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A dynamic water accounting framework based on marginal resource opportunity cost

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Abstract

Many river basins throughout the world are increasingly under pressure as water demands keep rising due to population growth, industrialization, urbanization and rising living standards. In the past, the typical answer to meet those demands focused on the supply-side and involved the construction of hydraulic infrastructures to capture more water from surface water bodies and from aquifers. As river basins were being more and more developed, downstream water users and ecosystems have become increasingly dependent on the management actions taken by upstream users. The increased interconnectedness between water users, aquatic ecosystems and the built environment is further compounded by climate change and its impact on the water cycle. Those pressures mean that it has become increasingly important to measure and account for changes in water fluxes and their corresponding economic value as they progress throughout the river system. Such basin water accounting should provide policy makers with important information regarding the relative contribution of each water user, infrastructure and management decision to the overall economic value of the river basin. This paper presents a dynamic water accounting approach whereby the entire river basin is considered as a value chain with multiple services including production and storage. Water users and reservoirs operators are considered as economic agents who can exchange water with their hydraulic neighbours at a price corresponding to the marginal value of water. Effective water accounting is made possible by keeping track of all water fluxes and their corresponding hypothetical transactions using the results of a hydro-economic model. The proposed approach is illustrated with the Eastern Nile River basin in Africa.

1 Introduction

As water resources are increasingly used for various purposes, there is a need for a unified framework to describe, quantify and classify water use in a region, be it

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a catchment, a river basin or a country. The first water accounting exercises focused on the physical resource, trying to describe the status of water resource use and consequences of water resources related actions (Molden, 1997). Water accounting procedures were quickly enriched by linking water use to relevant productivity indicators (Molden and Sakthivadivel, 1999) in order to provide water managers with strategic information on water allocation in a region. This information can then be used to design water saving strategies, to examine the potential for water reallocation, to identify water using activities that require more detailed analysis, etc.

The success of water accounting is such that it has become an integral part of environmental water accounts in many countries, such as Australia (Vardon et al., 2007), and by the United Nations through the System of Environmental-Economic Accounting for Water (SEEAW). Although it is increasingly adopted, there is no unified procedure to established water accounts, nor is there an agreement on how water accounts must be presented.

National water accounts typically aggregate water use data at a scale corresponding to the economic data that are used to establish national income accounts, which rarely coincide with hydrologic boundaries. This aggregation has an important limitation: national water accounts should not be used directly to design policy interventions at a lower scale, like the river basin scale. In closed river basins, for instance, the aggregation implies that water accounts do not properly capture the interconnectedness amongst water users, as well as between water users and ecosystems.

However, with the availability of both sophisticated hydrologic models and remote sensing data, hydrologists are now able to track of water fluxes in complex river basins. When linked to productivity indicators, detailed water accounts can be established in which various watershed processes are represented. Kirby and Mainuddin (2006), for example, propose a water account of the Mekong river basin in which water supplies and demands are aggregated at the sub-basin scale. Zhu et al. (2009) describe the water accounting system in the Yellow River basin in China and discuss the specificities of the Chinese water accounting system. Karimi et al. (2013a) present Water Accounting

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Plus (WA+), an extension of the water accounting framework proposed by the International Water Management Institute (IWMI) in the 90ies. The extension allows the consideration of more watershed processes including the important role of land use. The new framework is implemented in the Indus basin (Karimi et al., 2013b). A water accounting framework for an international river basin, the Orange river in Southern Africa, is discussed in Lange et al. (2007). Their framework is largely based on information from each country's national water accounts.

Since many water accounts are established on an annual basis, the relationship between the seasonal hydrologic variability and water productivity cannot be analyzed. Hence, policy interventions requiring a finer temporal and spatial scales, such as drought management, cannot be guided by traditional water accounting methods. Kirby and Mainuddin (2006) address this issue and propose a dynamic, seasonal, water accounting approach in which the major water uses are considered. Those efforts are useful but the linkage to the economic data is often implicit due to the mismatch between the spatial and temporal scales of the hydrologic and economic variables. Moreover, storage services are also ignored despite the fact that storage infrastructures contribute to basin-wide benefits and/or costs (Tilmant et al., 2012).

Another limitation relates to the use of water productivity (income generated in an industry per cubic meter of water used) instead of water value. Users value water at its marginal use (Griffin, 2006) and this value changes with the quantity used. Thus, by using a fixed water productivity value, the economic information produced by a water account cannot be used in situations where the quantity of water available changes (due to a drought or a water project changing supply). The benefits are likely to be overestimated, while the losses may be underestimated. The approach presented in this paper avoids this limitation by using information that better reflects the water value to the user, rather than a fixed water productivity. This makes the economic results more useful to support decisions on water system operation and expansion.

