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# Understanding the trade-offs between climate change-induced aridity and agricultural water demand in the Souss basin, Morocco

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The concept of integrated water resource management requires an in-depth analysis of water inflows into a river basin. Population growth and the uncertainties associated with climate change are causing increased water stress and droughts, which are impacting agriculture. Hence the need for studies on the impact of climate change on demand-supply interactions in river basins. In this study, a generic decision support system, ModSim, was used; for the first time in the region; to examine the agricultural water usage and demands over Souss basin in Morocco. ModSim was calibrated over the period from 1990 to 2019 using recorded data about physical processes and hydraulic infrastructures features and management. The simulations succeeded in replicating different deficit episodes at the various irrigated perimeters. During the simulated period from 2012 to 2019, it was observed that the water supplies for the different dams in the basin experienced a decline ranging from 38% to 89%. As a result, the average total unmet demand for surface water from reservoirs in irrigated areas reached 201 $mm^3$ between 1990 and 2019 and the monthly average demand increases by 55% in the dry season, compared to the demands in the rest of the year. The significant amount of unmet demand across all sites suggests that demands are satisfied by the withdrawal of water from groundwater resources. The adopted approach has proven to be a useful decision support tool to understand water resources planning challenges. Water managers require such reliable tools to represent the basin's water trade-offs. Thus, additional investigation to improve the representation of groundwater/surface water interaction approaches is required to enhance the evaluation of the consequences of different uses, especially in arid and semi-arid regions with significant water stress such as Souss. A conceptual framework as well as a detailed discussion have been produced in order to guide efficient water management and governance.

KEYWORDS

decision support system, ModSim, water allocation modeling, climate change, Souss

# 1 Introduction

Water is a very valuable resource that is needed for human life, production, and ecosystems. In the last few decades, policy and scientific debates have paid more and more attention to this resource (Cook and Bakker, 2012; Le Page et al., 2012; Seif-Ennasr et al., 2021). Due to natural and anthropogenic causes, Morocco is currently facing a serious water crisis, with water shortages and water pollution (Bouchaou et al., 2008; Malki et al., 2016; N'da et al., 2017; Danni et al., 2019; Hssaisoune et al., 2020; Ez-zaouy et al., 2021; Mansir et al., 2021). This water crisis has threatened the country's agricultural production (Balaghi, 2017; Brouziyne et al., 2020; Achli et al., 2022). Therefore, special attention must be paid to water resources management as part of water governance in order to prevent the negative effects of water crises (Qian, 2016; Brouziyne et al., 2018; El Bilali et al., 2021).

The impacts of climate change are becoming more evident in Morocco and more regions of are impacted by drought in the last decades which placed the country in a worrying water situation (Ezzine et al., 2014; Benabdelouahab et al., 2015; Bijaber et al., 2018). Located in central-western Morocco, the Souss watershed experiences notable fluctuations in water resources and supplies across various scales. These variations are influenced not only by climate variability but also by anthropogenic activities, highlighting their interconnected impact on the region's water availability. (Bouchaou et al., 2011; Malki et al., 2017; Seif-Ennasr et al., 2017; Abahous et al., 2018a; Ait Brahim et al., 2019; Attar et al., 2022). As a result, efforts have been made to develop optimal strategies for the planning and management of available water resources. In the past few years, Morocco has put in place a variety of policies and initiatives in order to guarantee better water management. Even with new policies of integrated water resource management in Souss-Massa, which began with mobilizing a total capacity of 364 mm$^3$ of surface water resources by constructing dams, as well as the projection of using non-conventional sources of water (desalinization, reusing wastewater), the water budget of the region is still limited. These initiatives have not yielded desirable results since more in-depth knowledge of water resources and decision support systems (DSS) are needed to help better allocate the limited water resources in the region and instore a participative approach (Le Page et al., 2012; Berhe et al., 2013; Borden et al., 2016; Hadri et al., 2022).

The significance of water resources in sustaining and advancing various sectors underscores the need for effective management strategies. In the field of water resources management science, many approaches and methodologies have been used worldwide. Models served as invaluable tools for comprehending and predicting the spatial and temporal variability in water management, they offer a systematic approach to understanding the hydrological processes within the basin, enabling the estimation of catchment water balance (Qi and Altinakar, 2011; Allain et al., 2020; Brouziyne et al., 2021; Momm et al., 2022; Wang et al., 2022; Guemouria et al., 2023; Ouarani et al., 2023; Rafik et al., 2023). Those models contributed to the enhancement of water management practices, offering a scientific foundation for decision-making to ensure the sustainable and efficient utilization of this vital resource (Le Page et al., 2012; Apostolaki et al., 2019; Zare

et al., 2019; He and Jiao, 2022; Malmir et al., 2022). Furthermore, AI and machine learning are for water management (Rajaee et al., 2019; Yaseen et al., 2019; Zounemat-Kermani et al., 2020). These approaches, including optimization and statistical learning, also simulate groundwater time series and integrate with other models. AI's success in processing water quality data, making it essential for river water quality monitoring, management, and policy development (Tiyasha et al., 2020).

The goal of using DSS in water resources management is to consider the best possible use of the limited supply of water (Mourad and Alshihabi, 2016). To allow a spatial mapping of the watershed, mathematical models are used to provide an in-depth analysis of the different components of the water sector. The research and design of water resource systems has extensively utilized optimization models (Loucks et al., 2005). In the case of a monoculture, the issue of irrigation scheduling has been examined extensively (Bras and Cordova, 1981; Rao et al., 1992). Several scientists have examined the distribution of a limited water supply for the irrigation of a multicultural area (Rao et al., 1992; Gorantiwar and Smout, 2005).

In recent years, a wide variety of ModSim applications have been carried out. The model has been successfully applied to model both the quantity and quality of water in several regions (Larson and Spinazola, 2000; Sharon et al., 2001). At the basin scale, Modsim has been as well used to examines the water productivity of crop yields, to analyze the water balance and to determine the different water allocations (Shourian et al., 2008; Mousavi and Shourian, 2010; Berhe et al., 2013; Vaghefi et al., 2017). An enhanced version of ModSim called as GEO-ModSim has been created in order to connect ModSim to a GIS for the administration of spatial datasets (Triana and Labadie, 2007). Despite the importance of such model in the optimization of the water allocation among different users, no previous specific studies have been carried out in the basin.

The main objective of this study is to assess the agricultural water use and demand of a complex basin under a semi-arid climate. In addition, the study was carried out to quantify the current water demands and assess the impact of recent climate change on the water balance of four agricultural perimeters in the study area. The study will help evaluate the unmet temporal demand for irrigation water. The results of such study can be used to improve water resources management at the local and basin scale and contribute to the scientific literature on the hydrological impacts of human intervention.

# 2 Study area

The Souss basin is located in central-western Morocco (Figure 1). The High Atlas Mountains are on the north side of the basin, the Anti-Atlas Mountains are on the south side, the Siroua Massif is on the east side, and the Atlantic Ocean is on the west side.

