Agricultural Water Management 310 (2025) 109357

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

An agent-based model of farmer decision making: Application to shared water resources in Arid and semi-arid regions

Imane El Fartassi[a,b,c,*], Alice E. Milne[a,1], Helen Metcalfe[a], Rafiq El Alami[c], Alhousseine Diarra[c], Vasthi Alonso-Chavez[a], Joanna Zawadzka[b], Toby W. Waine[b], Ron Corstanje[b,1]

[a] Net-zero and resilient farming, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, United Kingdom
[b] Cranfield University, College Road, Cranfield, Bedford MK43 0AL, United Kingdom
[c] Mohammed IV Polytechnic University, Benguerir, Morocco

ARTICLE INFO

Keywords:
Agent-based modelling
Irrigation management
Water scarcity
Soil salinization
Morocco

ABSTRACT

The study presents an agent-based modelling framework that integrates behavioural and biophysical models to investigate shared irrigation water management in an arid region. The behavioural model simulates farmers' decisions about their water irrigation sources (dam or groundwater) and whether to continue cultivating in the face of drought. This model was parameterised using survey data. The biophysical model component quantifies the impact of water availability and irrigation sources on soil salinity accumulation and its effects on crop productivity. Applied to the Al Haouz Basin, in Morocco, the integrated model reveals several key findings: (1) Increased groundwater access through water abstraction authorization can initially boost productivity but leads to widespread salinisation and farm abandonment, particularly under climate change scenarios. (2) Scenarios with reduced dam water availability demonstrate that mixed irrigation strategies mitigate short-term productivity losses but fail to prevent long-term soil salinity issues. (3) Land abandonment is significantly influenced by the level of water abstraction authorizations, with higher abstraction leading to more severe environmental degradation and social impacts. (4) Policy scenarios reveal that there is a theoretical optimal level of groundwater abstraction that maximises productivity while minimising land abandonment and salinity build-up. These results highlight the complex trade-offs between short-term gains and long-term sustainability, emphasising the need for holistic water governance policies that balance individual and collective interests.

1. Introduction

Climate change projections indicate increasing aridity and water scarcity globally, with concerning implications for rain-fed agriculture (IPCC, 2022). This is particularly concerning as the frequency and intensity of drought events continue to rise, posing significant challenges to agricultural and water management systems. Studies using climate change projections have consistently demonstrated the intensification of droughts driven by rising temperatures and altered precipitation patterns (Tran, Do, et al., 2024; Tran, Tapas, et al., 2024). In Africa, these dynamics are already playing out through more extreme droughts and constrained water resources (Masih et al., 2014). The expansion of irrigated agriculture and recurrent drought periods further exacerbate these issues, threatening the renewability and sustainability of water resources. Over-extraction of groundwater, reduced aquifer recharge, and increased salinisation, contribute to a vicious cycle that undermines both environmental and agricultural stability, with significant knock-on effects on food security. Additionally, the growing demand for fresh drinking water intensifies groundwater extraction, placing even greater stress on already limited water supplies. Research highlights that climate change and intensified human activities are altering streamflow patterns, reducing sediment loads, and compromising water availability (Nguyen et al., 2024; Tran et al., 2023). These pressures strain dam reservoir resources, forcing farmers to rely increasingly on unsustainable groundwater withdrawals across the continent (MacDonald et al., 2012; Otoo et al., 2018). This trend is especially pronounced in arid and semi-arid climates of Africa, where groundwater buffers against acute water scarcity in the short-term (Bouchaou et al., 2024). However,

* Corresponding author at: Net-zero and resilient farming, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, United Kingdom.
E-mail address: imane.el-fartassi@rothamsted.ac.uk (I. El Fartassi).

[1] These authors are joint senior authors on this work

https://doi.org/10.1016/j.agwat.2025.109357
Received 17 July 2024; Received in revised form 10 January 2025; Accepted 2 February 2025
Available online 13 February 2025

imbalanced extraction-recharge ratios raise questions about the long-term sustainability of groundwater resources across Africa (Aeschbach-Hertig and Gleeson, 2012). Improving agricultural water use efficiency through integrated management frameworks can help mitigate escalating water stress and economic vulnerability for farmers in drought-prone regions.

In Arid and semi-arid regions, the exacerbation of existing water shortages demands context-specific policy interventions to promote more sustainable and resilient cropping systems (Mabhaudhi et al., 2016). Such regions are particularly vulnerable due to high evapotranspiration rates and limited natural recharge of water sources, which are further exacerbated by climate change and land-use pressures (Aeschbach-Hertig and Gleeson, 2012; Wada et al., 2010). Theoretically, optimised cropping patterns and irrigation schedules could increase production and water use efficiency at the landscape level by reducing water wastage, aligning crop water needs with regional hydrological cycles, and minimising adverse environmental impacts such as salinity build-up (Gleeson and Richter, 2018; Kamal et al., 2021). However, individual farmers may have differing objectives and constraints that do not align with these landscape-level goals. Furthermore, the cumulative effects of decentralised decision-making can produce unintended regional consequences (Meinzen-Dick, 2014), such as aquifer depletion and inter-farmer conflicts over resource allocation (Di Baldassarre et al., 2015; S. Foster and Garduño, 2013). Integrated management frameworks are needed to balance farm-level interests with broader social and environmental considerations surrounding water resources in drought-prone areas.

Extensive groundwater pumping for irrigation has depleted aquifers and compromised the long-term sustainability of groundwater resources (Gleeson and Richter, 2018). Increasing water withdrawals during periods of peak crop water demand have led to a steady drop in groundwater storage and modifications to aquifers' hydrogeological characteristics. Evaporative losses from irrigation coupled with inadequate natural recharge in many regions (Wada et al., 2010) can induce the formation of saline groundwater through evaporite sedimentation, increasing soil salinity—a condition that often prevails in arid and semi-arid systems during drought (Salman et al., 2019). Moreover, anthropogenic activities and land-use changes have significantly altered hydrological dynamics, contributing to reduced streamflow, increased saltwater intrusion, and diminished agricultural productivity (Nguyen et al., 2023). Given increasing evidence of interconnections between surface and groundwater, integrated management frameworks are needed to account for the wider socio-environmental impacts of intensive groundwater extraction (Foster and Garduño, 2013).

Biophysical models can represent water system dynamics that influence resource availability, quality and crop yields Models quantifying spatiotemporal build-up of soil salinity could provide dynamic feedback to farmer decision-making models (Daliakopoulos et al., 2016). Biophysical models can quantify the dynamics of various environmental processes, which then interact with the decision-making processes of human agents (Letcher et al., 2013).

Agent-based models (ABMs) provide a framework to capture human-environment interactions, allowing the exploration of how changes in environmental conditions shape human behaviour, and conversely, how human decisions impact environmental outcomes over time (An, 2012; Kremmydas et al., 2018).

Prior applications indicate that ABMs can facilitate sustainability assessments for agricultural water usage involving multiple stakeholders (Bulatewicz et al., 2010; Noël and Cai, 2017). However, while some studies have attempted to incorporate human behaviour (An, 2012; Schlüter et al., 2019), the role of human behaviour is often overlooked due to data limitations and difficulty verifying assumptions. Survey data can be used to parameterise behavioural models and capture heterogeneity across decision-makers. An integrated framework coupling biophysical and behavioural models enables holistic and robust climatic and policy simulations for providing insights into coupled human-environment issues (Kremmydas et al., 2018).

Integrating environmental variability factors directly into agent rules creates a coupled mechanism linking salt accumulation from intensive groundwater-dependent irrigation and behavioural adaptations over time. Capturing these environmental feedback and constraints is critical for simulating farmers' adaptive behaviours in response to drought, degraded water quality, and other shocks, especially in vulnerable African regions. Integrating behavioural and biophysical models enables a better understanding of the feedback loops between environmental conditions and human decisions (Filatova et al., 2013; Ng et al., 2011).

This paper presents an integrated ABM approach coupling biophysical and behavioural models of agricultural water usage. The approach is applied to a case study of shared irrigation resources across a community of farmers relying on dam releases and/or groundwater in an arid region of Morocco. By capturing the diversity of farmers' water-sourcing strategies and behavioural drivers, the model fosters transparency and enables scenario analyses of policy interventions aimed at balancing sustainable water allocation across heterogeneous users.