Another important contribution of this paper is to provide a structured framework for better use and understanding the results of hydroeconomic models. The sheer amount

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of information produced in such models, especially in large scale applications (like Jenkins et al., 2004) makes results interpretation often challenging. Given the increasing perception and incorporation of the water's economic value for water planning and management worldwide, it is expected that such models will bring relevant contributions in the design and operation of water systems in the years to come, turning the best use of their information equally important. The water accounting approach presented in this paper integrates critical information produced by hydroeconomic models, including the water value, storage value and dynamic water fluxes, allowing one to track the economic effects of changes (droughts, system's expansion, climate change) to individual elements in the system (users, infrastructure, the environment).

The proposed framework rests on two main observations: (i) water scarcity demands good understanding of water fluxes, uses and economic values for effective management, and (ii) that the marginal resource opportunity cost (MROC) of water is the best indicator to signal water scarcity. Based on these two observations, MROC is used to establish water accounts and bridge the gap between hydrological and economic processes. The marginal resource opportunity cost of water (MROC) is an indicator of the aggregated economic impact of water scarcity and how much the users would be willing to pay (WTP) to mitigate that scarcity (Pulido-Velazquez et al., 2103). In other words, it corresponds to the at-source marginal value of water (Tilmant et al., 2008), which varies in space and time according to several factors including the (relative) imbalance between supply and demand, the topology (hydraulic connectivity) and nature of water uses (e.g. rival vs. non-rival). MROC is best determined with hydro-economic models, which integrate essential hydrologic, economic and institutional information of a river basin in a single, coherent, computational framework. Pande et al. (2011), for example, use a hydro-economic model to analyze the interdependence between various hydrological processes and the marginal value of water at the sub-basin scale. Kiptala et al. (2014) attempt to link the hydro-economics of green water use in the upper catchments of the Pangani basin, with the blue water use further downstream in the main stem of the river.

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To establish water accounts based on MROC, the basic idea is to exploit the results of optimization-based hydro-economic models and combine allocation decisions with their corresponding marginal water values. In other words, by tracking water allocation decisions, including storage, and the spatial and temporal changes in the marginal value of water, one can establish an economic-based, dynamic, water accounting for a system involving multiple uses (offstream and instream, river vs. non-rival) as well as multiple reservoirs. To achieve this, the framework requires the unbundling of production and storage services; that is, reservoirs are considered as separate economic agents that are financially independent of the hydraulically connected water users (e.g. farmer, power company, industry).

The paper is organized as follows. It starts with a review of hydro-economic modelling with an emphasis on optimization-based approach and the typical results one can expect. The hydro-economic water accounting framework for a multireservoir systems involving a mix of instream and offstream uses then presented. Section 3 is devoted to the case study, which is followed by the analysis of the results. Finally, conclusions are presented in Sect. 5.

2 Material and method

2.1 Hydro-economic modeling

Over the past two decades, hydro-economic modeling has emerged as one of the most common tools to analyze water resources systems, especially water resources allocation problems. Hydro-economic models usually require a network representation of the river system in order to physically connect various sources of supply with the scarcity-sensitive water demands. Recent reviews on hydro-economic modeling can be found in Harou et al. (2009), Brouwer and Hofkes (2008) and Heinz et al. (2007).

There are basically two classes of hydro-economic models: optimization-based vs. simulation-based. In an optimization-based hydro-economic model, an objective

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function is to be maximized (or minimized) subject to physical, institutional and/or economical constraints. This prescriptive approach is often adopted by economists. Simulation-based hydro-economic models, on the other hand, are essentially descriptive in the sense that they require the allocation policies be specified by the analyst like any other input. This second approach has emerged from the hydrological sciences and can be considered as an extension of rainfall–runoff models that are widely used in hydrology (see e.g. Seyam et al., 2002 and Brown et al., 1990).

Although both approaches have their own advantages and disadvantages, the fact that an optimization-based model simultaneously determines the allocation decisions and the marginal costs of the binding constraints makes it attractive here since it will be a key feature in the proposed methodology. As it is well known in optimization theory, when an optimization problem is solved, the solution procedure not only provides the optimal decisions but also the marginal costs of the binding constraints, i.e. the limiting resources or factors that prevent further improvement of the objective function.

In a network representation of the water system, a water balance must be evaluated at each node in order to determine the amount of water available for the demand sites connected to that node. In other words, at a given node, the mass balance equation ensures that water is allocated to the connected water users to the extent permitted by water availability at that node. In case of water shortage, the marginal cost associated with the water balance indicates the shadow price of water, i.e. what the users would be willing to pay for an additional unit of water (Young, 2005). In situation where water is plentiful, this shadow price will be zero or even negative if the surplus causes damages (e.g. like during a flood event). In the remaining of this paper, the term MROC will be preferred to the shadow price of water even though they are strictly identical. MROC can, in principle, be also derived from simulation-based hydro-economic models, but the procedure is more computationally demanding, especially for large networks. The basic principle is to assess the change in basin-wide benefits (costs) after changing the availability of water at a given node by one unit. The process must be repeated for all nodes and for various combinations of water availabilities throughout the system.

