irrigation sites (figure 2). Consequently, food and energy production in other basins in Ethiopia are based on water supply assumptions and historic capacity factors. Domestic and industrial water demands are neglected because of their small contribution to total withdrawals [49]. Minimum environmental flow demands are not explicitly constrained, but are implicitly guaranteed by the operational intention of Nile surface water reservoirs to regulate the seasonal flow and ensure water availability for downstream use during low discharge periods.

The operational choices with regard to the outflow and storage of water in reservoirs have a direct impact on hydropower production, and hence on other forms of generation within the electricity balance. Driven by monthly national and international demand, adjusted for transmission losses, our model decides on the deployment of
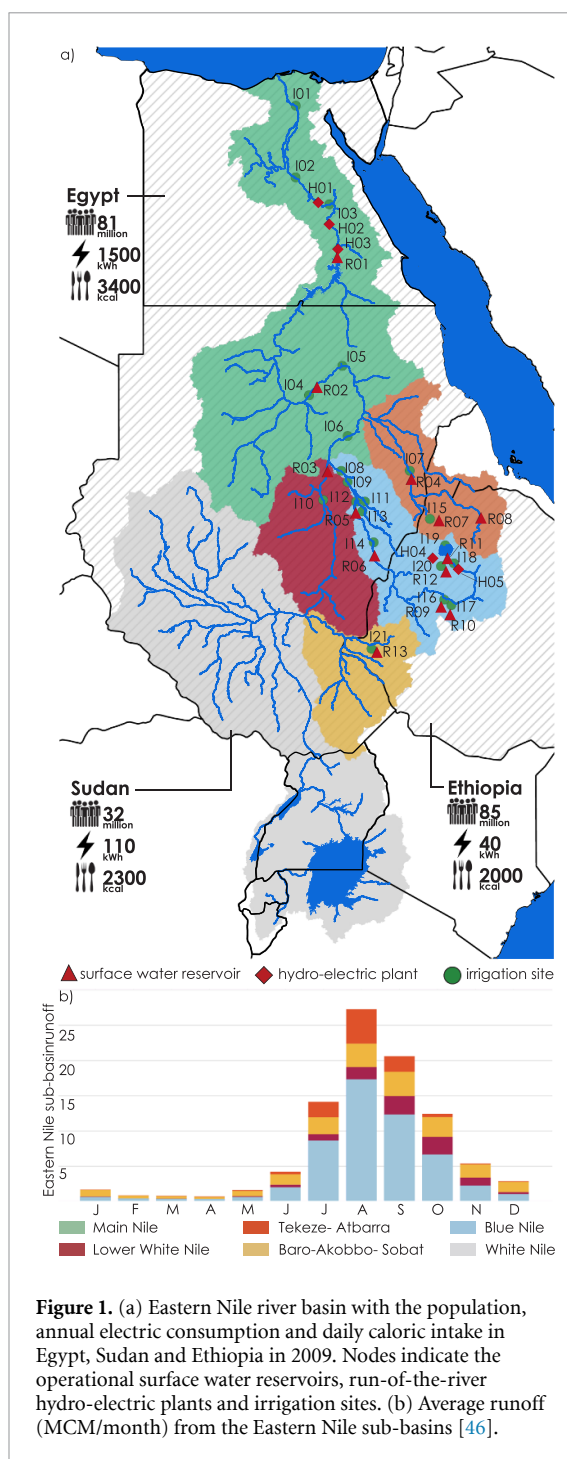
**Figure 1.** (a) Eastern Nile river basin with the population, annual electric consumption and daily caloric intake in Egypt, Sudan and Ethiopia in 2009. Nodes indicate the operational surface water reservoirs, run-of-the-river hydro-electric plants and irrigation sites. (b) Average runoff (MCM/month) from the Eastern Nile sub-basins [46].



**Figure 2.** System boundaries with dynamic network representation of the river and river-infrastructure in the Eastern Nile basin. Infrastructure names, commissioning years and characteristics are found in the SI-B.

fossil plants in addition to hydropower and renewable production.

In addition to the allocated volume of water for irrigation, decisions are made on cropping patterns. Each irrigated agricultural site is characterized by a unique mix of feasible crops out of the thirty-three included in this study (SI-C). The composition of irrigated agricultural sites outside the ENB and rainfed areas is imposed as a boundary condition (SI-J.3). Agricultural yield, computed using FAO's crop-water production function [48], depends on location specific agronomic and climatic conditions, water supply (effective irrigation and precipitation)

and on-farm management practices (SI-J.8). By processing some of these crops, in total 40 vegetal items distributed over all major food groups are accounted for, covering the majority of cultivated and consumed products in the region [6, 10, 50–52] (SI-D). The crop and (deficit) water allocation is driven by the national demand for food and feed, adjusted for distribution and storage losses, and perfectly elastic international wholesale prices (that vary annually; this follows the

small country assumption for the ENB [53]). Food demand is derived from the size of the population, the per capita caloric intake and the nationwide average dietary composition [10]. Demand for meat and dairy products is converted into a feed demand with feed conversion efficiencies [54] and nation specific feed basket compositions.

## 2.3. Optimizing the WEF resource planning

Optimization techniques are used to search for the best WEF resource allocation operations using the existing infrastructure constraints, without being restricted by existing operational rules. Optimality is herein defined as the set of operations that results in the maximum macro-economic benefits, while being limited by physical and institutional constraints (SI-H). Operational decisions are therefore, amongst others, made about reservoir operations, cropping patterns and surface water allocation for irrigation (SI-E). Economic benefits are generated with the sale of electricity and food products at international wholesale prices, and costs are associated with the import, transportation and production of these items. Because of the operational character of this study, only variable costs are included.

Rather than computing optimal operations in a single optimization over the 240 time steps (20 years with a monthly resolution) within the study period, we apply a Model Predictive Control (MPC) approach; an advanced control method [55] where optimal control actions are computed for a smaller finite time horizon iteratively in a receding horizon fashion. In this receding horizon implementation, by recomputing actions using new information about the system and only implementing the optimal actions in the first time step of the prediction horizon and then optimizing again, both feedback to past disturbances and anticipatory actions to predicted ones are achieved. Compared to a single optimization, the iterative nature of an MPC approach allows to study spatially larger scale problems, and provides a more truthful representation of optimising reservoir operations and agricultural decisions with limited knowledge of the future.

We compute optimal monthly operations over a horizon of 3 years using predicted weather and demand conditions, while simultaneously satisfying aforementioned constraints. By applying only the optimal outputs in the first month of the horizon in simulation (to replace the real hydrologic and anthropogenic processes), using real weather and demand conditions, and updating the system states using measured information before shifting the optimization horizon to the next monthly time step, this feedback strategy allows us to act on discrepancies between the predicted and actual (modelled) system states that origin from changes in exogenous drivers (e.g. weather and river discharge), such that unwanted dynamic properties are acted on and

compensated before they occur. Although the uncertainty related to crop cycles fall within a year, we use a horizon of 3 years to plan for policy objectives (e.g. agricultural self-sufficiency), resilience against droughts and the filling of newly commissioned infrastructures. By using this 3 year moving horizon, and the need for a start-up time to reduce the impact of initial parameter settings, the 240 step iterative optimization-simulation process of the 1990–2009 period requires data in the period 1989–2012.

Within the MPC framework, a nonlinear program (NLP) solver is used to allow an adequate representation of hydropower generation and food production. Despite the local convergence for non-convex problems, an interior point solver is preferred here over global optimization techniques because of its feasibility in solving the large scale sparse NLPs [56] resulting from a spatially and temporally explicit operational WEF model.

