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Economic valuation of groundwater over-exploitation in the Maghreb

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ABSTRACT

The agricultural sector is recognized as particularly vulnerable to the effects of climate change. In semi-arid areas, the performance and durability of irrigated systems are often difficult to manage. Understanding agriculture's response to water scarcity, institutional change and policy interventions is important in order to better define the different agricultural development pathways. The purpose of this paper is to carry out an economic assessment of the costs of groundwater over-exploitation in the Maghreb. This was achieved by using bio-economic modeling in three case studies: the Saïss plain (Morocco), El Haouaria plain (Tunisia) and Sétif plain (Algeria). A set of indicators (land use, farm gross margin, the dual value of water and labor requirements) was calculated for each case study in two scenarios (a business-as-usual (S_BAU) scenario and a return-to-equilibrium (S_RtE) scenario) over a period of 15 years, from 2021 to 2035. Our results show that (i) the state of the aquifer and its over-exploitation level determine the extent of future changes; (ii) in the case of significant groundwater over-exploitation, restoration costs are higher than over-exploitation costs (Saïss plain); on the other hand, in the case where the over-exploitation rate is lower (El Haouaria and Sétif plains), the over-exploitation and restoration costs are close; (iii) both scenarios show significant structural and social changes, and without the effective implementation of environmental and social policies, they lead to high economic losses.

1. Introduction

Water data in Maghreb countries is generally known, but water resources are limited, irregular, and vulnerable. Water availability in this region is below the critical threshold of 1000 m^3 per capita (each country has a capacity of no more than 300 m^3/capita/year), and freshwater withdrawal increasingly exceeds freshwater resources in Algeria and Tunisia, while Morocco withdraws only about 50 % of its freshwater resources.[1] In these geographical areas, groundwater is an essential source of water supply used in many socio-economic sectors, notably in agriculture (Table 1). A large part of irrigated agriculture in particular relies on groundwater, which represents 62 %, 28 % and 35 % of irrigated land in Algeria, Morocco and Tunisia, respectively. Population increases, improved living standards, the development of irrigated agriculture (Debojyoti, 2020) and new activities, especially tourism, have drastically increased groundwater use in Maghreb countries over the last 50 years. This has led to very high rates of groundwater withdrawal, and the over-exploitation of renewable and fossil groundwater in many aquifers (RNE, FAO, 2015; Donkor and Abdurazakov, 2019; Elmahdi et al., 2022), notably in Algeria and Tunisia. Indeed, declining freshwater availability due to groundwater over-exploitation is already detectable from large-scale satellite gravity data (GRACE) (Gonçalvès et al., 2013; Donkor and Abdurazakov, 2019).

This situation may be further aggravated as climate change is increasingly expected to reduce rainfall in the area (Oualkacha et al., 2017; MedECC et al., 2020). In the semi-arid zone of the Mediterranean Basin, most climate-change projections actually anticipate important reductions in future potential aquifer recharge (MedECC et al., 2020). Consequently, growing water scarcity in the southern Mediterranean region is expected to have significant negative impacts on food

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[1] United Nations. 2020. Global SDG database. https://unstats.un.org/sdgs/indicators/database/

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Table 1
Descriptive statistics[a] on water abstraction (by source and sector) and irrigated areas in Algeria, Morocco and Tunisia in 2021.

Variables	Algeria	Morocco	Tunisia
Total renewable groundwater resources (10^9 m^3/year)	1.52	10	1.60
Total renewable surface water resources (10^9 m^3/year)	10.15	22	3.42
Total renewable water resources (10^9 m^3/year)	11.67	29	4.62
Total freshwater withdrawal (10^9 m^3/year)	9.80	10.57	3.86
Fresh groundwater withdrawal (10^9 m^3/year)	8.10	2.32	2.82
Fresh surface water withdrawal (10^9 m^3/year)	1.70	8.25	1.05
Agricultural water withdrawal (10^9 m^3/year)	6.67 (64 %)	9.16 (88 %)	2.71 (75 %)
Municipal water withdrawal (10^9 m^3/year)	3.6 (34 %)	1.06 (10 %)	0.82 (23 %)
Industrial water withdrawal (10^9 m^3/year)	0.19 (2 %)	0.21 (2 %)	0.06 (2 %)
Area equipped for irrigation by groundwater (1000 ha)	842 (62 %)	430 (28 %)	365 (35 %)
Area equipped for irrigation by mixed surface water and groundwater (1000 ha)	14 (1 %)	7 (0.5 %)	512 (49 %)
Area equipped for irrigation by surface water (1000 ha)	373 (27 %)	1013 (67 %)	146 (14 %)

[a] FAO AQUASTAT Dissemination System. https://data.apps.fao.org/aquastat/?lang=en&share=f-538f38b8-8326-4ff0-8fb7-a40e82dae296

production, and to affect the types of crops grown. Moreover, the availability of water for agriculture will probably face further constraints due to competition with demand from urban areas, tourism, and the industrial sector. Rising water scarcity and the resulting decline in agricultural production are therefore also expected to accelerate migration, especially in the most agriculture-dependent economies, and increase dependency on food imports (Lemaitre-Curri and Tode, 2020; Papamichael et al., 2022). For example, earlier studies by Croitoru and Sarraf, 2010 estimated the overall cost of water degradation and groundwater over-exploitation in Tunisia at 0.6 % of GDP in 2004, with the greatest cost in the agricultural sector, mainly because of the impacts of salinity and waterlogging on irrigated agriculture.

In this context, many groundwater conservation and management efforts have been implemented by public authorities. However, the majority of them focus on protecting groundwater for drinking purposes and other human uses, through integrated management, water loss reduction, the prioritization of the most critical activities, the mobilization of alternative water resources, and artificial recharge. In fact, little attention has been given to the integrated management of groundwater resources, and the viability of groundwater biodiversity and Groundwater-Dependent Ecosystems (GDE), which have become major environmental concerns in the Mediterranean Basin (Lemaitre-Curri and Tode, 2020), has been neglected. The management of groundwater and GDEs should increase their total economic value, for a broader understanding of the relevant processes and issues associated with GDE management, and to help design consistent policies. The design and implementation of effective measures for the sustainable use and allocation of groundwater resources therefore require a comprehensive assessment of the costs associated with groundwater over-exploitation, and of their distribution.

The aim of this study is to conduct an economic valuation of the costs of groundwater over-exploitation in the Maghreb, as well as to estimate the potential restoration costs of groundwater resources. In fact, in this study, we focus on the role of groundwater as a regulating service, specifically its contribution to irrigation and subsequent impacts on crop production, which we evaluate through shadow pricing to reflect its economic value. By concentrating on irrigation, we address the primary economic market values of groundwater in the Mediterranean Basin, where agricultural productivity heavily depends on this resource. Moreover, this approach highlights the importance of such ecosystem services for farmers, in relation to other necessary input costs within their agricultural systems (e.g. Kleftodimos et al., 2021).

In order to do so, three representative case studies were selected with the help of local experts, one in each country where trade-offs exist between agricultural activities (and other economic activities, such as tourism, industry, etc.) and the selected aquifers.

The DAHBSIM bio-economic model (Flichman et al., 2016) was used for the evaluation of the above costs, and the aquifer dynamics were included in order to assess the impacts of groundwater uses and socio-economic changes on different scales (from farm-level to regional level) over a period of 15 years. A Business-as-Usual scenario was developed for the economic valuation of groundwater over-exploitation costs, while a scenario proposing the implementation of a quota was used to assess restoration costs. The use of such models is of paramount importance to address emerging issues in cases where trade-offs exist between agricultural activities and the degradation of ecosystem services, and to inform private and public stakeholders in their decision-making process (Wätzold et al., 2006; Drechsler et al., 2007; Longo et al., 2021). However, despite the need for such approaches, they remain scarce in the literature.

The first section of the paper presents the theoretical and analytical framework on which this work was based. The second section provides a step-by-step analysis of the methodology of the DAHBSIM model and its water module, in which we integrated the dynamics of the aquifer. The results obtained having been presented in the third section, the fourth discusses the main findings. Finally, the last section draws the conclusions and summarizes the limitations of our study.

2. Analytical framework

2.1. Economic valuation of groundwater resources

Several studies have tried to conduct an economic valuation of groundwater resources (Bierkens et al., 2019; Fenichel et al., 2016; Loomis and Haefele, 2017; Suter et al., 2021). However, the selected methodology depends on the type of values of the services offered by the ecosystem to be quantified (National Research Council, 1997; Ma et al., 2016; Soula et al., 2023). In the case of non-market values, such as recreational services, the majority of the studies applied stated preferred techniques, such as travel-cost methods and choice modeling (Rolfe and Dyack, 2010). However, when it comes to market values, several modeling approaches exist for quantifying the economic importance of groundwater resources (Koundouri, 2004; Richey et al., 2015; Koundouri et al., 2017; Lezzaik and Milewski, 2018; Manisha et al., 2023). The majority of these studies focus on the use of different hydro-economic models (Pulido-Velazquez et al., 2008) in order to estimate the potential costs and benefits of groundwater use. They promote new practices and assess possible solutions for groundwater provision, and/or design effective policy measures which can lead to improved uses (Koundouri et al., 2017).

The majority of these models use econometric approaches to quantify the marginal water values of production and consumption based on the existing behaviors of the stakeholders involved (Kindler and Russell, 1984; Arbués et al., 2003; Young and Loomis, 2014). Other approaches use optimization models, with the use of mathematical programming, in order to assess the optimal behavior of stakeholders in the face of constraints (Howitt, 1995). However, these approaches typically operate on a broader scale by optimizing water supply and demand on a large scale, such as the region or basin. Moreover, few studies (Baccour et al., 2024; Crespo et al., 2019; Kahil et al., 2016) take into account the complex representation of agricultural systems in a landscape, as well as the complex decision-making process of farmers in relation to irrigation systems, crop selection, adaptation strategies, labor allocations, etc. Bearing in mind that the majority of policy measures in the EU suffer from low farmer participation, as they fail to address socio-economic issues (Gaujour et al., 2012; Del Corso et al., 2015), it is of paramount importance to include farmer decision-making in the economic valuation of groundwater uses (Tiwari et al., 1999; Harik et al., 2023; Kumar and Pant, 2023), especially in areas like the Maghreb where agriculture is the main water consumer (Faysse et al., 2011; Tringali et al., 2017). Indeed, groundwater over-exploitation will have a significant impact at farm level as it will affect water uses, cropping patterns, incomes, labor requirements, self-consumption, and the overall resilience of agricultural systems (Faysse et al., 2011; Lejars and Courilleau, 2015; Soula et al., 2023). In fact, several studies have tried to assess the complex trade-offs that emerge between the decisions of farmers and groundwater use, however these studies focus on the impact of groundwater over-exploitation on crop production (Ma et al., 2016) with the use of biophysical models, or they use econometric household models which neglect the complex biophysical process of crop production and the impact of water stress on yield outcomes (Shiferaw et al., 2008).

