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Analysis of water demand and management rules in the Senegal River watershed: contribution of the weap21 model

Abstract

Covering an area of 325,000 km² with average rainfall of 700 mm, the Senegal River basin, like all river basins in West Africa, was affected by the droughts of the 1970s, leaving it vulnerable. In response to this situation, the Organization for the Development of the Senegal River has implemented a number of programs and projects aimed at optimizing water resource management in the various sub-watersheds. It is in this context that the inadequacy of drinking water production from groundwater has been noted, resulting in the use of surface water through reservoirs and dams to meet this ever-increasing demand. Unfortunately, however, this new approach has encountered certain difficulties, largely due to high evaporation, silting, and rapid population growth. Faced with such difficulties in mobilizing water resources, the OMVS decided in 1986 and 1988 to build the Diama and Manantali dams to offer more opportunities for water, electricity, and hydro-agricultural development. With a view to improving the management of this infrastructure, the methodological approach adopted in this study consisted of using WEAP models as decision-making tools for water assessment and allocation. This approach is based on several axes: simulating watershed flows using WEAP; evaluating the capacity of the various structures; and evaluating the satisfaction of water dLemand in a context of climate change. Our results first reveal a break in 2006 in terms of rainfall, characterized by an upward trend in rainfall. This daily time step modeling using WEAP shows that the model performs well, with satisfactory performance parameters (performance criteria: NASH=0.79, R^2 =0.89, BIAS=-0.07, and RMSE=3.99).

Keywords: WEAP21 model, hydroelectric regulation, transboundary water management, governance of the Senegal River basin

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Introduction

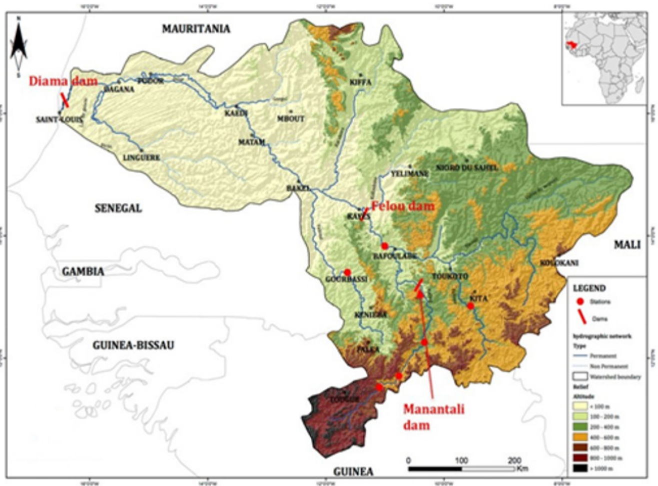
Like other countries in the Sahel region, the Senegal River was affected by the droughts of the 1970s, which revealed the basin's vulnerability to significantly low and irregular rainfall over time and space. This situation led to an exceptional awareness of water issues, marking a decisive turning point from which all successive governments have made water management a priority and a major focus of development policy in the countries (Guinea, Senegal, Mali, and Mauritania) that share the basin. This awareness led to the formulation, for the first time in 1986, of a water policy focused on urgently meeting the water needs of the population and strengthening the response capabilities of government services, with the support of numerous donors. Since then, the implementation of various water policies, strategies, and action plans has led to the construction of two large dams: the Diama Dam for hydro-agricultural purposes and the Manantali Dam for hydroelectric power generation.

Many scholars have recommended the use of water management-related software for assessing water resources and needs. The Water Evaluation and Planning (WEAP) system, which was developed by the Stockholm Environment Institute (Rakoutondrabe et al, 2007), is an integrated water resource planning tool that provides a comprehensive, adaptive, and user-friendly policy analysis framework.[1] Integrated water management at the watershed level is a management approach that considers all activities that impact water resources within a watershed in a sustainable manner without compromising the viability of ecosystems.[2] WEAP is a practical instrument for water resource planning and policy analysis that combines water supply in the context of demand-side management, as well as water quality and ecosystem preservation and protection.[3]

In order to prevent noticeable water problems, it is necessary to understand current and future water resources and user water needs at the watershed level. To achieve this, appropriate tools are available, such as the Water Evaluation and Planning System (WEAP) model, which operates on the principle of water balance and is easy to use for analyzing various water development and management scenarios (Yates et al., 2005). The aim is to develop a decision-making tool to guide the sustainable management of water resources in the upper Senegal River basin.