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When a water resources allocation problem in a river basin is formulated as a hydro-economic optimization problem, the objective function Z to be maximized typically includes the economic net benefits across all water uses over a given planning period. Let t be the index of time ($t = 1, 2, \dots, T$), b_t be the aggregated (basin-wide) net benefits at time t , q_t be the vector of hydrologic supply, x_t be the vector of allocation decisions, w_t be the vector of state variables, α be a discount factor and v be a terminal value function. With the above definitions, the objective function of the hydro-economic problem can be written as:

$$Z^* = \max_{x_t} \left\{ \mathbb{E}_{q_t} \left[\sum_t^T \alpha_t b_t(w_t, x_t) + \alpha_{T+1} v(w_{T+1}) \right] \right\} \quad (1)$$

where \mathbb{E} is the expectation operator and Z^* is the total benefit associated with the optimal allocations $(x_1^*, x_2^*, \dots, x_T^*)$.

This function will be maximized to the extent permitted by the constraints, which can be of physical, institutional or economical nature. Define g a set of functions constraining the allocation decisions, h a set of functions constraining the state of the system and f a set of functions describing the transition of the system from time t to time $t + 1$. The optimization problem has the following set of constraints:

$$g_{t+1}(x_{t+1}) \leq 0 \quad (2)$$

$$h_{t+1}(w_{t+1}) \leq 0 \quad (3)$$

$$w_{t+1} = f_t(w_t, x_t, q_t) \quad (4)$$

Of interest are the constraints (4) which include the mass balance equations in the river basin:

$$s_{t+1} - \mathbf{R}(r_t + l_t) - \mathbf{I}(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t \quad (5)$$

where s_t is the vector of storages at time t , r_t is the vector of controlled outflows, l_t is the vector of uncontrolled outflows, i_t is the vector of withdrawals, \mathbf{R} and \mathbf{I} are the

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of both the allocation decisions and the corresponding MROC. Production services include a wide range of activities, ranging from the production of runoff or blue water (hydrologic services) as well as activities for which water can be considered as a production input (economic services): municipal and industrial uses (M&I), hydroelectricity generation, irrigation, navigation, etc (Fig. 1). Storage services, on the other hand, are associated to reservoirs and their ability to move water over time in order to increase its availability when it becomes more valuable (e.g. during the low flow season). Because a given storage facility may be valuable to various water using activities, and to keep the accounting framework as general as possible, production and storage services are individually considered. In other words, the framework rests on the assumption that each activity, whether it is production or storage, can be represented by a separate economic agent.

To illustrate those concepts and for notational simplicity, we will imagine a system with a cascade of J multipurpose reservoirs as depicted on Fig. 2. The water stored in each reservoir can be used for both consumptive (e.g. irrigation) and non-consumptive uses (e.g. hydropower generation). Let us further imagine that this system is managed by a river basin authority (RBA) whose mandate would essentially consist in (i) efficiently allocating water between the different elements of the system and (ii) preserving the hydrologic integrity of the river basin and thus ensuring the quality of the hydrologic services (here the production of blue water). Finally, note that the elements of the system depicted on Fig. 2 are independent economic agents; there are J reservoir operators, J irrigation district associations and J power companies and one river basin authority.

In that system, the economic value of a service, whether it is storage or production, corresponds to a hypothetical transaction between two hydraulically connected agents: the upstream seller and the downstream buyer. The transactions are hypothetical because they are not observed in practice; they are implicit to the economically efficient allocations identified by the hydro-economic model. In other words, a financial transaction always accompanies a water flux but in the opposite direction as illustrated

on Fig. 2. The clearing prices of those transactions are the MROC (λ_t). Similarly, the economic value of blue water at site j , i.e. the natural runoff generated over the area drained by reservoir j , is given by the product between $q_t(j)$ and $\lambda_t(j)$.

To sum up, the transactions are based on the following principles:

- RBA sells to the J reservoirs the natural flows $q_t(1), q_t(2), \dots, q_t(J)$ at a price $\lambda_t(1), \lambda_t(2), \dots, \lambda_t(J)$ respectively. RBA charges for the water entering the system in order to cover the costs associated with its mandates (e.g. conservation, coordination, compensation, etc.);
- reservoir j sells to the hydropower plant j , denoted HPP $_j$, a volume $r(j)$ at a price $\lambda_t(j)$. Here a reservoir charges the hydropower station for the volume of water released through the turbines. The price is the marginal value of the water kept in storage;
- reservoir j sells to the irrigators j (IDA $_j$) a volume $i(j)$ at a price $\lambda_t(j)$
- the downstream reservoir $j + 1$ buys a volume $r(j)$ at a price $\lambda_t(j + 1)$ from the hydropower plant j . The water that was bought by the hydropower plant from the upstream reservoir can be sold back to the downstream reservoir but at a price corresponding to the value of water in that reservoir.