2. Methodology

2.1. Study area

The study region is situated in the Al Haouz Plain of the Tensift watershed in central Morocco (Fig. 1). The Tensift watershed covers an area of 6000 km^2 and includes approximately 3100 km^2 of irrigated area. Across the watershed, groundwater is extracted for several uses including drinking water, leisure activities and intensive agriculture. Groundwater depth has decreased substantially since the early 1970s, with a marked increase in depletion rates since the late 1990s, reaching an average drop of −0.9 m year-1 across most of the area.

The main study site is an irrigated area known as "Perimeter R3" (Fig. 1). It is located 40 km East of Marrakech city and covers approximately 2800 ha. The study area falls within the semi-arid continental climate and is characterized by a large inter- and intra-annual variability in precipitation, with an average annual rainfall of 250 mm. The soil type is predominantly clay to loam, and the topography varies from 188 to 1453 m above mean sea level. Wheat is the dominant crop in this area (Kharrou et al., 2021).

2.2. Water allocation and management

To channel water from the dam to the farmed areas, an irrigation infrastructure was installed in the year 2000. There are three different sources of irrigation water in R3: groundwater, dam or river diversions (Duchemin et al., 2009). The Haouz Agricultural Development Regional Office (ORMVAH) is the local agricultural office in charge of the management of irrigation water in the Al Haouz basin. It manages the irrigation infrastructure and allocates irrigation water from the dam according to the scheduling defined at the beginning of the agricultural campaign. The water allocation is based on the dam water level and negotiations with farmers. Farmers pay for the water rights. The water price is determined by the local water authorities and water distribution is based on the land area under cultivation. The water stored in the dam is channelled to the irrigation network. It is then diverted and pumped onto crops, by gravity, through a hierarchic network of overhead concrete canals (Fig. 2).

In R3, the irrigation infrastructure can serve an average of 40 ha per tertiary canal. Recently, in drought years, the water allocation is typically 4000 $m^3.ha^{-1}$ but can be as low as 324 m^3/ha. In extreme drought conditions, the water allocation can potentially reach zero, significantly limiting the available water for irrigation.

All farmers in the irrigated perimeters belong to water users' associations and have a right to dam water. However, not all irrigated areas are covered by the infrastructure, leading farmers without dam access to typically rely on groundwater. The Tensift Watershed Agency (ABH-T)

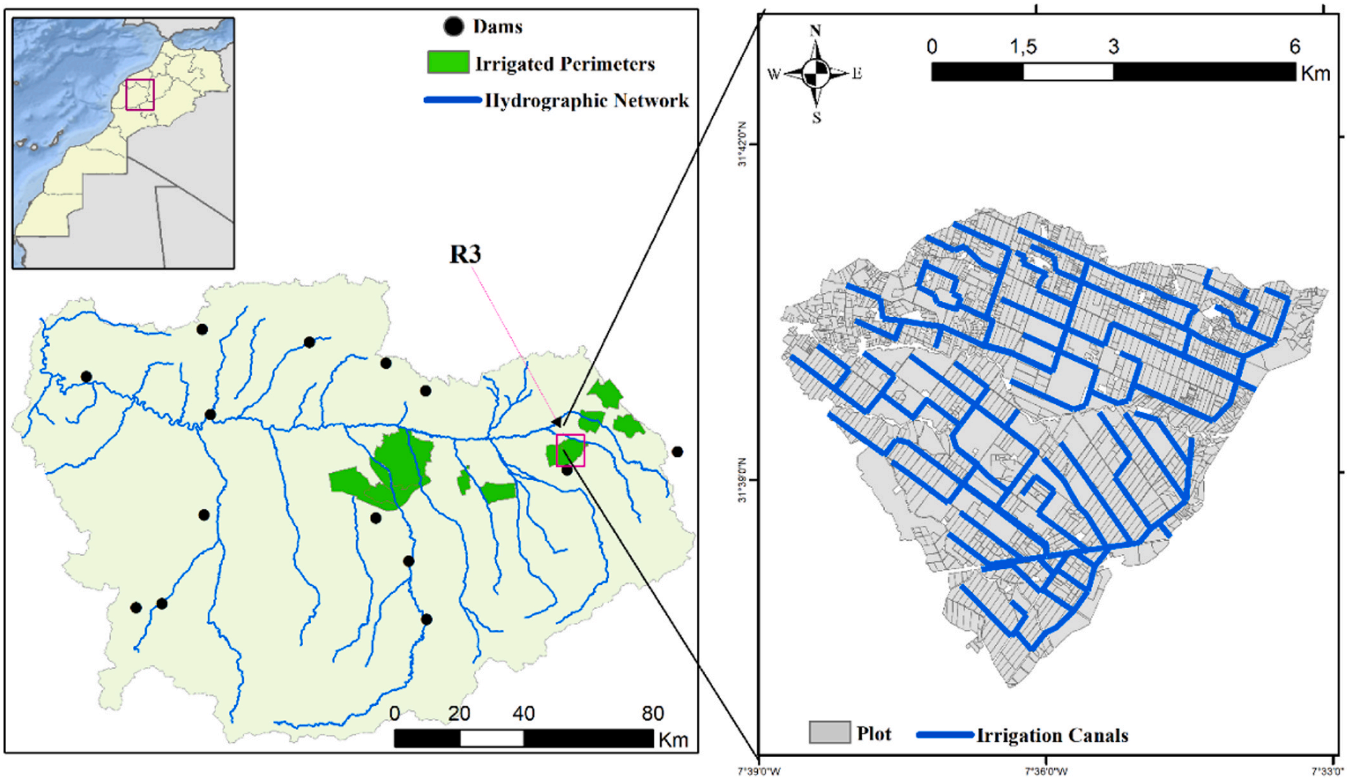

Fig. 1. Location of the study area: R3 perimeter, Al Haouz Basin, Morocco.

Fig. 2. Irrigation system consisting of elevated concrete canals arranged in a hierarchical structure.

issues permits for groundwater abstraction. In response to ongoing groundwater depletion, the ABH-T has started to limit the number of permits authorized.

2.3. Model structure

The modelling framework combines behavioural and biophysical components to simulate the dynamics of shared irrigation water management in the study region (Fig. 3). The behavioural model uses an agent-based approach to simulate the irrigation choices and adaptations of individual farmers, who can access water from the dam, groundwater, or a combination of both sources. This agent-based component captures the heterogeneous decision-making processes of farmers and their water-sourcing behaviours over time.

The biophysical model represents the water system, capturing factors such as dam fill rates, soil salinity accumulation, and crop yields. This biophysical component provides the environmental context within which the farmers' decision-making occurs.

2.4. Behavioural model structure

In the model, agents can be categorized into one of three water-user types: dam-only users, groundwater-only users, and mixed irrigation users.

Dam-only users face the decision of whether to invest in additional infrastructure to access groundwater, in addition to the dam water they currently use. This decision represents a key choice point for these agents.

We based the structure of this decision-making model on interviews conducted with farmers to identify the key influences on their irrigation management choices (El Fartassi et al., 2024). Analysis of the survey data, using structured equation modelling underpinned by the theory of planned behaviour, showed that *attitude* and *perceived behavioural control* (PBC) were the most significant factors, while *subjective norms* were not significant, in underlying farmers' irrigation source decisions (for details see El Fartassi et al. 2024). Therefore to model this decision process, we assign each agent variables representing *Attitude* and *PBC*.

The *Attitude* variable reflects the farmer's positive or negative evaluation of using groundwater. This evaluation is influenced by crop yield, which depends on water supply and water salinity. The *PBC* variable captures the farmer's perceived ease of implementing ground-water extraction. This perception is determined by affordability and operational constraints which in our previous analysis (El Fartassi et al., 2024) we showed were related to farm size and ownership.