Study area

The Senegal River basin covers an area of 325,000 km², distributed between Senegal, Mali, Mauritania, and Guinea. The river system has four major tributaries: the Bafing, Bakoye, Falémé, and Upper Senegal (Map 1). Several resilient infrastructure projects are located within the Senegal River basin. These projects include dams used for agricultural and hydroelectric purposes. The Senegal River basin is characterized by two seasons: a rainy season (from approximately May/June to October) and a dry season (from November to April/May). Rainfall therefore varies depending on location relative to the equator. It decreases from south to north, ranging from 1600 mm to 2000 mm/year in the Upper Basin, 500 mm to 600 mm/year in the Upper Valley, 300 mm to 400 mm/year in the Middle Valley, and 200 mm to 300 mm/year in the Lower Valley and the Delta. Rainfall is variable both temporally and spatially (varying between the four climatic zones).



Map 1 General overview of the Senegal River watershed.

Data source

This work was carried out using several types of data (hydrological, climatic) from the following stations:

I. Bafing Makana on the Bafing

II. Kidira on the Falémé

III. Bakel on the Senegal.

Data configuration

The WEAP tool was developed in 1988 by the Stockholm Environment Institute. It is intended to be a flexible, integrated, and transparent planning tool for assessing the sustainability of current demand and distribution and for exploring alternative long-term scenarios. WEAP was first applied in Central Asia at the Aral Sea in 1989 by the Stockholm Environment Institute (SEI). Over the years, it has been applied in many countries and river basins.

WEAP stands out for its integrated approach to water system simulation and its policy orientation. WEAP places water demand (water use patterns, equipment efficiency, reuse, costs, and allocation) on an equal footing with supply (flow, groundwater, reservoirs, and water transfers) (Yates et al., 2005). The choice of WEAP software used in our work is justified by its availability, accessibility, and the availability of input parameters. The WEAP model is based on the construction and evaluation of scenarios for the evolution of water resource systems. It offers continuous integration between semi-distributed hydrological models and water resource allocation models (Yates et al., 2005).

The WEAP software license was obtained by the Stockholm Environment Institute (Sweden). Thus, the specificity of the «Water Evaluation and Planning System (WEAP)» model lies in its ability to proceed by an integrated approach, allowing both the simulation of natural components, i.e. hydrological inputs, evaporation, runoff, but also anthropogenic components, dams, pumping stations, agricultural developments etc. Its role is to assist the planner (Figure 1).