To illustrate how the transactions are calculated for the hypothetical system showed on Fig. 2, one must start with the upstream reservoir (site 1) whose water balance equation is

$$\Delta S_t(1) - e_t(1) = r_t(1) + l_t(1) + i_t(1) - q_t(1)$$

where i_t , e_t and l_t are irrigation water withdrawals, evaporation losses and spillage losses respectively. The financial transactions between the institutions around this

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reservoir are based on

$$\lambda_t(1)(\Delta s_t(1) - e_t(1)) = \underbrace{\lambda_t(1)r_t(1)}_{\text{HPP}_1} + \underbrace{\lambda_t(1)l_t(1)}_{\text{RBA}} \quad (7)$$

$$+ \underbrace{\lambda_t(1)i_t(1)}_{\text{IDA}_1} - \underbrace{\lambda_t(1)q_t(1)}_{\text{RBA}}$$

- 5 where the signs + and - mean that the reservoir is “selling to” and “buying from” respectively. In the previous equation we can see that the reservoir is selling $r_t(1)$ to the hydropower company who owns the hydropower plant 1 (HPP₁), $l_t(1)$ to reservoir 2 through RBA, $i_t(1)$ to the irrigation district 1, and is buying $q_t(1)$ from RBA.

Then, for the immediately downstream reservoir 2 we have

$$10 \Delta s_t(2) - e_t(2) = r_t(2) + l_t(2) + i_t(2) - q_t(2) - r_t(1) - l_t(1)$$

and

$$\lambda_t(2)(\Delta s_t(2) - e_t(2)) = \underbrace{\lambda_t(2)r_t(2)}_{\text{HPP}_2} + \underbrace{\lambda_t(2)l_t(2)}_{\text{RBA}} \quad (8)$$

$$+ \underbrace{\lambda_t(2)i_t(2)}_{\text{IDA}_2} - \underbrace{\lambda_t(2)q_t(2)}_{\text{RBA}}$$

$$15 - \underbrace{\lambda_t(2)r_t(1)}_{\text{HPP}_1} - \underbrace{\lambda_t(2)l_t(1)}_{\text{RBA}}$$

The main difference with the most upstream reservoir 1 is that the downstream reservoir (here reservoir 2) is now buying water coming from the immediately upstream reservoir (here reservoir 1). We can compute these balances until we reach the last

20 reservoir J where

$$\Delta s_t(J) = r_t(J) + l_t(J) + i_t(J) - q_t(J) - r_t(J - 1) + l_t(J - 1)$$

and

$$\begin{aligned}
 \lambda_t(J)\Delta s_t(J) = & \underbrace{\lambda_t(J)r_t(J)}_{\text{HPP}_J} + \underbrace{\lambda_t(J)l_t(J)}_{\text{RBA}} \\
 & + \underbrace{\lambda_t(J)i_t(J)}_{\text{IDA}_J} - \underbrace{\lambda_t(J)q_t(J)}_{\text{RBA}} \\
 & - \underbrace{\lambda_t(J)r_t(J-1)}_{\text{HPP}_{J-1}} - \underbrace{\lambda_t(J)l_t(J-1)}_{\text{RBA}}
 \end{aligned}
 \tag{9}$$

Once those transactions are calculated, the water accounts can be established for various spatial and temporal scales depending on the policy objective at hand. The multi-reservoir system in the Eastern Nile river basin will be used to illustrate the framework.

2.3 The Eastern Nile River basin

As its name indicates, the Eastern Nile River basin drains the Eastern part of the Nile basin, a region that covers much of Ethiopia, Sudan and Egypt. The Eastern Nile River basin includes the Blue Nile, the Baro-Akobo-Sobat, the Atbara and the main Nile, i.e. the entire Nile basin except the White Nile which drains the Equatorial lakes (Fig. 3). The hydrological regime of the Blue Nile and the Atbara is characterized by a very high seasonal and inter-annual variability, while the White Nile has more constant discharges. With more than 70 % of the annual discharge of the Nile coming from these two highly variable rivers, the Blue Nile and the Atbara (Sutcliff and Parks, 1999), Egypt would be exposed to a significant hydrological risk without the High Aswan Dam and its multiyear storage capacity.

The dominant uses of the Nile waters are irrigated agriculture and hydropower generation, which are mostly taking place in Egypt and Sudan. The largest hydraulic infrastructures are listed in Table 1 and the current largest reservoir is Lake Nasser in Egypt (High Aswan dam – HAD). If the two downstream riparian countries currently have the

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lion's share in terms of irrigated agriculture and hydropower generation, this is likely to change in the near future as Ethiopia is now developing majors infrastructural projects in the Blue Nile Basin such as the Tana-Beles irrigation/hydropower project and the Grand Ethiopian Renaissance Dam (GERD). The latter will have a storage capacity of 65 km^3 (more than the annual flow at the border between Ethiopia and Sudan) and a power station of 5000 MW. Other power stations further upstream on the Blue Nile are also on the drawing board in Ethiopia. The topology of the system with these recent ongoing and planned developments is depicted on Fig. 4.