In our ABM, the *Attitude* variables are each assigned values between zero and one. A value of zero indicates the farmer has a completely

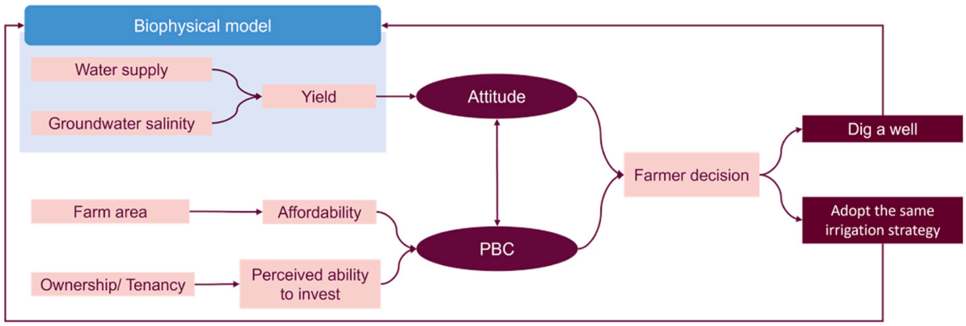

Fig. 3. A decision-flow diagram illustrating the integration of the biophysical and behavioural models and the key factors influencing farmers' irrigation management decisions.

negative attitude toward using groundwater, while a value of one means the farmer perceives groundwater as an essential option for irrigation.

Perceived behavioural control is modelled through two components. First *Affordability*, which is represented by a value between 0 (completely unaffordable) and 1 (completely affordable). The second component relates to the *Perceived ability to invest*. This variable is also represented by a value between 0 (completely constrained) and 1 (completely unconstrained) to capture the farmer's perceived ease or difficulty in making long-term investments in the land. In our model, if the agent's *Attitude*, and *PBC (Affordability* and *Perceived ability to invest)* values all exceed a threshold of 0.5, the farmer applies for authorization to adopt groundwater extraction as part of their irrigation strategy (Fig. 3). The adoption of groundwater in the model is also influenced by regulatory constraints, particularly the water abstraction authorizations. In our model, only a certain number of water abstractions are authorized annually (see 2.7 Scenarios). Authorizations are allocated randomly. If the application is successful, the farmer transitions to a mixed irrigation strategy.

In our study area, continued drought conditions have led to some farmers abandoning cultivation. The second modelled decision captures this behaviour. It applies to all agents, regardless of their current water source, except those who have only just transitioned to mixed irrigation. We model this by sampling the number of consecutive years a farmer can tolerate a loss in profit from drought from a Poisson distribution with mean λ. If this value is exceeded, then the farmer abandons cultivation.

2.4.1. Model dynamics

The model has an annual time step. At each time step, the *Attitude* and *Affordability* variables are updated, and new decisions are made.

We assume that farmers' attitudes towards groundwater usage are influenced by their yield outcomes. To capture this, our model simulates interactions among farmers based on their yield comparisons. Specifically, we update each farmer's *attitude* towards groundwater usage based on the comparative performance of their yields with those using mixed irrigation ($\overline{Y}_{\mathrm{mix}}$) Then the attitude of the dam water user is updated by:

$$A_i(t+1) = A_i(t) + \alpha(\overline{Y}_{\mathrm{mix}} - Y_i) \text{ for } i = 1, \ldots, n_{\mathrm{Dam}} \quad (1)$$

where α is a scaling factor that determines the magnitude of the agent's attitude and n_{Dam} is the total number of dam users. The attitude adjustment is bounded between 0 and 1 to ensure it remains within a plausible range. In practice, farmers often compare their yield outcomes through informal social interactions, such as discussions at local markets, farmer gatherings, or community meetings. These interactions provide an opportunity for farmers to share experiences, assess each other's practices, and evaluate outcomes such as yield and profitability. In many rural communities, yield comparisons are facilitated through word of mouth, which can influence perceptions and decision-making related to groundwater use and irrigation strategies. This peer-to-peer knowledge exchange is particularly prevalent in Moroccan agricultural communities, where social networks play an essential role in spreading information and fostering the adoption of new practices (Amrouk, 2021). Such comparisons are crucial for our model, as they help simulate how farmers' attitudes towards groundwater usage evolve in response to observed outcomes.

In our model, we assume that a farmer's *PBC* will be affected by their interactions with others in their social network. To capture this, we use opinion dynamics (Milne et al., 2020). Opinion dynamics refers to the mathematical modelling of how individuals' beliefs or behaviours change over time as they interact with others in their social network (Castellano et al., 2007). In this context, opinion dynamics is used to simulate how farmers' perceptions about agricultural practices, such as adopting a new irrigation technology, evolve based on their social environment. The approach models how individuals' attitudes are influenced through repeated interactions, leading to either convergence of opinions or the maintenance of diversity within the group, depending on the strength and nature of social ties (Acemoglu and Ozdaglar, 2011). At each time step, agents interact with other agents whose farms are of similar or larger size. We assume that farmers' opinions about relative affordability are influenced by the opinions of farmers who operate at their scale or larger scales, reflecting how farmers often look to both their peers and larger operations for guidance (see explanation below).

To update the *Affordability (x)* of the agent *i*, the model randomly selects up to $n_{\max}$ agents for interaction. The model employs a weighted average approach according to the following equation:

$$x_i(t+1) = w_{i1}x_1(t) + w_{i2}x_2(t) + w_{i3}x_3(t) + \ldots + w_{in}x_n(t) \text{ for } i = 1, \ldots, n_{\max} \quad (2)$$

where w_{ij} is the weight agent *i* gives to agent *j*'s opinion. The weights must be greater than or equal to zero and sum to one.

In our model, we assume that the perceived ability to invest in the land is affected by the type of tenure which does not change over time.

2.5. Initial conditions

In our model, we generate a population of agents that are representative of the farmers in the case study area. The initial conditions are defined in terms of farm area, soil salinity, access to dam water, access to groundwater and type of tenure.

2.5.1. Simulated areas

To generate the farm areas for our agents, we first fitted a lognormal distribution to the farm areas reported by the farmers in our survey (El Fartassi et al., 2024). The fitted distribution had parameters $\mu = 1.88$ and $\sigma = 1.20$ (Figure_A-1, Figure_A-2, Table_A-1). We then randomly sampled from this distribution until the total sum of the agent's farm areas matched the study region. This resulted in 248 farmers. These farmers were classified into small (<5 ha), medium (5–20 ha) and large (>20 ha) (Table 1) (El Fartassi et al., 2024).

Table 1
Distribution of farm area according to observed and simulated data.

Farmer typology	Observed total area (%)	Simulated total area (%)	Simulated farmers
Small	31	34	102
Medium	52	49	108
Large	17	18	38
Total	100	100	248

2.5.2. Access to dam water

To estimate the surface area having access to the dam water, we assume that the irrigation canals cover a radius of 30 m (plots located up to 30 m from the irrigation canal can be irrigated). Based on this assumption, 78 % of the study area has access to the dam water (Fig. 1). Therefore, we randomly allocated agents as having access to the dam up to a total area of 78 %.

2.5.3. Access to groundwater

For our initial state, we assume that 72.58 % of the simulated population of farmers have access to the dam only, 22.18 % to groundwater only and 5.24 % to mixed irrigation.

To initialize values for the *Attitude*, and *PBC* variables (*Affordability* and *Perceived ability to invest*), we sampled from beta distributions parameterized to capture the attitudinal differences across irrigation categories, with on average most positive attitudes associated with those who already use groundwater-only and least positive for those using dam only (Table 2). We note that setting the initial *Attitude and PBC* conditions of the agents using dam water to low values prevented abrupt shifts to mixed irrigation in the early simulation and let the system dynamics play out.

For initial *Affordability* values, we assigned beta distributions to different farmer typologies (small, medium, and large) based on the concept of economies of scale (Michael, 2009). This approach assumes that larger-scale farmers have higher affordability (Table 2).

To simulate initial *Tenancy* values, we characterized 90 % of agents as owners and 10 % as renters, based on our survey. Separate beta distributions were configured for each type of tenancy, reflecting differences due to ownership status (Table 2).

2.6. Biophysical model

Our model describes the dynamics associated with irrigation water supply and yield response.

2.6.1. Irrigation resources

We consider two primary irrigation water sources available to the agents in our model: groundwater and dam water.