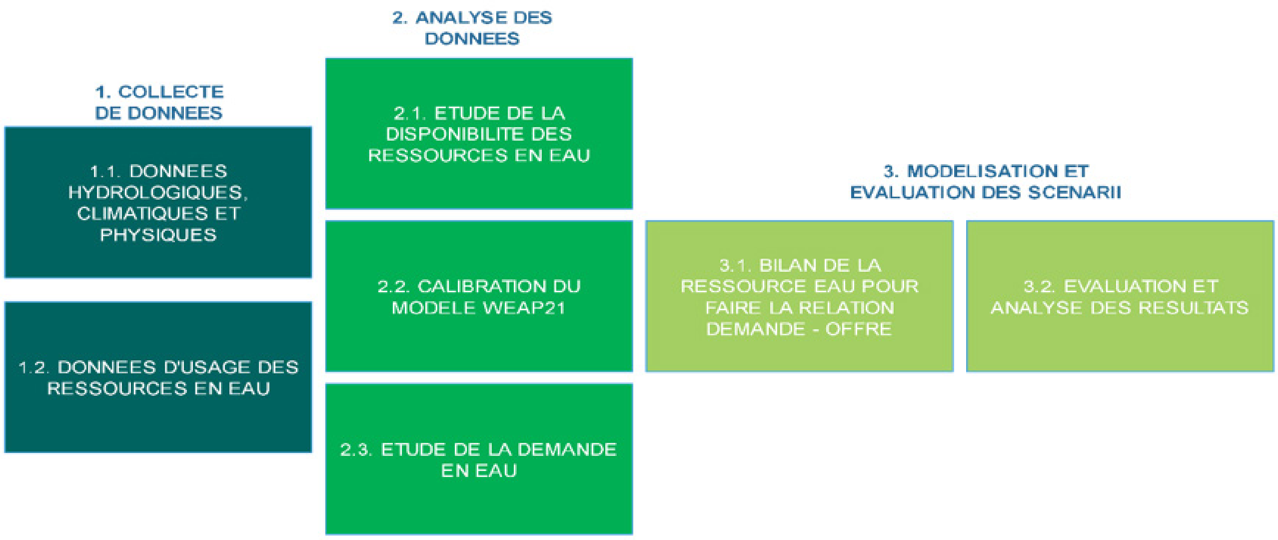


Figure 1 Schéma méthodologique de la modélisation WEAP.

Below is a diagramm that describes the modeling process with WEAP. In each case, demand calculations are based on a disaggregated accounting of various measures of social and economic activity (number of households, hectares of irrigated agriculture, industrial and commercial value added, etc.). In the simplest cases, these activity levels are multiplied by the water use rates of each activity (water use per unit of activity). Each activity level and water use rate can be individually projected into the future using a variety of techniques, ranging from the application of simple exponential growth rates and interpolation functions to the use of sophisticated modeling techniques that leverage WEAP's powerful integrated modeling capabilities. More advanced approaches can incorporate hydrological processes to determine demand (e.g., crop evapotranspiration calculations to determine irrigation requirements). To parameterize the model, several stations were considered in relation to the different sub-basins of the Senegal River, with a reference date. The stations used for testing the model are Bafing Makana on the Bafing River, Gourbassi on the Falémé River, and Kayes on the Senegal River (Map 2).

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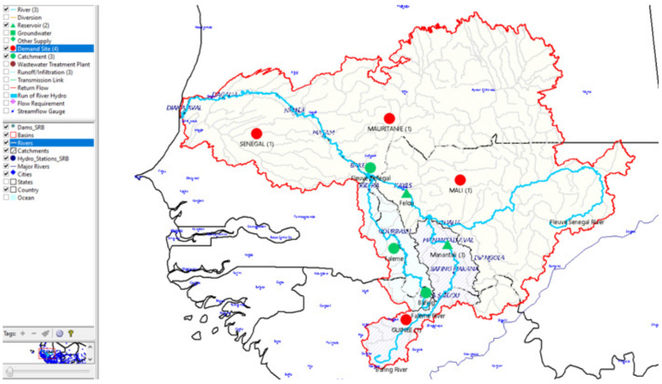

Map 2 Schematic representation of the Senegal River basin.

Scenario development

WEAP is relatively simple and easy to use for testing the effects of different water management scenarios. Hydrological, meteorological, and water supply records for the study area were collected and arranged as input data to fit the WEAP model. The results are easy to visualize for comparing different scenarios. The Sustainability Index (SI), as proposed by Chaudhary et al.[4] and illustrated by equation (1), is used by the model as a framework to assess the ratio of aggregate possible water demand to the corresponding current supply. This validates medium- and long-term water fulfillment for supply and demand under varying flow dependency conditions.

$$SI = \begin{cases} \frac{(S-D)}{S} & S > D \\ 0 & S \leq D \end{cases} \qquad (1)$$

where S is the quantity of water available and D is the water demand.

The development of scenarios is based on future assumptions and expected increases for the various indicators. Thus, the WEAP model allows for the adoption of possible water resource management processes based on the results generated by the model. In this analysis, we consider two scenarios: the baseline scenario and a scenario for increasing the irrigated area and reducing crop water requirements. The scenarios addressed «what if» questions, such as what happens if the economic development model changes, or what happens if more efficient irrigation technology is implemented.

The model was validated using a new dataset covering the period from 2006 to 2023. Given the break observed in 2006, the sample differential distribution test was used to validate the model. It should be noted that the new series (2006-2023) was not used when calibrating the model. Validation consisted of checking the calibration that had been carried out previously and determining whether the model could be used operationally in the study basin. To do this, the input parameters (Kc, CRS, FRR, ZCR, and DPE) from the calibration were entered into the model to simulate the period 2006-2023, and the response was compared to the observed flows using performance criteria (Nash, PBIAIS, RMSE, and correlation coefficient).

Interpretation of results

To carry out this preliminary work of allocating water resources according to the needs of users in the Senegal River watershed, the Water Development and Management Master Plan was considered as the basic reference.