Therefore, this study seeks to conduct an economic valuation of groundwater over-exploitation with the use of a dynamic bio-economic model, by trying to integrate the complex trade-offs previously mentioned.

2.2. Methodological overview

This work primarily tries to conduct an economic valuation of the costs of groundwater over-exploitation in the Maghreb. Two-thirds of groundwater resources are allocated to the agricultural sector in this region. Our approach therefore placed the selected aquifer at the center of the analytical model, in order to examine its dynamics in relation to the water demand that emerges from local agricultural systems. The first STEP of our analysis was therefore to select an aquifer (for each case study), define its natural boundaries and water balance, and identify the local agricultural systems that use solely this aquifer for irrigation. Then we attached all the associated water consumption categories that emerged from other economic activities (e.g., drinking water, tourism, and industry) to the water balance, as an exogenous parameter.

As a second STEP, with the help of local experts, we carried out a site-specific characterization of the agricultural systems in each case study (Blanco-Gutiérrez et al., 2011). This approach allowed us to create representative farm-types, and to feed the DAHBSIM model. Each farm-type represents a large number of local agricultural systems with common technical, economic, agronomic, and environmental characteristics (El Ansari et al., 2020; El Ansari et al., 2023). Technical and economic parameters were attached to all the farm-types in relation to water use, water access, pumping systems, etc. In STEP 3, we defined the scenarios to be simulated over a 15 year-period together with a panel of experts, including researchers from the Sahara and Sahel Observatory (OSS), experts from The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), and stakeholders from each case study. Finally, in STEP 4 the simulation results were expressed via multi-level indicators in order to represent the different environmental, economic, and societal impacts of the scenarios tested.

2.3. Case studies and farm characteristics

As mentioned above, one characteristic case study was selected in each country with the help of the panel of experts. The selection was based on a large list of criteria in order to represent the diversity of groundwater resources in the Maghreb as well as the issues with over-exploiting the aquifer and the availability of data. Three aquifers (Fig. 1, Table 3) with different water balances, over-exploitation rates, and supporting agricultural systems were therefore identified and validated by the panel of experts.

- Morocco: Saïss Plain – Meknes Region

The Saïss plain is characterized by an important aquifer system which extends over an area of 2200 km^2. It is one of the main aquifer systems in Morocco and contributes to the drinking water supply and

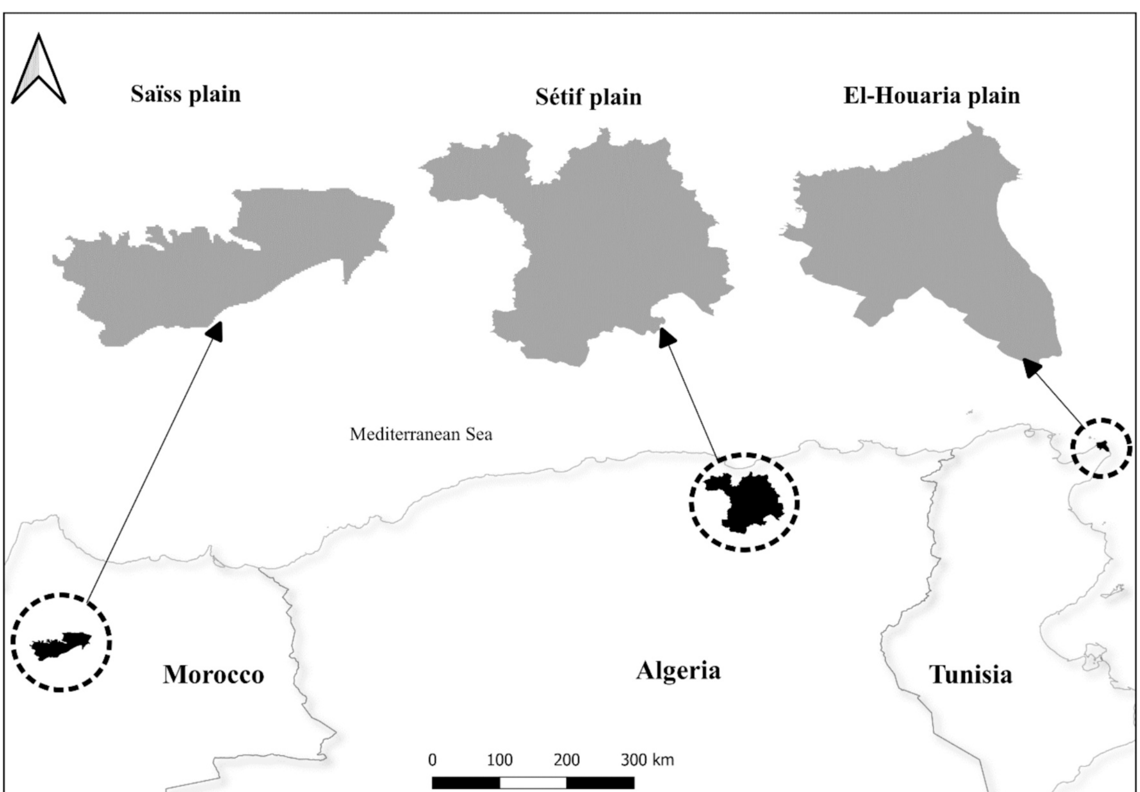


Fig. 1. Study area map.

development of the agricultural sector with a utilized area of 160,000 ha. In 2000, the government of Morocco lost control over irrigation regulations and as a result, a significant increase in irrigated agricultural systems was observed (Benouniche et al., 2011; Dugué et al., 2015; Lejars and Courilleau, 2015). Indeed, in 2021, the irrigated agricultural land area reached 50,000 ha, or 31 % of the total utilized agricultural area. Among these 50,000 ha, 45,316 ha depend exclusively on the aquifer for irrigation (Ministry of Agriculture and Maritime Fisheries statistics, in Dugué et al. (2015)).

However, this rapid increase in irrigated agricultural land in combination with climate change and population increase led to an over-exploitation of groundwater resources. Indeed, the superficial aquifer is already overexploited, which causes an imbalance in the overall aquifer system as well as the drying up of certain springs (Agence du bassin hydraulique du Sebou, 2021). In fact, the Saïss aquifer is heavily used for irrigation (about 160 M m^3 of withdrawal in 2012), and it also contributes to the drinking water supplies of rural areas (100 M m^3 in 2012). Over the period from 1980 to 2012, the average deficit (less inflow than outflow) was around 100 M m^3/year, which shows that the aquifer has been over-exploited for a long time. Nowadays, the water deficit of the aquifer system of the plain is still growing, and amounted to 137 million m^3 in 2020 (Agence du bassin hydraulique du Sebou, 2021).

In order to characterize local agricultural systems, primary data was obtained from a survey of 286 agricultural households conducted in 2014 by the International Center for Agricultural Research (ICARDA), the National Institute for Agricultural Research (INRA) of Morocco and the CIHEAM-IAMM Montpellier (El Ansari et al., 2020). This data was then validated and enriched with the help of the national focal point of Morocco. We thus distinguished 10 different farm-types that are predominant in the area. However, many of them are dry-farming systems and as a result, we identified three representative farm-types (Table 2) with significant irrigation levels (El Ansari et al., 2020):

- MF1: Intensive production systems that mainly focus on onions and potatoes and represent 44 % of the total irrigated area. These households apply 143 kg/ha of nitrogen fertilizer, use 5770 m^3/ha of water for irrigation, and 55.6 working days/ha on average, which leads to average potato and onion yields of 25.4 t/ha and 33.2 t/ha, respectively.
- MF2: Semi-intensive cereal monoculture households that mainly cultivate cereal crops (wheat and barley) and represent 17 % of the total irrigated area. These households are characterized by intermediate nitrogen fertilizer application levels and labor requirements at 83 kg/ha and 15.09 person-days/ha, respectively, with low drip irrigation application levels (410 m3/ha).
- MF3: MF3 farms specialize in fruit tree crops, which provide more than 80 % of their total gross margin. Their size is generally between 15 and 35 ha. These households are characterized by high nitrogen fertilizer application levels (110 kg/ha), and they employ more permanent highly-skilled workers (two to five) in order to carry out tasks requiring technical expertise (pruning, spraying) and to supervise temporary workers. The majority of farms seek to have more than one water source with high drip irrigation application levels (2500 m3/ha). These farms largely resort to bank loans and state aid. Thanks to their focus on fruit production, they generate a far higher income per family worker than the other types. They can increase their area by buying land despite very high prices, which can vary from MAD 300,000 to 500,000 per hectare in the Saïss plain for land with groundwater access.

- Tunisia: El Haouaria plain – Nabeul Governorate

The El Haouaria plain is located in the extreme northeast of Cap-Bon (Nabeul Governorate). It is surrounded by the forests of Dar Chichou and Djebel El Haouaria, and the Mediterranean Sea on both sides, and covers a total surface of 143.5 km^2. The groundwater resources in this plain constitute a valuable natural resource for the region as they exclusively supply all the different economic sectors (i.e. agriculture, industry, tourism, and drinking water) (Ghazouani and Mekki, 2016). The aquifer system of the El Haouaria plain is composed of a deep aquifer and a phreatic zone. According to recent estimates, the recharge of the shallow aquifer represents 33 M m^3 per year, and 5.2 M m^3 per year for the deep aquifer (Ghazouani and Mekki, 2016; Ferchichi et al., 2020; Calvaruso et al., 2021). Irrigation is provided from groundwater through wells, and from deep groundwater through boreholes. However, the total number of wells has increased from 2961 to 5364 between 1969 and 2020, with over 75 % of wells having been deepened. The same trend was observed for the number of boreholes, which increased from 7 in 1975 to 78 in 2020 (Ghazouani and Mekki, 2016; DGRE, 2020). Consequently, the excessive exploitation of aquifers has led to the qualitative (salinity and nitrate pollution) and quantitative degradation of the water resources of

Table 2
Main characteristics of representative farm-types in the different case studies.