We assume that the total volume of water available to agents from the dam in the year t is $D(t)$ m^3, and this is given by:

$$D(t) = D(t-1) - W_f(t-1) + r(t-1) \quad (3)$$

Table 2
The proportion of sampled *attitude*, *affordability* and *tenancy* values.

	Sample Size	α	Β	Proportion > 0.5
Irrigation category				
Groundwater-only	55	8	7	0.62
Mixed	13	5.5	4.3	0.54
Dam-only	180	6.4	8.6	0.23
Farmer typology				
Small	102	8.4	7	0.71
Medium	108	9	6	0.84
Large	38	10	5	0.95
Types of tenancies				
Owner	223	9.1	5.9	0.95
Renter	25	7.5	7.5	0.64

where $W_f(t-1)$ is the total amount of water allocated to agents from the dam in the year $t-1$ and $r(t-1)$ is the dam replenishment. The main sources of replenishment are rainfall and streams. To estimate the dam replenishment under steady-state conditions, we assume that the water allocated to the agents using the dam under initial conditions is equal to the amount replenished in a non-drought year.

Depending on the agents' choices and the extent of the shared irrigation infrastructure, they can choose to irrigate from one source or a mixture with a predefined dam extraction rate $E_D(t)$.

For agents choosing both sources of irrigation, we assume that an agent uses their full water allocation and complements with groundwater extraction. We assume a cap on their needs for dam water equal to the crop water requirement CWR. The dam extraction rate is given by:

$$E_D(t) = \min(CWR, d) \quad (4)$$

Where $d = \frac{D(t)}{n_{\text{Dam}}}$.

2.6.2. Soil salinity

To capture the observed impacts of using groundwater as an irrigation source on soil salinity (measured as electrical conductivity (EC)), we describe the salinity dynamics for each agent's land (i) using a discretised exponential model following (Ayers et al., 1985):

$$S_i(t) = \max(S_0, \varphi - [\varphi - S_i(t-1)]W(EC_w)) \quad (5)$$

where $S_i(t)$ is the salinity of the soil at the time t, S_0 is the lowest plausible soil salinity for that area (See supplementary data for full derivation A.5.1), φ is the carrying capacity, i.e., the maximum value that S_i can take, and W is a function of the salinity of the water applied (EC_w).

Based on Kamal et al. (2021), the water salinity of the Al Haouz aquifer varies from 0.33 to 6.8 dS.cm^{-1}. To set up our simulation, we assume that groundwater and the dam salinity are equal to 6.8 dS.cm^{-1} and 0.02 dS.cm^{-1}. The EC_w in dS/m value is calculated:

$$EC_w = \beta EC_G + (1-\beta)EC_D \quad (6)$$

where β is the proportion of water used that comes from the ground.

Whilst it is known that using saline water to irrigate can lead to a build-up of salinity in soil (Gurmessa et al., 2022), the complexity of the processes involved and the variation in those processes from location to location hinder the soil salinity quantification from year to year. Ayers et al. (1985) provide equations to relate the salinity of water applied to increases in soil salinity over time-based on assumptions about rooting depth and leaching fraction. In our model, we assume that irrigation is done by gravity flow, which has an efficiency of 60 % (Bouaziz and Belabbes, 2002). Ayers et al., (1985) estimate that after 3 – 5 years of irrigation with a leaching fraction of 0.4 the soil will have a salinity equal to 0.9 times that of the water applied. Therefore, we assume:

$$W(EC_w) = \left(\frac{\varphi - 0.9EC_w}{\varphi - S_0}\right)^{\frac{1}{3}} \quad (7)$$

where $S_0 = 0.01$, and $\varphi = 22$.

To assign salinity values to each agent's land, we used the soil salinity values observed from our survey (El Fartassi et al., 2024) and fit an exponential probability distribution. The fitted distribution had mean mu = 4.24 (Figure_A-3, Figure_A-4, Table_A-3). We sampled a single random value for each agent's land from this distribution. Although large farmers in our survey stressed issues related to salinity, we found no notable interaction between farm size and salinity in our data (El Fartassi et al., 2024). Thus, we allocated random values for each farm.

2.6.3. Yield response function

For simplicity, we assume a generic crop based on wheat, which is the most commonly grown crop in the study region (El Fartassi et al., 2024). The yield response function for this crop calculates the yield obtained by an agent given the salinity of the soil in their field (S_i) and the amount of water supplied (w). We assume a multiplicative function of yield response to water and salinity with yield ($Y_i(t)$) given by:

$$Y_i(t) = \Psi(w) Y_r(S_i) \quad (8)$$

where $Y_r(S_i)$ is the relative yield salinity response function and $\Psi(w)$ is the water response function. to describe the response to salinity we adopt the function given by (Van Genuchten and Hoffman, 1984):

$$Y_r(S_i) = \frac{1}{1 + \left(\frac{S_i}{EC_{e\ 50}}\right)^{P_{Yr}}} \quad (9)$$

where EC_{e50} is the value of salinity at which crop yield is reduced by 50 % and P_{Yr} is the steepness of the decreasing sigmoidal curve (Fig. 4a).

To parameterise the irrigation yield response model, we used the MATLAB version of the AquaCrop model (AquaCrop-OS) developed by Foster et al. (2017). AquaCrop model parameters for wheat, relevant to our study region were taken from (Oulaid et al., 2024). The typical sowing dates for R3 are from early December through to the end of January. We selected a representative sowing date of 24th December and ran the AquaCrop model with weather data from 2002 – 2003 to derive irrigation dose-response curves for flood irrigation. We fitted irrigation response curves to the AquaCrop-simulated yield data using the *Genstat* Generalized Linear Models assuming a log-logistic response curve and extracted the Irrigation parameters for a sowing date corresponding to the 24th of December with total irrigation as a dependent variable. (Fig. 4b, Table_A-2).

2.7. Scenarios

2.7.1. Theoretical scenarios

We considered two theoretical scenarios. In the first, we assume a constant dam fill rate, where the dam replenishment is sufficient to support irrigation throughout. This represents stable water availability. In the second, we consider a decreasing dam fill, where the dam replenishment gradually diminishes over time, simulating reduced water availability (Table 3).

2.7.2. Realistic scenario

To simulate more realistic scenarios of dam water provision, we used data on water allocation from ORMVAH, spanning from the 1987–1988 season to the 2019–2020 season. This dataset provides information on the actual volume of water delivered for agricultural use (Table_A-4). In the dataset, water needs are represented as a constant 310 units, based on crop requirements, practices, and environmental conditions. The annual irrigation rate is the ratio of allocated water to estimated water needs, capped at 1 to normalize excess. We fitted a non-parametric distribution (kernel density) to these data to model the variability in the dam irrigation rate. From this fitted distribution, we drew a single set of 50 values, each representing the annual irrigation rate for one of the 50 years of the simulation.

Table 3
Summary of the different scenarios explored in the study.

Scenario	Description
Theoretical - steady dam fill rate	– Assumes a steady dam fill rate with sufficient replenishment to support irrigation throughout the simulation period.
Theoretical - decreasing dam fill rate	– Considers a decreasing dam fill rate over time, simulating reduced water availability.
Realistic	– Uses historical data on actual water allocation. – Calculates annual irrigation satisfaction rates as the ratio of allocated water to estimated water needs. – Employs kernel density estimation to generate a distribution of satisfaction rates for sampling.
Climate Change	– Builds upon the realistic scenario. – Incorporates a 12 % reduction in dam fill rate compared to the last 10 years of the Realistic scenario. – Reflects projected climate change impacts of increased aridity and reduced water availability in the region.