Agriculture

Based on the reference data, the 2007 water requirements were allocated according to agricultural land area. For an area of 1,025 hectares under cultivation, and considering off-season crops with the highest water demands, the Guinean portion of the basin required 21,115,000 m³ (SDAGE 2011). For the same year, Mali's off-season crop requirements for 682 hectares were estimated at 14,049,200 m³. This brings the total water requirement for Mali's off-season crops to 32,177,200 m³. For Mauritania, in the current situation (2007-2008), the cultivated area for winter crops amounts to 13,540 ha and for off-season crops to 3,847 ha. The water requirements for these crops amount to 291,826,200 m³. In Senegal, to meet the current water needs of the 31,321 ha cultivated off-season and the 29,312 ha of winter crops (2007-2008), 1,105,424,219 m³ of water would be required (Table 1).

Table 1 Irrigation water requirements for the year 2007-2008 in the Senegal River basin. Source: SDAGE 2011

Country	Current needs (m³) 2007-2008
Guinea	21,115,000
Mali	32,177,200
Mauritania	291,826,200
Senegal	1,105,424,219
Totals	1,450,542,619

The total volume of water required for the 2007-2008 season to meet the needs of irrigated crops in the Senegal River basin was 1,450,542,619 m³ (SDAGE, 2011). The dominant agricultural system is traditional. It is largely extensive and dominated by food crops, primarily cereals and tubers. According to field survey results, small farms predominate: 64% of farms cover less than 2 hectares, and only 4% cover more than 7 hectares. These are generally poorly equiped farms, where work is carried out mainly by family labor using rudimentary tools. Cash crops consist of cotton, coffee, and fruits and vegetables.

Hydropower in the River

In order to implement an efficient and balanced development model, the states of Mali, Mauritania, and Senegal, within the framework of the OMVS (Senegal River Basin Development Organization), undertook the partial development of the Senegal River basin by constructing the Diama and Manantali dams, along with the recently completed (2013) run-of-river Felou dam. The water resources harnessed by these two hydroelectric dams and their associated infrastructure enable the development of at least three important sectors: irrigation, hydroelectric power generation, and navigation. For hydroelectric power, the expected production from Manantali is at least 800 GWh. With the construction of the dams, recession agriculture represents a smaller share than before (an average of between 50,000 hectares cultivated on both the left and right banks (Table 2) This situation results from the partial control of water flow (regulation from Manantali, dikes, etc.) and the increasing proportion of developed land dedicated to irrigated agriculture. During the rainy season and the hot off-season, the main crop remains rice. However, during the cool dry season, the following crops are grown: onion, tomato, okra, potato, maize, sorghum, and watermelon, peanut.

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Table 2 Characteristics of existing and planned dams in the basin

Dams	Types of dam	Watercourse	Storage Capacity (mm³)	Dead volume (mm³)	Turbine capacity (m³ / s)	Installed power (MW)
Diama	Salt-free	Senegal	5900	2500	-	-
Manantali	Reservoir	Bafing	11300	3300	491	200
Koukoutamba	Reservoir	Bafing	3600	700	400	280.9
Boureya	Reservoir	Bafing	5500	2650	370	160.6
Gourbassi	Reservoir	Falémé	2100	600	60	25
Félou	Along the water's edge	Senegal	-	-	500	60
Gouina	Along the water's edge	Senegal	-	-	700	140
Balassa	Along the water's edge	Bafing	-	-	31.3	180.9

For this study, scenario analysis was conducted to assess changes in future water demand due to population growth rates and the potential of irrigated land. However, livestock consumption rates are expected to remain constant, and the trend is projected to follow the same pattern as increasing water demand. Given the scale of the basin, domestic consumption was not considered; only agricultural use is included, pending further investigation.

These scenarios differ depending on the hydroelectric facilities considered and the integrated water demands. It does not necessarily describe evolution of system, but allow all of even of test a few types of instructions chosen arbitrarily from an infinity.

