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DOI
10.1007/s10668-024-05151-x

Publication date
2024

Document Version
Final published version

Published in
Environment, Development and Sustainability

Environment, Development and Sustainability
https://doi.org/10.1007/s10668-024-05151-x

A water–energy–food nexus analysis of the impact of desalination and irrigated agriculture expansion in the Ain Temouchent region, Algeria

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Received: 14 December 2023 / Accepted: 13 June 2024

Abstract

The need for an integrated approach to sustainable resources management to achieve the Sustainable Development Goals has become widely recognized. Population growth, climate change, environmental degradation, and scarcity of resources have been identified as the major factors affecting society's future. Given the fundamental societal needs for food, energy, and water, the Water–Energy–Food (WEF) nexus has emerged as a useful sustainable resource management framework and has been widely applied. However, in the Middle East and North Africa (MENA) region, there have been relatively few studies that adopt a nexus approach. In this study, the Ain Temouchent region in Algeria is used as a WEF Nexus case study. The region has a strong agricultural-based economy and the increased intensity of agricultural production in the region has resulted in the overuse of groundwater resources. Establishing a reverse osmosis desalination plant with a daily production capacity of 200,000 m^3 significantly alleviated the resulting water crisis, yet its energy consumption and environmental impact raise several questions. This study identifies the critical links between the WEF sectors and using this understanding, the dynamics between them are assessed using System Dynamics Modelling. The study reveals that any further increase in agricultural production in Ain Temouchent may lead to excessive use of groundwater resources. Although desalination can help alleviate the water crisis, its high energy consumption raises concerns. The analysis shows that the use of surface water and recycled wastewater for irrigation could be possible alternatives. The study emphasizes the value of adopting a WEF nexus approach to achieve a balance between agricultural development, energy sustainability, and water resource management in the Ain Temouchent region.

Keywords Ain Temouchent · Algeria · Desalination · Irrigated agriculture · System dynamics modelling · WEF nexus

Extended author information available on the last page of the article

1 Introduction

Water, energy, and food (WEF) resources are often viewed through the water–energy–food (WEF) nexus (Hoffman, 2019), where it is recognized that actions in one sector frequently have effects in the other. Therefore, a holistic, systems-thinking perspective of these resources is increasingly necessary. It is estimated that global food demand will increase by 60% by 2050, global energy consumption by 50% by 2035 (80% by 2050), and total water withdrawals by 50% by 2025 in developing countries and by 18% in developed countries (Botai et al., 2021; Flammini, 2014). This situation is attributed to factors including, but not limited to, population growth, societal development, and climate change, and will lead to degradation and insecurity of critical resources (Hoff & Ulrich, 2017) unless more sustainable means of resources supply can be attained. High rates of resource extraction could lead to resource scarcity and may jeopardize the well-being of future generations (Raekwon & Director, 2013). For example, considering that 30–50% of global food production is wasted, this results in a degradation (or inefficient use) of 1.47–1.96 Gha of arable land, 0.75–1.25 trillion m^3 of water, and 1–1.5% of the global energy consumption (Flammini et al., 2014). Given that all these resources are increasingly demanded, cutting food wastage and losses should be seen as essential to saving water and energy resources being wasted as a by-product. In this context, it has been suggested that adopting a nexus approach is an effective strategy to face this connectedness (Mabhaudhi et al., 2021), moving from sectoral approaches towards an integrative approach considering the interface between the WEF sectors, resources demand, and global development (Aboelnga et al., 2018; Mabhaudhi et al., 2018; Sušnik et al., 2023). Over the past decades, the WEF nexus has become central to discussions regarding developing and monitoring the UN Sustainable Development Goals (SDGs). The MENA region, and Algeria in particular, are nexus 'hot spots', suffering resource scarcity, resource security challenges, and socio-economic development. It is within this context that this research takes place.

The scarcity of water resources, groundwater pollution, industrialization, and agricultural intensification, along with demographic changes, have contributed to making the Middle East and North Africa (MENA) region water-scarce (Aboelnga et al., 2018). At the same time, the MENA region holds 43% of the world's oil reserves, and its renewable energy potential is considerable, yet 35 million inhabitants still lack access to electricity. In terms of agricultural production, it is the largest importer of wheat in the world, as Egypt, Turkiye, Algeria, and Morocco in total purchased one-fifth (1/5) of the overall wheat imports bought during 2022, valued at US$12.5 Billion (https://www.worldstopexports.com/), resulting in exposure to market forces and production in distant regions. Ensuring long-term water and food security is essential, as water shortages prevent the region from meeting its food needs. Studies have shown that wheat yield in the MENA region has experienced a c. 15% decline from 1976 to 2005 (Masia et al., 2021), while other studies have suggested that agricultural production could further decrease by 20% in 2027 compared to 2000 (Aboelnga et al., 2018). Achieving regional WEF security is recognized as a significant challenge in the Arab Strategic Framework for Sustainable Development (ASFSD). Several MENA region nations have, (partly) adopted a nexus approach, showing promising results. For example, the Gulf Cooperation Council (2023), bringing together Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, has adopted solar energy to desalinate seawater to satisfy the region with water. Jordan has developed the energy potential of wastewater by exploiting biogas from wastewater treatment plants (WWTPs). Tunisia has adopted solar pumping to extract groundwater for agriculture.

However, this has led to the overexploitation of groundwater in several parts of the country (Aboelnga et al., 2018).

Despite progress towards integrated management of resources in MENA countries, Algeria and other countries have not made significant progress in adopting an integrated approach to water, energy, and food. This is attributed to constraints such as lack of experience and insufficient planning (Hoff & Ulrich, 2017). With a rapidly growing population and an urbanization rate exceeding 50%, Algeria's WEF demands are increasing significantly. Energy production is the largest industrial user of water, and its expansion necessitates improved access to water resources, a need that competes with other economic sectors. Natural gas and oil account for almost all of Algeria's primary energy consumption, with only 3.39% of installed energy capacity from renewable energy sources. The government aims to diversify the energy mix, bringing the share of renewable electricity generation to 27% by 2030 (Algeria - RCREEE, 2020). Algeria faces pressure on water resources due to several factors, such as resource scarcity and high-water demand. This situation has led to the adoption of desalination, predominantly through Reverse Osmosis (RO). However, introducing desalination plants has resulted in a notable rise in energy consumption, representing a connection between the water and energy sectors and leading to competition with water for food production. Given that current energy production relies on fossil fuels, it becomes evident that the promotion and integration of renewable energy sources are imperative to power new desalination facilities if the 2030 targets are to be met (Drouiche et al., 2022). In Algeria, the agricultural sector consumes 59% of freshwater withdrawals and requires improvements in water resources use efficiency and the adoption of new approaches to water demand management has been called for (Oulmane et al., 2022). The high and growing water demand for energy, coupled with the water demand in agriculture and the shortage of water resources, leads to WEF nexus issues currently confronting Algeria: how can the country generate sufficient clean energy supply and food while navigating water resources constraints?

Algeria has only a few studies carried out on the WEF nexus (Drouiche & Aoudj, 2015; Drouiche et al., 2022; Khacheba et al., 2018). Of these, only Drouiche et al., (2022) present a quantitative analysis of the potential for desalination in securing Algeria's water supply for domestic and agricultural uses but do not assess the whole WEF nexus from a system-thinking perspective. In addition, previous studies consider Algeria as a whole, not accounting for locally-specific conditions. There are some studies on the WEF nexus in the wider MENA region (Daher & Mohtar, 2017; Hoff et al., 2019; Maftouh et al., 2022), and in countries such as Egypt (Abdelzaher et al., 2023; Sušnik et al., 2013) and Tunisia (Sušnik et al., 2012).