## 2.4. Cooperation scenarios

By considering information sharing between agents following each MPC iteration, four cooperation scenarios (figure 3) are developed. Building upon one another (table 1), these scenarios describe the full scope between unilateralism and full regional coordination. Unilateralism is, with an optimised national planning of resources and infrastructures, an improvement over today's individual infrastructure planning, but comes closest to the current situation in terms of cooperation. It refers to the political situation where a state acts unilaterally without being dependent on or sharing information with other states. Hence, products can only be traded on the (infinite) international market and electricity is traded under predefined long term contracts. Long-term (annual) electricity trade quantities are modelled as agreed; they are computed using a single optimization prior to the start of the iterative MPC runs with the aim of optimally redistributing the national shortages and surpluses calculated with capacity factors for all (hydropower) plants (SI-I.2). Assuming that countries can trace the runoff upstream (either perfect or imperfect with hydrological models and remotely sensed inputs), a downstream country estimates the border inflow at a specific point in the unilateral scenario from a quadratic relation with this runoff generated upstream, i.e. this relationship provides a prediction of the average water consumption in upstream countries for a given upstream runoff. This predictive quadratic relation is computed as the least-square error fit between the monthly sum of runoff generators upstream of the border and the resulting border flow, over the period studied from 1990 to 2009.

The associated uncertainty in inflow is reduced in the flow-information sharing scenario as outflow predictions over the duration of the optimization horizon are shared in downstream direction. Subsequently, within the trade-information sharing
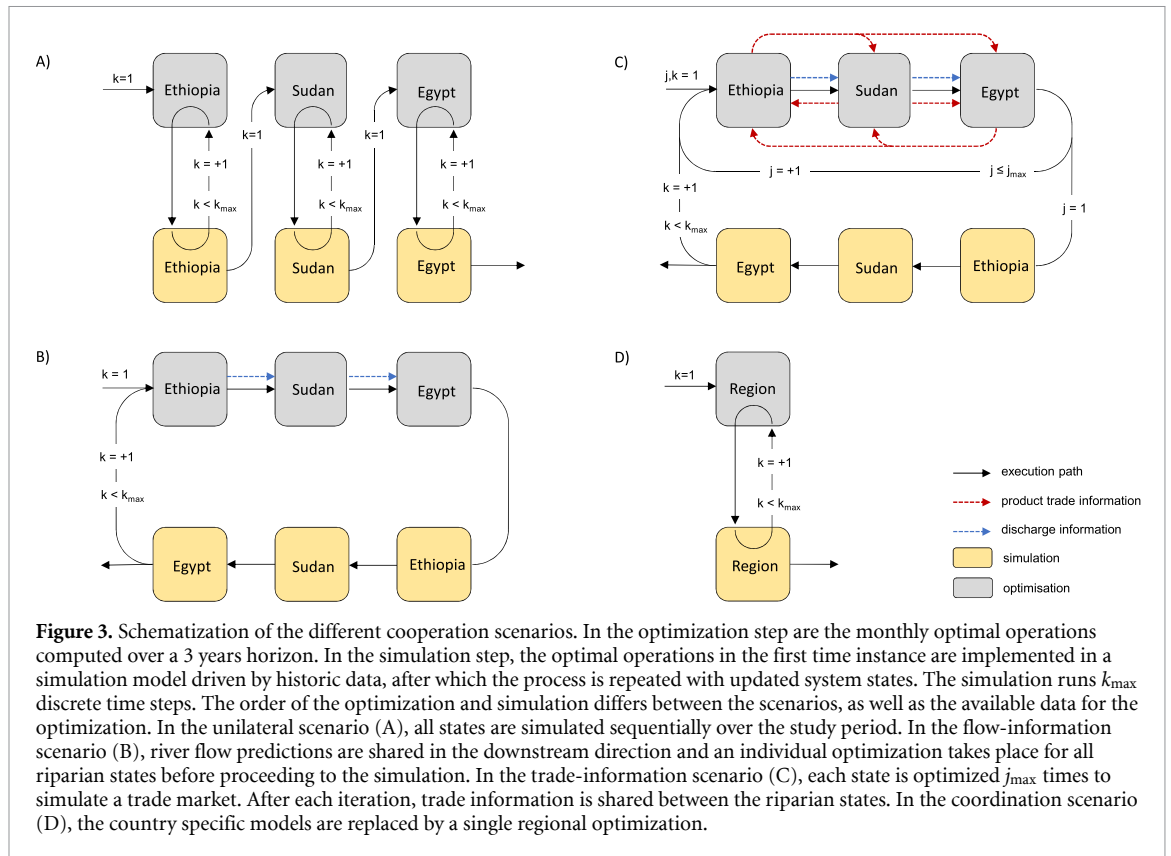
**Figure 3.** Schematization of the different cooperation scenarios. In the optimization step are the monthly optimal operations computed over a 3 years horizon. In the simulation step, the optimal operations in the first time instance are implemented in a simulation model driven by historic data, after which the process is repeated with updated system states. The simulation runs $k_{max}$ discrete time steps. The order of the optimization and simulation differs between the scenarios, as well as the available data for the optimization. In the unilateral scenario (A), all states are simulated sequentially over the study period. In the flow-information scenario (B), river flow predictions are shared in the downstream direction and an individual optimization takes place for all riparian states before proceeding to the simulation. In the trade-information scenario (C), each state is optimized $j_{max}$ times to simulate a trade market. After each iteration, trade information is shared between the riparian states. In the coordination scenario (D), the country specific models are replaced by a single regional optimization.

**Table 1.** Characteristics of cooperation scenarios ranging from unilateralism (U) via sharing flow (F) and trade (T) information to regional coordination (C).

|  | U | F | T | C |
|---|---|---|---|---|
| Economic benefits maximization | National | National | National | Regional |
| Resource consumption planning | National | National | National | Regional |
| International product trade | × | × | × | × |
| Long term electricity market | × | × | × | × |
| Sharing river discharge predictions | — | × | × | × |
| Regional product trade market | — | — | × | × |
| Short term electricity market | — | — | × | × |

scenario, predictions for product exports and electricity shortages in the next time-step are shared regionally. Through multiple optimization iterations passing expected flow information downstream and product information in both directions (figure 3(c)), the scheme converges to a simulation of an optimised regional trade market, enabling regional commerce and monthly varying electricity trades. In each first optimization out of a set of two consecutive optimizations, riparian states (agents in the regional market) can tender for the not yet allocated part of products made available by other regional states, after which (part of) the available quantity is reserved for each interested state (giving priority to the geographic closest partner if demand exceeds availability). In each second optimization, the interested state determines whether it is still interested in importing the allocated quantity, given that other demanded products are not available or are available to a lesser extent (SI-I.2).

The full regional coordination scenario builds upon, but is fundamentally different from the previous scenarios in that planning and economic optimization no longer takes place at the national but regional level. Although unrealistic politically, it provides a benchmark for economic efficiency in resource planning in other scenarios.

### 2.5. Scenarios and evaluation metrics

To validate modelled river flows and quantitatively compare agricultural production quantities in the unilateral cooperation scenario with available historic data sets, the Prediction Efficiency (PE) and Normalized Absolute Relative Error (NARE) are computed (see SI-A.1) [57]. The PE measures the model's ability to reproduce the variation present in the data. A PE value equal to 1 indicates a perfect fit, while a value equal to or smaller than zero indicates that the model is incapable to reproduce the time variations in the

data. The NARE indicates how well the model captures the range of magnitudes in the data.

The remainder of the analyses focus on the differences between the cooperation scenarios. Economic benefits are discussed on the basis of a balance sheet for the individual states and the region, both for simulations with perfect and imperfect meteorological forecasts. In the perfect forecast scenario, the meteorological forcing is known in advance for the complete three years horizon. In imperfect forecast scenarios, we assume that planning under uncertainty is instinctively based on short-term meteorological memory, rather than on a full stochastic approach. The planning optimisation is therefore based on a naive single sample realization, using river runoff and meteorological data dating 5 years back (the average return period of the el-Niño [58], the main climate driver in the region [59]). Hence, there is a mismatch between the forcing used in the optimisation (i.e. planning) and operational simulation of the plans (see SI-I.1).