For example, the first scenario (S1) reproduces the current conditions of the basin's development. In this scenario, Manantali is the only water intake structure in the basin. The basin's installed capacity is 200 MW and the irrigated area is estimated at 75,000 ha (SDAGE, 2011). This scenario does not take into account navigation, which is not yet controlled in the basin. scenario 2 (S2) takes into account A layout total of their valley And of delta with multiplication by three Agricultural development along the river and consideration of river navigation between Kayes and St- Louis will increase the irrigated area from 75,000 hectares to 255,000 hectares. The commissioning of the Félou and Gouina power plants will bring the total installed capacity to 400 MW. MW (Figure 2). In these two scenarios, Manantali East THE alone dam regulator, Félou and Gouina operate over time water therefore does not are not taken into account in the regulation. Comparing the two scenarios allows us to assess Manantali's capacity to cope with an increase in low-water support needs. Scenario 3 would be analyzed under the effect of the development of the upper basin on the river's hydrological regime, on the productivity of downstream power plants, and on meeting the increased demands of the valley and the delta.

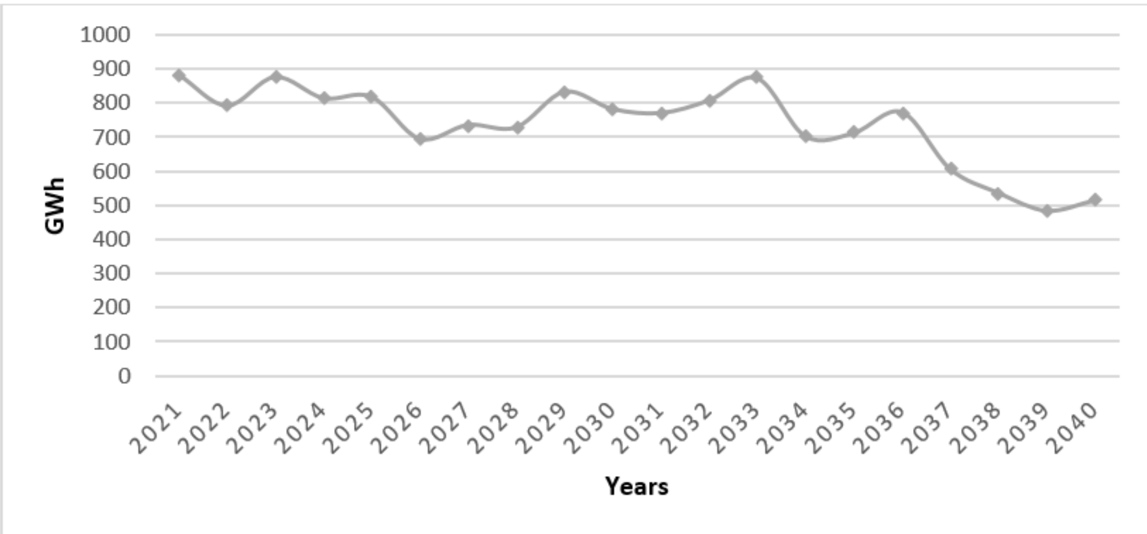

Figure 2 Simulated Production at Manantali (GWh)/year.

Thus, three political scenarios are conceivable:

I. Policy 1 prioritizes hydroelectricity over other uses;

II. There policy 2 favors THE support of the bass waters on hydroelectricity ;

III. Policy 3 would give equal priority to all uses of the basin.

This model is not exhaustive ; many parameters are not taken into account due to gaps in the database.

Discussion

In this study, the results obtained are comparable to the work of Ghenim A. and Megnounif A.,[5] which found that the Tafna watershed supplied water for the various uses of over 2 million people. This watershed, equipped with 5 dams with a total capacity of 385 hm³, has experienced a rainfall deficit estimated at approximately 25% since the mid-1970s. This decrease in rainfall has led to a steadily increasing decline in surface and groundwater resources in the region. The seasonal forecast of natural flood volume in Bakel (Pouget et al, 2021) details two approaches: (1) modeling based on statistical analysis of monthly rainfall forecasts on a grid covering West Africa; (2) modeling based on statistical analysis of the contributions of the river's three main tributaries. The search for the best indicator for forecasts in the Weap model led to the use of the sum of the inflows at Oualia, Gourbassi, and Balabori, upstream of the future Koukoutamba dam. Thus, water allocation models, sometimes called water availability models, are essential tools for effective water resource management and decision-making tools for all concerns related to water resource development.[6] Li et al.[7] developed an optimization model for resource allocation toward the sustainable management of the link between water, food, and agricultural energy under uncertainty. Water allocation involves distributing water to different regions and sectors without sufficient consideration of the amount of water consumed after distribution.[8] The spatial and temporal limitations and inequalities of water supply hinder the increase in water demand indicated by the density of headwater nodes in the river system. It requires an equal proportional water allocation determined by the model.[9]