It is clear that there is a need to fill knowledge and research gaps regarding the WEF nexus in Algeria, especially in locally specific settings. In light of these challenges, this paper presents a quantitative WEF nexus analysis in the Ain Temouchent region in Algeria. The region is renowned for its intensive agricultural activities, which has led to the excessive depletion of groundwater reserves (Benkhamallah et al., 2020), and coupled with severe drought periods, agricultural output has been affected, impacting food security and the availability of surface and groundwater reserves (Kali, 2022). An RO desalination plant has been established to alleviate the pressing water crisis, with a capacity of 200,000 m^3 day^{-1}, of which 50% is distributed to Oran (Fig. 1; BWC, 2010). At the same time, concerns have arisen regarding the desalination plant's energy consumption and environmental impact. To meet the region's energy requirements, especially electricity, a combined gas electricity power station was constructed in 2012 (Sonelgaz, 2021). Ain Temouchent therefore offers an under-explored nexus hot-spot

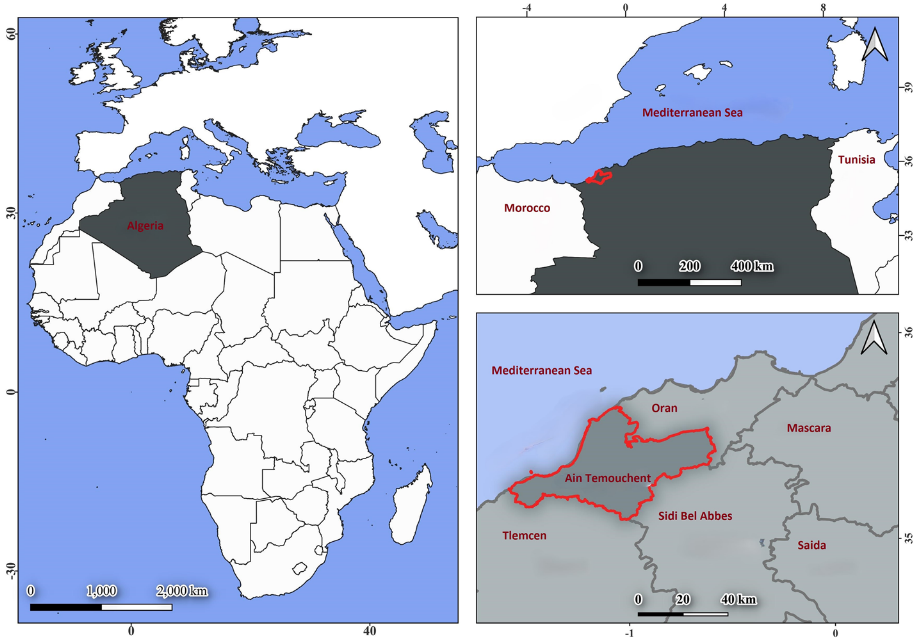

Fig. 1 Location of Ain Temouchent region, Algeria (Zoubida Nemer, 2023)

case study with water, energy, and food-related security and sustainability aspects in a region already experiencing climate and development related challenges. The near-future resources sustainability of the MENA region could have much wider implications, especially for energy supply (oil, gas), and food production and export. It is therefore an important region to study and better understand. At the same time, the issues described are largely inter-related (e.g. water for food, energy for water), thus an integrated nexus approach is crucial to further understand synergies and trade-offs for regional development.

Given these interconnected aspects, the primary objectives of this study are to identify and analyse the links between the WEF sectors using System Dynamics Modelling (SDM) and to use this model to explore the interrelations among the WEF systems in Ain Temouchent. In this context, the research aims to achieve improved understanding of the WEF nexus in Ain Temouchent, especially regarding the interplay between availability and demand of different resources; assessing water supply based on various water sources in the region (desalination, surface water, and groundwater) and considering the associated energy costs; and considering water demand for agriculture, energy production, and domestic use. The work aims to contribute to analyzing trade-offs and synergies among the WEF sectors in the region, and to propose actionable decision and policy-related recommendations on how to further local development in a sustainable way. For example, increasing the irrigated area in the region will affect the water irrigation demand, while at the same time, increasing desalination production impacts energy consumption. The model developed in this work provides a platform to test scenarios relevant in Ain Temouchent and provides information that can guide future resources planning by providing decision makers with better information to develop and apply policies and regulations and technological advancements in water, energy, and food systems.

By illustrating the dynamics between resources through the modelling in this study, it is hoped nexus can be better understood in the local context. Relevant solutions and recommendations for developing effective policies in the region will be proposed, helping to strike a balance between agricultural development, energy sustainability, and water resources management in the Ain Temouchent region of Algeria. It is hoped that this work will lead to greater awareness of the need for a systems thinking mentality on the region. This work aims to lead to improved policy and resources development decisions for improved sustainable development by proposing concrete, locally-relevant recommendations emanating from the findings of this research that aim to suggest how multiple resources can be developed without compromising the security of the other critical resources. It is hoped that this work will promote similar studies and wider nexus considerations throughout Algeria and the wider MENA region.

2 Data and methodology

2.1 Study area

Ain Temouchent, situated in north-western Algeria (Fig. 1), is bordered by the Mediterranean Sea to the north, the Tlemcen region to the southwest, Sidi Bel Abbes to the southeast, and the Oran region to the east. Ain Temouchent encompasses an area of 2376 km^2 with an 84 km coastline (ANIREF, 2018), and a population estimated at 443,755 in 2022 (Housing and Health Department, 2022). This region falls within the hydrographic basin of Oranie-Chott-Chergui, characterized by a Mediterranean climate with hot summers and mild winters. The region experiences two distinctive periods: a dry period during the summer months (June, July, August), with significantly reduced precipitation, and a humid period spanning the rest of the year, marked by alternating wet and relatively dry months. Due to its geographical location and hydrogeological characteristics, the region needs additional resources and infrastructure development to meet its water resource requirements.

As mentioned in the introduction, Ain Temouchent is crucial for regional food production, yet is water scarce and relies on fossil-based energy despite abundant renewable options. In addition, the region is especially under-studied, hence the need to better information about the interconnectivity of WEF resources and on how policy interventions may impact across multiple resources sectors. The Ain Temouchent region as the central point of this study seeks to highlight insights that have significant local relevance and can be applied across similar regions in Algeria such as Oran and Mostaganem regions. This approach aims to support sustainable development and aid in developing policy interventions that can be expanded to other countries. The area has three primary water sources: surface water, groundwater, and non-conventional water, mainly seawater desalination and the reuse of treated wastewater (consuming considerable energy resources). The surface water supply is approximately 28,736 m^3 day^{-1} transferred from Tlemcen region to the treatment plant, which is currently operational only during the maintenance period of the desalination plant. Groundwater resources are estimated at 9500 m^3 daily (Department of Water Resources and Water Security, 2021). The area has faced severe water crises, particularly during drought periods, a water-related challenge. In the area, the Department of Water Resources report that 99% of the urban population is connected to the public drinking water network. However, of the people connected, presently, 40% has daily access to drinking water supply (DWS), while 40% have access every two days, and the rest every three or more days. So while the connection rate is high, not everyone gets a physical water supply every day. Therefore, the government is trying to improve the region's DWS. Consequently, a seawater desalination plant was established with a capacity of 200 000 m^3 day^{-1} using RO technology. Of the desalinated production, 50% is transferred to the Oran region (BWC, 2010). The electricity consumption of the desalination plant is 4.15 kWh m^{-3} water produced (BWC, 2010). For wastewater treatment, the region has several infrastructure facilities, including six lagoons and three wastewater treatment plants. However, treated wastewater is not reused, instead being discharged into rivers or the sea, which offers an opportunity to enhance water supply for multiple purposes in the future.

Agriculture is substantial, covering > 76% of the total area, amounting to 180 994 hectares, across 8 159 farms, and consuming considerable water and energy resources. Collective farms occupy the most valuable agricultural land, encompassing 119 976 hectares, or 67% of the useful agriculture area (UAA). The region's agricultural focus lies on field crops, including cereals occupying around 147,000 hectares, 12,656 hectares for viticulture, 8780 hectares for market gardening, 2890 hectares for arboriculture, and 393 hectares of citrus (Department of Agricultural Services, 2021). To enhance food supply, government is planning to construct a new dam for irrigation. A combined cycle gas electricity station has a capacity of 1200 MW. Operating since 2012 primarily on natural gas and having a backup diesel option during emergencies, the plant has played a pivotal role in securing the region's energy supply and promoting economic development. With this plant, the electricity supply connection rate in the area is 94%, with a 73% connection rate to the gas supply (Sonelgaz, 2021).

2.2 Methodological process

The steps summarised in Fig. 2 were followed to assess the region's water energy food nexus. Each main step is outlined in detail in the following sections.

2.2.1 Conceptualization of the nexus system (qualitative assessment)

This stage develops a conceptual map to identify the interlinkages and nexus issues between the WEF sectors in the region. Conceptual maps help to understand a system's connections and boundaries, and does not require any modelling expertise (Sušnik et al., 2022). In addition to a conceptual map of the system, a causal loop diagram (CLD) was developed. CLDs are a graphical representation of the interlinkages within the system elements to understand causal relationships among system elements by identifying causal links between two variables and connecting variables in closed feedback loops (Ford, 2009). Feedback loops represent circular cause-and-effect relationships and can be positively represented by an arrow with a (+) sign, which means that a change (increase/decrease) in A will have the same change in B (increase/decrease), or negatively using an arrow with a sign (−) meaning that any change in A (Increase/Decrease) causes a change in B in the opposite direction (decrease/Increase) (Purwanto et al., 2019). As positive feedback example, an increase in population will cause a need for more water for irrigation and more energy for pumping and harvesting. For negative feedback, increasing water demand will result in decreasing water availability.