The hydro-economic model of the Eastern Nile basin is based on the schematization shown on Fig. 4. The schematization of Baro-Akobo-Sobat is not included in Fig. 4 as this sub-basin is still natural, with no/minimal water resources development. The allocation decisions are chosen to maximize expected net economic returns from irrigated agriculture and hydropower generation over a planning horizon of 10 yr and for 30 different hydrologic scenarios. Since the objective of this study is not to mimic current allocation policies, we made the assumption that countries would cooperate in order to maximize basin-wide benefits. Under this assumption, the stochastic multistage decision-making problem (Eqs. 1–4) can be solved, for example, by stochastic dual dynamic programming. This algorithm has been described in details in Goor et al. (2010) and in Marques and Tilmant (2013). Note that the proposed accounting framework could be established with the help of any other hydro-economic model, centralized or decentralized, as long as it provides allocation decisions and the corresponding MROC.

3 Analysis of simulation results

The analysis of SDDP-derived simulation results will be done for year 5 only in order to avoid the effects of the boundary conditions, i.e. the initial storage volumes and the zero terminal value function (Goor et al., 2010). After convergence of the SDDP algorithm,

a variety of results including MROC, outflows, storage levels and evaporation losses are available at each node of the system.

To illustrate the water accounting framework, we will first examine the following items on an annual basis:

- The value of blue water at site j . This is the economic value of runoff generated between node j and the immediately upstream node(s). This information could be used, for example, to prioritize soil and water conservation measures in the river basin.
- The opportunity cost of evaporation losses at site j . It corresponds to the benefits forgone faced by downstream agents due to evaporation losses from a man-made reservoir at site j .
- The opportunity cost of irrigation withdrawals at site j is the benefits forgone in the basin due to the consumptive use at site j .
- The value of turbinized outflows at site j gives the economic value of non-consumptive use at site j .

Table 2 list the average annual water accounts for the Eastern Nile basin for the items listed above, while figure (5) provides a spatial distribution of the average annual water accounts.

The analysis of these items reveals that the average annual economic value of blue water in Ethiopia worth more than USD 5.6 billion, which is significantly more than the amount measured in Sudan (USD 3.9 billion). Note that a significant portion of the value of blue water in Sudan corresponds to the White Nile originating from the Equatorial Lakes but entering the system at Karthoum to form the Nile river. In other words, if the water accounts were to be established for the entire Nile Basin, much of that amount (USD 2.53 billion) would actually be located in headwater of the White Nile (Uganda, Rwanda, Burundi, Tanzania, Kenya).

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Despite much lower storage capacity, the annual opportunity costs of evaporation losses from man-made reservoirs in Sudan is significantly higher than that in Ethiopia: USD 462 vs. 78 million respectively. This is due to the fact that the evaporative power of the atmosphere is much lower in Ethiopia than in Sudan. Again, this result indicates that large reservoirs should be built upstream. Note that Lake Tana is considered here as a natural reservoir. For Lake Nasser in Egypt, the opportunity cost is also significant (about USD 1 billion yr^{-1} , twice as much as Sudan) due to the combined effect of inadequate topography and dry climatic conditions.

For the irrigation activities, the average annual economic value of bulk water in Egypt is about USD 5 billion, which is consistent with MWRI (2005). In Sudan, the opportunity cost of water diverted to the irrigation schemes exceeds USD 1.2 billion yr^{-1} , which is still hundred times higher than that in Ethiopia (USD 12 million). With the economic parameters chosen for this study, it does not appear to be economically efficient to irrigate in Ethiopia where the MROC of water is high due to the presence of a cascade of non-rival uses downstream. This result shows that, from an economic standpoint, irrigation should take place downstream, after water has been used for hydropower generation in Ethiopia (Whittington et al., 2005).

The economic value of bulk water used for the production of hydroelectricity reaches, on average, almost USD 1 billion in Ethiopia, USD 283 million in Sudan and 693 million in Egypt. These amounts are directly proportional to the productivity ($\text{MW m}^{-3} \text{s}^{-1}$) of the power stations which, in turn, is influenced by the topography (the unit productivity increases with the head on turbines and thus with the hydraulic gradient).

On a shorter time step, it might be interesting to assess the value of storage services at site j . This is the economic value associated with water transfers over time. i.e. from the high-flow to the low-flow season, at a particular site in the basin. Here again, the benefits and costs are felt by downstream agents. In terms of storage, when GERD will be online, Ethiopia will be able to smooth the imbalances between supplies and demands throughout much of the basin. Those storage services worth on average USD 891 million yr^{-1} . This is significantly higher than the combined value of storage

services in Sudan and Egypt, which are valued at USD 79 and 228 million yr⁻¹ respectively. This stresses the importance of storing water as far upstream as possible in order to take advantage of the hydraulic gradient and to have the largest number of water users downstream who can benefit from regulated flows (Whittington et al., 2005).