Study areas		Agricultural activities	UAA (ha)	Irrigated area (%)	Water source	Estimated water quantity (m3/ exploitation)	Over-exploitation rate of the aquifer (%)	Representativeness (%)	Livestock
Morocco	MF1	Vegetable crops + cereal crops	3.88	80	Boreholes	22,388	180	44	Yes
	MF2	Cereal crops + legume crops	4.41	10	Well/irrigation association	1808		7	Yes
	MF3	fruit tree crops	25	100	Boreholes	62,500		39	No
Tunisia	TF1	Fodder + livestock	2.49	81	Well/irrigation association	2520	105	46	Yes
	TF2	Vegetable crops + legume crops (peanuts)	1.45	100	Well/irrigation association	4220		43	No
	TF3	Vegetable crops + legume crops (peanuts) + cereal crops	6.8	100	Boreholes	23,690		10	No
	TF4	Vegetable crops + legume crops (peanuts) + cereal crops + tree crops	50.7	87	Boreholes	81,370		1	No
Algeria	AF1	Vegetable crops + cereal crops + livestock	18	67	Boreholes	14,251	NA	30	Yes
	AF2	Vegetable crops + cereal crops + tree crops + livestock	46	61	Well/wadi and retention pond	14,216		24	Yes
	AF3	Fodder + cereal crops + livestock	10	50	Well	3800		46	Yes

Table 3
Groundwater balance: inflow and outflow of groundwater systems in 2021.

Inflow (Mm^3/an)				Outflow (Mm^3/an)			
Study areas	Saïss	El-Houaria	Sétif	Study areas	Saïss	El-Houaria	Sétif
Natural recharge (precipitation)	90	**23**	NA	**Irrigation**	198	37	NA
Inflow from other basins	84.5	5.2	NA	**Domestic consumption**	100	2	NA
Irrigation return flow	40	10	NA	**Others**	81	1	NA
Total	214.5	38.2		**Total**	379	40	
Groundwater balance (Mm^3/an)					**−164.5**	**−1.8**	

Source: (Agence du bassin hydraulique du Sebou, 2021; DGRE, 2020).

Table 4
Effect of different scenarios on farm gross margin (FGM): minimum, maximum, mean and average variation compared to 2021 of FGM per ha, per farm and at the level of the different case studies in the S_BAU and S_ RtE scenarios over a 15-year simulation period.

	Indicators	FGM (€[a]/ha)		FGM (€ /farm)		Global FGM (€)	
		S_BAU	S_RtE	S_BAU	S_RtE	S_BAU	S_RtE
El Haouaria	Min	427	434	1727	1721	10,364,916	10,326,729
	Max	1220	1268	3489	3527	20,931,744	21,164,611
	Mean	838	837	2609	2598	15,655,565	15,590,442
	2021	960		2930		17,581,776	
	Average variation compared to 2021	−131	−146	−344	−363	−2,063,797	−2,177,272
Saïss	Min	226	167	2489	1836	124,459,289	91,791,950
	Max	298	286	3273	3142	163,659,495	157,081,972
	Mean	257	177	2826	1944	141,299,391	97,191,034
	2021	286		3142		157,100,000	
	Average variation compared to 2021	−31	−117	−338	−1283	−16,909,908	−64,168,863
Sétif	Min	878	878	14,924	14,924	24,713,766	24,713,766
	Max	1491	1181	20,127	20,070	33,330,735	33,235,204
	Mean	1318	1036	17,795	17,617	29,469,105	29,173,510
	2021	878		14,924		24,713,766	
	Average variation compared to 2021	228	170	3077	2885	5,095,007	4,778,298

[a] Tunisia: 1TND = €0.3; Morocco: 1 Dirham = €0.092 and Algeria: 1DZD = €0.0068.

Table 5
Effect of different scenarios on the dual value of water (DVW): minimum, maximum, mean and average variation compared to 2021 of the DVW per m^3, per farm and at the level of the different case studies in the S_BAU and S_ RtE scenarios over a 15-year simulation period.

	Indicators	DVW (€ /m3)		DVW (€ /farm)		Global DVW (€)	
		S_BAU	S_RtE	S_BAU	S_RtE	S_BAU	S_RtE
El Haouaria	Min	0.025	0.037	151	218	906,685	1,299,430
	Max	0.153	0.154	944	910	5,663,980	5,444,719
	Mean	0.082	0.085	503	504	3,022,282	3,017,685
	2021	0.037		227		1,359,478	
	Average variation compared to 2021	0.048	0.052	296	306	1,779,788	1836,385
Saïss	Min	0.157	0.408	1173	1633	25,108,257	24,493,761
	Max	0.568	0.803	4248	3211	90,913,761	48,170,092
	Mean	0.352	0.602	2628	4495	56,281,835	36,108,349
	2021	0.183		1432		29,357,798	
	Average variation compared to 2021	0.118	0.201	881	1501	18,880,000	12,060,000
Sétif	Min	0.000	0.126	0	449	0	744,304
	Max	0.375	0.411	1484	1464	2,458,128	2,423,785
	Mean	0.164	0.268	649	954	1,075,241	1,579,313
	2021	0.158		626		1036,126	
	Average variation compared to 2021	0.003	0.032	12	114	19,673	188,863

the plain with a continuous threat of seawater intrusion. Moreover, a drop in the piezometric level of 1 to 2 m/year on average was also observed between 1972 and 2006 (Ben Hamouda, 2008). Finally, in 2021, the aquifer over-exploitation rate reached 111 % with an annual consumption of 42 million m^3.

The main water user in the plain is the agricultural sector, which covers 86 % of its total surface. Moreover, agriculture is the main economic activity of the area, with over 70 % of the local population working in the sector. This territory currently includes about 6000 farms, dominated by small systems with an average farm size of 2.68 ha (Ghazouani and Mekki, 2016; Ferchichi et al., 2020; CTV El-Houaria, 2021). For the characterization of local production systems, we extracted data from the literature (Ghazouani and Mekki, 2016; Ferchichi et al., 2020; Calvaruso et al., 2021), and conducted personal interviews with local farmers in the spring of 2021. We validated our findings with local stakeholders, and the panel of experts. As a result, we identified four representative farm-types (Table 2):

- TF1: Very small farms (less than 2.49 ha) which constitute approximately 46 % of agricultural holdings and specialize in sheep farming and fodder production.
- TF2: Small farms (less than 1.45 ha) which represent approximately 43 % of households and mainly grow vegetables and groundnuts.
- TF3: Diverse medium-sized farms (between 1.45 ha and 10 ha) which specialize in cereal crops and vegetables. They represent 10 % of local agricultural systems.

Table 6
Effect of different scenarios on agricultural labor requirements: minimum, maximum, mean and average variation compared to 2021 of the labor needs per ha, per farm and at the level of the different case studies in the S_BAU and S_ RtE scenarios over a 15-year simulation period.

Indicators		Labor requirements (AWU[a] /ha)		Labor requirements (AWU /farm)		Overall labor requirements (AWU)	
		S_BAU	S_RtE	S_BAU	S_RtE	S_BAU	S_RtE
El Haouaria	Min	0.32	0.31	3.02	2.95	6041	5973
	Max	0.49	0.49	5.16	5.05	8685	8570
	mean	0.43	0.42	4.14	4.07	7686	7549
	2021	0.46		4.87		8178	
	Average variation compared to 2021	−0.04	−0.05	−0.77	−0.80	−381	−714
Saïss	Min	0.578	0.542	6.362	5.96	318,110	298,047
	Max	0.716	0.620	7.878	6.82	393,900	340,860
	mean	0.669	0.581	7.354	6.39	367,706	319,641
	2021	0.667		7.34		367,076	
	Average variation compared to 2021	0.001	−0.026	0.013	−0.28	675	−14,052
Sétif	Min	0.471	0.442	6.36	5.96	7598	7119
	Max	0.584	0.505	7.88	6.82	9408	8141
	mean	0.545	0.474	7.35	6.39	8783	7635
	2021	0.544		7.34		8767	
	Average variation compared to 2021	0.001	−0.021	0.01	−0.28	16	−336

[a] Annual work unit (in our case this represents 225 working days of eight hours each).

Table 7
Global summary of different case studies: Average variation compared to 2021 of the farm gross margin, dual value of water and labor requirements at the level of the different case studies in the S_BAU and S_ RtE scenarios over a 15-year simulation period.

Scenarios	Case studies	Indicators (15-year overall average)		
		FGM (€ /farm)	DVW (€ /farm)	Labor requirements (AWU /farm)
Average variation compared to 2021 (S_BAU: over-exploitation)	Tunisia (El Haouaria plain)	−344	296	−0.77
	Morocco (Saïss plain)	−338	881	0.013
	Algeria (Sétif plain)	3077	12	0.01
Average variation compared to 2021 (S_RtE: restoration)	Tunisia (El Haouaria plain)	−363	306	−0.80
	Morocco (Saïss plain)	−1283	1501	−0.28
	Algeria (Sétif plain)	2885	114	−0.28
Average variation compared to 2021 (S_RtE – S_BAU)	Tunisia (El Haouaria plain)	−19	10	−0.03
	Morocco (Saïss plain)	−945	620	−0.67
	Algeria (Sétif plain)	−192	102	−0.27

- TF4: Large farms (UAA greater than 10 ha) which represent about 1 % of local systems and specialize in cereal crops, vegetables and perennial crops.