2.2.1.1 Conceptual map and CLDs The conceptual maps and CLDs comprise a 'high-level conceptual map' of the entire system (Fig. 3) and 'extended conceptual maps'

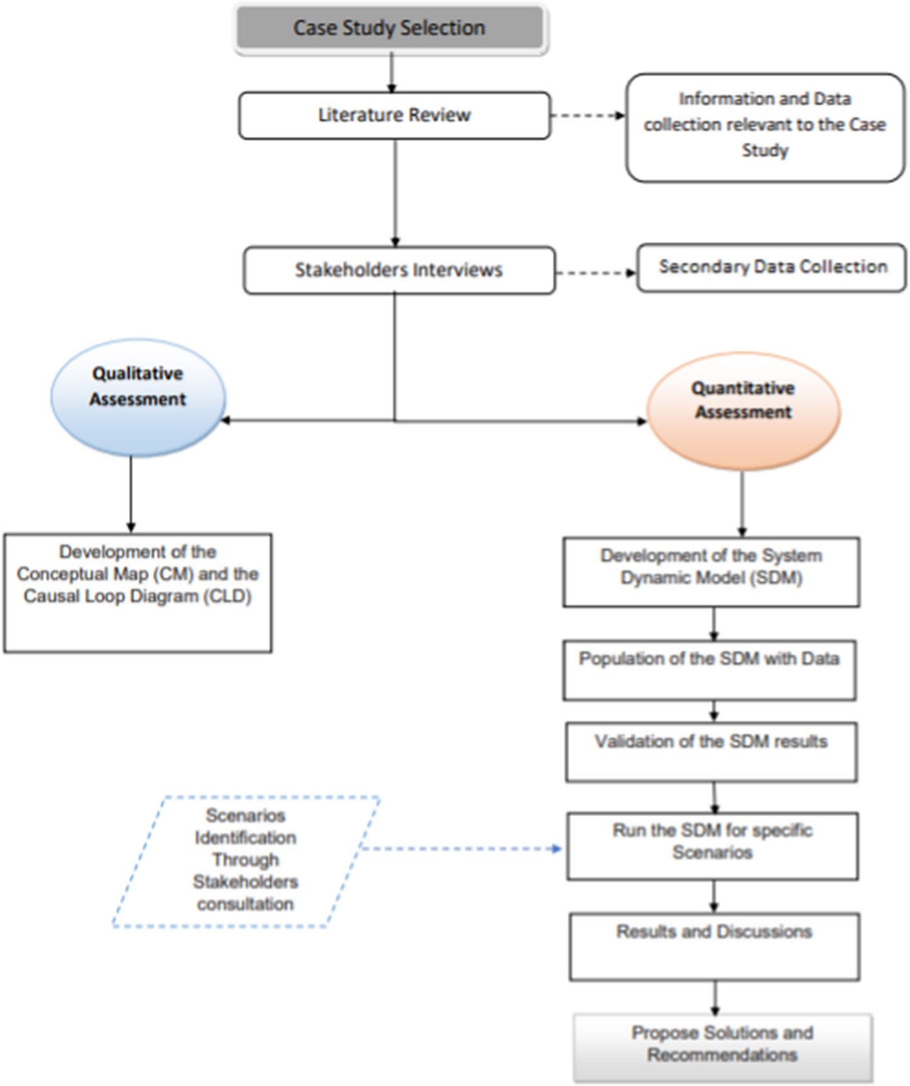

Fig. 2 Methodological process followed in this study (Source: authors)

for each WEF sector are found in the Supplementary Information (SI S1). Figure 3 highlights the main sectors and their connections, while the sectoral maps in the SI show more details about the links in each sector. The CLD (Fig. 4) represents the causal relationships among system elements by identifying causal links between two variables and connecting variables in closed feedback loops.

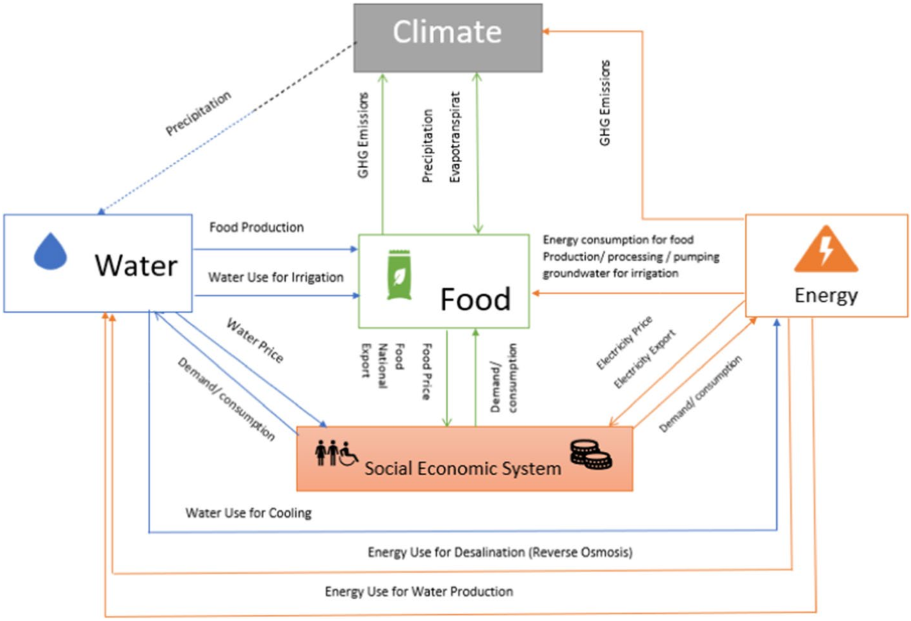

Fig. 3 Top-level Conceptual Model (Source: authors)

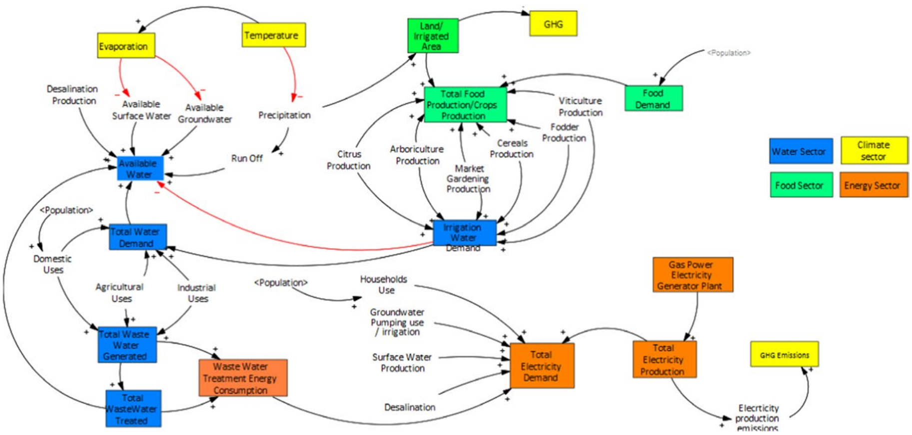

Fig. 4 Top-Level Causal Loop Diagram (CLD). See Sect. 2.1.1 for arrow polarity definitions (Source: authors)

2.2.2 Top-level map

The conceptual map (Fig. 3) shows the connections between the water, energy, food, climate, and social-economic sectors. Figure 3 shows the importance of energy in food production for pumping the groundwater needed for irrigation and the processing and transport of food. Power is required in water production, primarily in desalination and wastewater treatment plants. In turn, water is required in energy production, for example in the gas power electricity generation plant and for cooling in different industries. Water is crucial for the food sector for irrigated agriculture. The social-economic sector considers the population's water, energy, and food demand and gives insight into these sectors' importance in the region's economy. The climate is one of the map's sectors linked to precipitation, evapotranspiration, and GHG emissions. Due to the lack of access to data, the climate sector is not reproduced in the SDM.

2.2.3 Causal loop diagram (CLD)

The Causal Loop Diagram (CLD), (Fig. 4) shows that water availability is influenced by multiple factors, including desalination production, surface water, and groundwater. An upsurge in these sources of water results in an increase in water availability. However, these sources are negatively affected by evaporation, which decreases the volume of surface water. Furthermore, an escalation in irrigation water demand negatively impacts water availability. By following the connections within Fig. 4, it can be observed how a change in one variable (e.g., waste water treatment) many have impacts on other nexus sectors, such as energy demand. As such, a holistic understand of nexus system dynamics can be gained without recourse to expert modelling. Such exercises are very beneficial in communicating such concepts to non-expert stakeholders (Purwanto et al., 2019).