Figure 6 shows the average monthly values of blue water at key nodes throughout the basin. The first layers in dark blue are the incremental flows at the different nodes on the Blue Nile in Ethiopia (Fig. 4). The contribution of the Dinder and Rahad rivers, the last tributaries of the Blue Nile before the confluence with the White Nile in Sudan are in light blue. The two nodes of the Atbara branch, which flows from Ethiopia through Sudan, are in red. Finally, the White Nile is in grey. In August, during the high flow season, the economic value of runoff almost reaches USD 2.5 billion with more than 70 % coming from Ethiopia (dark blue). During the low flow season, the economic value of the Blue Nile is negligible compared to the White Nile. In April, for instance, the Blue Nile only contributes to 22 % of the economic value of runoff in the basin. Those monthly economic values follow closely the hydrological regime discussed in the previous section because two large reservoirs in the system, HAD and GERD, tend to equalize the marginal water values across time periods (equimarginal principle).

4 Conclusions

This paper proposes an alternative approach to establish water accounts in multipurpose multireservoir systems. The approach exploits the results of traditional, optimization-based, hydro-economic models such as allocation decisions and marginal water values (marginal resource opportunity cost). By keeping track of the product between the water fluxes and their corresponding water values, it is possible to establish water accounts reflecting the scarcity of water. The approach is illustrated with the Eastern Nile River Basin in Africa where the dominant uses are hydropower generation and irrigation.

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The results indicate that the average annual economic value of runoff corresponds to USD 9.5 billion, which can then be split between irrigation activities (USD 6.1 billion), hydropower (almost USD 2 billion) and evaporation losses from man-made reservoirs (USD 1.5 billion). The approach makes it also possible to analyze the contribution of storage services to the overall value of the system. For the case-study, the Grand Ethiopian Renaissance Dam, which is currently under construction on the Blue Nile, could provide as much as USD 821 million of storage services annually.

The proposed approach could be implemented with any hydro-economic model as long as water fluxes and marginal water values are computed. In this study we made an important assumption; namely that basin-wide allocation is economically efficient. This assumption could be relaxed if a decentralized hydro-economic model were to be available for this case study. It would allow us to establish water accounts for various levels of cooperation and institutional complexity in the basin.

More complex hydrologic processes, such as infiltration, rainfall and subsurface flows, could also be valued if they are adequately represented in the hydro-economic model. However, despite recent advances in the field of optimization, there will always be a trade-off between model complexity and applicability. For the case study, it was beyond the scope of the present research effort to include more complex hydrological processes at the scale of that river basin.

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Table 1. Main completed dams and hydropower plants in the Eastern Nile River basin.

Name (Country)	River	Live Storage (hm ³)	Capacity (MW)	Lateral irrigation (yes/no)
Tis Abbay I and II (ET)	Blue Nile	0 (run-of-river)	86	no
Tana-Beles link (ET)	Blue Nile	0 (run-of-river)	270	no
TK-5 (ET)	Atbara	9200	300	no
Roseires (SU)	Blue Nile	6900	275	no
Sennar (SU)	Blue Nile	480	15	yes
Khashm El Girba (SU)	Atbara	630	17	yes
Jebel Aulia (SU)	White Nile	2800	30	yes
Merowe (SU)	Main Nile	8300	1250	no
High Aswan Dam – HAD (EG)	Main Nile	105 900	2100	no
Old Aswan Dam (EG)	Main Nile	0 (run-of-river)	500	no
Esna (EG)	Main Nile	0 (run-of-river)	90	no

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Table 2. Annual water accounts in million USD – Eastern Nile basin.

Country	Node	Blue water	Hydropower	Irrigation	Evaporation
Ethiopia	Lake Tana	450	0	0	0
	Tis Abbay I&II	0	1	0	0
	Tana-Beles	0	69	0	0
	Tana-Beles irrigation	0	0	12	0
	Karadobi	1555	0	0	0
	Beko-Abo	176	0	0	0
	Mendaya	1285	0	0	0
	GERD	1854	897	0	78
	TK-5	303	47	0	0
	Sub-total	5623	1013	12	78
Sudan	Roseires	0	0	0	62
	Upstream Sennar	0	0	236	0
	Sennar	0	0	531	28
	Downstream Sennar	527	0	88	0
	Khashm El Girba	899	1	189	0
	Jebel Aulia	2530	0	117	253
	Nile – evaporation1	0	0	74	0
	Merowe	0	282	0	119
		Sub-total	3957	283	1236
Egypt	HAD	0	524	62	1011
	Old Aswan Dam (I&II)	0	160	0	0
	Esna	0	10	0	0
	Delta	0	0	4832	0
		Sub-total	0	693	4895
	TOTAL	9580	1989	6143	1551

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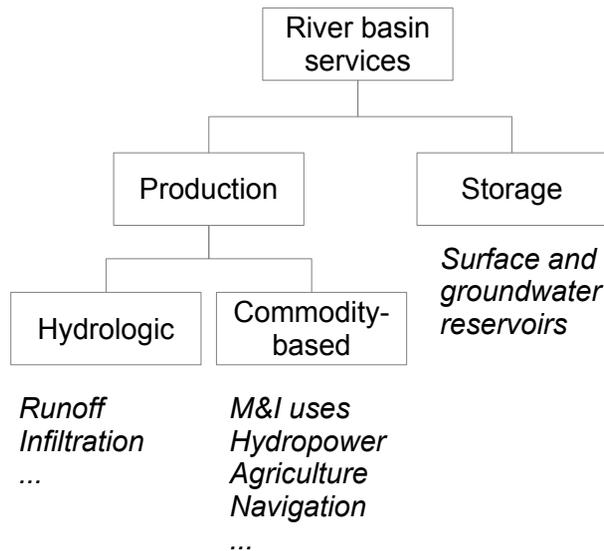


Figure 1. Production and storage services in a river basin.