In recent decades, monthly observations highlight substantial seasonal irregularities, notably a decreasing trend in precipitation and a simultaneous increase in average monthly temperatures (Figure 2). The mean annual temperature changes from 14°C to 20°C from north to south. In the summer, the maximum
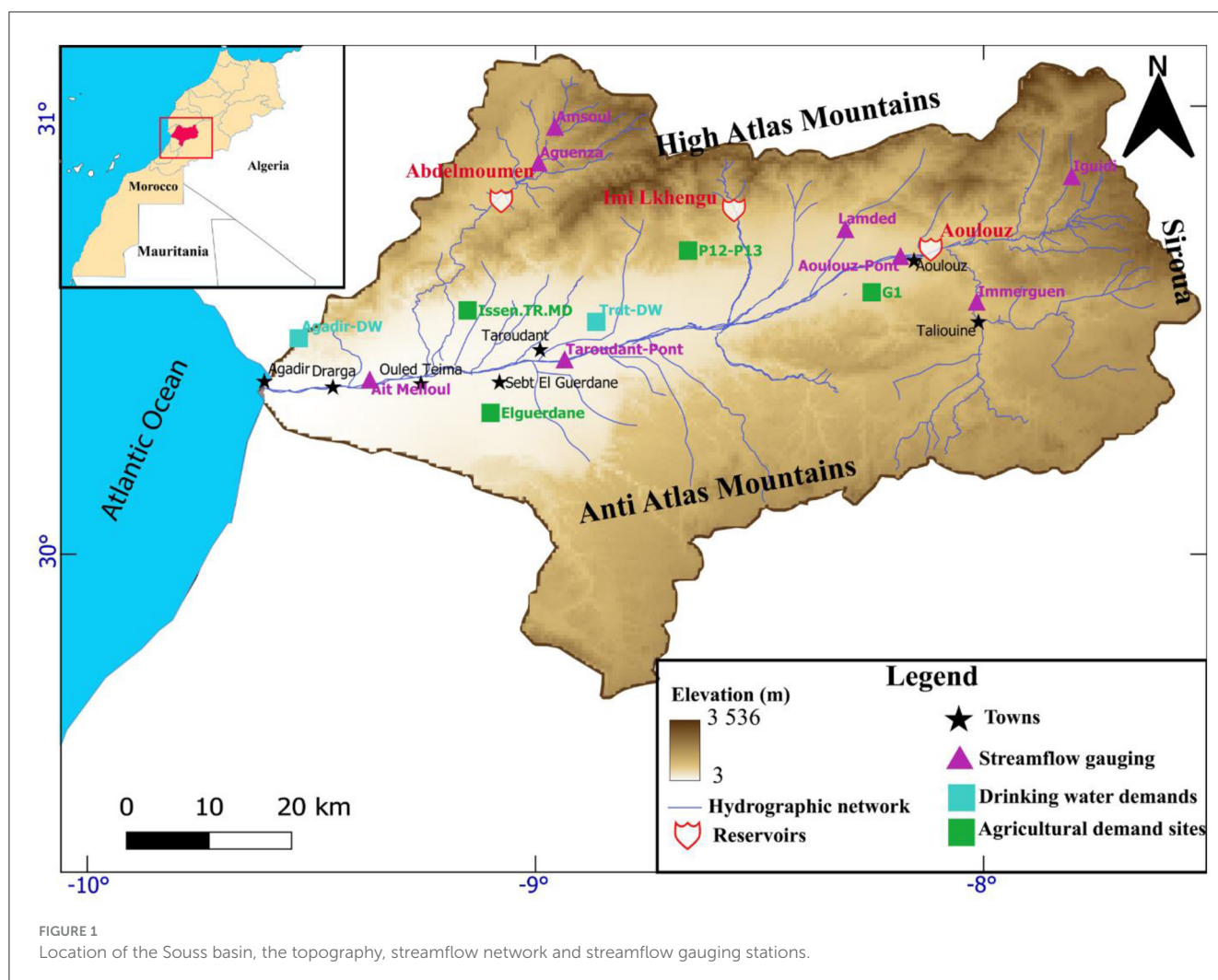
FIGURE 1
Location of the Souss basin, the topography, streamflow network and streamflow gauging stations.

temperature can reach 49°C while in the winter the temperature sees lows of −3°C. Precipitation has an average of 600 mm in the High Atlas, 150 mm in the Anti Atlas and the plain gets an annual average of 200 mm (Ait Brahim et al., 2017; Seif-Ennasr et al., 2017; Abahous et al., 2018b).
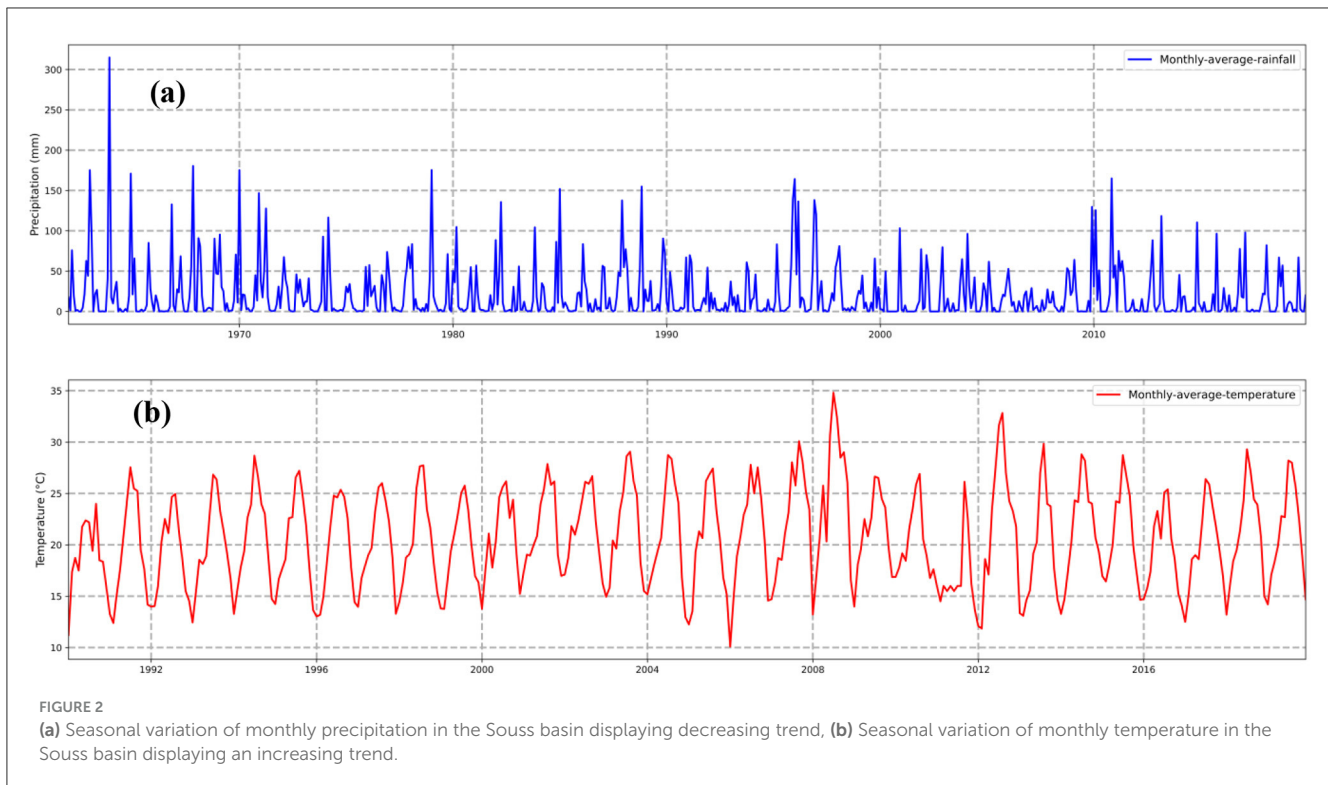
According to the RCP 4.5 (optimistic Representative Concentration Pathway 4.5 Wm−2 toward 2100) and RCP 8.5 scenarios (pessimistic Representative Concentration Pathway 8.5 Wm−2 toward 2100), the average temperature should rise by 1.5 and 2.5 degrees Celsius between 2045 and 2055, and by 3 and 6 degrees Celsius by the end of the century. On the other hand, climate change will affect precipitation. In both the RCP4.5 and RCP8.5 scenarios, precipitation will drop by 10% to 30% between 2030 and 2049, and by up to 60% between 2080 and 2099 (Seif-Ennasr et al., 2016).

The Hydraulic Basin Agency (ABHSM) has the legal authority to coordinate and manage the water and the administration of all the consumers and suppliers of water. The Souss-Massa Hydraulic Basin Agency collaborates with several stakeholders, including the Regional Agricultural Development Office of Souss-Massa (ORMVASM) and the National Drinking Water Office (ONEP), that supplies water to rural and urban consumers.

The agricultural development of the basin depends mainly on the Souss water table, and is supplemented by the releases of the three dams (Aoulouz, Imi-lkhengu and Abdelmoumen) of the basin. The volumes of the dams are mainly intended to satisfy the demand for drinking water in the basin. The areas supplied directly by the dams in the basin are grouped into four main areas (Figure 1).These perimeters are: (a) the G1 perimeter, (b) the Elguerdane perimeter, (c) the traditional Issen perimeter and the modern Issen perimeter (ISSEN. TR.MD) and (d) P12-P13. The main crops of these four perimeters are market gardening, cereals and citrus.

Based on the abundance of its natural resources, the Souss basin has considerable economic potential. The region's growth is mostly related to the agricultural sector, the fishing industry, tourism and the mining industry. In spite of its dry climate, the region is currently experiencing intensive agriculture production which constitutes the main economic system in the region. The agricultural area represents 100,000 ha. The majority of these lands are located in the Souss plain, which is known for its early crops and citrus fruit production

However, despite all these difficulties, the area is the first, in Morocco, in terms of exporting vegetables and citrus fruits. The

FIGURE 2
**(a)** Seasonal variation of monthly precipitation in the Souss basin displaying decreasing trend, **(b)** Seasonal variation of monthly temperature in the Souss basin displaying an increasing trend.

Souss region is responsible for 6.6% of the country's gross domestic product (GDP), as reported by the High Commission for Planning and deduced from an investigation into the years 2013–2017. On the other hand, 15.3% of the regional gross domestic product is contributed by the region's agriculture production.