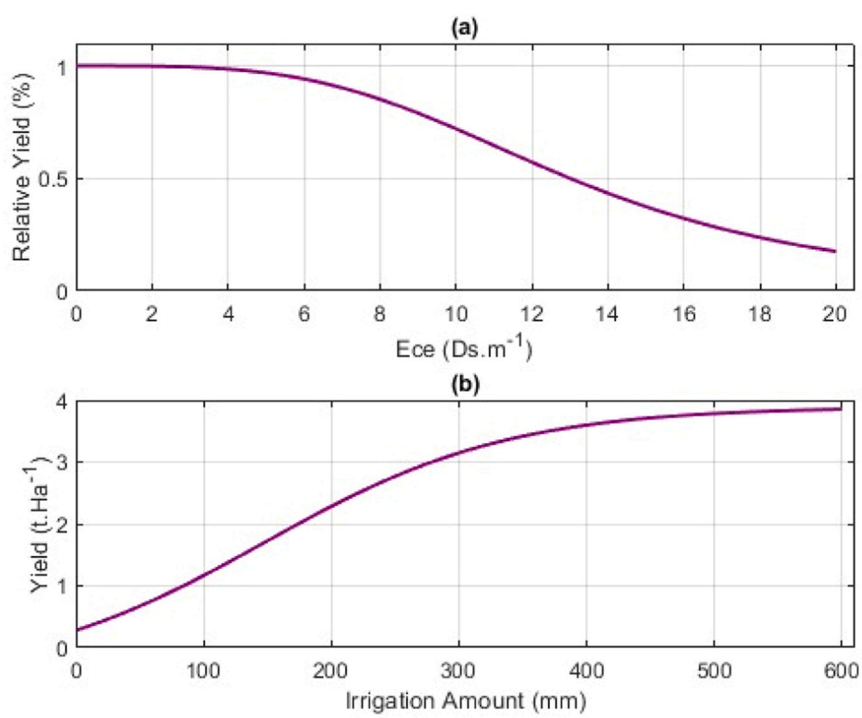

Fig. 4. (a) Relative yield response function of wheat to the soil salinity levels, represented by the electrical conductivity, where $EC_{e50} = 13$, $P_{Yr} = 3.6$. (b) Wheat yield response function to varying irrigation amounts.

2.7.3. Climate change scenario

Expanding on the realistic scenario approach, we introduced a climate change scenario that incorporated a reduction in water availability due to climate impacts. In this scenario, we assumed that the dam fill rate would decrease by 12 % compared to the values observed in the last decade of the realistic scenario. These assumptions are grounded in projections from the National Intelligence Council (NIC, 2009). This reduction in water availability was based on the projected climate change impacts for North Africa, which indicated a clear increase in temperature, a drying trend particularly along the Mediterranean coast, and potential variations in precipitation patterns. These projections were selected as they align with widely recognised climate models and studies for North Africa, such as those referenced in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (IPCC, 2023), which similarly anticipates a drying trend, higher variability in rainfall, and increased water stress in semi-arid regions. The climate change scenario is integrated into the model by reducing dam replenishment and increasing reliance on groundwater.

2.8. Simulated policies

We investigated the impact of changing the policy on the number of annual water abstraction authorizations across each of the dam fill rate scenarios described in Table 3. We explored the impact of varying the percentage of wells authorized annually with six policy scenarios in which 0, 2.5, 5, 10, 25, and 50 % of water abstraction applications are successful.

2.9. Simulations

We ran our model for each combination of dam fill rate and policy scenarios. Each simulation lasted 50 timesteps (years). All simulations were initialized with the same starting conditions for agent attributes. For each scenario combination, we ran 20 realisations of the simulations to account for stochasticity in the model. The choice of 20 realisations was based on standard practice in agent-based modelling, where multiple runs are conducted to capture the variability inherent in stochastic processes (Railsback and Grimm, 2011). Previous studies have demonstrated that 20 runs are generally sufficient to ensure that the output variability stabilizes, providing reliable estimates of the model's behaviour without excessive computational costs (Crooks and Heppenstall, 2012).

2.10. Sustainability metrics

To quantitatively assess the impacts and trade-offs between different water management scenarios, we calculated sustainability metrics related to agricultural productivity (Yield), environmental health (Salinity), and social impact (Land Abandonment), therefore adopting a holistic approach to sustainability assessment in line with the framework proposed by (Purvis et al., 2019).

2.10.1. Agricultural productivity

We recorded average crop yields across all agents using a given irrigation water source at each timestep of the simulation. We compared how productivity levels differed between agents relying on different water sources and how those productivity gaps evolved under varying resource constraints and policy settings. To quantify the impact of our various scenarios we calculated the total yield produced over the simulated period.

2.10.2. Environmental health

We monitored average soil salinity levels, again disaggregated by irrigation water source, over time. To quantity the impact of each scenario on soil salinity, we calculated the count of agents with soil salinity exceeding $EC_{e50} = 13$, the value at which wheat crop yield is reduced by 50 % (Fig. 4a).

2.10.3. Social impact

The social impact of agricultural practices is evaluated by examining the total number of agents that have chosen to abandon cultivating and the resulting non-cultivated land area.

3. Results

3.1. Theoretical scenarios

3.1.1. Steady dam fill rate

In the first scenario, we consider a theoretical steady dam-fill rate with a policy where, each year, 15 % of all water abstraction applications are successful. Fig. 5a illustrates the dynamics under this scenario, capturing various aspects of the irrigation system and farmer behaviour. Initially, the yield is similar across all irrigation users. Over time, the yield for groundwater users declines due to increasing soil salinity, which adversely affects crop productivity. In contrast, the yields for dam users and mixed irrigation users remain relatively stable, given that they are less or not impacted by soil salinity issues.

The number of groundwater users decreases sharply after around 15 years, corresponding with the rise in soil salinity. The number of mixed irrigation users increases initially, as some dam users switch to mixed irrigation to supplement their water supply.

Overall, the results indicate that while the dam fill rate remains constant, dam and mixed irrigation users can maintain stable yields and low salinity levels for some time, whereas groundwater users face faster significant challenges that result in a decline in agricultural productivity and increased land abandonment.

3.1.2. Decreasing dam fill rate

As with the previous scenario, we consider a decreasing dam fill rate scenario where, each year, 15 % of all water abstraction applications are successful (Fig. 5).

Initially, the average simulated yields were similar across all groups (Fig. 5b). Both the groundwater users and the dam water users experienced sharp declines in yields, with both groups reaching zero yields after about 18 years and 25 years, respectively. Mixed irrigation users also saw a decline in yields, but at a slower rate than the groundwater users, indicating they were less affected by salinity but still impacted by the overall water scarcity. For the dam-only users, the decline in yield was related to the increasingly limited water availability. For the groundwater and mixed irrigation users, the average yield reductions were linked to the buildup of soil salinity from groundwater use. Initially, the dam-only users had marginally higher average yields than the mixed irrigation and groundwater users. The limited water resource became the dominant factor, and the mixed irrigation users had the highest average yields over time.

At the start of the simulation, all irrigation user types exhibit relatively low EC_e levels around 4–6 dS^{-1} (Fig. 5c) The salinity levels for groundwater users increased significantly, reaching nearly 19 $dS.m^{-1}$ after 18 years when their crops failed. For mixed irrigation users, there was a notable increasing trend over time with some fluctuations, reaching higher EC_e levels towards the end of the iterations, although at a slower rate compared to groundwater users. Those who continue to rely on dam resources maintain relatively stable soil salinity levels throughout the simulation period. Their ECe values remain below 4 $dS.m^{-1}$.