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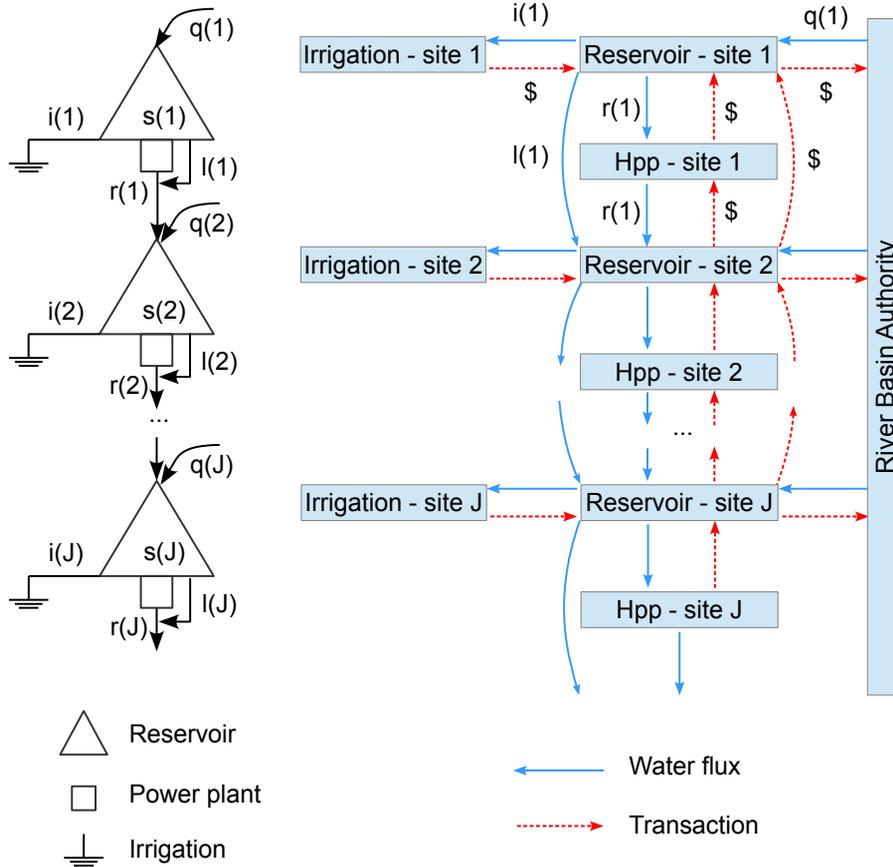


Figure 2. Cascade of J multireservoirs – water fluxes and financial transactions.

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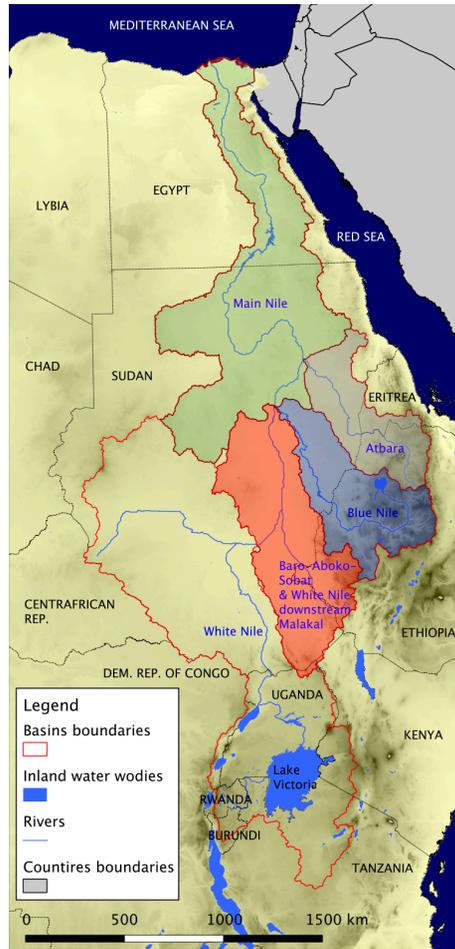


Figure 3. The Eastern Nile River Basin.