Implications for the production and consumption of WEF resources are firstly based on a comparisons of the spatial allocation patterns of agricultural water consumption (in BCM) and deficit irrigation; the latter metric being defined as the fraction of total water withdrawals used for deficit irrigation. In addition, national agricultural water productivity is computed by dividing the added economic value of agricultural outputs (difference between production value and variable costs) by the volume of river water used for irrigation. Finally, agricultural production patterns, and surface water storage and evaporation shifts are compared.

To study the implications for national and regional food security, the agricultural self-sufficiency metric is introduced. This metric indicates the extent to which a country's or region's agriculture is able to meet its own food consumption. A self-sufficiency target is added to the method to study this indicator (SI-H.4). In sequential experiments, by increasing the target level gradually in between experiments and penalizing failure to meet the target in the optimization, the maximum achievable self-sufficiency and the impact on an economic optimisation policy is studied. To study the full self-sufficiency potential, boundary conditions for the composition of irrigated agricultural sites outside the ENB and rainfed areas are relaxed, and re-import of products is allowed to circumvent limitations in food storage.

Finally, the impact of cooperation on the trade-off between agricultural water consumption and hydropower generation is studied. This trade-off is illustrated by varying the costs for alternative electricity sources (e.g. small diesel generators) required to close the gap between national electricity demand and generation. Higher alternative costs could alter the agricultural water consumption and increase the reservoir levels during dry periods to boost

cheap hydropower generation. The costs are stepwise increased from US$60 MWh$^{-1}$ to US$5000 MWh$^{-1}$ to represent the space between the international trade tariff [60] and the levelized costs of electricity generation with small diesel generators. The latter costs strongly depend on location and diesel price; nowadays ranging up to US$1500 MWh$^{-1}$ in some remote regions in the Eastern Nile and in future expected to range up to US$3000 MWh$^{-1}$ [61].

## 3. Results and discussion

### 3.1. Validation and comparison with historical data
River discharges in the unilateral scenario at Deim and Dongola, respectively located in Sudan close to the border with Ethiopia and Egypt, show excellent pattern similarities ($PE_{Diem} = 0.93$, $PE_{Dongola} = 0.81$) and small normalised magnitude errors ($NARE_{Diem} = 0.03$, $NARE_{Dongola} = 0.06$) with respect to discharge data obtained from the Sudanese Ministry of Irrigation and Water Resources. Given the limited possibilities to allocate the water resources in Ethiopia, the good performance at Diem is a validation of the regression and partitioning techniques used in the production of the runoff data-set and the description of flow (evaporation and seepage) losses. The somewhat larger, but still limited, deviations at Dongola are explained by larger numbers of upstream storage and consumption options, altering spatial consumption patterns compared to historic operations.

Although not relevant as a validation tool, comparing economically optimized crop patterns with historical production quantities from the FAOSTAT database provides insight into the performance compared to the non-optimized historic production. Although the optimised crop productions are in some cases in Egypt and Sudan correlated with data ($PE \approx 0.3$–$0.6$, $NARE \approx 0.2$–$0.5$), they are not meant to replicate/predict real past data. Figures and a more detailed discussion are found in SI-A.1.

### 3.2. Net economic benefits
The economic benefits and costs of the food and electricity sector for the individual riparian states and the ENB region are illustrated in figure 4, aggregated over the study period, for both the perfect and imperfect meteorological forecast simulations.

First, the results illustrate the agricultural sector's dominant contribution to the economic benefits. Limited national production and transmission capacity limit the variable costs for generation, while the absence of international connectors meant that regional trade was not possible during the study period. In addition, the results are illustrative of the wide discrepancy in the condition of the WEF infrastructure between states. Where use of the WEF infrastructure is profitable for Egypt and economically break-even in Sudan, the rainfed agriculture and limited irrigated areas are not sufficient to meet national
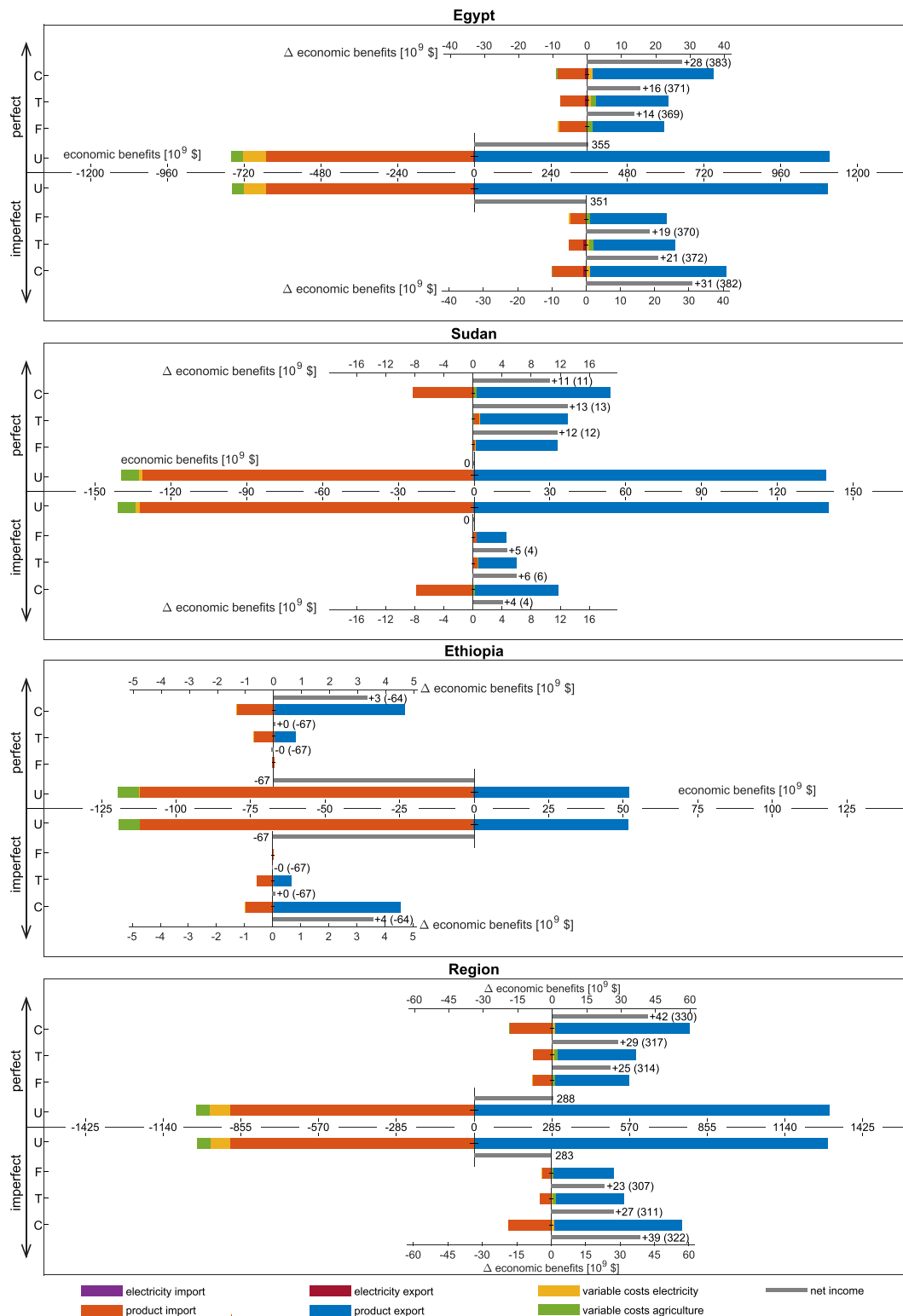
**Figure 4.** Import and variable costs and export income in the food and electricity sectors aggregated over the simulation period 1990–2009. The center bars (U) depict the incomes and costs in the unilateral scenario in both the perfect and imperfect forecast simulations in US$. Starting off from the net income (grey bar), the change in benefits with respect to the unilateral scenario is illustrated for the flow information (F), trade-information (T) and regional coordination (C) scenario. The first number next to the grey bar indicates the additional income and the second (between brackets) the total income. Hence, a positive change in costs (e.g. variable costs agriculture) represents a costs reduction (additional income). This figure illustrates that (a) the magnitude of benefits in the food sector outweigh the benefits in the electricity sector; (b) the negative net income in Ethiopia are caused by the large-scale import of food required to supplement the shortages in national production; (c) the economic benefits grow in all states with increasing levels of cooperation; and (d) imperfect meteorological forecasts have the largest impact on benefits in Sudan.