• Algeria: Sétif Plain

Sétif Province is located east of Algiers. It includes 60 municipalities, and extends over 6500 km^2, for a population of 1,489,979 inhabitants. Agriculture is the main activity of the region, and covers an area of 459,853 ha (10 % of irrigated land). Its agriculture is mainly based on sheep farming (513,017 head of cattle) and cereal production (193,892 ha) with a total number of 29,830 farms (Benniou et al., 2014a). The majority of water resources consumed by agricultural activities come from local dams and irrigation canals, while a small percentage of the aquifer is used for agriculture. Although the volume of water resources is substantial in this area, and we cannot speak of a global lack of water, the irrigation systems in place are old and responsible for significant water wastage, which creates occasional and localized deficits, and affects the economic viability of existing production systems. In fact, in the Sétif plain, many farms do not have access to water, whether underground or surface, in particular small farms (less than 10 ha) located in the south-east of the plain (Lupinko, 2018), while large farms use groundwater without restriction, and mainly with a gravity-fed irrigation system (DSA, 2017). Despite abundant water resources, the Sétif plain thus offers a contrasting situation regarding groundwater access, in terms of water used for agricultural activities. It therefore has no issues of water scarcity but of access to and management of this resource (DSA, 2017).

The study and typology of farms were carried out on an area of approximately 19,345 ha in the Sétif plain. In order to better characterize the agricultural systems of the plain, primary data was obtained from the study of Lupinko (2018). This initial data was validated and enriched with the help of local experts, thus concluding with the identification of 3 main farm-types (Table 2):

- AF1: Small farms (less than 20 ha) located in the hot semi-arid climate with the lowest rainfall in the region (between 200 and 300 mm per year). This type represents 30 % of the territory (Benniou and Brinis, 2006), and is characterized by the diversification of crops, and sheep and cattle breeding. These farms have their own private boreholes and consequently, enjoy unlimited access to water for irrigation.
- AF2: These farms are generally medium-sized (between 20 and 50 ha), and are often located in the area with a cold semi-arid climate which receives the most rainfall (between 400 and 600 mm per year). Farms of this type represent 24 % of the sample studied, and are characterized by the diversification of crops, cattle and sheep breeding as well as arboriculture. They have limited access to irrigation water, mostly used for arboriculture.
- AF3: Very small farming systems (less than 10 ha), located in the areas with a hot semi-arid climate and a cold semi-arid climate which receive around 400 mm of rainfall per year. This is the predominant production system in the territory (46 %), which specializes in rainfed cereal crops and sheep breeding, while it does not have access to water for irrigation.

The typology represents the variety of farms based on discriminatory criteria. A complex system is represented by a classification process. This modeling step aims to help reduce the diversity of farms. It provides a framework that can be used to study technical problems related to agricultural production, and to develop adapted solutions. Creating typologies requires both theoretical knowledge and a solid understanding of the field. This method is applicable for delimited areas and requires extensive data on the farming system.

As a result, typologies specifically support the extrapolation of ex-ante evaluations to larger spatial scales. However, our framework shows that the aggregation, upscaling, and generalization of farm typologies need to be carefully implemented. Taking into account the challenges of validity and the context dependency of data collection, the use of farm typologies for upscaling and generalizing across cases is still an empirical question. Farm typologies cannot solve all problems, and there will always be a trade-off between generalization and context sensitivity, even with increased data and improved statistical tools. In our framework, we suggest that generalization may not always be the most challenging issue for the corresponding farm typology.

These typologies could then serve as a basis for aggregating/upscaling individual farm-scale analyses to a larger spatial scale (region, landscape, watershed), to help stakeholders define new systems whose performance has to take into account trade-offs between production and environmental issues (El Ansari et al., 2020).

2.4. Modeling approach

In order to conduct the economic valuation of the costs of groundwater over-exploitation in the above case studies, we used the Dynamic Agricultural Household Simulation Model (DAHBSIM) (Flichman et al., 2016; El Ansari et al., 2023). This model is presented in the form of an “integrated modeling chain” and not as a unified generic model. It is therefore composed of several modules/components (Fig. 2 and Appendix 1) which are combined with each other in order to represent the different spatial scales of analysis: infra-plot, plot/farm/territory of the aquifer. More information on the different components of the model is provided by Flichman et al. (2016).

The main sub-models are:

- The biophysical model computes the water stress coefficient in year 1 in its first step. In its 2nd step, it computes the water stress coefficient for the following years. A similar procedure is used concerning nitrogen.
- The crop model contains the equations describing the cropland allocation, labor use, rotation constraints, etc.
- The farm model contains the equations defining the resource constraints.
- The household model contains the equations defining household demand and time allocation.
- The livestock model computes the feed requirements of different types of livestock and its feedback is consistent with the rest of the model, as it takes into account balances of feed consumption as well as manure for crop fertilization.

The crop module (Appendix 1) briefly simulates soil water (including water use and drainage) and nitrogen balances (both organic and mineral) and their effect on yields. It assesses the performance of each farm over multiple years and for multiple crops through an “input-output” matrix. This matrix describes current or innovative farming practices as well as their impact on yields and the environment. This matrix also presents the cost associated with each of these practices. The yields of each cropping system as well as certain environmental variables (water consumption, nitrate, organic matter) are simulated by using a crop model. This model is also generic and modular in order to take into account the diversity of the systems to be simulated. It is directly connected to the farm model in order to simulate the impact of the farmer’s production choices on the farm’s economy and on the environment simultaneously, in a systemic approach. Irrigation water withdrawals (volume) also come into play in this model.

The model links modules related to household crop production, food consumption (using a linear expenditure function), and economic and

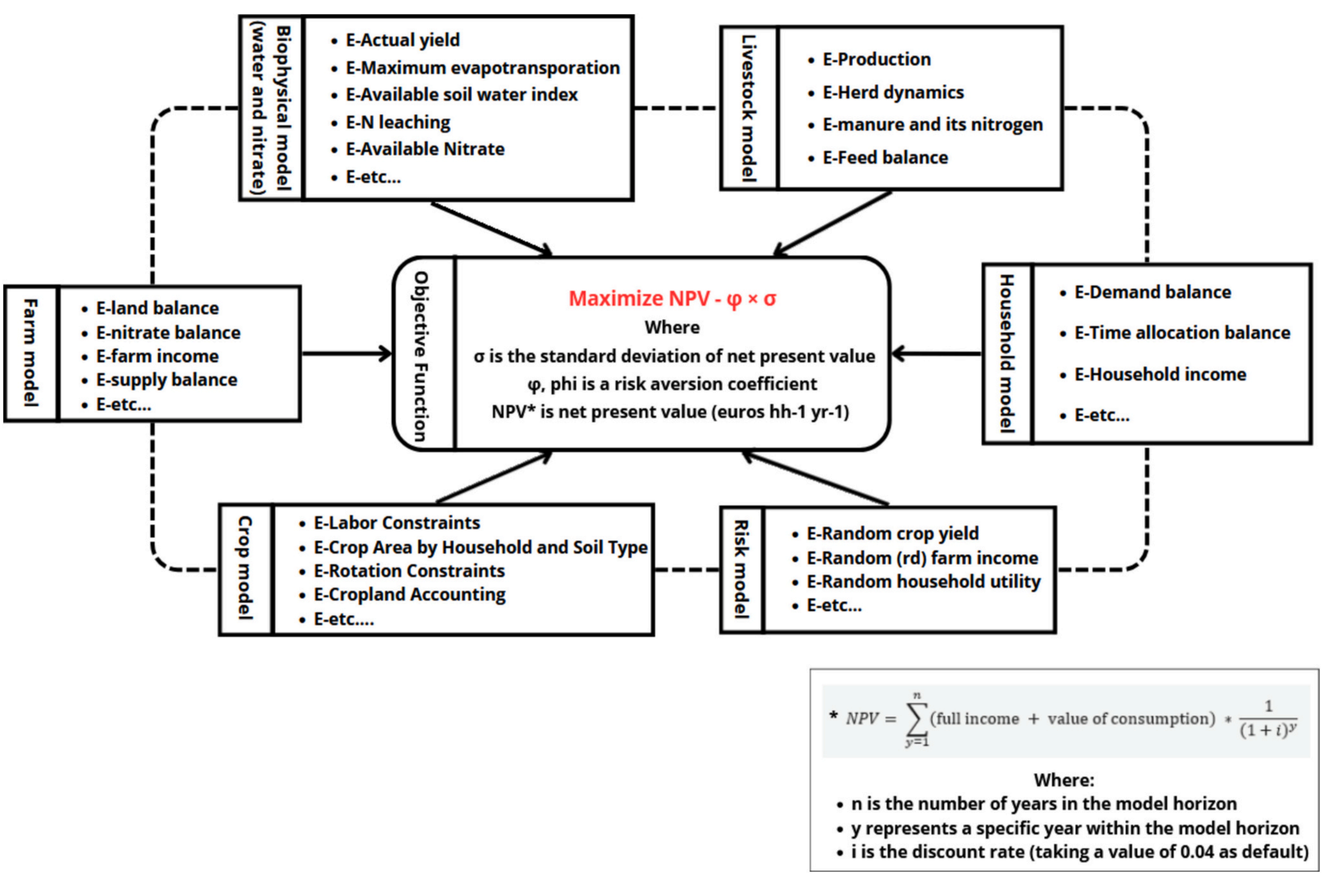


Fig. 2. Overview of model structure.

resource-use factors. The model allocates land, labor, water and cash to different crop and livestock production activities given a set of constraints. The constraints consider the supply and demand of different resources; for example, the household cannot allocate more land to crops than is available, monthly labor demands cannot exceed the household's supply of labor, total cash expenditures cannot exceed total income, and the household cannot allocate more water to crops than is available. In the model, the household simultaneously determines its crop and livestock production, food consumption, and labor allocation decisions.

The DAHBSIM bio-economic model is based on a mathematical programming method that optimizes an inter-temporal objective function (household utility) subject to a set of constraints, based on observed economic conditions (such as prices and costs) and biophysical conditions including rainfall and soil properties (such as soil texture), based on the mean-standard deviation method (Hazell and Norton, 1986).

$$U = NPV - \varphi\sigma \tag{1}$$

where, NPV represents the net present value, φ the risk aversion coefficient, and σ the standard deviation of income due to yield and price variability. The model considers two sources of risk, price and yield variability, while we assume that farmers are risk averse. We assume that the yield variability risk for each crop follows a normal distribution, and prices also conform to a normal distribution. The parameters for these distributions are estimated using the time series data from 2008 to 2018. In economic analyses, when making decisions in uncertain situations, the expected utility hypothesis is commonly used (Lien and Hardaker, 2001). Therefore, the expected utility of farmers' net present value is calculated as the average utility derived from the incomes of 50 states of nature following a probability distribution.