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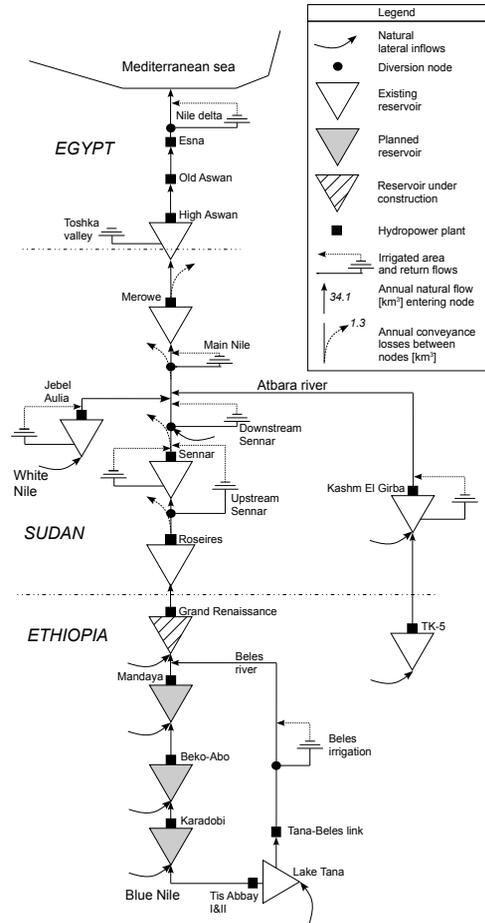


Figure 4. Schematization of the Eastern Nile River Basin.

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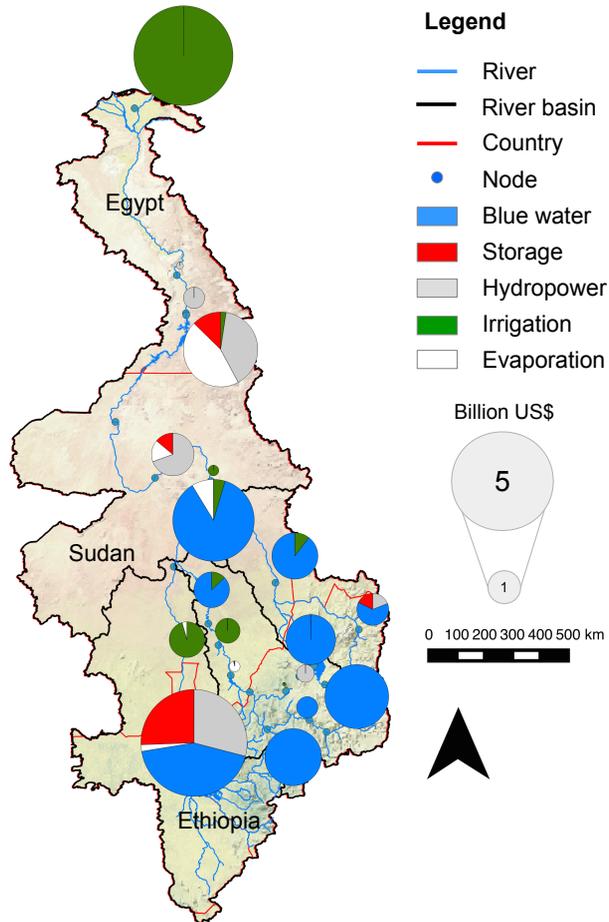


Figure 5. Average annual water accounts – Eastern Nile River basin.

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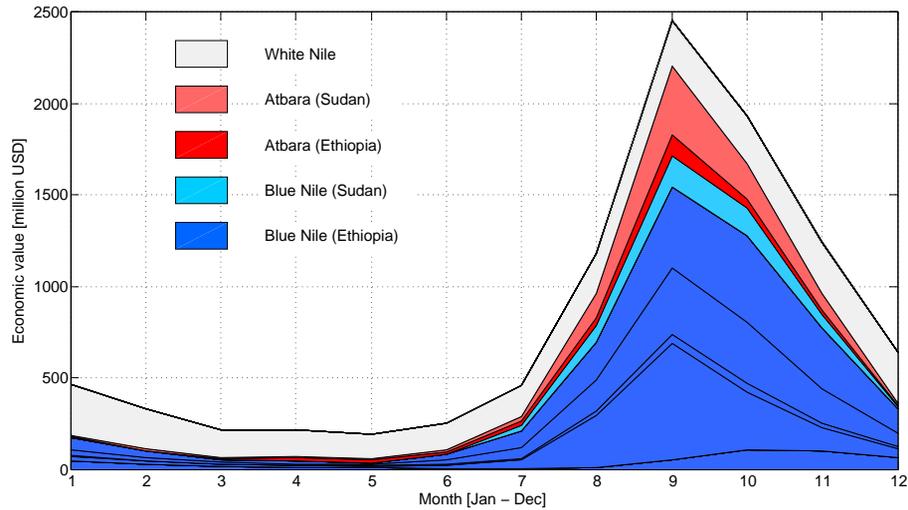


Figure 6. Average monthly values of blue water in the basin.

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