2.2.4 System dynamics modelling (quantitative assessment)

System Dynamics Modelling (SDM; Ford, 2009) is a modelling approach to deal with complex systems. Originally developed to study complexity and feedback in industrial settings, it has since been applied to analysis of the interlinkages between the WEF nexus sectors and their responses toward external factors, including population growth, climate change, and implementation of governmental policies (Sušnik et al., 2022). It has been applied to understand and analyze the complexity of interactions among the water, energy, and food sectors, and of policy interventions therein (Bakhshianlamouki et al., 2020; Sušnik et al., 2021; Wang et al., 2023; Wen et al., 2022;). It has used to deal with water management in transboundary basins (Elsayed et al., 2022). Following the development of CMs and CLDs, an SDM was built using stock-flow diagrams (SFDs) to represent the Ain Temouchent WEF nexus, using the CLD as a guide and maintaining a focus on water–energy interaction, mainly the energy consumption for desalination and on water food nexus, focusing on the intensive agriculture production leading to the overexploitation of the groundwater. SD models consist of three main modelling elements: stocks that store material over time; flows that move material into and out of the stocks; and convertors that alter the rate of the flows. Elements are connected with arrows that transfer information within the model. Partial differential equations calculated stock levels at every modelling timestep (which can be adjusted as necessary). Parameters in SDMs can be constants, time-series', or equations defined from statistical, physical, or empirical sources. As SDMs are built from the bottom-up, there is flexibility in combining scientific disciplines so long a relationships between variables can be defined, hence its usefulness for exploring the WEF nexus and the impact of policy. More details about SDM and its applications can be found in Ford (2009). This work developed the model using STELLA Professional (https://www.iseesystems.com/), a dedicated SDM software. The model runs at the regional scale with a monthly timestep running for four years (48 months) from 2018 to 2021.

2.2.5 Data

The data mapping and collection consisted of identifying the primary data needed for populating the components of the SDM with data. At this stage, each dataset's units, scales, and sources were identified and harmonized (Masia et al., 2022). Table 1 summarises the data used in this study, the units, and references to data sources. In addition, local water, energy, and food experts were interviewed (using semi-structured interview techniques) to gain additional insights into the local interactions and to cross reference data. Stakeholders interviewed included the Water Department of Ain Temouchent region staff, the Agriculture Services Department, and the Energy Department. Farmers and academics at local universities were also interviewed. For confidentiality reasons, names remain anonymous. The SI provides a summary of the interviewees, along with a sample of the questions that were administered (SI S2).

2.2.6 Model validation

Validating the SDM is crucial to verify its performance, relevance, and accuracy. Ensuring the accuracy of a model through quantitative validation is an essential process involving a comparison of historical data with simulated data. In this study, the R-squared (R^2) metric was used. R-squared (R^2) validation is a statistical measure utilized to evaluate the effectiveness of a model in explaining the variability in the data it is attempting to predict. R^2 ranges between 0 and 1, where 0 means the model does not present any of the data's variability, and 1 indicates that the model perfectly explains all the variability in the data. In this paper R^2 is the calculated variable, compared against a measured or observed variable. It can therefore represent multiple parameters such as water demand, cereals production, or waste water generation.

2.2.7 Scenario definitions

Using information gathered during the interview process (see Sect. 2.1.3 and SI S2), insights were gained on development programs and goals and targets for each WEF sector. This information was combined with national reports on the case study to establish a list of relevant scenarios for testing in the SDM (Table 2). Due to the unavailability of future/forecast data, the scenarios were tested using the time frame from 2018 to 2021. These scenarios were designed to assess potential outcomes of policy implemented.

2.2.7.1 Water sector Thirteen scenarios were tested (Table 2). The first three focus on desalination, as only 50% of desalinated water is available for the region. With the government's plan to construct a new desalination plant in the Oran region, all desalination production locally should be reserved for Ain Temouchent. Therefore, two scenarios were tested at 75% and 100% production capacity. The scenario where only 25% of water is distributed was selected because only half of the membrane blocks are operational during maintenance. Scenarios WS-04 to WS-07 relate to surface water supply (Table 2). Because the treatment plant does not provide treated water in the region, the region relies on the desalination plant. This suite of tests aimed at evaluating the effect of different production levels from the treatment plant on water availability. To preserve groundwater from overexploitation, two scenarios, WS-08 and WS-09, applied to groundwater, were tested. Scenario WS-08 tested

Table 1 Overview of the primary data

Sector	Data	Unit	Dataset availability	References/sources
Water	Desalination	m^3 month^{-1}	2018–2021	BWC (2010)
	Groundwater	m^3 month^{-1}	2018–2021	Ain Temouchent Water Resources and Water Security Department (2021)
	Surface Water	m^3 month^{-1}	2018–2021	Ain Temouchent Water Resources and Water Security Department (2021)
Energy	Electricity generation	kWh month^{-1}	2018–2021	Sonelgaz (2021)
	Electricity Demand per capita in Ain Temouchent	kWh month^{-1} capita^{-1}	2018–2021	Algeria: Electricity Demand per Capita | Statista (2023)
	Energy to desalt one cubic meter of water	kWh m^{-3}		BWC (2010)
Food	Irrigated Area per crops	hectares	2018–2021	Ain Temouchent Agriculture Services Department (2022)
	Water to irrigate 1 ha of each crop	m^3 hectare^{-1} month^{-1}		FAO Statistics, 2010
	Crop production per hectare	Tons hectare^{-1} month^{-1}		Algerian Agriculture Ministry (2019)

Table 2 Scenarios tested in the System Dynamics Model

Sector	Code	Scenario	Change from Baseline	Baseline
Water	WS-01 WS-02 WS-03	Desalinated Water distributed to the Ain Temouchent region	25% 75% 100%	50%
	WS-04 WS-05 WS-06 WS-07	Surface water treatment plant capacity	25% 50% 75% 100%	0%
	WS-08 WS-09	Groundwater Use	0% 50%	100%
	WS-10 WS-11	Run-off Mobilisation in the Ain Temouchent region	25% 50%	19%
	WS-12 WS-13	Drinking water supply for all population	Daily Once two days	Daily Once two days Each three days
Energy	ES-01	Second gas power Electricity generation plant		One gas-power Electricity generation plant
Food	FS-01 FS-02 FS-03	The capacity of a new dam for irrigation purposes	25% 50% 75%	0%
	FS-04	Reuse of Wastewater treated in irrigation		Only cereals are irrigated with wastewater treated
	FS-05	Increase the Reuse of wastewater treated for cereal irrigation	20%	5%
	FS-06	Increase the irrigated area for cereals	4000 (ha)	2844 (ha)

0% groundwater use, while WS-09 tested 50%. Additionally, two scenarios were tested for run-off capture and use (WS-10 and WS-11) to understand the effect of mobilizing 25% and 50% of surface water run-off. Variations in drinking water demand are the remaining water sector scenarios (WS-12 and WS-13).

2.2.7.2 Energy sector The Ain Temouchent region has an adequate energy supply, particularly concerning electricity. Therefore, only one scenario (ES-01; Table 2) was tested to determine the impact of implementing a new gas-powered electricity generation plant in the region.

2.2.7.3 Food sector The government is planning to construct a new dam for irrigation. Three scenarios (FS-01 to FS-03; Table 2) with different production capacities were tested to evaluate the impact of having a dam for irrigation. In the region, only cereals are irrigated with wastewater treated (WWT), so another scenario was tested to evaluate the irrigation of other crops with WWT (FS-04; Table 2). Additionally, a scenario was tested to understand the effect of increasing the amount of WWT used to irrigate cereals (FS-05; Table 2). In accordance with government aims to maintain food security, an increase in irrigated cereals area was tested to assess its impact on food production, water, and energy consumption (FS-06; Table 2).

3 Results

3.1 System dynamics model (SDM)

3.1.1 Top level model

The SDM comprises 172 interconnected variables, with seven stocks, 15 flows, and 150 convectors, and represents the system as accurately as possible with the available data. The top-level SDM (Fig. 5), shows the interaction among sectors shown in Fig. 3. Figure 6 shows detailed interactions among water system. SI S3 provides a comprehensive list of the model variables, units, and equations utilized in the model. The sub-models for the remaining resource sectors are shown in SI S4, along with a brief description.

3.1.1.1 Water The water system (Fig. 6) comprises different sources including surface water for irrigation, surface water treated at a plant, groundwater for irrigation, and groundwater for drinking supply. Additionally, desalination is used. Based on data, water demand is divided into three categories: population water demand for domestic use, water demand for agriculture, and water demand for energy production (thermal power generation). The population water demand is linked to the population system, irrigation water demand is related to the food sector, and water demand for energy production is connected to the energy system. Wastewater is generated from domestic and industrial uses.

3.1.1.2 Energy Given the lack of energy data, the model focused on the electricity supply (SI S4). The model accounts for electricity consumption across various activities, including domestic supply, irrigation, water production, desalination, and wastewater treatment. The food system was linked to electricity consumption for groundwater pumping in irrigation, while the population sector was linked with electricity for domestic use.