## 3  Methods

In this research, we provide a methodological framework that was developed in order to analyse the water management in the study area basin. The Methodology adopted for the study is illustrated in Figure 3. The figure provides the steps that were taken in order to successfully implement the model.

### 3.1  Data availability

Meteorological time series data, crop surface data, data on water demand and data on water supply were all utilized in this study. The inputs for ModSim were gathered from a variety of different sources including the streamflow simulation of missing data using the GR2M model (Mouelhi, 2003; Mouelhi et al., 2006) and calculation of crop water requirements.

Climate data for (1990–2019) from nine stations in the Souss basin were obtained. Data on the flows of the tributaries of Oued Souss were obtained from the Agency of the hydraulic basin of Souss-Massa (ABHSM). The flows were selected for the stations of the tributaries of Oued Souss (Iguidi, Immerguen, Lemdad, Amsoul, Aguenza) and the stations located at Oued

Souss (Aoulouz.Pont, Taroudant.Pont, Ait Melloul). ModSim was calibrated and evaluated using flow data.

In order to finish preparing the missing data, the rainfall-runoff model GR2M (Mouelhi, 2003; Mouelhi et al., 2006) was used. Precipitation and potential evapotranspiration are the primary factors that were considered by the model. The model was chosen for its simplicity and to overcome the over-parameterization of other complex models (Zamoum and Souag-Gamane, 2019). The GR2M model has been successfully applied in various geographical and climatic contexts. Planning and management of water resources are the two main applications of the GR2M model (Dezetter et al., 2008). The GR2M model has been the solution and the tool that is being loosely used to predict monthly runoff in ungauged watersheds (Zamoum and Souag-Gamane, 2019), as well as the reconstruction of monthly runoff information (O'Connor et al., 2021). In the case of lack of data, the simple structure of the model makes it the best solution to simulate monthly flows correctly (Bachir et al., 2015).

Irrigation site data were collected through consultations with governmental organizations Regional Agricultural Development Office (ORMVASM). The consultations included the identification and location of agricultural perimeters, water sources, crop surfaces, and irrigated areas. The data were used to estimate crop water requirements. In addition, additional perimeter data were extracted from reports and studies on the Souss basin.

Table 1 displays the different hydrological and demands inputs used for ModSim. The simulation is calibrated based on the period 1990–2009 flow measured on the Souss River at the Taroudant-Pont and Ait Melloul measuring sites. The period 2010–2019 was used for the validation of the model.
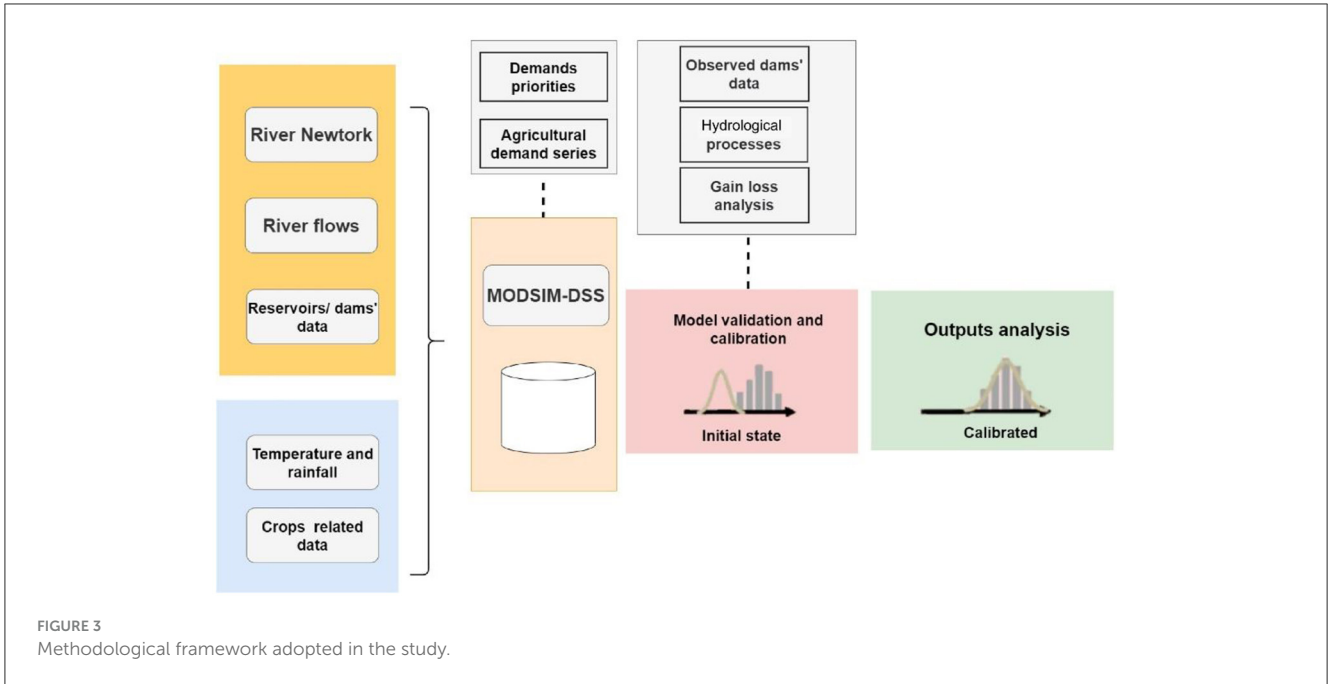
**FIGURE 3**
Methodological framework adopted in the study.

**TABLE 1** ModSim input data.

| Data | Timeseries length | Source |
|---|---|---|
| Temperature and rainfall | Monthly (from 01/1990 to 12/2019) | Local climate and water management authority: Hydraulic Basin Agency of Souss-Massa (ABHSM) and Regional Agricultural Development Office of Souss-Massa of Souss-Massa (ORMVASM). |
| Streamflow and rivers data | Monthly (from 01/1990 to 12/2019) | Local water management authority: Hydraulic Basin Agency of Souss-Massa (ABHSM) |
| Reservoirs/dams data Details on: Hydraulic reports of the dams Maximum and minimum volumes Elevation-area-capacity Groundwater seepage/infiltration coefficients | Monthly time series (from the date of commissioning of each dam to 12/2019) | Local water management authority: Hydraulic Basin Agency of Souss-Massa (ABHSM). |
| Crop related data | Details on the evolution of the planted crop surfaces. Monthly time series (from 01/1990 to 12/2019) | Local management authority: Regional Agricultural Development Office of Souss-Massa of Souss-Massa (ORMVASM). |
| Demands priorities | | Local water management authority: Hydraulic Basin Agency of Souss-Massa (ABHSM). |
| Agricultural demands series | Monthly time series (from the 01/1990 to 12/2019) | Calculated |

## 3.2 ModSim

The decision support system program ModSim was first developed in 1978 at Colorado State University (Shafer and Labadie, 1978). In ModSim, links and nodes reflect the physical and hydrological properties of a river basin system as well as artificial and conceptual components to simulate the complicated administrative and legal systems affecting water allocation. These links and nodes are required to ensure the mass balance of the network (Labadie, 2010).

ModSim solves a network flow optimization problem for each time period $t = 1,\dots,T$:

$$\text{Minimize} \sum_{k \in A} c_k \ q_k \tag{1}$$

subject to

$$\sum_{k \in Oi} q_k - \sum_{j \in li} q_j \ = \ b_{it}(q) \ \text{for all nodes I} \in \text{N} \tag{2}$$

$$l_{kt}(q) \ \leq \ q_{kt} \ \leq \ u_{kt} \ (q) \ \text{for all links k} \in \text{A} \tag{3}$$

A represents the set of all links in the network, the group of node is represented by N. $O_i$ is the group of links that start at node i. $I_i$ is the group of links that end at node i ; $b_{it}$ represents the gain (positive) or loss (negative) that occurred at node I during the time period t; $q_k$ is the flow rate in link k; $c_k$ represent the costs or water right priorities per unit of flow; in link k. $l_{kt}$ and $u_{kt}$ are lower and upper bounds, respectively, on the flow in link k at time t. $b_{it}$, $l_{kt}$, and $u_{kt}$ are network flow vector q functions (Labadie, 2010).