Initially, DAHBSIM is a nonlinear model, however, we changed it to a linear one in order to better integrate the yield variability into farmer decision-making, and to determine the feasible optimal crop combination and how these crops will be allocated to increase production. The Net Present Value is calculated as the household income from crop and animal production plus the value of self-consumption.

$$NPV = \sum\nolimits_{y=1}^{n} \left(household_{income} + self_{consumption}\right) \times \left(\frac{1}{1+i}\right)^{y} \tag{2}$$

where, NPV is the net present value (USD per household per year), n is the time horizon (number of years), y a specific year within the time horizon, i the discount rate[2] with a value of 0.04 as default, f $household_{income}$ represents off-farm income plus revenues (is [the value of all crop (yield) and livestock production sales, based on their market price and quantity sold] minus all variable input costs with a financial cost), and self-consumption is the value of food consumption from on-farm production based on market prices.

Calibration of farming models is necessary before examining agricultural producers' responses to policy changes. Well-calibrated farming models with many variables is critical for optimized agriculture management and decision making. There are several calibration methods which quantify the degree of fit between model predicted and observed values.

For example the historical crop-mix approach is used mainly for aggregate or sector level analysis (Liu et al., 2020; McCarl, 1982; Önal and McCarl, 1991). By assuming that observed past crop choices are optimal, it constrains farmers' crop allocations to resemble past choices, such as historical mixes, without finding the explicit economic cost function. According to this method, farmers' choices are located at the extreme points or corners of the convex constraint set (e.g, a simplex algorithm for solving LP problems). The approach's disadvantage is that historical ranges limit future choices.

The preferred approach for calibrating farming models is now positive mathematical programming (PMP), which is an effective tool for estimating crop-specific marginal cost functions and replicating farmers' observed crop allocations exactly. The use of PMP in trade modeling and other resource management settings has increased (Howitt, 1995; Howitt et al., 2012; Liu et al., 2020; Mérel and Howitt, 2014). This method has been extended over time by incorporating external information, like supply elasticities, and the principle of maximum entropy (ME), to acquire parameter estimates for the whole cost matrix (Howitt, 1995; Howitt et al., 2012; Liu et al., 2020; Mérel and Howitt, 2014).

In our case, DAHBSIM model does not use PMP for calibration, but maximizes utility based on gross margin and risk aversion. Our study used a set of states of nature for crop prices and yields to calculate the standard deviation of farm household income. Our standard deviation calculation is based on levels of simulated farm household income and historical variability in crop yields and prices (FAO, 2022). These variable yields and prices capture two sources of production and market risk encountered by farmers (Komarek et al., 2020).

The first simulation year is used as the base year to evaluate the performance of the model by comparing the simulated and observed data. The variables selected for the evaluation of the performance of the model included crop areas, crop income, etc. In this step, the model was solved for several values of the risk aversion coefficient. In this step, several risk-aversion coefficients were tested. The risk aversion coefficient selected was the one allowing the smallest difference between observed data and those simulated. This evaluation is carried out based on the Percentage Absolute Deviation (PAD) (Hazell and Norton, 1986) for each variable which was computed as:

$$PAD = \frac{(X_{sim} - X_{obs})}{X_{obs}} * 100 \tag{3}$$

Where: X_{sim} is the simulated value of the variable that requires calibration, X_{obs} is the observed value, and PAD is Percentage Absolute Deviation.

Although PMP could improve calibration, it didn't alter the overall trends in the allocated area for each crop. Moreover, Positive Mathematical Programming (PMP), relies heavily on observed data and actual policy measures, while our normative approach is designed to examine the effects of hypothetical policy scenarios. This distinction is critical as our study aims to explore potential outcomes under proposed, yet unrealized, policy measures. PMP, while effective for replicating observed behaviors under current conditions, may not fully capture the dynamics of future, uncertain scenarios where historical data is less relevant or unavailable. By calibrating the model using a risk-aversion coefficient and simulating variability in yields and prices, our approach provides a robust framework for analyzing the impacts of hypothetical policy changes. This allows us to explore the range of possible responses and outcomes, offering valuable insights for decision-makers even in the absence of real policy interventions.

As mentioned, for the calibration of, the model, we used the risk-aversion coefficient and validated it with the Percentage Absolute Deviation (PAD) for each farm-type. Indeed, the observed PAD values vary between 6.8 % and 14.2 %, which is acceptable according to the literature (Hazell and Norton, 1986). Moreover, according to local experts, the risk aversion coefficient varied between 1.2 and 1.6 among the different farm-types, which according to the study of (Hardaker et al., 2015) corresponds to a moderate risk aversion attitude. This research exclusively focuses on groundwater resources as an input in agricultural systems. In fact, the water requirements for every single farm type are calculated for each year. The results can be aggregated across the study area by using the weight of each type of farm volume to assess agricultural groundwater withdrawal (Appendix 1.2). In addition, the

[2] The discount rate is used to convert future values of income into their present value. The discount rate affects prices in the same way for all scenarios and years. The discount rate in 2021 for the three countries are: Tunisia = 4.6 %; Algeria 3.7 % and Morocco = 2.7 %. with an average of 3.67, so we decided to use 4 % for all the case studies.

DAHBSIM model is not directly linked to a hydrologic model, and lacks a specific hydraulic component. From a hydrological point of view, our model often uses generic hydrologic and climate data (precipitation, water withdrawal by sector, water availability, evapotranspiration, etc.). This aggregation could help simplify the computational process, but it could also overlook some of the spatial interactions that occur in the field among different ecosystems and sectors. Interactions between hydrological components could be better represented in future studies. Nevertheless, this approach allows us, for the very first time, to assess the impacts of groundwater over-exploitation or restoration on farmers' decision-making process.

2.5. Simulation scenarios

Following the necessity to take action against water scarcity and groundwater over-exploitation, two different medium-term scenarios were designed and validated by local experts over a period of 15 years, from 2021 to 2035. This 15-year simulation period was chosen according to experts, as it was deemed sufficiently long to cover a wide range of rainfall conditions, and for designing agricultural policies (the model is dynamic and could run over other periods). The first scenario is a Business-As-Usual scenario (S_BAU), which aims to examine the impacts of groundwater over-exploitation on local production systems and local communities. According to this scenario, no policy changes regarding water use take place, while farmers select the most profitable crops with a view to maximizing their incomes. The second scenario implies the implementation of a water use quota to secure the water balance of aquifers, especially in Morocco and Tunisia. Indeed, as mentioned before, in these two case studies groundwater over-exploitation represents more than 100 % of the recharge of the relevant aquifers (DGRE, 2020; Agence du bassin hydraulique du Sebou, 2021). The continuous over-exploitation of groundwater resources may thus lead to the degradation of the aquifers and consequently, to the collapse of regional agricultural systems. Therefore, this scenario – which is called Return to Equilibrium (S_RtE) – proposes a water-use quota in order for the recharge of the aquifer to be equal to its uses. However, it is important to highlight that the situation is different in Algeria. As mentioned before, the majority of the water used comes from local dams, while only 10 % of the water used for irrigation comes from the aquifer (0.19Mm^3) (DSA, 2017). The quota here therefore serves as a provision for the future. In other words, the implementation of a quota in Algeria aims to stop the use of groundwater resources for irrigation, which may allow groundwater to serve as a valuable water resource for future generations (Mozas and Ghosn, 2013; Talbi and Al Any, 2022).

3. Simulation results

In the different study areas, aquifers are usually considered to be a natural solution to water scarcity, and are used to overcome a wide range of situations. The exploitation of aquifers brings with it the problem of average annual recharge and the difficulties involved in its management. Over-exploitation may be defined as the situation in which, for some years, average aquifer abstraction rate is greater than, or close to the average recharge rate (Custodio, 2002). It can lead to negative consequences such as soil compaction, aquifer depletion, water quality deterioration, well abandonment. It can also have indirect effects such as environmental, socio-economic, and political instability (Alfarrah and Walraevens, 2018; Benfetta and Ouadja, 2020; Faysse et al., 2011; Ibáñez et al., 2008; Jamali et al., 2020). In this research, over-exploitation costs make it possible to quantify the impacts of groundwater depletion on the agricultural sector, notably on farms (S_BAU). However, restoration costs are used to assess the impacts of establishing groundwater balances on the agricultural sector (S_RtE). The different scenarios were simulated using the DAHBSIM model. The following section presents the main results of these simulations with regards to: i) land-use allocations and cropping patterns, ii) farm gross margin (FGM), iii) the dual value of water (DVW), and iv) labor allocations.

3.1. Land-use allocations and cropping patterns

Farmers, as land owners, play a critical role in land-use decisions at a local level. Land use is determined by a variety of factors (defined by model constraints). The impact of these factors is not equally distributed between different farm types, as for each typology the model evaluates the impact of these prime factors through its particular set of endowments, such as its biophysical factors, infrastructure, and financial capital.

In general, the continuous decline in water availability forces farmers to switch to more productive crops, in order to better use water resources and make sure they receive a minimum income. However, the ones who do not possess enough funding to invest in innovative irrigation practices are forced to leave part of their land uncultivated, change to rainfed crops, or abandon agriculture in the medium term.

More specifically, in the S_BAU scenario farmers continue to cultivate the most productive crops and overuse available groundwater resources. According to the model simulations (Fig. 3), areas dedicated to vegetable crops increase by 417 ha, 2604 ha, and 632 ha in the El Haouaria, Saïss and Sétif plains, respectively. Moreover, in the El Haouaria and Sétif plains, areas dedicated to cereal crops decrease by 963 ha and 905 ha between 2021 and 2035 respectively, compared to 2021. On the contrary, there is a significant increase of 1326 ha in areas dedicated to cereal crops (half of the average variation in the vegetable area) in the Saïss plain over the same period. This area increase is the direct consequence of increased cereal yields due to an intensification of crop production methods (significant use of groundwater). Crop rotation could also be another cause of this increase. In the other two cases, however, supplementary[3] irrigation is used for cereal crops.