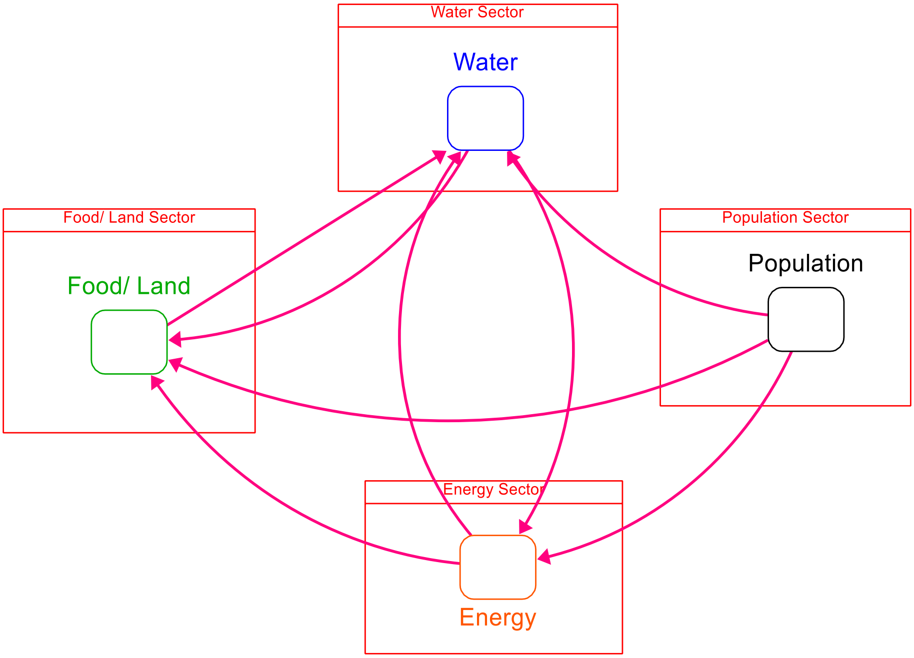

Fig. 5 Top-level System Dynamic Model (SDM) for Ain Temouchent region, Algeria (Source: authors)

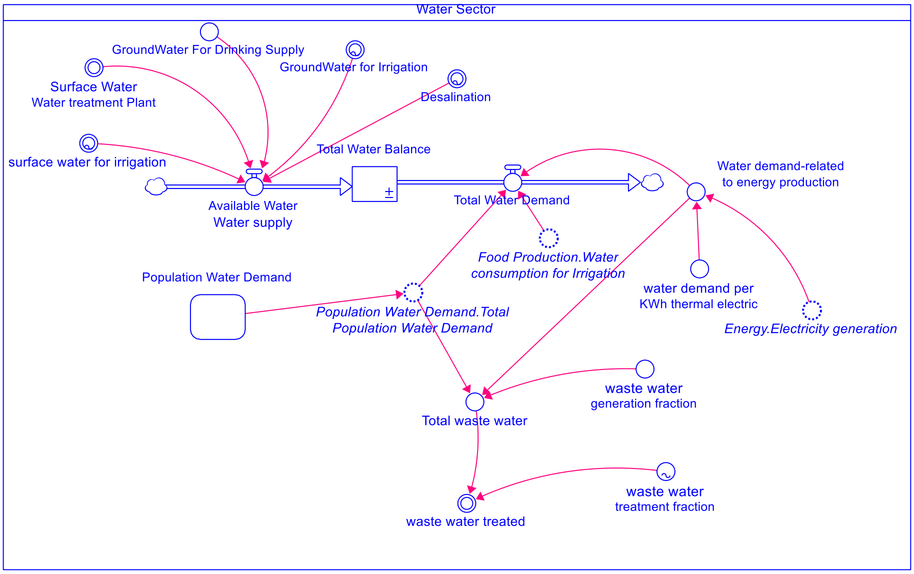

Fig. 6 Water sector—SDM (Source: authors)

3.1.1.3 Food The irrigated area encompasses six main crops cultivated in the region: cereals, viticulture (grapes), citrus, arboriculture (the cultivation of trees and woody plants), fodder, and market gardening. The water irrigation balance includes three different models based on the water sources utilized for irrigation (SI S4).

3.2 Model result validation

The model's performance has been evaluated against historical data not used in the SDM from 2018 to 2021 (Fig. 7). Results overestimate population water demand by c. 40% (Fig. 7a), while cereal production is less well represented in the model (Fig. 7b), likely due to the paucity of data and may reflect real-world conditions such as weather conditions, soil quality, and crop management practices. For wastewater generation and treatment, when the time series are compared (Fig. 7c, d), the SDM is shown to give values well in the range of observations, with the low R^2 value being attributed to factors not considered in the model, such as plant size, wastewater treatment technology used (which were not made available), and the accuracy of the observed data. Despite this, the model output is of the same order as the observations, missing only the temporal fluctuations. Furthermore, the population alluded to in the wastewater report is approximately 350,000 individuals, whereas the population simulated in the model exceeds 420,000.

3.3 Scenarios analysis

The SDM served as the basis for assessing the scenarios outlined in Table 2. The reference scenarios function as a benchmark against which the effects of scenarios can be measured.

Figure 8 represents the water results from the SDM for scenarios WS-01 to WS-13. Figure 8a shows results for scenarios WS-01 and WS-03. All other results fall within this range. Scenarios WS-01, WS-02, and WS-03 indicate that desalination can sufficiently supply the population water demand. There is a steady rise in baseline water supply (black line, Fig. 8a) as increasing proportions of surface water generated by the treatment plant are utilised. Although the increase is modest, it suggests that surface water holds promise in meeting the water demands of the population. The water requirements of the population can be fulfilled without utilizing groundwater, which is used for irrigation. Current supply is not sufficient to meet total water demand, where irrigation is by far the largest water user, showing a clear water–food nexus conflict between irrigation and other water users. Irrigation water demand is not met during specific months, predominantly between March and October (Fig. 8a).

Potentially, water supply can increase dramatically by harnessing surface water runoff. However, these volumes are rarely feasible to capture and exploit in practice (Department of Water Resources and Water Security, 2021). After modelling scenarios WS-12 and WS-13, it was revealed that providing a daily drinking water supply to the entire population is possible through desalination, which can meet domestic water demand with the current level of desalinated water produced, i.e. 50% of the total (Fig. 8b). Increasing water supply, especially via desalination, implies a significant rise in the energy demand—a water–energy nexus (4.15 kWh m^{-3} water produced; BWC, 2010). This is explored further below in this section.

Within the food sector, Fig. 9a shows a small rise in available irrigation water that could be obtained through constructing a dam for irrigation purposes. Figure 9b portrays