FIGURE 4
ModSim model network.
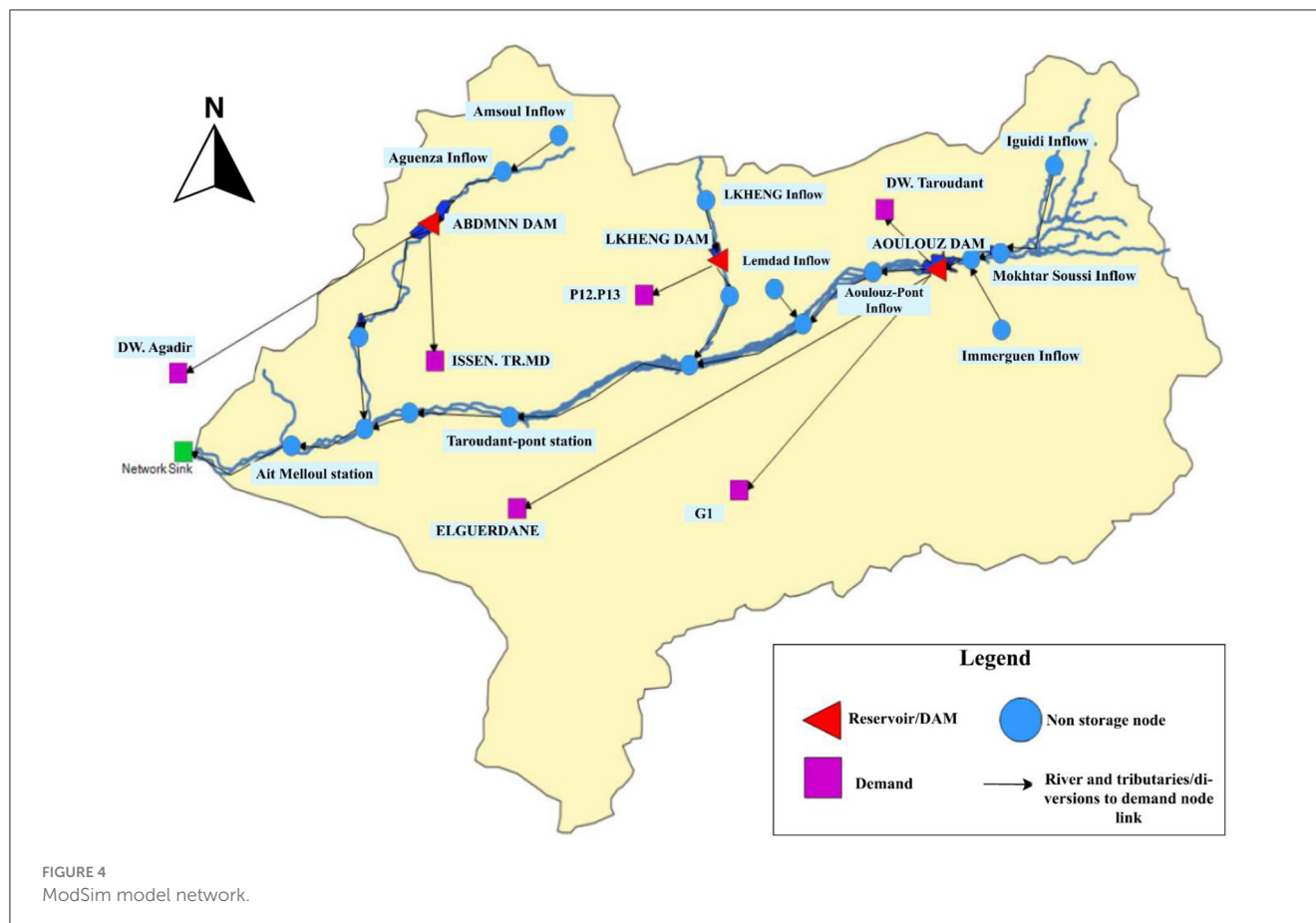
## 3.3 Network schematization

Using ModSim, the Souss basin system was represented with nodes and links (Figure 4). The nodes represent the reservoirs (dams), demands and confluences of rivers. The links represent the sections of the rivers or diversions linking the dams with the consumer demands. The three reservoir nodes represent the three dams Aoulouz Dam (AOULOUZ DAM), Imi-lkhengu Dam (LKHENG DAM) and Abdelmoumen Dam (ABDMNN DAM). The irrigation demand nodes represent the agricultural perimeters: The G1 perimeter, the modern and traditional Issen perimeters (Issen.TR.MD), Elguerdane perimeter and the P12–P13 perimeter. The two applications DW.AGADIR and DW.Taroudant represent the two drinking water demands of the two cities Agadir and Taroudant respectively.

## 3.4 Irrigation demand

To get the monthly average values of evapotranspiration, the equation developed by Blaney and Criddle (1962) is used. The equation is the most frequent and extensively used particularly in dry and semi-arid regions as well as in areas with a lack of data (Espadafor et al., 2011; El-Nashar and Hussien, 2013; Valipour et al., 2017). In this study, the irrigation water demand was estimated by combining data collected from the regional development office

(ORMVASM) on the perimeter crops, the types of crops and the calculated evapotranspiration. Crop coefficients were provided by FAO document 56 (Allen et al., 1998). Cultivated areas were multiplied by water requirements to determine agricultural water demand.

In this study we considered two development paths to make the analyses. In the first period (1990–2006), the dams provide a small part of the discharges for irrigation and the irrigation of relied mainly on pumping from the groundwater. The period (2007–2019) where the area started to adopt new policies to safeguard the agricultural areas namely the project to safeguard the citrus growing area of Elguerdane which consists of a transfer of an annual volume of water from the Aoulouz dam, and the rehabilitation of small and medium irrigation schemes in the Souss region. The information on the two periods was built based on information from the official document which is the Master Plan for Water Resources Management in the Souss Massa Drâa region, which provides the regional planning of water resources management in the region.

## 3.5 Model calibration and validation

In order to construct a solid reference for modeling for the scientific community in the area, and since no previous Decision Support System tool was performed in the Souss basin,

important efforts were made to push the model to replicate the historical processes of the study area. ModSim is not provided with automatic calibration or parameters estimation capabilities. Manual calibration can be very time-consuming, and this has been one of the biggest challenges of this first use of the model in the Souss basin. The calibration of the model was performed by adopting the knowledge of the physical parameters of the watershed, the hydrologic processes, and the experience with the model. The assessment of the calibration and validation was based on the manual inspection of the results over time. The trial-and-error procedure was adopted to adjust the parameters while comparing and evaluating the observed and simulated outputs using graphical plots. The approach was by making the best estimation of the network parameters and the actual data and then making sure that predicted flows match the trends and general tendency of the observed data.

The gain loss analysis of the network was first performed for the Souss basin. Then the first 19 years (1990–2009) of the data sets were used for the calibration and the last 9 years (2010–2019) were used for the model verification. Different assumptions were used for the simulation to develop the unexplained gain and loss terms firstly analyzed.

The first calibration (hydrologic calibration) was used in the model to calibrate its water mass balance and to define the model accuracy and deficiencies in the input data, then the second calibration was performed using the observed reservoir volumes as target storage to represent the different operations of the reservoirs. The calibration was performed to meet the flow levels observed in the gaging stations along the Souss river, using observed flows from the calibration time for the water deliveries, and the infiltration coefficient of the bed of the wadis, reservoir seepage loss coefficient and the evaporation of the dams.

In the absence of any prior initiatives to determine infiltration coefficients in the basin, a considerable effort is being made, but it is still not sufficient. Significant efforts were made to determine the importance of the infiltration processes in the area and determine the volume part that will participate in the recharge of the groundwater. The ModSim model was an ideal opportunity to adjust these parameters taking into consideration the geology of the bed of Oued Souss and of its tributaries.

The determination coefficient ($R^2$), the Nash–Sutcliffe coefficient (NSE), and the per cent bias (PBIAS) were the three statistical indicators that we looked at in order to confirm that there was a maximal concordance between MODSIM estimated flows and observed flow records :

$$R = \left( \frac{\sum_{i=1}^{n} (o_i - o_{avg})(S_i - S_{avg})}{((\sum_{i=1}^{n} o_i - S_{avg})^2 \sum_{i=1}^{n} (S_i - S_{avg})^2)^{0.5}} \right) \quad (4)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (o_i - S_i)^2}{\sum_{i=1}^{n} (o_i - S_{avg})^2} \quad (5)$$

$$PBIAS = \frac{\sum_{i=1}^{n} (S_i - O_i) * 100}{\sum_{i=1}^{n} o_i} \quad (6)$$

Where:

$O_i$: the value of the observed parameter during interval i

$S_i$: the value of the simulated parameter during same interval i

$O_{avg}$: the observed average values of the parameters per time period

$SP_{avg}$: the simulated average values of the parameters per time period

n: total time intervals.