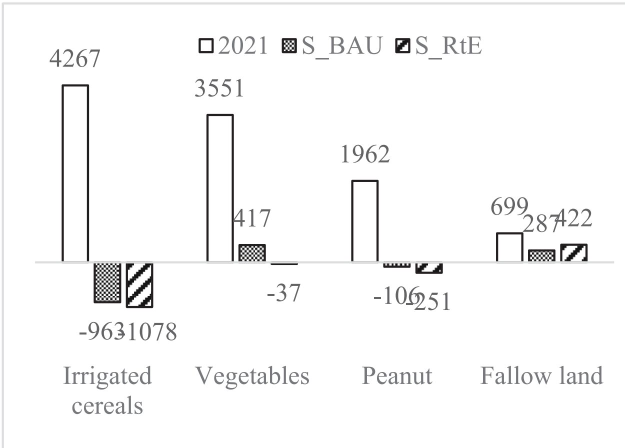
In the S_RtE scenario, we noticed that the most profitable and water-consuming crops reduce significantly in the three case studies, especially in the case of vegetables, for which there is a decrease of 13 ha in the El Haouaria plain, 1546 ha in the Saïss plain and 858 ha in the Sétif plain compared to 2021. In addition, farmers also have to reduce the areas dedicated to perennial crops in order to respect the water quota. For instance, in the Saïss plain, farmers reduce the areas dedicated to perennial crops by 14,633 ha to adapt to this new situation. In the same context, fallow land areas increase in the El Haouaria plain, while areas dedicated to cereal crops increase in the Saïss and Sétif plains. This outcome is due to low water availability, which forces farmers to turn to crops with lower water needs, or to leave part of their land uncultivated.

3.2. Farm gross margin

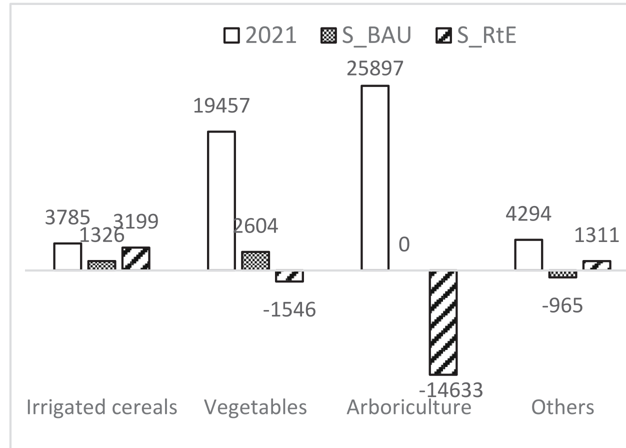
Between 2021 and 2035, in the S_BAU scenario FGM varies between €1721 /farm (€427 /ha) and €3489/farm (€1220/ha) with an average of €2609 /farm (€838/ha) in the El Haouaria plain. In the Saïss plain it varies between €2489/farm (€226/ha) and €3273/farm (€298/ha) with an average of €2826/farm (€257/ha). In the Sétif plain it varies between €14,924/farm (€1105/ha) and €20,127/farm (€1491/ha) with an average of €17,795/farm (€1318/ha).

In general, both in Morocco and Tunisia current agricultural practices could lead to a decrease in FGM over 15 years (Table 4). During this period, there is a downward trend in FGM in the El Haouaria and Saïss plains, which results in an average annual loss of €344/farm and €338/farm, respectively. This decrease is linked to additional costs for access to water generated mainly by rising energy costs for pumping and increased well depths. On the contrary, the situation in Algeria is

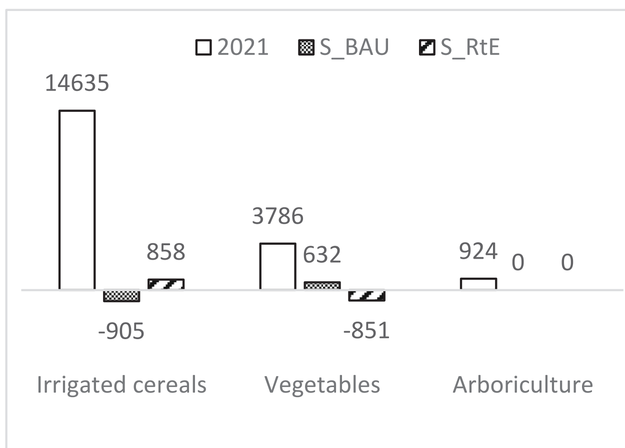
[3] Supplemental irrigation is described as the addition of limited amounts of water to plants under insufficient water supply by rainfall to overcome the adverse effects of drought (Oweis et al., 1999)



(a) El Houaria Plain (Tunisia)



(b) Saïss Plain (Morocco)



(c) Sétif Plain (Algeria)

Fig. 3. Effect of different scenarios on land use: average variation compared to 2021 of the main crop areas per ha at the level of the different case studies in the S_BAU and S_ RtE scenarios over a 15-year simulation period.
For all variables the variation compared to 2021 is calculated using the following formula:
$X_{compared\ to\ 2021} = \sum_{i=1}^{14} \frac{X_{ni+1} - X_{2021}}{15}$ with ni = {2021, …., 2034}.

different as FGM increases by €3077/farm in the Sétif plain along with a greater demand for water resources. This increase is mainly due to a shift from cereal to vegetable production that increases cash income. As mentioned above, this case study does not suffer from water scarcity (the groundwater resource has not yet been over-exploited, despite its deterioration), Algerian farmers may thus keep cultivating in the same way without observing a negative impact on their incomes.

Regarding the S_RtE scenario simulations (Table 4), the implementation of the water quota has a significant impact on farm gross margins. As water becomes scarce, farmers have to change their cropping patterns, and this negatively affects their incomes. For example, in the Saïss plain the average annual loss in gross margin reaches €1283/farm, while in the El Haouaria plain it equals €363/farm. Similarly, to the S_BAU scenario, the situation is different in Algeria. An increase in FGM is also observed in the S_RtE scenario (+2885 €/farm), but it is not as significant as in the BAU scenario. Therefore, the 10 % reduction in water availability for each farm type results in a decrease in FGM compared to the S_BAU scenario. The main factor behind the decrease was the shift from vegetable production to cereal production to deal with the decline in water availability. The positive effect of this scenario is that the groundwater has not yet been over-exploited, but it clearly shows the sensitivity of the agricultural system to water availability.

3.3. The dual value of the water constraint

In this sub-section, we focus on examining the dual value of the water constraint for the examined agricultural systems in the two proposed scenarios. Usually, in linear programming, the dual value of a constraint is also known as the shadow price, and expresses the effect on the objective function if an additional unit of the examined constraint is preserved. In our case, it is used to describe the impact of the water constraint on optimal decisions, which indicates the marginal increase in income caused by a one-unit increase in water availability. According to our findings, farmers assign significant value to water resources in both scenarios, as a decrease in the available stock by one unit (m^3) has to be replaced by high energy or pumping costs, which results in higher opportunity costs. Particularly in S_BAU, over the 2021 to 2035 period, farmers have to pay €0.082 extra on average for an additional water unit (m^3) in the El Haouaria plain, €0.352 in the Saïss plain, and €0.164 in the Sétif plain. This increase occurs because farmers face increased energy and pumping costs every year in order to have access to the same amount of water resources. However, in the S_RtE scenario the dual values of the water constraint increase significantly due to the existence of the quota. In other words, as water becomes scarce, farmers face different opportunity costs, as they cannot maintain their cropping patterns, and therefore assign higher values to every additional water unit. For instance, in the case of the Saïss plain, where groundwater resources are scarce, the dual value of the water constraint increases from €0.352/m^3 to €0.602/m^3.

In Table 5 the value that farmers assign to water varies between €0/m^3 to €0.8/m^3. Similar studies (Esteban and Albiac, 2011; Hérivaux and Rinaudo, 2016; Closas and Rap, 2017; Pereau et al., 2019; Tahamipour Zarandi and Hosseini Fakhr, 2022) that evaluated the economic importance of groundwater over-exploitation or pricing policies for the provision of aquifers reported lower prices. We should thus retain the outcomes of this modeling approach to reflect the economic importance that farmers attach to groundwater resources. However, we should be cautious in comparing these findings with other modeling attempts in terms of context and specifications that may not be logical.

3.4. Labor allocations

All farmers in both scenarios hire seasonal workers in order to cover their labor requirements. However, those requirements are directly linked to the selected cropping patterns. In the S_BAU scenario, labor requirements increase slightly (Table 6), thus reaching an average of 4.14 AWU/farm (0.43 AWU/ha), 7.354 AWU/farm (0.669/ha) and 7.35 AWU/farm (0.545 AWU/ha) in the El Haouaria, Saïss and Sétif plains, respectively. As the existing cropping patterns stay the same in this scenario, the labor allocations also remain similar, with a slight increase due to higher irrigation labor requirements.

Alternatively, the S_RtE scenario shows a significant decrease in labor allocations (Table 6), which is essentially linked to the variation in land use (e.g. increase in fallow land, abandoned agricultural land, etc.), and in particular to the increase in areas dedicated to crops which require less labor (cereal crops). Compared to 2021, the drop in water availability leads to an average annual loss of 0.8 AWU/farm in the El Haouaria plain, and 0.28 AWU/farm in the Saïss and Sétif plains.

3.5. Economic impact of groundwater over-exploitation

In both scenarios, the different uses of the examined aquifers lead to significant structural and social changes as they affect the stakeholders involved differently (Table 7 and Fig. 4). In the case of S_BAU, the continuous over-exploitation of groundwater resources leads to increasing irrigation costs due to higher pumping costs and water scarcity (Table 7). The increase in pressure on the aquifer has led to losses in agricultural income in the El Haouaria (−€344/farm) and Saïss plains (−€338/farm) compared to 2021. On the other hand, this scenario could have a positive social impact. However, an increase in labor demand has been observed in the Saïss (+0.013 AWU/farm) and Sétif plains (+0.01 AWU/farm).