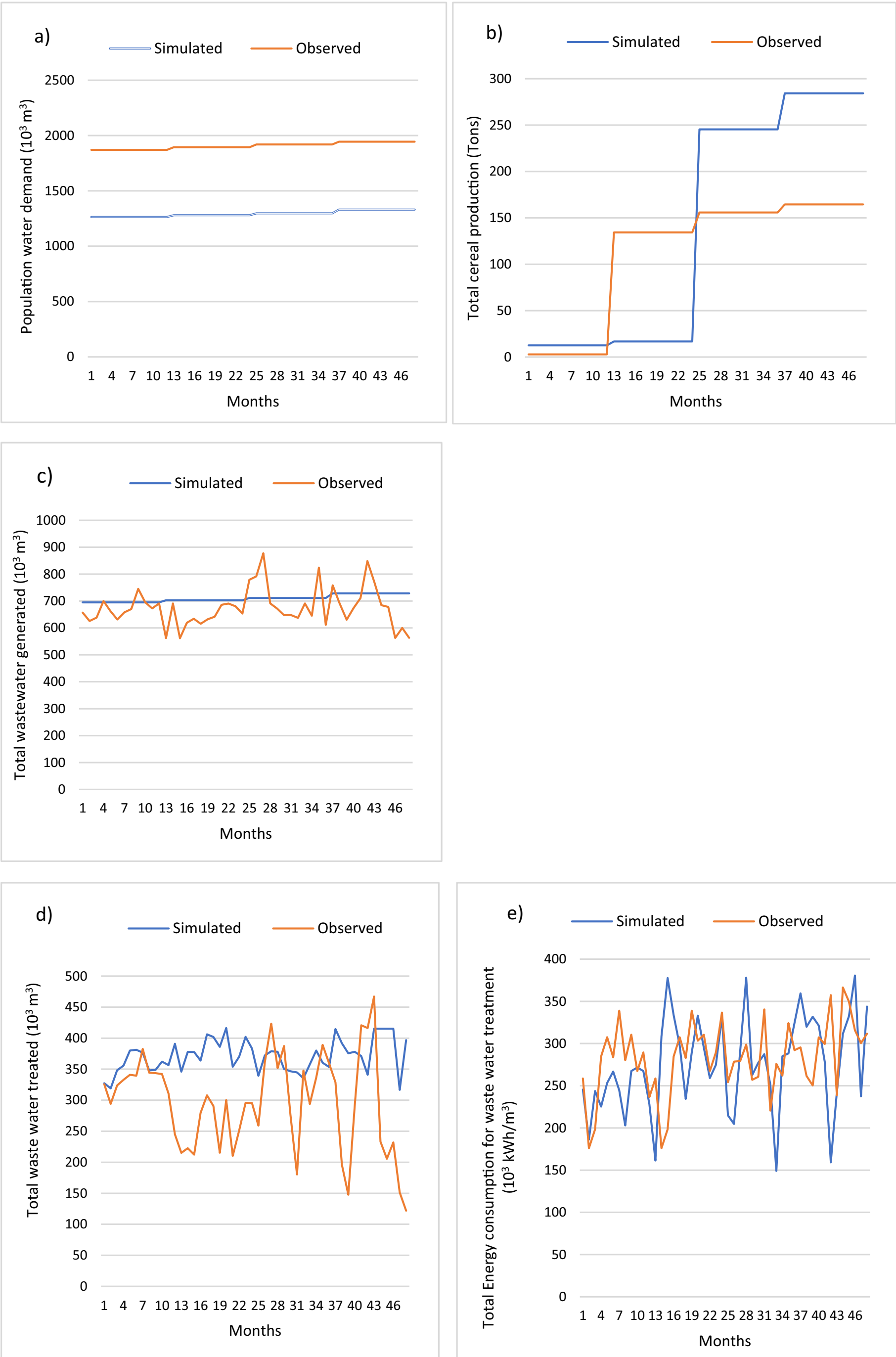

Fig. 7 Model Results Validation (Comparisons between historical data and simulated data); **a** Population water demand, **b** Total cereal Production, **c** wastewater generated, **d** wastewater treated, **e** energy consumption for wastewater treatment

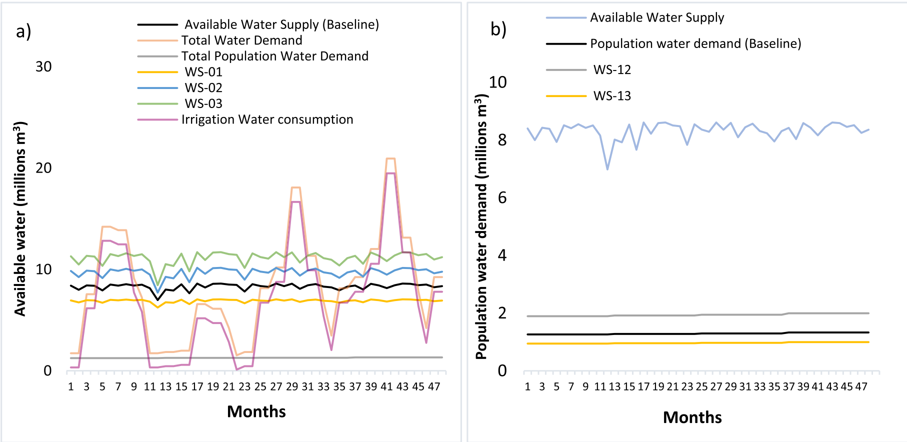

Fig. 8 **a** Available water supply and Water demand under scenarios WS-01 to WS-11, **b** population water demand under scenarios WS-12 and WS-13

the effects of irrigating crops with treated wastewater, reducing groundwater used in irrigation. This approach has been put into practice for cereal irrigation. By using other water sources, the groundwater supply is put under less stress and lower amounts of energy are needed for groundwater pumping. However, by increasing treated wastewater volumes, an increase in energy is implied. Figure 9c illustrates how an increase in cereals area could impact food production, showing a substantial increase in production, which would help secure the food supply in the region, but would lead to an increase in water demand for agriculture.

Figure 10 demonstrates that as the desalinated water distribution percentage rises, so does the electricity necessary for desalination, quantifying this clear water–energy nexus link. Nevertheless, current data suggests that this rise in energy demand can be met (Fig. 10a). The drop at about month 13 is due to a maintenance period in December 2018, in which half of the membrane blocks were functioning in the desalination plant. As a result, the production of water decreased, leading to the decrease in electricity consumption. Figure 10b indicates a significant increase in energy requirements for surface water production under scenarios WS04, 05, 06, and 07. That is, by increasing water supply from surface water sources, energy demand increases rapidly, and elucidating a less-considered water–energy nexus relationship. Based on Fig. 10c, it becomes apparent that the energy required for the desalination of water (WS-03) and 100% surface water (WS-07; blue line, Fig. 10c) far exceeds the capability of the current power generation plant (black line), suggesting a trade-off between energy supply and water supply in Ain Temouchent. Similarly, Fig. 10d highlights the increasing water requirements when expanding cereal cultivation, indicating a potential conflict between water and food objectives.

These results indicate not only the close links between the WEF sectors in Ain Temouchent, but also that policy implementation in any one of the sectors will have potentially significant implications for resources security in the other resource sectors. This modelling effort is the first of its kind in the region, offering new and important information to policy and decision makers who can now start to identify where the most critical trade-offs may lie.

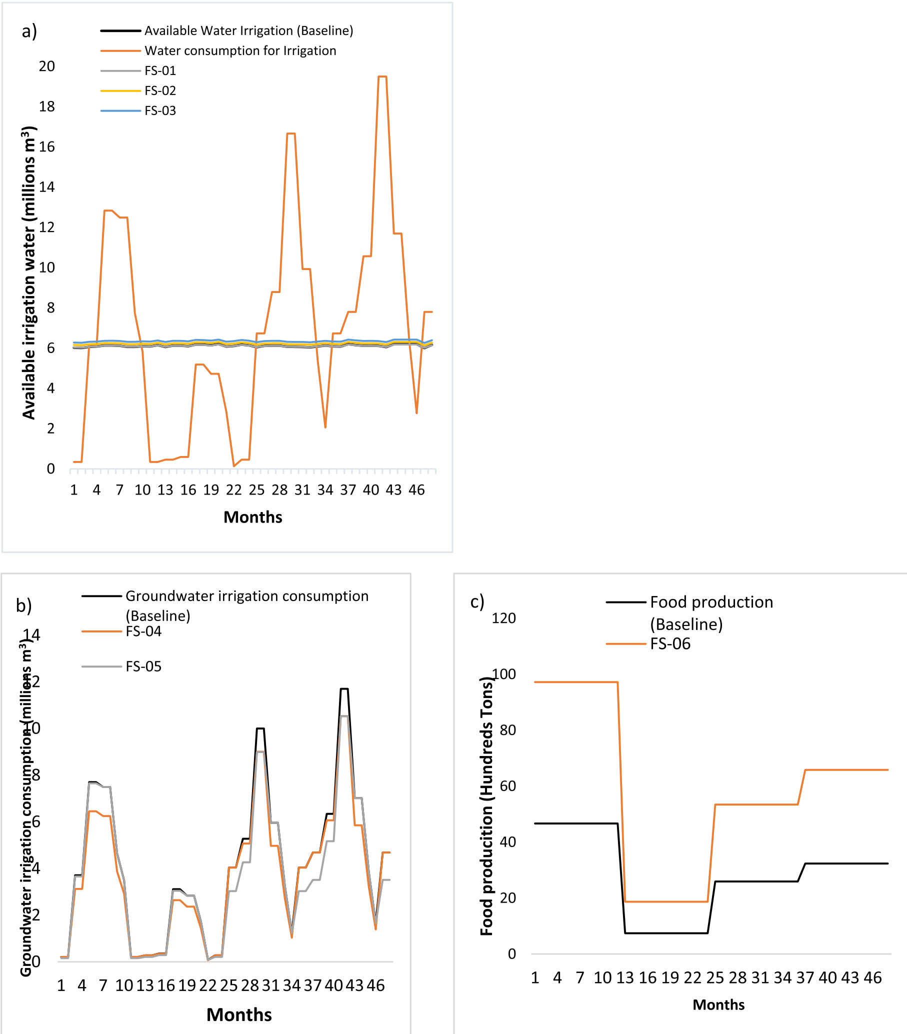

Fig. 9 Food sector model results under scenarios FS-01 to FS-06. **a** Available irrigation water, **b** Groundwater irrigation consumption, **c** Food production

4 Discussion

Results clearly demonstrate that the water, energy, and food sectors are impacted in different ways, and that the water and energy sectors are very closely coupled due to the energy-intensive nature of desalination processes (Fig. 10). Desalination is a crucial solution to tackle the region's water scarcity, however, this comes at a high energy cost, as well as damage to marine ecosystems (Droiche et al., 2022). This energy, if not generated from clean sources, would lead to increased greenhouse gas emissions and particulate pollutant loads. The other impact of desalination is the brine generated and disposed of in the sea, potentially affecting aquatic ecosystems and fish stocks (Belatoui et al., 2017; Djoher,