# 4 Results and discussion

## 4.1 Streamflow simulation

Modsim-DSS has been used in several studies, and for many climatic conditions, including semi-arid climates (Cheong, 2008; Shourian et al., 2008; Fereidoon and Koch, 2018; Behboudian and Kerachian, 2021), but rarely in the African context. In fact, ModSim has been used in Ethiopia (Berhe et al., 2013) to analyze the water allocation to the upper, middle, and lower valleys of the Awash Basin at different levels of irrigation development. The approach developed in this study provides a first application of water allocation modeling of the Souss basin in Morocco. The development of the model calibration, and the design of the basin operating rules are a major achievement of this study. As this is the first time such a model has been applied in the region, Modsim-DSS has shown acceptable results in reproducing the hydrological processes that occur in a semi-arid environment.

After calibration, the observed monthly flows compared to the simulated flows, both ModSim simulated dams' inputs and hydrological stations installed in the Souss river reasonably match the observed data. Figure 5 illustrates the differences between the flows of simulated and observed volumes of the inputs of Abdelmoumen and Aoulouz dams throughout the calibration (1990–2009) and validation (2010–2019) periods. For the two periods, the coefficients $R^2$, NSE values are $> 0.6$. These findings suggest that ModSim is effective at reproducing observed data.

The hydrological calibration was carried out to meet the flow values reported by the gauging stations along the Oued Souss. This was achieved by utilizing data from the Taroudant Pont and Ait Melloul stations. The calibration process involved adjusting the infiltration coefficients of the Oued Souss beds, considering the loss coefficient at reservoir levels, and accounting for evaporation.

The simulated and observed flows for the calibration period (1990–2009) at the two stations Taroudant Pont and Ait Melloul are shown in Figure 6. The comparison indicates that model has well captured the general pattern observed at the two stations. The coefficients calculated are shown in Figure 6.

According to the results, ModSim tends to underestimate high flows (−30% to −38% of under estimation), as seen in the figures as well as the values of the PBIAS. This indicates that the inputs hydrologic data set may be missing certain tributary inflows that supply the Souss River. This may be explained by the fact that the right bank of the basin has a large number of tributaries which have a significant supply during flood periods but due to lack of data these supplies have not been taken into consideration. However, ModSim, on the other hand, is able to reliably follow low flows, which is likely of more significance given that the model is being used in the study to evaluate water allocation policies not the flood control operations. According to the findings of recent research, the
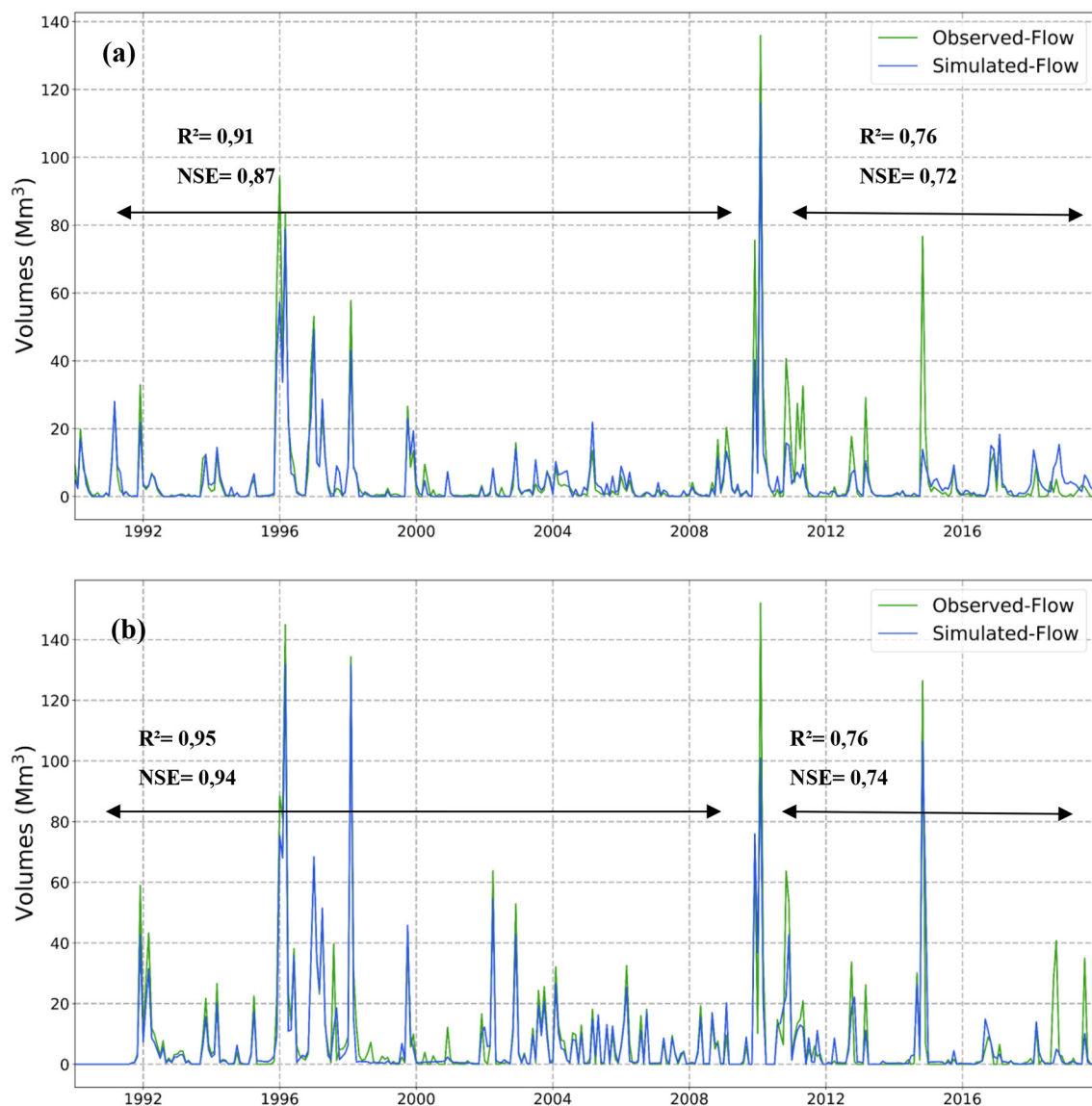
**FIGURE 5**
Simulated and observed monthly dams' inputs during the calibration and validation periods at **(a)** Abdelmoumen dam, **(b)** Aoulouz dam.

general decrease in surface water flow that has been occurring in the Souss region since the early 1970s is directly related to the decrease in annual precipitation (Ait Brahim et al., 2017).

The inflows from the dams have been decreasing during the whole study period, which can be linked to the drought periods that the region has experienced during this period. Drought-related studies in the study area (Bouchaou et al., 2008; Tagma et al., 2009) found similar results, continuous periods of drought and climate variability have impacted the hydrology of the High Atlas Mountains, which feed the main dams and aquifer of the basin.

## 4.2  Water demand

Results of agricultural demands for water are shown in Figure 7. With the increase of the temperature and the decrease of the precipitations, the agricultural water demand starts to increase in

a significant way, which exceeds a value of 600 mm$^3$ during the hot season. The monthly demand declines to 300 mm$^3$ in the wet season (the monthly average demand increases by 55% in the hot season, compared to the demands of the rest of the year).