demands in Ethiopia. Outcomes show that increased levels of cooperation yield higher regional economic incomes for both perfect and imperfect meteorological forecasts, without significant economic contraction in any riparian state. With a regional increase in net economic benefits of US$25, US$29 and US$42 billion, returns increase with 9%, 10% and 15% in the flow-information, trade-information and coordination scenarios respectively. The major gain is achieved by sharing river flow information, but there are no benefits for Ethiopia in this scenario because of the upstream location. The greatest benefits result from changed production and trading patterns when resources are coordinated regionally, but go along with a redistribution of the additional benefits obtained in the trade-information sharing scenario. The basin-wide annual benefits of approximately US$2 billion in this scenario are in line with magnitudes found in previous studies [21, 22, 24].

The altered meteorological forcing in the unilateral imperfect forecast optimization results in small changes compared to the perfect forecast scenario. A larger difference occurs in the flow-information sharing scenario in Sudan. Due to the limited presence of dams on the Ethiopian tributaries, uncertainty in inflow remains considerable in this scenario in Sudan, cutting back national incomes. The small impact of uncertainty in Blue Nile discharge in Ethiopia is explained by the abundant availability of river flow during the wet season and the historic limited possibilities for consumption. In Egypt, uncertainty in inflow remains limited because most tributaries of the main Nile upstream of the AHD are regulated. Imperfect meteorological forecasts do therefore not hinder but, with an increased inflow from Sudan in this one case, promote economic production in Egypt.

### 3.3. WEF balance implications

These changes in basin wide net benefits result mostly from spatial changes in agricultural water consumption, cropping patterns and resulting water productivity.

Results show that, with respect to the unilateral reference scenario, sharing river flow information increases surface water withdrawals for irrigated agriculture in Sudan by 15.6 BCM (+3%), without disrupting the supply of the claimed volumes into Egypt, and reduces the consumed volume in Egypt by 27 BCM (−2%) over the simulation period. A reverse trend is observed in a regionally coordinated system, where a reduction of 26.3 BCM (−5%) in Sudan and 1.5 BCM (−14%) in Ethiopia is accompanied by an increase of 30.6 BCM (+2%) in water withdrawals within Egypt. Hence, in the less likely scenario that the riparian states would be in a trade and regulatory union (cf the EU), where they choose to coordinate infrastructure and distributional implications are settled institutionally, it appears to be

advantageous to take the river losses for granted and to allow the production of water-intensive crops to take place in Egypt, where the potential yields are high, growth stages relatively short and farm losses small. This shift in water consumption, and hence agricultural production, is reflected in an increase in internal (regional) trade (see SI-A.3). In future, if upstream countries further develop irrigation capacity and improve irrigation practices to increase yield, the optimal water use in a coordinated scenario would shift to some extent favouring more agricultural production upstream than presented in this study.

In addition to these lumped national trends, shifts were observed within national borders. Figures 5 and 6 present respectively the spatial water withdrawals and the percentage of water withdrawn used for deficit irrigation at the different irrigated areas. The flow-information sharing scenario shows an increase in water consumption and a decrease in deficit irrigation in the Sudanese Blue Nile (node I8-I14), which is not at the expense of withdrawals in downstream Sudanese irrigated areas. Since the inflow from Ethiopia remains unchanged with respect to the unilateral scenario, sharing river flow information allows Sudan to use the available resources more effectively. In the regional cooperation scenario, a drop in water withdrawals in the Sudanese irrigated areas along the Main Nile, being characterised by high potential evapotranspiration rates and on farm losses, is observed. Along, deficit irrigation increases in most Ethiopian and Sudanese irrigated areas. Hence, in a coordinated system where most agriculture takes place in Egypt, the agricultural area is not limiting, but the temporal availability of water resources.

The spatial heterogeneity in optimised preferences for different crops across the basin is generally also evident from the agricultural water productivity of irrigation in figure 7. Our computations of agricultural water productivity differs on two fronts when compared to the widely applied valuation of US$0.05 m$^{-3}$ for agricultural water use in the Nile Basin literature [21–24]. Our work not only illustrates a difference in the order of magnitude, but more importantly, it provides insight into the large difference in valuation between riparian states; emphasizing the need for spatially explicit modeling approaches. The remarkably high water productivity in Ethiopia for the given magnitude of the on-farm losses is explained by the relatively high precipitation and low potential evapotranspiration rates as compared to the regional averages, limiting the need for river water irrigation. The increase in agricultural water productivity in Sudan in the flow-information scenario is the result of the more effective consumption. In Egypt, further growth is driven by a changing cropping pattern, creating more value using less water. The growth in productivity in the coordination scenario in Sudan and Ethiopia, despite the
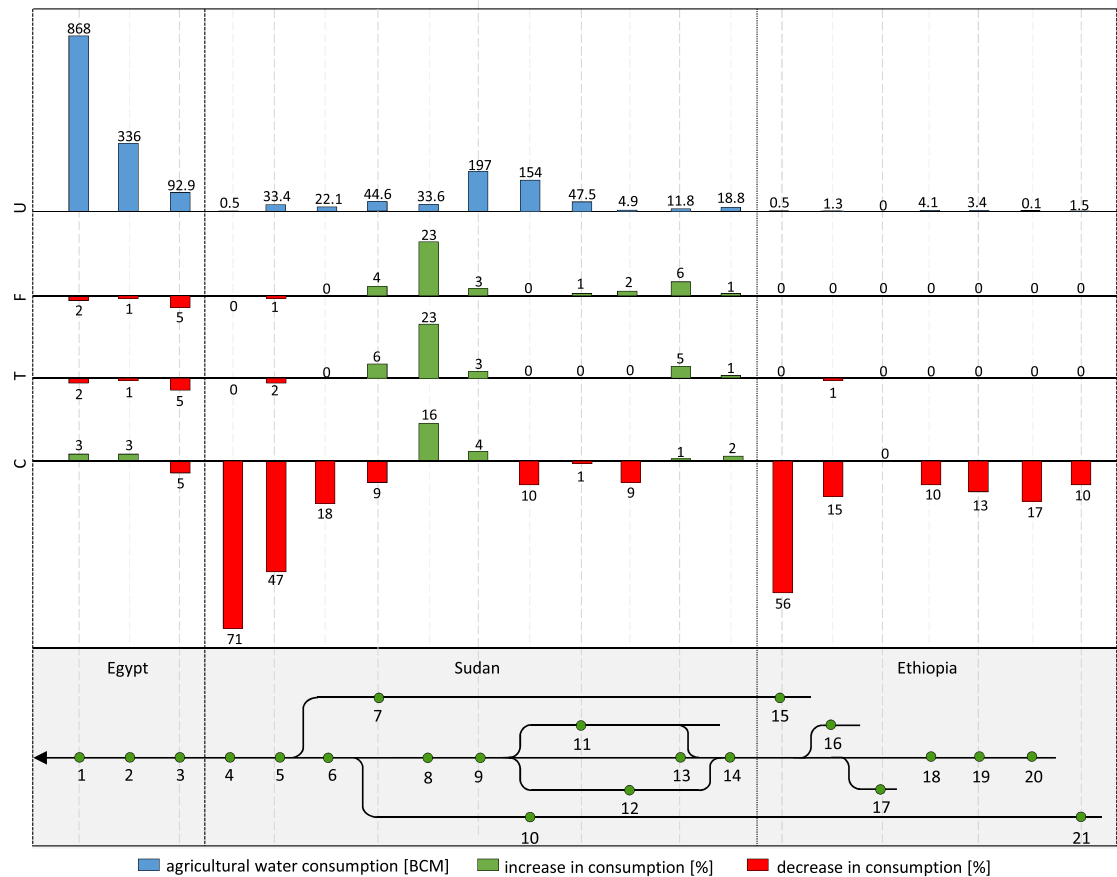
**Figure 5.** Illustration of the agricultural water consumption in the various irrigated areas in the ENB. The bars arising from the U (unilateral) axes indicate the aggregated surface water withdrawals in BCM over the simulation period (1990–2009) in the unilateral scenario. The bars arising from the F, T and C axes respectively illustrate the percentage change in consumption in the flow-information, trade-information and coordination scenarios. The figure visualizes the enhanced effectiveness in agricultural planning in Sudan when sharing flow information, and a clear downstream reallocation in consumption in a regional coordination scenario.