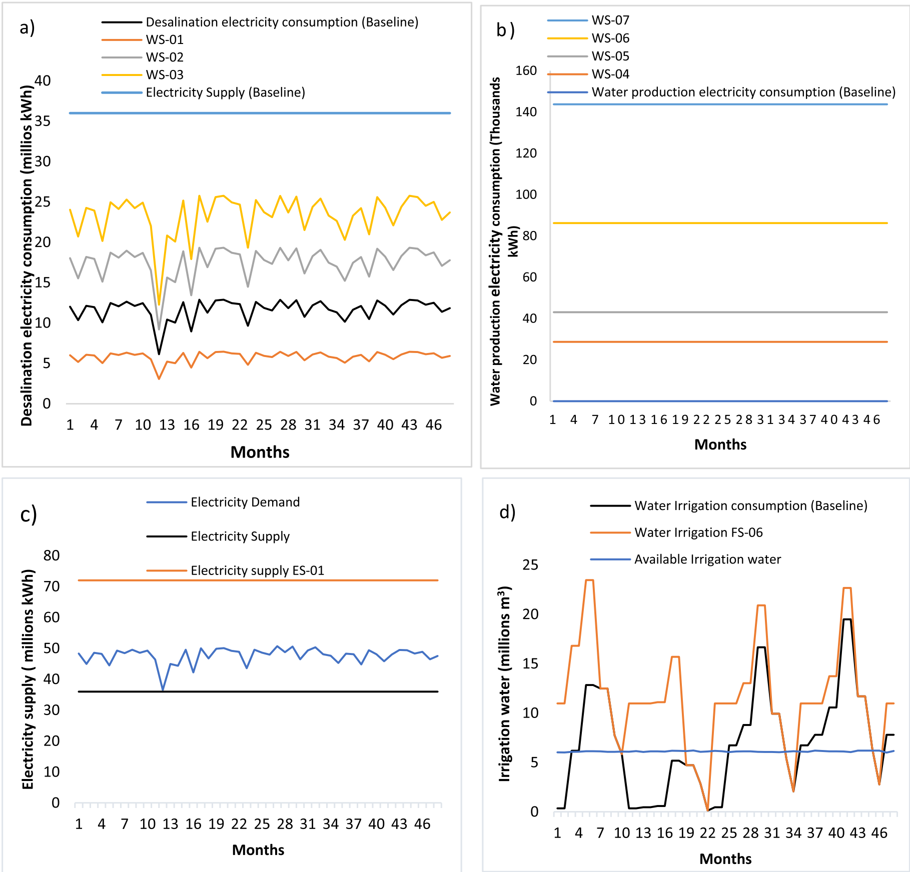

Fig. 10 Impacts of scenarios on all sectors (Water, Energy, and Food); **a** Desalination electricity consumption, **b** Water production electricity consumption, **c** Electricity supply, **d** Irrigation water consumption

2020; Mohammedi, 2013). It is crucial to develop energy-efficient desalination technologies such as hybrid solar energy plants aiming to reduce greenhouse gas emissions and the carbon footprint, thus fostering a sustainable environment and efficient economy (Dawoud, 2012). Desalination plants intake and outfall systems can harm marine environments, for example by altering local marine chemistry. To minimize these impacts, optimizing the location, design, and operation of intake/outfall structures is necessary. Effective and sustainable measures include using deeper, less biologically active areas, adding physical and behavioral barriers, optimizing flow velocities and screen designs, and ensuring proper maintenance and material quality (Elsaid et al., 2020). Desalination plants require considerable funding to construct. For example, a plant with capacity of 10,000 m^3 day^{-1} costs in the order US$10 million, while a plant with capacity of 100,000 m^3 day^{-1} may cost 10 times that amount (Huehmer et al., 2011). This excludes operating costs, and does not include environmental costs associated with ecological degradation. Therefore, a full cost–benefit analysis for the construction of a new desalination plant would be essential.

Although presently half of produced desalinated water is distributed to another region, the remainder is sufficient to meet the local population's water needs. Should the new desalination plant be implemented in the other region, Ain Temouchent will have adequate water supply, which could promote and support development in many economic sectors and could lower the dependence of agriculture on groundwater. This means that the WS-12 scenario regarding daily access to drinking water supply for the population could be achieved, but with a significant energy implication (Fig. 10b).

Although the increase in water supply resulting from scenarios WS-04, WS-05, WS-06, and WS-07 (increasing water supply from the existing treatment plant) is lower than that coming from an increase in desalination, it still increased freshwater availability. The advantage of this solution is that there is no need for new infrastructure or investments, as well as additional energy requirements being lower. The current treatment station under has a daily water production capacity of 250,000 m^3. In contrast, desalination requires building a new plant and the associated infrastructure, requiring substantial financing. The main challenge with the water treatment plant is that the surface water is provided from the releases of two dams (Beni Bahdel and Hammam Bougherara; ANBT, 2023) in a neighbouring region (Tlemcen region), which itself suffers from water stress and droughts (Bencherif, 2020). As such this may not be reliable or feasible water supply solution in the long term, especially under climate change.

Recent studies have shown that some of the region's aquifers are polluted (Benkhamallah et al., 2020), and seawater intrusion poses a significant threat to groundwater reserves, especially near the coast, a problem worsened by excessive pumping in heavily populated coastal areas in Ain Techoument (Benkhamallah et al., 2020; Nadjla et al., 2021). In the context of this work, preserving groundwater from overexploitation in the region is crucial to prevent further deterioration, as tested in scenarios WS-08 and WS-09 which relate to reducing groundwater pumping. The challenge locally lies in reducing the dependence of agricultural activities on groundwater. The agricultural sector should explore alternative water sources for longer term irrigation viability (forming a water and food nexus), such as surface water supply or utilising treated wastewater where possible, which were tested in scenarios FS-01 to FS-05. In a further nexus link, by reducing groundwater use, the energy demand for pumping and extracting the groundwater is reduced, positively impacting the environment by protecting aquifers, water quality, and reducing greenhouse gas emissions from the use of diesel pumps. The reduction of groundwater pumping, with suitable replacements, could represent a WEF nexus wide win–win for the region by maintaining irrigation water supply, reducing energy costs and greenhouse gas emissions associated with diesel pumps, and allowing for the continuation of food production for local food security and economic development.

Constructing a new dam for irrigation, tested in scenarios FS01-FS03, in the Ain Temouchent region has numerous impacts. On the positive side, such a dam would increase freshwater availability for irrigation, albeit marginally (Fig. 9a), allowing for a slight expansion of irrigated areas/productivity. This may lead to an increase in food production leading to food security in the region and improving nutritional status of the population, as well as perhaps giving the opportunity for economic growth through exports. Dam operations require energy, which could be provided from a new power gas electricity generator plant, albeit with negative environmental impacts. It may be possible to generate energy by installing a PV system, such as described in (Kougias et al., 2016; Nebey et al., 2020). Additionally, the dam design could be modified to provide hydropower production (Kucukali et al., 2021), thus reducing external power needs, and generating clean energy. The dam could help reduce the groundwater burden for irrigated agriculture, another nexus wide win–win scenario. However, the construction of new dams is costly and time consuming. Moreover, it will have considerable environmental impacts such as altering river flows, and impacting on agriculture and fisheries in downstream areas, as well as potentially impacting on local communities. Therefore, a thorough impact assessment would need to be carried out to determine if the marginal benefits outweigh the damages.

Using treated wastewater for irrigation (scenario FS-05; Fig. 9b) can free up freshwater availability. The region has several wastewater treatment plants, producing almost 700,000 m^3 $month^{-1}$, making it a reliable water source as wastewater flows reliably and regularly through the year. If treated to a suitable standard, the wastewater can be a valuable nutrient-rich water source, improving soil fertility and crop production. However, adhering to strict quality requirements is essential to ensure its safety. The wastewater treatment plant in the Tlemcen region uses treated wastewater for irrigation without affecting groundwater quality (Bemmoussat et al., 2019), and this approach could be used in Ain Temouchent to supply irrigated agriculture, reducing the dependency on groundwater. The downside, apart from the need to control quality and overcome safety concerns, is that additional treatment implies an energy cost, which ideally would be met through renewable energy resources.

Constructing a new gas-powered electricity plant (scenario ES-01; Fig. 10c) will enhance energy security for agriculture, industry, and household use. However, such power plants typically require water for cooling systems. Water is already vulnerable in the region, therefore the additional water demand would need to be carefully considered to determine if it could be sustainably supplied without compromising other water users. The first plant in the region is situated on the coast and uses seawater in the cooling process. This helps to reduce the conflict between water availability for energy production and other sectors, such as agriculture (Sonelgaz, 2021), and could be an option here.