A comparison of the water demand and the shortages recorded by all the perimeters every month is shown in Figure 7 which highlights the unsatisfied water demand. The increased demand in the summer season had led to an increase in the shortage in this period. The agricultural sector in the region is the most water-consuming where problems of water lack arise most in the hot period (May–Sep). This is explained by the fact that these months correspond to the dry seasons. In parallel, the groundwater pumping for irrigation will grow continuously during this period under the increase in demand. In contrast to the findings of Hadri et al. (2021), a study conducted in another Moroccan semi-arid area, the correlation between SPI (Standardized Precipitation Index) and SWI (Water-Level Index), shows is an increase in the
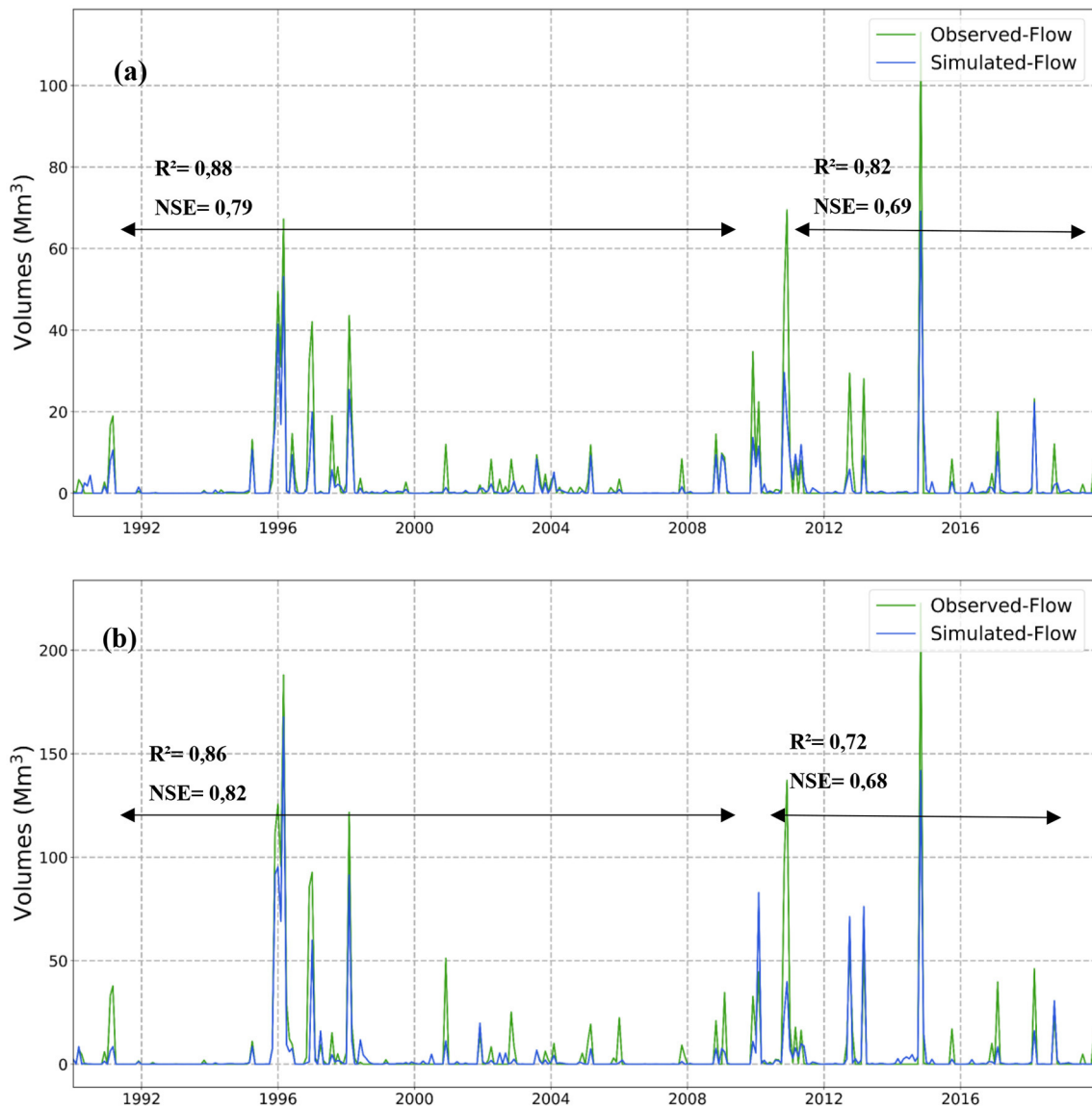
FIGURE 6
Simulated and observed monthly flows during the calibration and validation periods at stations **(a)** Taroudant-Pont, **(b)** Ait Melloul.
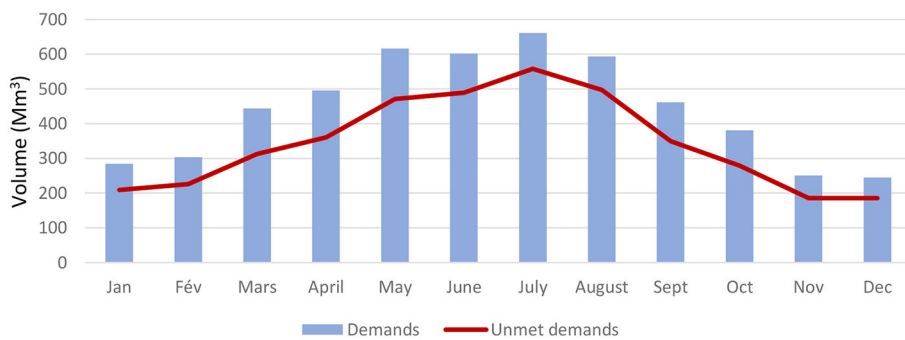


FIGURE 7
Monthly distribution of demand and unsatisfied demand during the simulation period (1990−2019).

use of groundwater to irrigate the primary crops. Hadri et al. (2021) also emphasized the significance of this time of year, which marks the beginning of the season for the development of many types of crops.

On the other hand, the findings of Lovelli et al. (2010) and Dettori et al. (2017) suggest that climate change has also induce increases in water demand (especially for irrigation), due to increased seasonal temperatures and evapotranspiration. Significant increases in temperature and decreases in precipitation lead to significant increases in water deficit and thus irrigation requirements. In fact, for some crops, the substantial increase in temperature and evapotranspiration demand leads to an anticipation of the thresholds for the beginning of the growing season and the harvest period (Lovelli et al., 2010; Dettori et al., 2017).

Figure 8 presents an overview of the annual total water requirements, supply, and unmet demand for the four perimeters (G1, Elguerdane, P12-P13, and Issen.TR.MD). Results from 1990 to 2019 show an average total water demand of 180 mm$^3$, with the average total unmet demand that reached 163 mm3, constituting a substantial 92% of the total demand. Peak demand and unmet demand reached 206 mm$^3$ and 201 mm$^3$, respectively, emphasizing the need for improved water resource management. Affected by factors such as precipitation, available supply from dams, and actual evaporation, unmet demand from the agricultural sector is lower in years with more precipitation (such as 1990–1991). In contrast, unmet demand increases in other years. These results are related to the work of Bouchaou et al. (2008) and Tagma et al. (2009), which pointed out that the Souss region has had a number of problems related to a lack of water frequent, long-lasting droughts, and climate change especially in the last decades (Latifa et al., 2017; N'da et al., 2017; Oumarou Danni et al., 2017; Ez-zaouy et al., 2023).

Irrigation accounts for a large part of water use in the study are. Moreover, the stored water in the dams is used for drinking water needs in the basin. Calculated delivered water supplies from each dam is shown in Figure 9, the figure shows the summary of water withdrawal from dams in the entire Souss basin for the period 1990–2019. The simulation period witnessed a considerable decrease in the supply levels from the different dams. The supplies decline in the last years (2012–2019) by 52% for Aoulouz dam and 89% for ABDMNN dam, while the supplies have decreased by 38% for lkhengu dam (Figure 9). The differences among different supply sources fluctuate during the simulation period, resulting from changes in the available water inputs each year.

In the studied perimeters, the extension of market gardening and citrus fruits, which require a lot of water, is unsuited to the potential of the aquifer, and constitutes a threat to the sustainability of groundwater resources (Choukr-Allah et al., 2017). In addition, during periods of surface water scarcity, farmers have to rely heavily on groundwater to compensate for the lack of river flow and the absence of supply from reservoirs (Heidecke et al., 2010; Seif-Ennasr et al., 2016). As a result, the Souss aquifer is subject to continuous intensive use that does not allow it to regenerate (Seif-Ennasr et al., 2021).

The annual water supply does not match the demand for all perimeters. Figure 9 indicates that the unmet demand has always

been important during the study period. During the period 2007–2019, after the rehabilitation of the perimeters and the supply of the different perimeters by dam releases, the unmet water demand amounts have slightly decreased. However, it has increased from 82% to 94% for the Issen perimeter and this is mainly due to the decrease in the Abdelmoumen dam inflows (Figure 5) which is the main source of irrigation releases for the traditional and modern perimeters of ISSEN. After the realization of the two projects that aim to supply the two perimeters Elguerdane and G1 with water from the Aoulouz dam, the unmet water demand has decreased to 87% and 91% respectively (Figure 10).

Even though the releases from the dams have reduced the demands of the two perimeters, the unmet demand remains high at these sites. The results suggest that the unmet demand is significant for all demand sites. Indeed, the demands will be met by the uncontrolled withdrawal of water from groundwater resources. These findings are in line with Hirich et al. (2017) and Seif-Ennasr et al. (2017) who discuss the development of the Souss region resulting in increasing demand for irrigation and a major loss of groundwater reserves.

Identical conclusions have been made by Bouchaou et al. (2017). The spatio-temporal decrease in groundwater levels observed in the area is related to the successive years of drought as well as to the considerable intensification of pumping (Bouchaou et al., 2017). On the other hand, and by analyzing the evolution of the levels of the groundwater resources of the Souss basin (Ait Brahim et al., 2017; Hssaisoune et al., 2017), demonstrated that the groundwater resources have shown a decrease in the last years. This decrease concerns all irrigation areas. They confirmed that groundwater resources are seriously affected by the succession of drought years and overexploitation mainly caused by agriculture. Over the past four decades, annual water level declines have averaged 0.5–2.5 meters (Hssaisoune et al., 2020).