Water management models are effective tools for addressing water scarcity. Indeed, simulations of water supply and demand can support decision-making processes for regional water resource planning. Water management models have been the subject of numerous studies and applications. Examples of water management models used in previous research include MODSIM, WEAP, AQUATOOL, RIBASIM, and WARGI-SIM.[10] They utilize the WEAP model within various scenarios. However, most allocation models developed have only considered activities around water resources and not their interconnections. You et al.[8] developed a stochastic nonlinear programming model used for water allocation over multiple time periods with multiple objectives. The model aims to allocate water while taking into account both human and ecological needs. The core of the model is the DAMOS (Multi-Objective Decision Analysis) and ROWAS (Rule-based Object-oriented Water Resources System Simulation Model) modules, which are applied together to analyze water allocation within the framework of projected economic growth and protection, and to formulate a water quantity and quality control plan at provincial boundaries. DAMOS is a multi-objective decision support model. It was designed to consider society, the economy, the environment, water resources, and investments based on the macroscopic mechanism of their relationships. The interaction between resources and capital is abstracted under the mechanism of promoting water to the socio-economics.

The eligible model is necessary to analyze the compromise solution for multidimensional decision-making. In recent years, water scarcity and the accompanying problems within the context of deteriorating water conditions have spurred further research on water allocation.[8] Other studies have decided to extend the developed model to a larger scale, considering more complex correlations between water, food, and energy, and incorporating more forms of uncertainty to improve its practicality and applicability.[7]

Demand-side concerns, such as water consumption patterns, equipment efficiency, reuse methods, pricing, and water allocation schemes, are treated with equal importance by the model alongside supply-side concerns, such as stream flow, groundwater supplies, reservoirs, and water transfers.[11] Several studies around the world have been conducted using WEAP. Another study using the WEAP model focused on Strategic Decision-Making in Sustainable Water Management.[12] WEAP has been used to assess future water demand in Boumerzoug, in the upper sub-catchment of the Kébir-Rhumel basin.[13] In Syria, an estimation of water supply and demand by 2050 using the WEAP model was conducted.[14] In Somalia, WEAP was used for the assessment of the Streamflow and Evapotranspiration at Wabiga Juba Basin.[15] In the Mediterranean region and in arid and semi-arid climates such as Algeria, the WEAP model has been extensively utilized in various studies. For instance, to analyze water resources and their uses in the Oued Kébir Ouest watershed.[16] These studies demonstrate the valuable role of WEAP in assessing water management strategies in regions facing water scarcity challenges. The WEAP model is highly regarded for its ability to simulate water resource systems and support decision-making in water management. Studies have shown its effectiveness in analyzing scenarios, assessing climate change impacts, and aiding water allocation planning across different scales. Overall, it is a valuable tool for water resource management.[17–25]

Conclusion

In many river basins, numerous infrastructures withdraw, store, and discharge large quantities of water from shared rivers. Ensuring the overall coordination of all these interventions is one of the most important challenges in water resource governance in these basins, especially in the current context of climate variability and change. Furthermore, framing resource allocation in terms of quota distributions among riparian states or major users creates intractable situations where each party defends its own interests without regard for those of others. The OMVS's decision, reaffirmed in the 2002 Water Charter, is to allocate available water resources among various sectors—domestic and livestock consumption, agriculture, energy, navigation, ecosystems, etc. In doing so, it appears that the OMVS (Senegal River Basin Development Organization) had been practicing the Water-Food-Energy-Ecosystem Nexus well before this paradigm emerged in 2011, following the convergence of a series of global crises – notably the food crisis, the energy crisis, and the financial crisis against a backdrop of climate change and unsustainable pressure on freshwater resources. The task of allocating water resources among different sectors of use is a crucial technical undertaking to ensure the sustainability of a basin, especially a transboundary one. The WEAP21 model is indeed the model that allows for the integration of management policies and assumptions specific to the study area in order to implement an efficient regulatory model in a transboundary basin.

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None.

Conflcits of interest

The author declares there is no conflcit of interest.

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