growing share of deficit irrigation, is the result of a limited specialization in crop production. In absence of a regional trade mechanism in unilateral scenarios, the high transportation costs in the international market make it economically favourable to grow crops with low maximum achievable yields. However, the relatively cheap import of crops from other countries within the region, when compared to the import costs from the external world, make is beneficial for the countries to specialize their production and trade internally. Although total product imports (expressed in mass) increase by 6.6% as a result of this specialization, there is a US$2.3 $\times$ 10$^9$ reduction in transport costs due to a decrease in international trade by 4.5%.

This specialization, although limited, is reflected in changing cropping patterns between the cooperation scenarios, shown in figure 8 as annual harvest areas per food group in the unilateral and coordination scenario. In Egypt there is a small increase in production, especially in the last 5 years, but the cropping pattern changes minimally. Considerably more forage is grown in Sudan, intended for consumption in Egypt, at the expense of cereals and sugar production.

In Ethiopia, annual harvested areas and production are declining, as is the inter-annual variability (SI-A.4). Coinciding, there is a shift from the production of cereals and roots to the production of nuts and vegetables.

These regional changes in agriculture modify the spatial storage pattern over the ENB surface water reservoirs. Figure 9 illustrates the national cumulative monthly surface water storage and net reservoir evaporation in the unilateral scenario, and the differences (real increase and decrease) between the unilateral and cooperative scenario. Compared to the historical unilateral reference scenario, the storage increases in Egypt and decreases in Sudan in the cooperative scenario. These changes are mainly due to a decrease in storage in the Jebal Aulia reservoir (R03), located along the White Nile, and an increase in the AHD (R01). Although counter-intuitive, this downstream relocation is possible because of the reduced consumption along the main Nile in Sudan, and is despite the higher potential evaporation rates preferred because of the flatter storage-surface ratio of the AHD, minimizing the evaporation losses per additional unit of water stored. Despite an overall increase
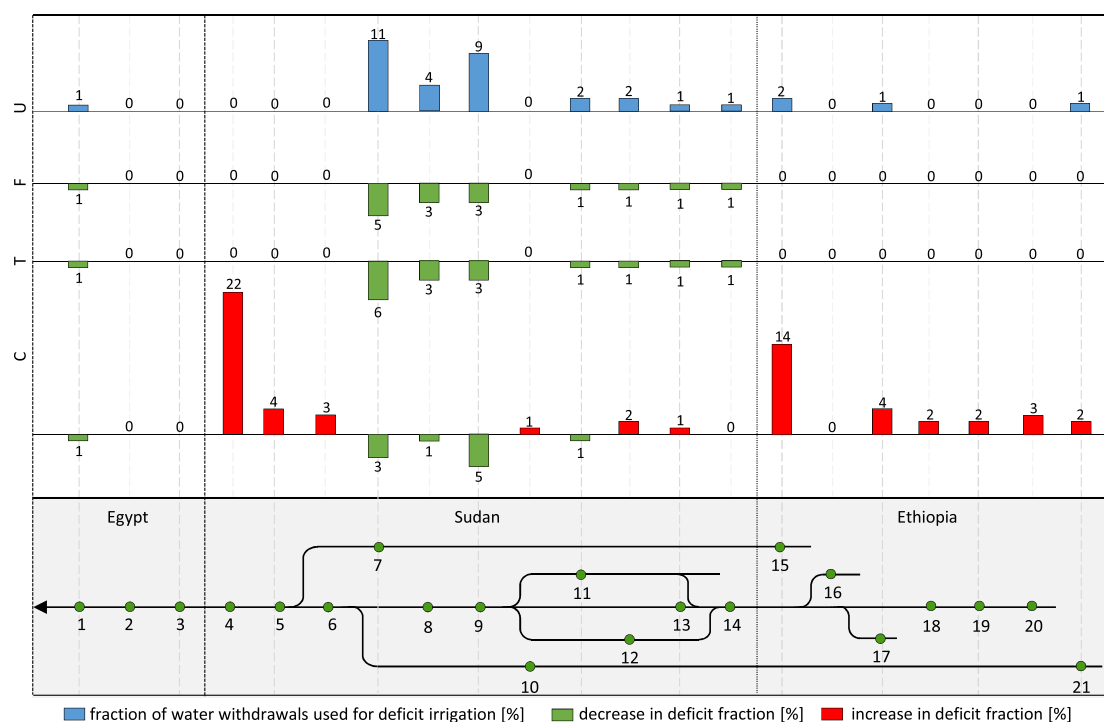
**Figure 6.** Illustration of the fraction of water withdrawals used for crop deficit irrigation in the various irrigated areas in the ENB. The bars arising from the U axis illustrate the percentage of the river water withdrawals used for deficit irrigation in the unilateral scenario.The bars arising from the F, T and C axes respectively illustrate the absolute change in deficit irrigation fraction in consumption in the flow-information, trade-information and coordination scenarios. The patterns match the agricultural water withdrawals in figure 5. The increase in deficit irrigation in the regional coordination scenario (with no uncertainty) indicates that the regional agricultural area is not limiting production, but the temporal availability of water resources.
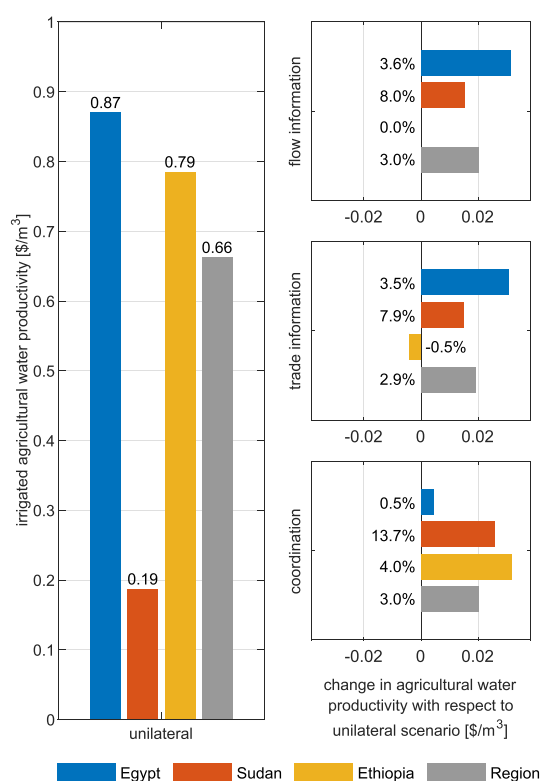