The initial number of dam users is high, but it declines gradually as more farmers switch to mixed irrigation or cease cultivation (Fig. 5d). The number of groundwater users starts decreasing after around 9—10 years, corresponding with the rise in soil salinity and decreasing yield. By year 14, almost all groundwater users had ceased cultivation. Mixed irrigation users increase as dam users switch to mixed irrigation to supplement their water supply as the dam fill rate declines. Due to

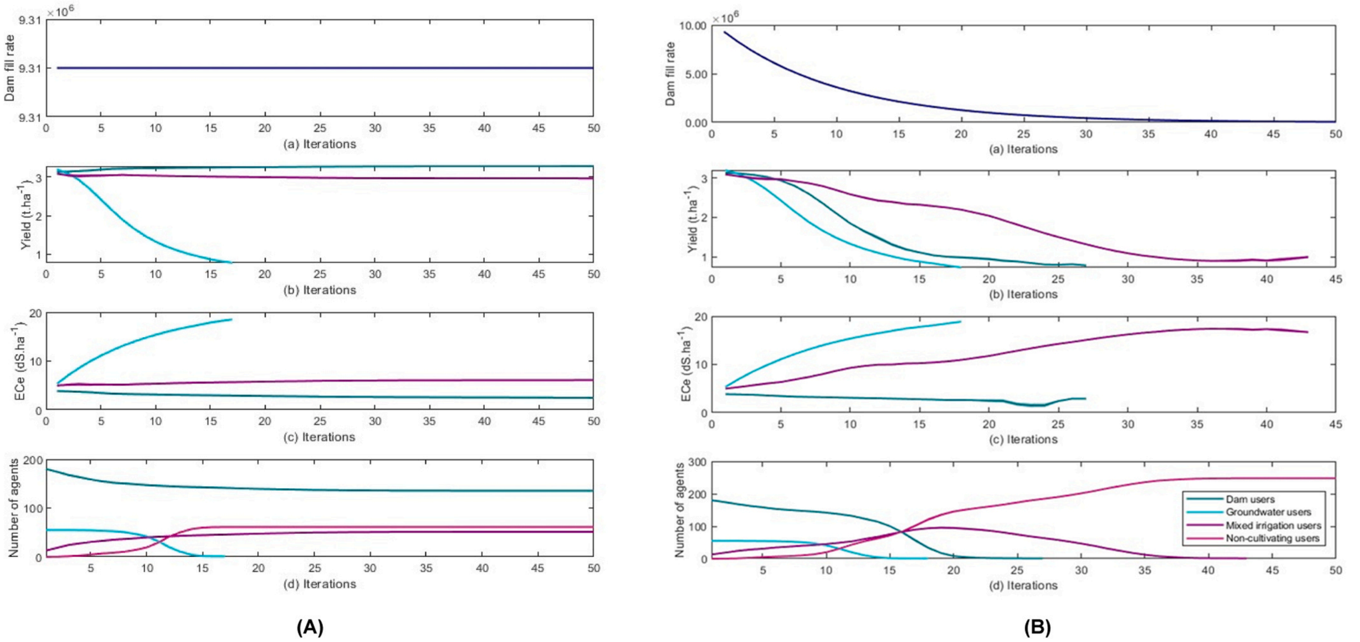

Fig. 5. Changes over 50 iterations under a policy where 15 % of annual water abstraction applications are successful, considering theoretical (A) steady and (B) decreasing dam fill scenarios. The subplots present changes n (a) dam fill rates, (b) crop yield, (c) water salinity levels, and (d) the proportion of agents updating their irrigation strategy. The shaded areas represent the standard errors across 20 simulation runs.

increasing soil salinity from using saline groundwater and reduced availability of dam water impacting the overall productivity, the number of mixed irrigation users stabilised and then decreased as they ceased cultivation.

3.2. Sustainability metrics and scenario analysis

In this section, we only consider the following three scenarios: 1) theoretical decreasing dam fill rate, 2) realistic scenario, and 3) climate change scenario.

3.2.1. Agricultural productivity

In the theoretical decreasing scenario, the total yield increased as the percentage of authorized water abstractions grew from 0 % to around 25 % (Fig. 6). After this point, the yield remained relatively constant, exhibiting minimal change with further increases in water abstraction authorizations. This is indicative that allowing a moderate level of water abstraction expansion boosted the overall total yield. Additional authorizations beyond a certain point resulted in minimal improvements to the total yield.

The realistic scenario showed a quite different pattern. Total yield declined steadily from the beginning as the percentage of authorized water abstractions increased. The decline was steepest with small increases in water abstraction authorizations but continued at higher authorization levels.

In the climate change scenario, as the percentage of authorized water abstraction increased from 0 % to 2.5 %, there was an increase in total yield. Then, it began to decline as authorization rose beyond 2.5. This decline was attributable to the balance between groundwater availability and soil salinity levels. Increased water abstraction authorizations initially provided more water for irrigation, but past a certain threshold, the salinity build-up associated with groundwater use negatively impacted crop productivity. Our results show a theoretical optimum point for water abstraction authorizations at 2.5 % (Fig. 6), determined at the catchment scale rather than at the individual farmer level.

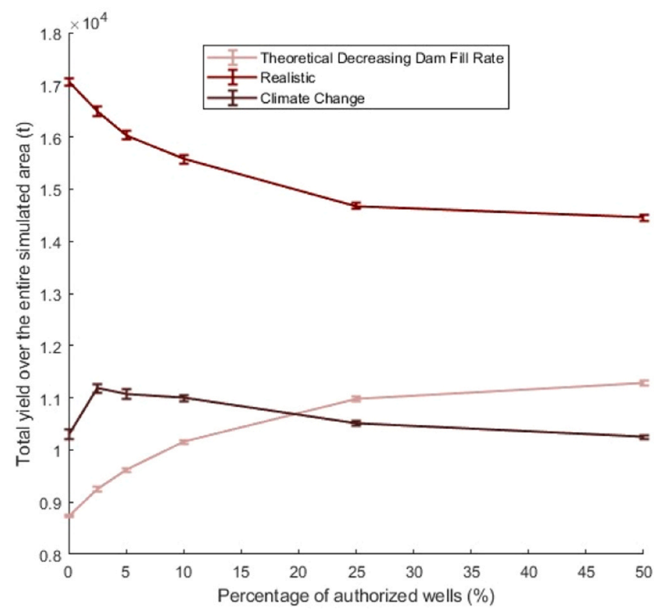

Fig. 6. Changes in total yield (summed across different irrigation water sources: dam, groundwater and mixed) over the entire simulated area per scenario and policy setting. Error bars represent the standard deviation across 20 simulation runs.

3.2.2. Environmental health

All three scenarios showed a steep increase in the count of agents exceeding the ECe_{50} salinity threshold as the percentage of authorized water abstractions increased, followed by a plateau at higher authorization levels.

For the theoretical decreasing scenario, the initial conversion to mixed irrigation was slow compared to the realistic and climate change scenarios (Fig. 7 & Fig. 8). This is because, in this theoretical scenario, the depletion of water resources occurred gradually over time. Unlike the other scenarios, where water scarcity arose more randomly and

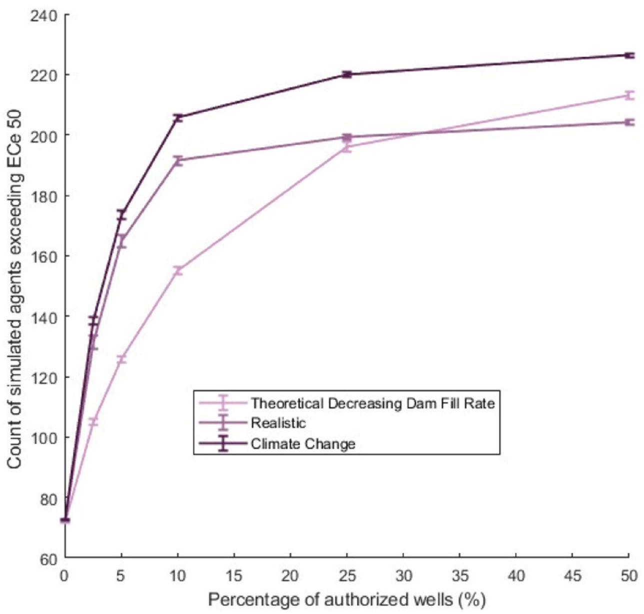

Fig. 7. Changes in the average count of farmers exceeding the critical soil salinity threshold (ECe_{50}) at which wheat yields are reduced by 50 %, under different scenarios (theoretical decreasing, realistic, and climate change) and across a range of water abstraction policies (0–50 % of wells authorized). Error bars represent the standard deviation across 20 simulation runs.

sporadically, the theoretical scenario presented a more controlled and predictable depletion pattern. As a result, agents had a more extended period to continue cultivation before reaching critical salinity levels.

The realistic scenario demonstrated a steeper increase in the number of farmers exceeding the salinity threshold as more water abstractions were authorized. This implied that under realistic conditions, even low levels of water abstraction authorizations can rapidly lead to widespread salinity, and the situation stabilised at a more severe level.

The climate change scenario showed the highest count of farmers exceeding the salinity threshold. Climate change exacerbated the impact of water abstraction authorizations on soil salinity due to increased, intensifying reliance on saline groundwater. Consequently, more farmers were pushed beyond the critical salinity threshold, leading to higher rates of land abandonment.