Climate analyses in Morocco, established in the framework of the 3rd National Communication of Morocco to the United Nations Framework Convention on Climate Change, suggest that the average annual temperatures will increase for the period (2016-2035) from 1.0 to more than 1.8°C and precipitation will decline by between 3 and 30% (UNFCC, 2016). According to the conclusions of these climate change studies, many authors (Bouchaou et al., 2017; Elame et al., 2020; Seif-Ennasr et al., 2021) have claimed that because of the drought, there has been a huge rise in the overexploitation and the use of groundwater for irrigation. Our findings provide strong support to those conclusions as well.

The future development plans of agriculture and their potential impact on water supplies in the Souss basin should also be examined. The unsatisfied demands highlighted in this study have been of course satisfied through pumping which harms the groundwater resources of the Souss basin. In addition, the region has been equipped with development plans, namely the Generation Green strategy and the Plan 2020–2027, to enable this region to continue its territorial development and contribute to the national socio-economic growth. As a consequence, the influence of climate change on the hydrology of the area and the water demand will likely become much more pronounced which will certainly affect the water balance. Therefore, a simulation of the interactions between the hydrological cycle and water users in the region to
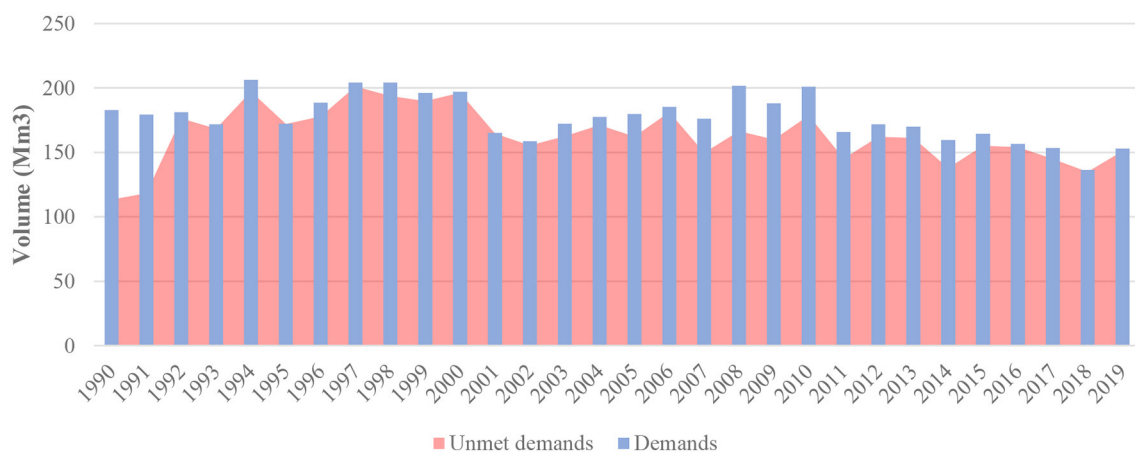
Annual distribution of demand and unsatisfied demand during the simulation period (1990−2019).

explore the medium- and long-term future scenarios in the region under climate change would be beneficial (Attar et al., 2022).

## 4.3 Conceptual framework for efficient water management

Water resources management in semi-arid basins, such as Souss in Morocco, requires holistic approaches (Parson and Fisher-Vanden, 1997; Davies and Simonovic, 2011; Bouchaou et al., 2017). To ensure economic and social stability and sustainable use of water resources, a conceptual model integrating the different challenges and opportunities of the basin will help to achieve the goal of sustainable use (Momm et al., 2022). The model will include a systematic approach where at each step the different pressures and drivers will be taken into consideration, and they will help to understand the interactions between the different components of the watershed and then produce improved decisions and measures.

The approach proposed herein (Figure 11) consists of two main steps: the starting point is the characterization of the current situation of the basin, and this is done through data collection or through the literature. After the data collection, a process must be conducted to distinguish the key causes that affect the water resources of the area. Then, the structure of the model will be extracted by analyzing the different relationships between the parameters of the framework (Qi and Altinakar, 2011; Apostolaki et al., 2019).

After determining the current situation of the basin, the various opportunities, challenges, and strengths that involve the basin's resources must be defined. The analysis will start with a detailed characterization of the different hydrological components and processes of the basin. This step also involves mapping the pressures and drivers on the water resources. The various changes and pressures on the state of the basin indicate the problems and constraints on the resources and human activities, and these problems and constraints may be exacerbated by current and future drivers (Maxim et al., 2009; Potschin, 2009; Kagalou et al., 2012;

Gari et al., 2018). This simulation will provide a picture of the basin's situation and will help develop informed responses as part of development plans for water-stressed regions.

Such an approach will help complex and semi-arid systems in mastering the relationships between production and resource sustainability (Terêncio et al., 2017; Terêncio et al., 2018; Brouziyne et al., 2018; Hssaisoune et al., 2020). In the next step, the design of this model will lead to the adoption and implementation of management policies to adapt to the different risks (Stocker et al., 2013; Schröder et al., 2019; Seif-Ennasr et al., 2021).

Farm management decisions are not always well understood, and agricultural production systems are rapidly evolving in response to changing customer expectations, food security concerns, and environmental impacts. In this context, the analyses adopted in this type of models will allow the generation of source-demand connections and the understanding of the effects of various conditions in time and space. Therefore, they allow specifying the different relevant measures that can be taken to decrease the negative impacts on the economy, society and the environment.

## 4.4 Research limitations and further research paths

In our study we used the water resource systems model ModSim-DSS to analyze the various water allocations of a semi-arid watershed as well as to illustrate the region's water balance at various irrigation perimeters. The analysis integrated the development of the agri-demand to examine the different consequences on a complex nationally important river basin system that combine major consumptive demands (agriculture and drinking water) and complex multifunctional infrastructures as well as the different development plans.

For meaningful assessment of results and crucial usage in decision making, models must be correctly calibrated and validated using observable data. Data is considered a classic issue in modeling dry areas. A considerable limitation of this proposed framework in
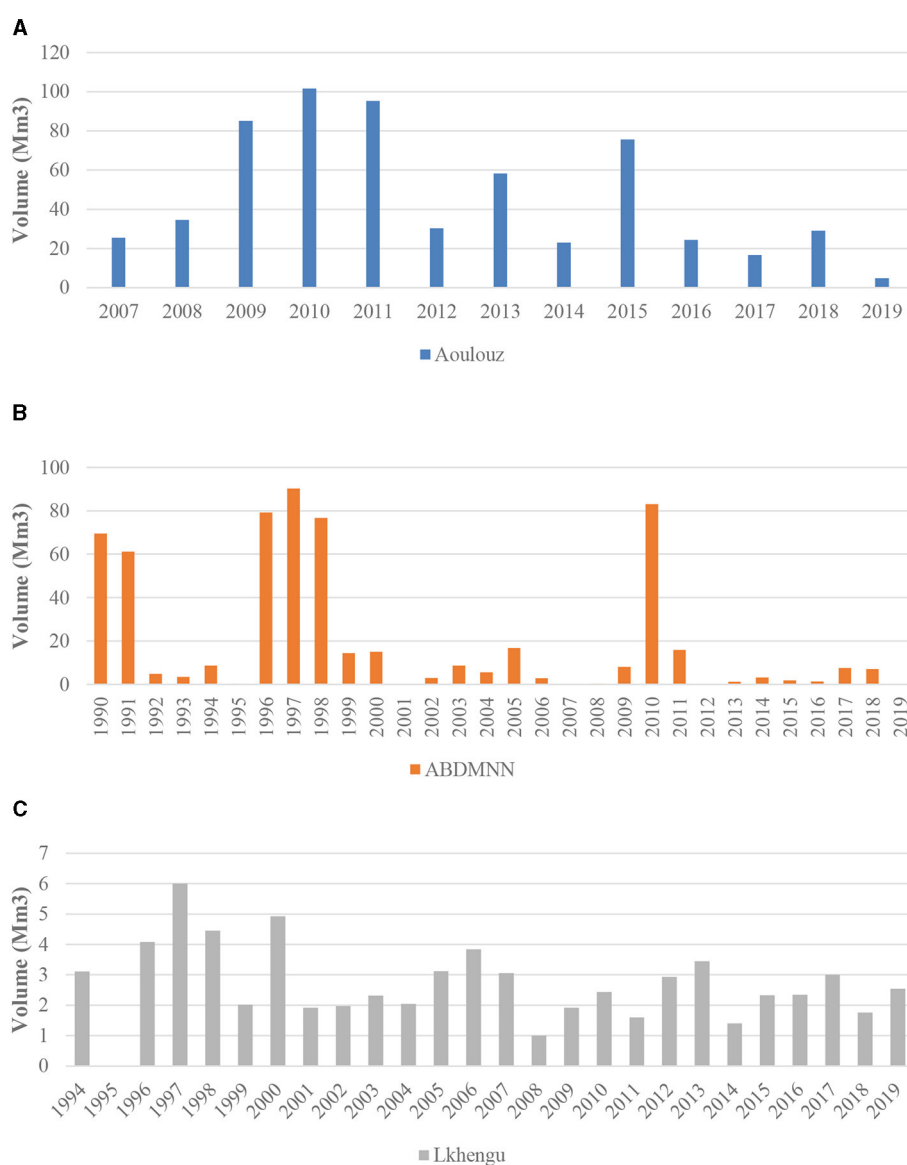
FIGURE 9
Delivered water supplies from each dam (1990–2019), **(A)** Aoulouz dam, **(B)** Abdelmoumen dam, **(C)** Lkhengu dam.