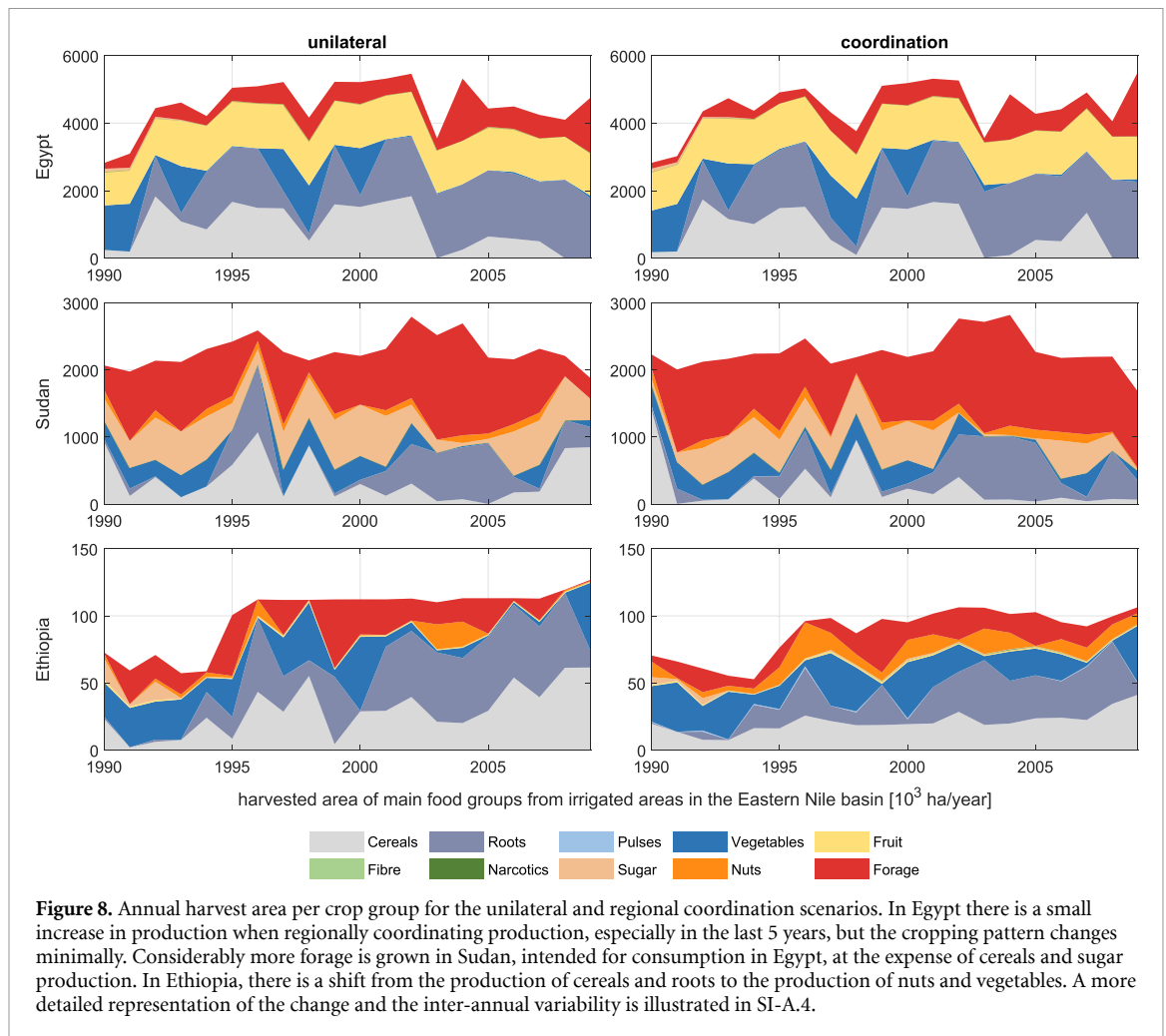**Figure 7.** Agricultural water productivity (US$ m$^{-3}$) in the unilateral reference scenario and changes (absolute and relative) in the other scenarios. Sharing flow information enables more effective agricultural planning in Sudan, resulting in a higher water productivity. In the coordination scenario Sudan's and Ethiopia's water productivity further increases due to regional specialization in crop production.
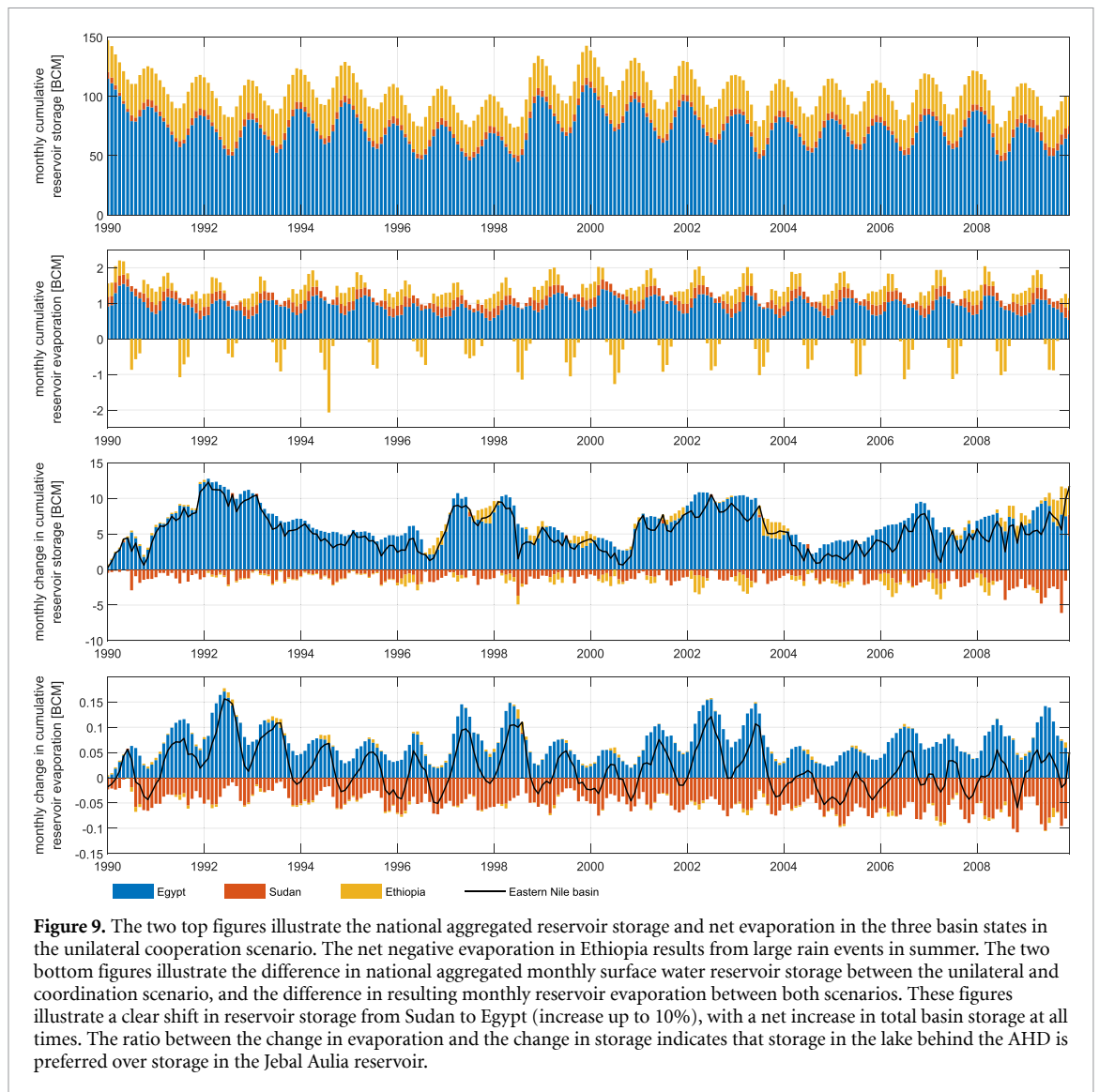
**Figure 8.** Annual harvest area per crop group for the unilateral and regional coordination scenarios. In Egypt there is a small increase in production when regionally coordinating production, especially in the last 5 years, but the cropping pattern changes minimally. Considerably more forage is grown in Sudan, intended for consumption in Egypt, at the expense of cereals and sugar production. In Ethiopia, there is a shift from the production of cereals and roots to the production of nuts and vegetables. A more detailed representation of the change and the inter-annual variability is illustrated in SI-A.4.

of 5.3% in regional storage, this keeps the growth in evaporation losses limited to 1.6%.