The theoretical scenario, with its gradual resource depletion, showed a slower initial rate of abandonment (Fig. 8). But, as water scarcity became more pronounced, the rate of abandonment accelerated, mirroring the later stages of the other scenarios. Policies allowing higher water abstraction authorizations led to more rapid and widespread land abandonment, driven by escalating salinity levels and declining agricultural productivity.

3.2.3. Social impact

In the theoretical decreasing scenario, the number of dam water users decreased steadily over time across all water abstraction authorization percentages (Fig. 8). The decline was gradual, with the rate of decline being proportional to the percentage of authorized water abstractions. As water became scarcer and the water abstraction authorization percentage increased, farmers increasingly switched to mixed irrigation to supplement their water supply. This transition was particularly pronounced between 25 % and 50 % authorization levels. Within this range, the initial decline in dam water users was quite rapid. After the initial steep decrease, the number of dam water users stabilized for a period before experiencing a further decline after 10–12 years. This transition was also reflected in the initial rise of mixed irrigation users, which peaked and then declined as salinity impacts took hold and the water resources continued to deplete. Land abandonment followed a distinct pattern, starting slowly but accelerating as more farmers exceeded the critical soil salinity threshold. For low authorization scenarios (from 0 % to 10 %), abandonment was primarily driven by water scarcity, as the rate of abandonment was faster compared to scenarios with a high percentage of water abstraction authorizations. For the latter scenarios, the rate of land abandonment was more or less consistent after 10 years, indicating that soil salinity may have been the primary driver. However, as time progressed, land abandonment steadily increased until sustainable cultivation became unfeasible, due to the combined effects of soil salinity and water scarcity.

In the realistic scenario, the number of dam water users decreased

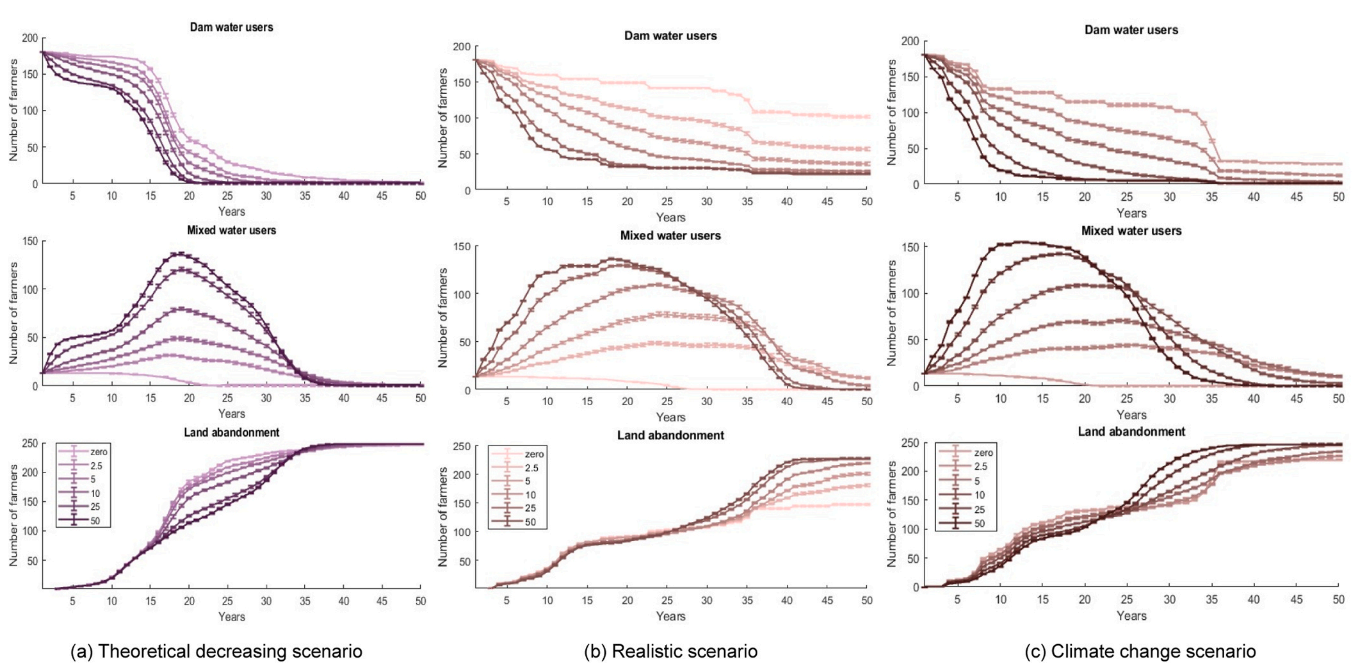

Fig. 8. Changes in the count of different groups of agricultural agents - dam water users, mixed irrigation users, and those abandoning cultivation - over 50 years, as the percentage of authorized water abstractions increases from 0 % to 50 %.

more rapidly compared to the theoretical scenario at higher water abstraction authorization percentages but slower at low water abstraction authorization percentages. The rapid decline in the first case was due to extreme water scarcity conditions arising more randomly, which accelerated the transition to mixed irrigation. Mixed irrigation users initially increased sharply for higher water abstraction authorization percentages, reaching a higher peak than in the theoretical scenario, as farmers quickly adapted to the diminishing dam water supply. However, the decline in mixed irrigation users also happened more rapidly, reflecting the faster onset of unsustainable conditions due to increased soil salinity. Land abandonment in the realistic scenario exhibited a distinct trajectory compared to the theoretical scenario. By year 35, under a 50 % water abstraction authorization, approximately 64 % of farmers (160 out of 248) had abandoned their land in the realistic scenario. In contrast, the theoretical decreasing scenario showed complete land abandonment by all 248 farmers within the same time frame. By year 50 in the realistic scenario, a proportion of farmers remained active, with the percentage of active farmers varying inversely with water abstraction authorization levels. Another significant difference between the two scenarios was the temporal pattern of land abandonment. The realistic scenario displayed a nearly stagnant period of land abandonment between years 15–25, characterized by a flat line in the abandonment curve. Conversely, land abandonment in the theoretical decreasing scenario did not exhibit a period of stagnation progressing continuously over time.

The climate change scenario presented the most severe outcomes. After approximately 10 years, the number of dam water users remained relatively stable for scenarios with 0 % and, to a slightly lesser extent for scenarios with 2.5 % water abstraction authorization. In contrast with relatively high authorization percentages (5–50 %), the number of dam water users decreased sharply, driven by the compounded effects of climate change, forcing a quick transition to mixed irrigation. Mixed irrigation users experienced a significant initial increase, but this peaked and declined more quickly than in the other scenarios. The impacts of climate change exacerbated soil salinity issues, resulting in mixed irrigation becoming unsustainable in a shorter time frame. Land abandonment was most pronounced in the climate change scenario. The rapid initial rise and the high plateau of land abandonment reflected the severe conditions under which farmers operated. The high percentage of water abstraction authorizations accelerated the transition to unsustainable practices, leading to a substantial number of farmers abandoning their land early in the iterations. The cumulative effects of climate change drove a higher and faster rate of abandonment compared to the other scenarios.

There is a sharp decrease in the number of active farmers at year 35 in the climate change scenario, which was also evident to a certain extent in the realistic scenario. This steep decline was particularly prominent for scenarios with 0 %, 2.5 %, and 5 % water abstraction authorization. This is a function of the underlying climate scenario parameters where at around that time farmers experienced episodes of drought. As a result of these severe and recurring drought events, a substantial number of farmers reached a critical threshold where cultivation was no longer viable, leading to a rapid increase in land abandonment.

4. Discussion

In this study, we developed an integrated agent-based modelling framework that couples behavioural and biophysical components to investigate the dynamics of shared irrigation water management in an arid agricultural region of Morocco. By modelling heterogeneous farmer decision-making and integrating this with a biophysical model of water availability, soil salinity, and crop productivity, the framework allowed us to investigate the feedback loops between environmental conditions and human management decisions. The scenario analyses conducted provide insights into the potential impacts of policy interventions aimed at regulating groundwater access through water abstraction authorization on the long-term sustainability of the agricultural system

Previous socio-hydrological studies often assume a relatively stable external environment, overlooking the interactions between farmers and the environment (Ghoreishi et al., 2021; Sanderson et al., 2017). In contrast, we explored multiple scenarios and how agents responded to those and those actions in turn affected those environments.