this study is the data quality and quantity. Due to the fact that semi-arid agricultural watersheds are susceptible to intense hydrologic and anthropogenic impacts, having access to relevant data is essential (Samimi et al., 2020). However, the flow measurement stations in the sections of Oued Souss and its tributaries have some gaps, the different floods that the area has experienced have damaged the different measurement tools which resulted in several missing records that could not be measure at the station, and the tributaries of the Souss river were not gauged for longer periods. The model performance was improved with the estimation of the missing either by the linear regression or the use of an external model to fill the gaps of the stations.

The study has known some limitations which need to be improved to deal with the different interactions of the basin in future works. Firstly, ModSim was carefully calibrated to better

understand and validate the different parameters characterizing the basin. The calibration integrated the customization features of the model. This later gives the opportunity to use automatic calibration to estimate the basin parameters. Basin parameters in the model need to be estimated with highest precision to ensure that the model's outputs can be based upon and that the model's simulations closely match observations (Maclean, 2009; Moradkhani and Sorooshian, 2009). Hence, the use of optimization algorithms to develop automatic calibration has shown interesting results (Sabzzadeh et al., 2016). With the automatic calibration, the determination of the parameter's procedure is formulated as an optimization problem through an objective function. These algorithms help to improve the objective function by looking at and testing different parameter values to help the model replicate the observed data.
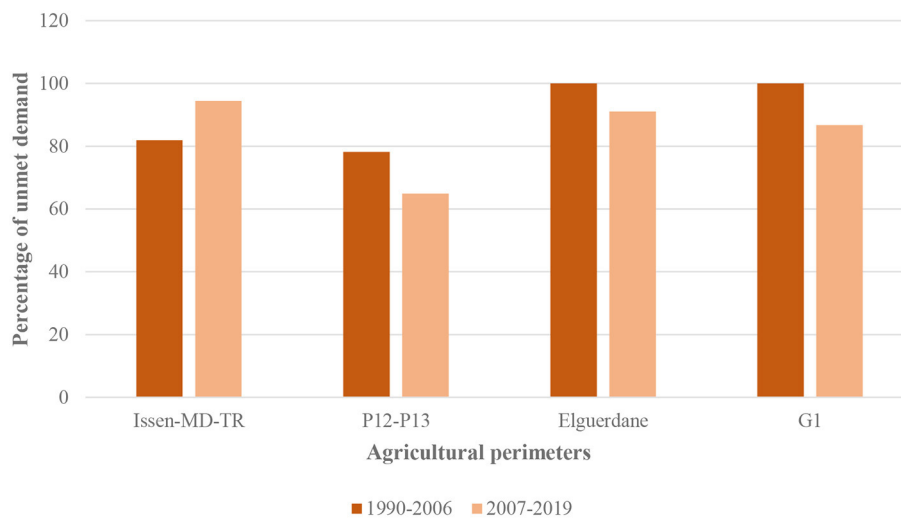
**FIGURE 10**
The percentage of unmet demand before and after the rehabilitation of the perimeters and supply of the different perimeters by dams.
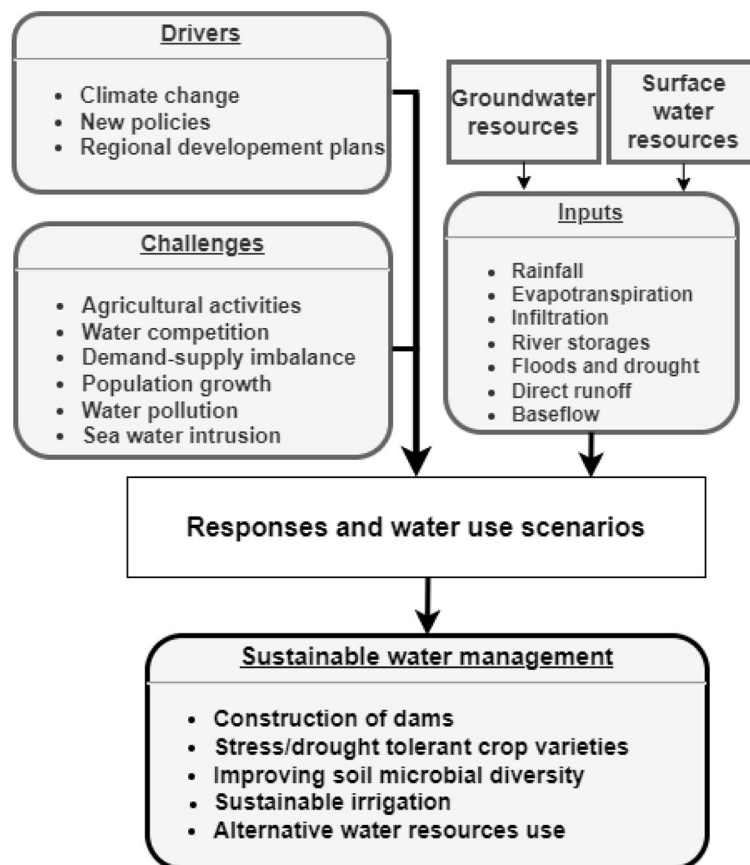


**FIGURE 11**
Schematization of the proposed conceptual framework with a sustainable water use goal.

In the study area, the infiltration process has never been previously studied. However, the soil-water infiltration plays an important function in hydrology as well as contributing to the groundwater recharge (Kale and Sahoo, 2011; Mahapatra et al., 2020). Different data-based and machine-learning strategies have recently been developed to improve the accuracy of estimates of water infiltration (Lange and Sippel, 2020; Panahi et al., 2021; Sun et al., 2021). These algorithms proved their effectiveness in

characterizing the variable affecting the infiltration process. It is also recommended to collect various data and use Machine learning algorithm power in the prediction of the infiltration process and infiltration rate (Panahi et al., 2021).

## 5 Conclusions

This work shows how ModSim, a generic DSS can be used to model water allocations. The Souss basin, which is located in Morocco, is selected for this ModSim application because of its relevance to water planning and management issues. All basin facilities, hydrological processes, and water use are included in monthly time-step simulations. The simulation of inflow required a significant amount of calibration effort. The inflows to the Aoulouz and Abdelmoumen reservoirs were successfully modeled using, resulting in a strong correlation with the inflows recorded at the dams. The model simulated flows were well matched to the observed hydrograph volumes for the gauging stations installed at Oued Souss.

The results indicate that the average total water demand for the period (1990–2019) is 180 $mm^3$, while the average total unmet demand is 201 $mm^3$ of the total demand. The monthly average demand increases by 55% in the hot season, compared to the demands of the rest of the year. With regards to the unsatisfied demand at the level of each perimeter, the largest unsatisfied water demand during the second period 2007–2019 occurs at the level of Issen perimeter with 94% of the demand remaining unsatisfied by the dam releases. The results also indicate that the other demand sites in the watershed have unmet demands that remain high for both periods. The unmet water demands will be probably satisfied by the uncontrolled withdrawal of water from groundwater resources. The study's findings and the use of ModSim highlight the importance of enhancing water governance in the Souss basin. More efforts to build representations of groundwater and surface water interactions are needed to improve water governance even further. More in-depth assessments and the use of advanced modeling methods may be required to better understand the consequences of various water uses, particularly in arid and semi-arid areas where water is limited.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

OA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing—original draft, Validation. YB: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing—review & editing. LB: Conceptualization, Methodology, Supervision, Writing—review & editing, Validation. AE: Writing—review & editing. YA: Writing—review & editing, Conceptualization, Supervision, Validation. AC: Writing—review & editing.

## Funding

## Acknowledgments

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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