From the results and discussion, given the local context, it is recommended to explore the following policy recommendations:

- *Desalination with renewable energy* There is an urgent need for desalinated water to meet the pressing drinking water demands in Algeria. This requires strict monitoring of the environmental impact and finding ways to explore renewable energy sources for powering the desalination plants to enhance sustainability and reduce dependence on fossil fuels. Countries such as Saudi Arabia, and the United Arab Emirates (UAE) integrated renewable energy as solar power to operate their significant and heavy desalination investments (Aboelnga et al., 2018);
- Expanding the irrigation area for cereals aligns with food security goals, but it will require careful water management for irrigation (land expansion is not an issue at present). This additional water would need to be sustainably supplied, using the interventions alluded to in the discussion;
- *Reuse of treated wastewater* increasing the use of treated wastewater is shown to be a win–win, it provides a sustainable water source for irrigation, thus conserving freshwater for domestic use. It requires minimal investments due to the pre-existing infrastructure and offers lower operational costs compared to the desalination process, which enhances water, food, and energy security in the region. Other countries in the MENA region facing water scarcity such as Jordan and Morocco could focus on treated wastewater to support their agricultural and water activities;
- Groundwater Preservation: It is essential to preserve and conserve groundwater by implementing restrictions on its withdrawals. Such measures would support groundwater replenishment and ensure the long-term sustainability of this vital resource, which is globally needed (Gleeson et al., 2012). In Yemen, the groundwater is over-extracted and this restriction would be a significant regulation to preserve this critical resource from deple-

tion (Alderwish et al., 2014). This could contribute to the potential reduction of greenhouse gas emissions by reducing the utilization of diesel pumps;

- The large-scale mobilization of runoff seems unlikely for practical reasons, although constructing small surface water capture ponds could locally provide additional irrigation water. This low-tech solution could be applied in both Algeria and the broader MENA region such as in Lebanon, where the decision-makers could benefit from its mountainous terrain to effectively use small-scale runoff mobilization;
- Building a new electricity gas power plant would satisfy the region's electricity demands and contribute to the country's economy through electricity export to foreign countries. Thus, the environmental impacts of such implementation should be sustainably considered;
- An agreement to release water from the dams in the Tlemcen region could be explored since the surface water treatment plant already exists and functions well. However, the potential for water shortages in Tlemcen may lead to intermittent supply, as well as hesitation over supplying scarce water to a different region.

Several countries in the MENA region such as Egypt, Morocco, Lebanon, Yemen, and Tunisia could adopt these policies, but this requires a tailored strategy considering each country's environmental, economic, and social aspects. Before opting for any solution there is a need to seek at the impacts on the other sectors. By considering these resource interactions, decision-makers have more information with which to determine the best way forward in terms of ensuring resource security and minimizing environmental impact in the region. The research in this paper has started to demonstrate these WEF connections, as well as hinting at those solutions that are more promising than others (e.g. treated wastewater reuse), although it must be acknowledged that there is no 'optimal' solution as there are always negative impacts to be considered.

The application of a nexus approach in the Ain Temouchent region can help support achieving multiple sustainable development goals (SDGs). For example, securing water through desalination and treated wastewater, scenarios tested in this work will help in achieving SDG6 (clean water and sanitation), while SDG7.1.1, related to electricity access, could be reached by implanting a new electricity power plant in the region. SDG2 (food security), could be reached by increasing the irrigated area for certain crops, and also providing more water for irrigation which helps in increasing food production. Economic growth (SDG8), could be promoted by advances across sectors, for example by creating job opportunities associated with desalination plant construction or in expanded agriculture. Ecosystems conservation (SDG15) could be enhanced by preserving the groundwater from over-exploitation and pollution by developing new water sources. SDG17 (partnerships) could be addressed through collaborative efforts among different agencies, institutions, and local communities. By carefully managing existing demand, and by considering interventions across the entire nexus, accounting for both positive and negative outcomes, a suite of solutions can arrive at that maximize potential benefits across sectors while minimizing detrimental impacts.

5 Limitations of the study and future research directions

The study has limitations that need to be acknowledged. Firstly, the analysis was based only on the WEF nexus in the Ain-Temouchent region of Algeria, so the results obtained cannot be generalized to other regions or countries. As this is the first study of its kind in

Algeria, there are no other studies to compare the results within the same country. Due to the lack of data, future scenarios could not be tested or projected, and the scenarios were tested using data for the years 2018–2021 to get an idea of their potential impacts. This may not necessarily reflect near-future conditions. The lack of data also affected the development of the SDM since the climate sector could not be represented in a reasonable manner. In the energy sector, only electricity as a source was implemented because no data was available for gas or other energy sources. Some variables were assumed based on a literature review and previous studies due to a lack of local data. Lastly, future studies could better consider the social and economic aspects of the WEF nexus, which are essential to understanding the complex interdependencies between these sectors.

To address these drawbacks, a number of future research directions are proposed:

(i) Improve local monitoring of WEF resources to enable more comprehensive data collection in the future, or use proxy data from nearby, self-similar settings where appopriate;
(ii) Integrating locally-specific climate and socio-economic projections into the SDM. This would help better assessment of, for example, future water availability, crop yields, and water, energy, and food demands;
(iii) Conduct a thorough socio-economic-environmental (cost–benefit) analysis of some of the solutions proposed here, for example for a desalination plant or a gas-fired power station. Such analysis would result in more information to more better-informed decisions about development pathways and could help maximise benefits while minimising costs;
(iv) Revise the modelling via a stakeholder engagement process, something not possible here due to time and financial constraints. Through such a process, the key issues, relationships, policies, and therefore modelling, may change to more accurately reflect the ongoing and near-future situation.

6 Conclusion

This study emphasizes the importance of understanding the interconnectedness of water, energy, and food (WEF) resources in Algeria's Ain Temouchent region. With population growth and climate change driving up demand for these resources, adopting a holistic approach is crucial to ensure long-term resource sustainability and security. This study is significant because it is the first of its kind in Algeria, emphasizing the need to adopt an integrated approach that considers the interconnections among different resource sectors and shows the potential cross-sectoral implications of policy actions. By using a qualitative systems map to elucidate the connections between the WEF resources sectors in the region, a quantitative system dynamics model was built and a suite of scenarios covering all resource sectors were subsequently tested to assess their impacts across resource sectors.

From the results, while desalination remains a good alternative for assuring a reliable drinking water supply, it is very energy intensive, and other environmental impacts related to brine disposal raise several questions about long-term viability, along with the cost of such facilities. Building new dams in the area could provide additional fresh water sources and reduce trade-offs between other sectors requiring water, but are expensive to build, take years to develop, and alter river flow regimes. It is also not clear just how significant to water supply gain would be. Relying on surface water transfers is another solution that could be implemented with cooperation between authorities, but exposes one region to the risks in another (e.g. periods of water shortage hampering water transfer volume). The use of treated wastewater is seen as a win–win solution for the region, offering a reliable water supply, being relatively cheap as at least some infrastructure already exists, and causing minimal detrimental impacts. Involving the community and stakeholders in decision-making, and promoting the use of treated wastewater for irrigation among farmers, may help its uptake. The region should consider using its significant renewable energy sources for irrigation and desalination, such as solar-powered pumps.

The study highlights the need for coordinated efforts towards a more integrative, systems-thinking approach to natural resources planning and policy in the region that considers the interdependence of the three sectors, promoting local economic development and resources security while minimising detrimental environmental impacts, hoping to guide the region in its development goals. As the Algerian experience regarding the WEF nexus approach is relatively recent, it is important to learn from others countries in the MENA and Mediterranean region such as Egypt, Jordan, Morocco and Tunisia, that have made progress in adopting the WEF nexus approach over the last few years.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10668-024-05151-x.

Acknowledgements We acknowledge funding from DUPC2, the programmatic cooperation between the Directorate-General for International Cooperation of the Dutch Ministry of Foreign Affairs and IHE Delft in the period 2016–2020 for contribution towards research, fieldwork and the writing of this manuscript. The authors are grateful to Zoubida Nemer, PhD student in geophysics at the University of Science and Technology Houari Boumediene, Algeria. For providing the map (Figure 1).

Funding This work was funded under DUPC2, the programmatic cooperation between the Directorate-General for International Cooperation of the Dutch Ministry of Foreign Affairs and IHE Delft in the period 2016–2020.

Data availability All data that can be made public is included in the paper or in the supplementary information. The authors may be contacted for any additional information or data that may be required and data will be released if it is able to do so.

Declarations

Conflict of interest The authors declare no conflicts of interests or competing interests arising from this work.

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