Note that the RtE scenario involves maintaining the balance between the inflow and outflow of groundwater every year by decreasing agricultural groundwater withdrawal. In the Saïss plain, this scenario showed that the decline in water availability for each farm type (implementation of a quota) significantly increases the loss in FGM (loss of €945/farm more than in the S_BAU) as water scarcity leads them to grow less profitable crops or to abandon part of their land (Table 7). In contrast, in the El Haouaria plain the restoration costs of the aquifer are slightly higher than its over-exploitation costs. This difference between the case studies lies in the fact that the El Haouaria plain aquifer is over-exploited by only 105 % (fewer sacrifices are needed from farmers, and it is easier for them to adapt to a water-use quota), while the over-exploitation of the Saïss plain aquifer reaches 180 %. The results for the Sétif plain demonstrated that both scenarios had positive effects on FGM. This is because the Algerian case study shows no water scarcity issues, as the majority of agricultural systems irrigate from regional dams, while only 10 % of irrigation water comes from the aquifer. Sétif plain's groundwater exploitation rate is also still at a low level (according to experts). Moreover, the majority of farmers use rainfed crops, as access to groundwater resources requires a specific license from the state (Talbi and Al Any, 2022). But the S_RtE scenario still has more significant impacts than the S_BAU scenario. In the S_RtE scenario, we noted a decrease in agricultural income, an increase in water prices and a decrease in labor demand compared to the BAU scenario. This further shows the sensitivity of the results to water availability.

4. Discussion

Groundwater is a critical resource for agricultural production in the Maghreb, as it supports the local economy and provides employment to local populations (Kuper et al., 2016; Houdret et al., 2017; MedECC et al., 2020). Increasing water scarcity is therefore expected to have significant negative impacts on food production and food security, thus affecting land use and decreasing the welfare of local communities (Mancosu et al., 2015; Kuper et al., 2016; Dinar et al., 2019). In our study we tried to carry out an unprecedented economic valuation of groundwater over-exploitation in this region, and to assess the potential costs and benefits of preserving these resources. Two scenarios were thus examined: an S_BAU scenario in order to assess the impact of current practices on water use, farm income, cropping patterns and labor allocations; and a restoration scenario for the implementation of a water

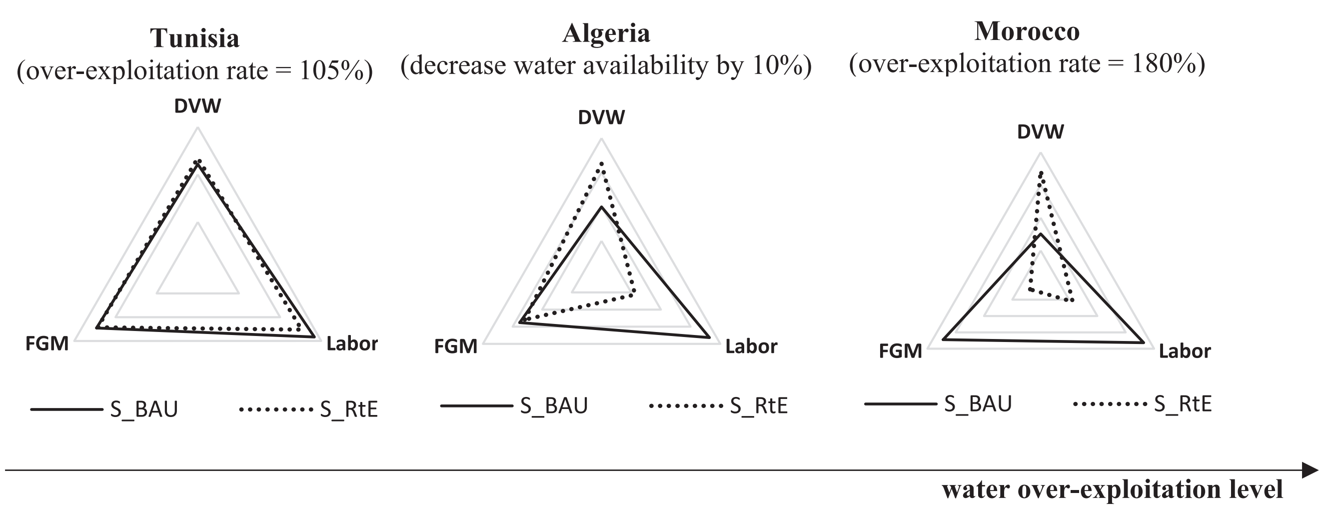


Fig. 4. The impact of the S_BAU and S_ RtE scenarios on standardized sustainable development indicators (farm gross margin, dual value of water and labor requirements).

quota in order to assess and compare the potential costs and benefits of preserving this environmental good (Havlík et al., 2005).

Our findings obtained through the DAHBSIM model simulations suggest that both scenarios may have significant impacts on water value, land use, labor allocations and farm incomes. Regarding the dual value of the water constraint, the results highlighted the fact that farmers assign significant value to the preservation of groundwater resources, which varies between €0.025/m^3 and €0.85/m^3. According to the existing literature, the cost of water capture, which is used for the economic valuation of groundwater resources, lies between €0.005/m^3 and €0.5/m^3 (Esteban and Albiac, 2011; Closas and Rap, 2017; Pereau et al., 2019). Similarly, the study of Pulido-Velazquez et al. (2008), which examines the monthly shadow prices of irrigation for agricultural production, highlighted an average value of groundwater supply equal to €0.24/m^3. Alternatively, to these findings, our results reported higher dual values of groundwater resources by taking into account the complex biophysical relationships that exist between water scarcity and crop production. Indeed, every additional water unit has a direct impact on yields, and consequently on farm profitability. Therefore, our findings emphasize that these previous approaches may have underestimated the economic value of groundwater over-exploitation by neglecting the complex trade-offs that emerge between farm households. Moreover, the inclusion of self-consumption in the objective function is particularly critical, as it directly impacts the prioritization of crops within the farm's water allocation strategy. Crops essential for household food security often take precedence, which may result in shadow prices that differ from those focused solely on market-oriented production. Hence, while shadow prices for high-value cash crops or greenhouse production in areas like the Souss Massa-Draa basin might exceed €1/m^3 (Elame et al., 2020), our results reflect the broader diversity of farm types, crop mixes, and household priorities included in the analysis.

Moreover, as water availability in different years and scenarios decreases, households have to increase the depth of their wells (in S_BAU) or alter their cropping patterns (in S_RtE) in order to compensate for any losses in groundwater resources, thus resulting in higher opportunity costs. Therefore, the observed dual values of our water constraint should be considered by public policy makers as an indicator of two important elements: firstly, they reflect the individual opportunity costs of the households, and consequently incorporate farmers' decision-making processes; and secondly, they provide a measure of the economic contribution of groundwater resources in agricultural production. In other words, they represent a monetary value that can incite both farmers and policy makers to preserve these natural resources. These results are in accordance with previous studies which support the inclusion of the marginal costs of the supply of an environmental good in effective policy incentives (Havlík et al., 2005; Kleftodimos et al., 2021).

In addition, this study allowed us to carry out an important trade-off analysis and assess the impact of different water uses on household incomes, cropping patterns and labor allocations. In fact, in the case of Morocco both scenarios showed important changes in all the aforementioned indicators. Indeed, in the Saïss plain the costs of groundwater over-exploitation are significantly higher than in the restoration scenario. The continued use of the existing production paradigm threatens the sustainability of the system and leads to decreasing incomes due to higher water costs, and decreasing yields and labor use. On the other hand, the implementation of a quota (S_RtE) improves the sustainability of the system. However, it enforces significant changes in cropping patterns, as the limited water resources lead farmers to switch to less water-intensive crops. From a public policy perspective, there is an imminent need to take action, for instance in the form of quota implementation or water pricing (Closas and Rap, 2017; Pereau et al., 2019; Tahamipour Zarandi and Hosseini Fakhr, 2022), as restoration costs (S_RtE) are higher than over-exploitation costs (S_BAU. Nevertheless, such policies should be site-specific and implemented gradually with the involvement of local collective action throughout the decision-making process, in order to guarantee social acceptance by farmers (Del Corso et al., 2015; Del Corso et al., 2017). Without any policy initiative the system may collapse, as inequalities and the concentration of land in the hands of large landowners increase, thus causing significant migration within the country and further threatening food security (Warziniack, 2013; Mancosu et al., 2015; Kuper et al., 2016; Dinar et al., 2019; Unfried et al., 2022).

In the case of Tunisia, the model showed similar economic values between the two examined scenarios, due to the fact that the rate of groundwater over-exploitation is lower than in Morocco. This is a strategic moment for policy intervention as the social costs for policy intervention and aquifer restoration are lower than the continuity of the existing production paradigm. Consequently, an effective water policy may significantly improve the resilience of local agricultural systems by preventing further degradation of groundwater resources, securing economically and environmentally viable production systems, and ensuring the employment of local communities (Lezzaik and Milewski, 2018; Lemaitre-Curri and Tode, 2020; MedECC et al., 2020; Talbi and Al Any, 2022; Unfried et al., 2022; Ingrao et al., 2023; Soula et al., 2023).

Finally, in the case of Algeria we cannot talk about restoration, as most irrigation systems are fed by regional dams. Moreover, local farmers have limited access to groundwater resources due to the difficulty in acquiring well licenses from Algerian authorities (Mozas and Ghosn, 2013; Dugué et al., 2014; Talbi and Al Any, 2022). Hence, in this case study the costs of restoration are significantly higher than those of over-exploitation. However, here the costs of aquifer restoration may be considered as the bequest value for preserving this natural resource for future generations (Subade and Francisco, 2014; Hynes et al., 2022).

To sum up, without the effective implementation of agro-environmental and social policies, both scenarios lead to high value losses. Most groundwater conservation and management efforts and policy options focus on protecting groundwater for drinking and other human uses, by reducing water losses, prioritizing the most critical activities, using alternative water resources (including desalinated water in coastal areas, or brackish aquifers) and artificial recharge (Hashemi et al., 2015; Steinel et al., 2016; Djuma et al., 2017; De Giglio et al., 2018; Manisha et al., 2023). The sustainable management of groundwater resources is a major challenge for local and national authorities as well as transnational cooperation, particularly in the most vulnerable areas, as it requires an integrated and participatory approach that takes into account the different territorial contexts, socio-economic environmental issues and groundwater-dependent ecosystem services (Faysse et al., 2011; Hérivaux and Rinaudo, 2016; Kuper et al., 2016; Benabdelkader et al., 2021; Harik et al., 2023). However, the selected policy measures should be carefully designed as they will affect the stakeholders involved differently. For instance, both scenarios in all three case studies showed significant changes in income, labor allocations and cropping patterns. Both farmers and territories will therefore experience different public and private costs. Consequently, the selection of the appropriate policy measures or a combination of the latter should be carefully designed and implemented in order to guarantee their viability. This finding has also been supported by the study of Blanco-Gutiérrez et al. (2011).