### 3.4. Optimizing economic benefits with agricultural self-sufficiency constraints

Figure 10 illustrates the achieved self-sufficiency level for the set targets, the agricultural production value (based on international wholesale prices) and the percentage drop in production value for the individual states and the region. The limited difference between the maximum achieved and the initial agricultural self-sufficiency in Sudan and Egypt illustrates the common ground of policies aimed at economic maximization and agricultural self-sufficiency in these countries. Ethiopia can, in contrast, at a loss of half its initial production value, achieve a higher self-sufficiency if the rainfed land resources are used alternatively. The contrast is possibly explained by the historical development of food patterns. Where diets in Sudan and Egypt are made up of economically profitably cultivated products, demand in Ethiopia is, due to food shortages originating from poor management and unfavorable meteorological conditions, partly based on food aid deliveries.

The ENB region can achieve a slightly higher production value under regional coordination than

in the unilateral scenario. Moreover the maximum self-sufficiency increases from 54% to 57%, indicating that the overal sufficiency while the associated decrease in production value drops from 17% to 11%. However, in order to achieve this small growth in regional self-sufficiency, Sudan and especially Ethiopia, will have to sacrifice strongly on their national self-sufficiency. As illustrated in figure 9 in SI-A.6, this decline in national self-sufficiency results from an increased specialisation and regional product trade, because of which an increasing percentage of food and feed consumption originates from neighbouring EN basin countries. As a result, in the coordination scenario presented, the percentage of regionally produced food increases in Egypt and strongly in Sudan, while slightly decreasing in Ethiopia. Although this may seem disadvantageous for Ethiopia at first glance, the regional self-sufficiency in a trade and regulatory union with mutual trust between the dependent agents is desirable. This is because, when compared to the unilateral scenario, the changing crop mix results in an increased national production value (figure 10) at higher food sufficiency-levels and an increased food security by reducing the vulnerability for local droughts, crop diseases or locust plagues.

**Figure 9.** The two top figures illustrate the national aggregated reservoir storage and net evaporation in the three basin states in the unilateral cooperation scenario. The net negative evaporation in Ethiopia results from large rain events in summer. The two bottom figures illustrate the difference in national aggregated monthly surface water reservoir storage between the unilateral and coordination scenario, and the difference in resulting monthly reservoir evaporation between both scenarios. These figures illustrate a clear shift in reservoir storage from Sudan to Egypt (increase up to 10%), with a net increase in total basin storage at all times. The ratio between the change in evaporation and the change in storage indicates that storage in the lake behind the AHD is preferred over storage in the Jebal Aulia reservoir.

## 3.5. Trade-off hydropower generation—agricultural water withdrawals

When using historic consumption data to force power demands, shortages are minimal, minimizing the impact of varying costs for alternative sources. Consequently, significant changes and trade-offs between these water users remain absent (figure 7 in SI-A.5). The trade-off between both sectors in a non-cooperative scenario presented by Digna in [23] is explained by the absence of transmission constraints, creating unbound possibilities to supply electricity to national and international consumers.

To illustrate this, the modelled power demand is doubled in additional simulations, assuming that demands exceeded the, by outages and transmission capacity limited, historic power supply. In these simulations, a clear trade-off is found in Egypt in the unilateral scenario (figure 11 and figure 8 in SI-A.4); illustrating an approximate 10% increase in hydropower generation by the AHD and Nile barrages and decrease in agricultural withdrawals. Hence, there is a clear temporal mismatch between hydropower

and downstream agricultural water demands. In the cooperative scenario, the model aims to minimize this trade-off in Egypt by reducing the agricultural water withdrawals from the Nile river in upstream countries. The largely unchanged hydropower generation for higher alternative costs in Sudan and Ethiopia in the unilateral scenario, despite significant shortages (4% and 44%, respectively), indicates that hydropower infrastructures operate at their storage and generation limits.

Although an enhanced trade-off seems obvious when hydropower generation capacity is no longer limiting power supply, especially when combined with competitive upstream agricultural expansion, increased reservoir storage capacity and the alteration of the unimodal flow regime, could have a profound impact on the severity of the final trade-offs (especially in downstream states). Shortly, during reservoir filling and succeeding operation, the GERD at the border between Sudan and Ethiopia will have a measurable impact on the presented results. The exact implications during the filling stage depend largely on
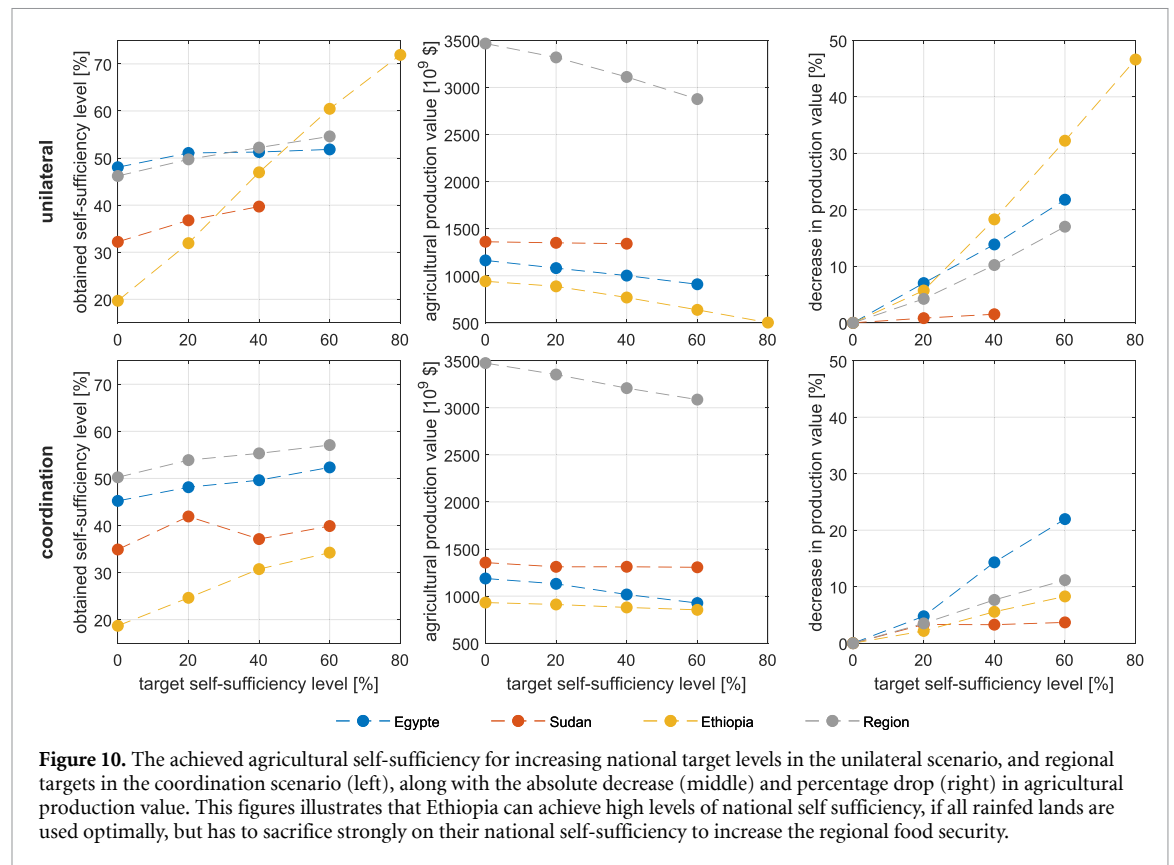
**Figure 10.** The achieved agricultural self-sufficiency for increasing national target levels in the unilateral scenario, and regional targets in the coordination scenario (left), along with the absolute decrease (middle) and percentage drop (right) in agricultural production value. This figures illustrates that Ethiopia can achieve high levels of national self sufficiency, if all rainfed lands are used optimally, but has to sacrifice strongly on their national self-sufficiency to increase the regional food security.



**Figure 11.** Trade-off between agricultural water consumption and hydropower generation with power demand equal to twice the historic consumption. Numbers indicate the costs (US\$ MWh$^{-1}$) of alternative sources for electricity generation. A clear trade-off is shown for Egypt in the unilateral scenario. In the regionally coordinated scenario, the optimisation reduces this trade-off in Egypt by decreasing the agricultural water consumption in Sudan as the cost of alternative electricity sources increases.

the agreements (especially during dry years) between states, but will negatively influence both agriculture and hydropower generation in Egypt. When operational, the dam with a storage of 74 BCM (1.2 times the average annual runoff of the Blue Nile), will boost the sale of cheap electricity, but alter downstream flow patterns drastically. More regularized flows are expected to facilitate spring irrigation in the Sudanese Blue Nile schemes and increase, with higher operational levels, hydropower generation in Sudan

[35, 62]. Increased upstream evaporation losses and water consumption in Sudan will marginally decrease hydropower generation and agriculture consumption in Egypt [35, 63].

## 4. Assumptions, limitations and future research

Despite extensive efforts to carefully select and cross-validate data sources, limitations in availability and subsequent assumptions do affect the model's spatial and temporal representations. Some main agricultural descriptors (e.g. management practices, fertilizer inputs and storage capacities) are described by uniform values within national boundaries and in time, while a description at smaller administrative units can provoke new system and management insights and might alter the spatial variability and specialisation. Likewise, a fine spatial description of network characteristics is lacking in the electricity sector. Although, due to the historical absence of interconnectors, this does not affect the current model results, a division into main and sub-networks [61] and a description of the regionalization of networks with appropriate capacity constraints is proposed to correctly represent future national and regional expansions.

Having emphasized the importance of spatial and temporal data integration in regional WEF models, we have drawn conclusions about optimal past cooperation operations using real but historic data; ongoing research could illustrate how new infrastructures, growing food and electricity demands and alterations in meteorological drivers affect the trade-offs and spatial distribution of WEF resource use and economic benefits of cooperation into future. One could then show how undesirable effects can be prevented and robustness could be increased by aligning the timing and size of new projects, spanning both intersectoral and transnational boundaries.

Additionally, we present some suggestions to improve the realism of modelled processes. By expanding and further integrating resource balances (e.g. land resources [64]), processes (e.g. energy for agriculture, animal product trade [65]), dependencies and evaluation metrics in the WEF framework, operational management could increasingly be studied in the context of WEF related SDGs; either related to environmental services (e.g. environmental flows, sediment management), quality of life or sustainability. Inclusion of memory to represent restrictions in farmer knowledge and tools (by a linear constraint) might limit the strong interannual price driven variability in agricultural production; implementation of a flow routing model will improve the characteristic representation of high and low flows; diversification of product origins in the international market and accounting for multiple transport mechanisms with associated costs will

provide a better representation of product trade flows; and allowing price variations between countries and networks will improve the representation of electric trade flows. Finally, a more realistic way of planning operations could be achieved by using a gradually, over the optimisation horizon, increasing uncertainty for model inputs (e.g. meteorology and prices) in a stochastic MPC implementation. This could go along with the implementation of more advanced downstream inflows predictions in unilateral scenarios. After all, with advances in information technology and modelling required to estimate downstream flows, it can be envisaged that downstream countries could already bridge the gap to the flow information sharing scenario through improved planning with better flow predictions.

## 5. Conclusions

With the availability of resources under pressure due to climate change and environmental degradation, optimal infrastructural operations are key to safeguard water, energy and food security as demands increase as a result of changing demographics and socio-economic behaviour. This paper focuses on the planning of these operations in a regional context where sub-optimal operational management has consequences not only for national sectoral trade-offs, but also for downstream livelihoods due to strong transboundary resource connectivity. Our work highlights the importance of spatially and temporally explicit model formulations in regional WEF nexus optimization studies and the functionality of the model formulation used to study the outcomes of transboundary resource coordination—taking the ENB states as an example.

Our scenarios indicate that with increasing levels of cooperation, the economic benefits would have increased monotonically for the whole basin. Despite the differences in relative benefits, there are no scenarios with significant deterioration in net benefits in specific riparian states, not even under the introduced uncertainty of imperfect meteorological projections. Over the historic twenty-year period, the flow-information-sharing, trade-information-sharing and regional coordination scenarios would have resulted in net benefits of approximately US$25, US$29 and US$42 billion for the region, increasing the returns by 9%, 10% and 15%, respectively, compared to the unilateral reference scenario. Because of limitations in electricity supply infrastructure and international interconnections, the vast majority of costs and incomes underlying these net economic benefits originates from the agricultural sector. The added value obtained by sharing river flow information would have been by far the greatest, and accounts for over half of the composition of benefits in the benchmark scenario of regional coordination. This information sharing, or improved information technologies

enabling a better inflow prediction, would have allowed Sudan to use the available water resources more effectively. Total water consumption would have increased, without disturbing the claimed inflow to Egypt, and deficit irrigation decreased. The strong dependence between this growth in economic return and the availability of perfect river inflow projections from Ethiopia, emphasizes the value of a predictable outflow from the future GERD reservoir for Sudan's agricultural sector and more generally the value of improved technology for operational river discharge predictions. Under regional coordination, a clear redistribution of water resources within and across the states takes place, but the absence of trade-offs between agricultural consumption and hydropower generation remains unchanged. Agricultural water withdrawals increase over the simulated 20 years period by a subtle 30.6 BCM in Egypt and reduce by 26.3 BCM in Sudan and 1.5 BCM in Ethiopia relative to the unilateral reference scenario, i.e. the growth of the economic benefits is one order of magnitude larger than the redistribution ($\approx$1.5 BCM yr$^{-1}$) of the annual river discharge (84–97 BCM yr$^{-1}$ [66]) between countries. This insight is explained by a revaluation of water resources as a result of a spatial shift in cropping patterns. Paired with changing crop and trade patterns—where Sudan grows more forage at the expense of cereals and Ethiopia more nuts and vegetables at the expense of roots and cereals—agricultural water productivity (US\$ m$^{-3}$) in Sudan increases by 14%, in Ethiopia by 4% and in the ENB by 3%.

In addition to these economic benefits, the redistribution of water resources over the surface water reservoirs in the regional coordination scenario would have led to an increase of the regional water storage with a minor increase in accompanying evaporation, improving the resilience of the regional system against long lasting droughts. Furthermore, when the riparian states would cooperate in a self-sufficiency policy, the countries could have achieved the same level of agricultural self-sufficiency with a smaller decrease in agricultural production value, i.e. the countries could have increased their food security and their resilience for price fluctuations in the external market at lower costs by regional coordination of their resources, through free trade.

These findings illustrate that the operational optimization framework with explicit modelling of constraints can account for spatial and temporal shifts and trade-offs while finding non-trivial solutions for multiple forms of national and regional cooperative resource management. Based on the operational choices that introduce shifts in cropping patterns, changes in water allocation for hydropower and agriculture, as well as the diversity in water productivity, we conclude that inadequate inclusion of spatial and temporal heterogeneity results in incomplete and potentially incorrect conclusions. In addition, our

work highlights the usability of operational optimization tools to study a more diverse set of collaboration scenarios to quantify the costs and benefits of specific interventions and agreements, both under perfect and imperfect foresight assumptions.

## Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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