5. Conclusion and further research

In this study, we tried to implement an unprecedented dynamic bio-economic model in order to carry out an economic valuation of groundwater over-exploitation in the Maghreb, as well as to estimate the potential restoration costs of groundwater resources. In order to assess these two issues, we proposed a plot-farm-territory analysis in order to analyze the emerging trade-offs between water availability, farmer decisions and yield production.

The results highlighted the fact that both scenarios will have significant impacts on water values, farm income, cropping patterns and labor allocations. In both Morocco and Tunisia, the costs for restoring the aquifer are higher than its over-exploitation. However, the implementation of a quota will have significant social costs which have to be covered by public authorities. We also noticed that the dual value of groundwater resources varies within the different case studies. In fact, as the rate of groundwater over-exploitation varies within the different case studies, the dual value of the water constraint is higher in those where water scarcity is more significant. In addition, the observed water values are higher in previous studies as they did not consider the links between water scarcity and crop production.

Nevertheless, groundwater management is extremely complex and the values of different parameters vary considerably under different contexts and scenarios of change, including climate change and human practices such as pumping. This makes it difficult to model and predict the behavior of a particular groundwater system. We have noted several limitations to our analyses. Our model does not consider that groundwater quality is likely to diminish as water tables decline, particularly in coastal area (Alfarrah and Walraevens, 2018). Furthermore, it tends to fail to address the viability of groundwater biodiversity and groundwater-dependent ecosystems that have become major environmental concerns in the Maghreb (Kløve et al., 2011; Griebler et al., 2014). While we acknowledge the broader ecosystem benefits provided by GDEs such as biodiversity support and water purification, the latter are not included in our economic valuation. Including the full range of GDE benefits would indeed reveal a much higher real cost of groundwater over-exploitation, thus suggesting that our results represent a conservative estimate. The actual costs of maintaining a “business-as-usual” scenario versus achieving equilibrium are probably far greater when considering these additional environmental values, which underlines the importance of sustainable groundwater management.

Despite the difficulties in obtaining data on groundwater in Morocco, Tunisia and Algeria, and the doubts regarding the accuracy and utility of such data, by using bio-economic modeling we were able to present a detailed overview of the costs related to groundwater over-exploitation as well as its restoration. The use of this type of model is a powerful tool for stakeholders as it provides information about different scenarios relative to current and future changes. Groundwater over-exploitation is both a current and future issue. The current situation should evolve with continuous monitoring, which may better establish development pathways that also promote groundwater management and highlight the origin of over-exploitation. It is important to understand the synergistic influence that links the over-exploitation rate with agricultural and socio-economic impacts, and to interpret this information under the current climate change scenarios for a broader understanding of the relevant processes and problems associated with groundwater management, and help design consistent policies.

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CRediT authorship contribution statement

Abderraouf Zaatra: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Georgios Kleftodimos:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Mélanie Requier-Desjardins:** Writing – review & editing, Validation, Methodology. **Hatem Belhouchette:** Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

There is no conflict of interest.

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Appendix 1. Appendix

This Appendix summarizes the details of the DAHBSIM model used for the study (adapted from (Komarek et al., 2017)).

1.1 Linear Expenditure System:

A linear expenditure system adopted by Louhichi and Gomez y Paloma (2014) is used here in order to estimate the food consumed per household each year.

$$p_x q_x = \gamma_x + \beta_x \left(household_{income} - \sum \gamma_j p_j \right)$$

With

$$0 < \beta_x < 1$$

$$\sum_x \beta_x = 1$$

$$q_x - \gamma_x > 0$$

Where, p_x is the price of a crop x, q_x the quantity of a crop x consumed by the household, and $\gamma_x \wedge \beta_x$ are the parameters in the Linear Expenditure System. Hence, $\sum \gamma_j p_j$is considered as a subsistence cost and $household_{income} - \sum \gamma_j p_j$ as the supernumerary income (Sadoulet and De Janvry, 1995).

1.2 Crop Module:

Fig. 1a describes the conceptual construction of the cropping system model. The model starts by calculating a potential yield in the absence of water or nitrogen stress. Water and nitrogen stresses are then applied to determine the yields made possible by water (*Yw*) and nitrogen (*Yn*) availability. The actual yield is the minimum value of *Yw* and *Yn*.

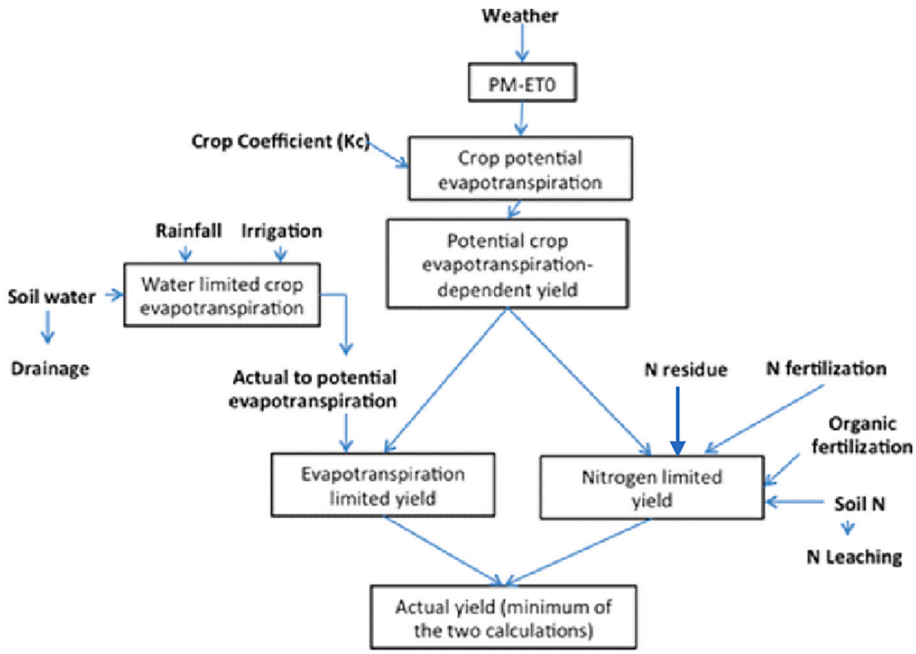

Fig. 1a. Flowchart of actual yield calculations in the summary of the cropping system module.

This module estimates water-limited yields for the cultivated crops using the following equation (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Y_w}{Y_m}\right)=K_y\left(1-\frac{ET_a}{ET_m}\right)$$

Where,
Y_w is the water-limited yield (kg/ha);
Y_m is the maximum yield (kg/ha);
K_y is the yield response factor (K_y equals 1 if the yield reduction is directly proportional to the reduced water use, superior than 1 if the crop response is sensitive to water deficits, while it is inferior to 1 if the crop is more tolerant to water deficit);
ET_a is the actual evapotranspiration (mm/day);
ET_m is the maximum evapotranspiration (mm/day).
Moreover, the module also estimates the nitrogen-limited yield using the following equation (Godwin and Allan Jones, 1991):

$$Y_N=Y_W\left(1-\frac{NC_{crit}-NCONC_a}{NC_{crit}-NC_{min}}\right)$$

Where,
Y_N is the nitrogen-limited yield (kg/ha);
Y_W is the potential growth after allowing water limitation considerations (kg/ha);
NC_{crit} is the plant critical nitrogen concentration (kg/ha);
$NCONC_a$ is the plant nitrogen concentration after new growth (kg/ha);
NC_{min} is the minimum plant nitrogen concentration at which point growth stops (kg/ha).
The aim of this module is to estimate the actual yield of each crop by using the minimum figures for water-limited and nitrogen-limited yields. In this study, the most important factor-limiting yield is water, due to low rainfall in the examined case studies.

Constraints:

1.2.1 Labor constraint

The total amount of labor used by the household equals total family labor availability plus hired labor from occasional workers at a given cost.

1.2.2 Land constraint

The total land allocation for crop production should not exceed the available agricultural land per soil type. The model includes 4 different soil types (sand, clay, loam, and other), however, their presence varies within the different case studies and household types. Moreover, it is not possible for farmers to rent additional land.

1.2.3 Rotation constraint

Due to agronomic rotational constraints, the household cannot grow the same crop type on the same plot of land, for a specific soil type, for two consecutive years. For example, the household cannot grow chickpea or faba-bean on the same plot of land, for a specific soil type, for two years in a row.

1.2.4 Water constraint

Water scarcity is a critical constraint on agriculture, and has become the single most important constraint to increasing food production, particularly for small farmers. We can distinguish two main types of water scarcity, namely physical scarcity and economic scarcity (Seckler et al., 1998). Physical scarcity is said to occur when there is not enough water to meet all demands. Economic water scarcity is described as a situation caused by a lack of investment in water, or a lack of human capacity to satisfy the demand for water. In the bio-economic model the scarcity of water is expressed by the following equation:

$$\sum_{c,m,pr,s,i,qs} cai(c,m)^{*}x(c,pr,s,i,qs,t) \leq A.water_j(t)$$

Where

- cai (c, m): the irrigation period per month and per crop (m3/ha);
- x (c, pr, s, i, qs, t): the area in hectares dedicated to crop c with previous crop pr, land status s, irrigation method i, soil qs, year t;
- $A.water_j(t)$: water availability for irrigation (m^3) per farm. The specific water availability for each farm-type *j* is determined individually according to their water techno-economic characteristics, crop orientation, market orientation, and relative size within the aquifer boundaries. For the estimation of the total water availability within the aquifer boundaries, we consider the water balance of the aquifer and subtract the consumption of other sectors such as drinking water, industry, tourism, etc.

Appendix 2. Appendix

Variations in agricultural water use (irrigation) between dry and wet years at the level of the different case studies in the S_BAU and S_ RtE scenarios

	Saïss		El-Houaria		Sétif-plain	
Scenarios	S_BAU	S_RtE	S_BAU	S_RtE	S_BAU	S_RtE
Dry year (2024 for Saïss, 2033 for El-Houaria and 2032 for Sétif) **(Mm^3)**	199.08	60	50	35.4	9.2	8.2
Wet year (2025 for Saïss, 2026 for El-Houaria and 2028 for Sétif) **(Mm^3)**	194.2	60	31	31	6.7	5.9

Data availability

Data will be made available on request.

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