We embedded a biophysical model into the ABM framework and explored multiple climate scenarios and how agents respond to. By integrating these components, we gained a more comprehensive understanding of the complex, nonlinear interactions between heterogeneous agents, their environment, and the socio-hydrological system as a whole. This captured the two-way feedback between physical and social processes, a critical aspect of socio-hydrological systems (Di Baldassarre et al., 2015).

Our model allows us to investigate the trade-offs inherent in the management of shared irrigation water resources in arid regions given different policy scenarios. This approach can provide valuable insights into the management of shared irrigation water resources and the potential impacts of various decision-making strategies on the system's sustainability and resilience. In our modelled scenarios, as the percentage of authorized water abstractions increases, the number of farmers abandoning cultivation rises dramatically, particularly under realistic and climate change scenarios. This trend suggests that while expanding groundwater access through authorized water abstractions may help maintain or improve yields in the short term, especially when dam water is depleting, the long-term environmental consequences, such as increased soil salinity, can lead to more farmers exiting agriculture. This finding corroborates studies that have documented the negative impacts of salinization on farm viability and livelihood sustainability in arid regions (Mkilima, 2023; Qadir et al., 2014).

The increasing trend in land abandonment, despite the rise in water abstraction authorizations, is a concerning observation that reflects broader sustainability challenges within the modelled agricultural system. This trend highlights the urgent need for the development and implementation of integrated water resource management policies. Such policies consider the long-term availability of both surface and groundwater resources, as well as the socio-economic implications of these resources on the agricultural sector and the wider community.

The rise in land abandonment levels highlights the need for careful consideration of the potential unintended consequences of permissive water abstraction policies. This is consistent with the findings of (Malek et al., 2019), who highlight the influence of policy shifts on farmers' land-use decisions, and Reidsma et al., (2018), who stress the importance of incorporating farmer decision-making processes in agricultural policy assessment models to capture potential unintended consequences.

Our results show that in the climate change scenario, there exists a theoretical optimum point for water abstraction authorizations (Fig. 6). This optimum is determined at the catchment scale rather than on an individual basis. By considering the entire catchment, decision-makers can identify a balanced point that maximises yield while ensuring the long-term sustainability of groundwater resources. This finding aligns with recent research that emphasizes the importance of integrated water resource management at the catchment level (Dao et al., 2024; Sadath et al., 2023)

Policy-makers must strike a delicate balance between ensuring adequate water access for agricultural productivity and preventing unsustainable groundwater extraction that can lead to soil degradation and eventual land abandonment. This challenge is particularly acute in arid and semi-arid regions, where water scarcity is a persistent concern, and farmers' livelihoods are heavily dependent on reliable access to irrigation water. Policymakers have a range of instruments at their disposal to align individual farmers' incentives with the sustainable use of shared groundwater resources. As highlighted in the literature, the establishment of groundwater extraction quotas can be an effective tool for regulating withdrawals and preventing overexploitation (Grafton et al., 2011; Jakeman et al., 2016). Additionally, financial incentives for adopting water-efficient technologies, such as drip irrigation, and shifting to salinity-tolerant crops could help farmers adapt to limited water resources while maintaining productivity (Meinzen-Dick, 2014; Qadir et al., 2014).

The lack of comprehensive groundwater monitoring and the focus on surface water resources, as observed in the study region, is a common challenge across many arid and semi-arid areas in Africa. By setting caps on the volume of groundwater that can be extracted, either at the individual or collective level, these policies create clear boundaries that incentivize more efficient and conservative water use practices among farmers. Enhancing community awareness and building capacity through participatory approaches can further support these efforts, ensuring that stakeholders are involved in resource management and that policies are contextually relevant and widely accepted (Malek et al., 2019; Voinov and Bousquet, 2010).

Developing integrated policy approaches that combine improved groundwater monitoring and accounting, economic incentives, regulatory frameworks, and meaningful stakeholder engagement will be crucial in navigating this balance (Gleeson and Richter, 2018). In addition, authorities should collaborate with local communities to promote land-use strategies that balance productivity with environmental conservation, such as encouraging mixed irrigation strategies in areas where both surface and groundwater resources are sustainable.

While the data sources are surveys from Morocco, the conceptual modelling framework integrates the TPB, a widely validated theory of human decision-making behaviour. The TPB framework incorporated in this study captures the key constraints and motivations facing farmers who are dependent on variable water resources, a common challenge across arid regions of Africa (Yazdanpanah et al., 2014). By grounding the agent-based model in the TPB, the factors influencing farmer choices over irrigation source usage have been comprehensively represented. This approach provides valuable insights that can be translated beyond the specific Moroccan case study, offering a transferable framework for understanding and addressing water management challenges in arid and semi-arid agricultural systems across Africa. Many of these regions face analogous pressures of water scarcity and competing demands for limited water resources (Wada et al., 2010; Wada and Bierkens, 2014).

The integration of behavioural and biophysical components within the ABM framework enabled a nuanced representation of farmer decision-making processes and their interactions with evolving environmental conditions. By parameterizing models behavioural models using survey data and grounding the behavioural component in the TPB framework, the model was able to incorporate key determinants of farmer irrigation choices, such as *attitude* and *PBC*, which have been shown to play a significant role in shaping agricultural water management decisions (El Fartassi et al., 2024).

The ABM approach captured the heterogeneity of irrigation strategies and their underlying drivers, assisting stakeholders and policymakers in designing interventions that better align with the needs and constraints faced by different farmer groups (Voinov and Bousquet, 2010). Consequently, this contributes to developing more equitable and effective water management policies, a key consideration in the context of arid regions where water scarcity exacerbates social and economic vulnerabilities.

5. Study limitations

While the integrated ABM framework developed in this study offers valuable insights into the complex dynamics of shared irrigation water management, it is important to acknowledge several limitations that should be considered when interpreting the findings.

Firstly, as far as possible, we parameterised the model using empirical data, but this was not always possible. Ad hoc choices based on expert knowledge were necessary for certain initial conditions and behavioural parameters. These parameters significantly influenced the rate at which agents respond to changing conditions in the model. Various combinations of initial proportions were explored in preliminary model runs. However, it is important to note that the specific quantitative results may be sensitive to these assumed starting conditions.

Secondly, while the TPB-grounded behavioural component captures a range of socio-psychological factors influencing farmer decision-making, other variables were not accounted for in the current framework. For instance, the model does not explicitly consider the role of extension services, which have been shown to shape agricultural water management practices in some regions (Osumba et al., 2021). Incorporating such additional behavioural determinants could further enhance the model's ability to represent the nuanced decision-making processes of farmers.

Thirdly, the biophysical model simplifies certain hydrological processes, such as the representation of groundwater dynamics and the interactions between surface water and groundwater. In reality, these processes can be highly complex, influenced by factors like aquifer characteristics, recharge rates, and lateral flow patterns, which may vary over space and time. Incorporating more detailed hydrogeological modelling could improve the accuracy of the simulated water availability and quality, particularly in regions with heterogeneous groundwater systems.

Finally, the study focuses on a single crop (wheat) and does not account for potential shifts in cropping patterns that farmers may adopt in response to changing water availability and soil conditions. Expanding the model to include a diverse crop portfolio, along with farmers' adaptive responses in terms of crop selection and management practices, could provide a more comprehensive understanding of the agricultural system's resilience under various policy and environmental scenarios.

Despite these limitations, the present study serves as a valuable infrastructure for investigating the complex trade-offs inherent in the management of shared irrigation water resources in arid regions. The integrated ABM framework and the insights derived from the scenario analyses can inform the development of more robust and context-specific water governance strategies, while also highlighting the need for further research to address the identified limitations and enhance the model's predictive capabilities.

6. Conclusion

The multi-metric ABM framework presented in this study offers a comprehensive, quantitative approach to assessing the sustainability of agricultural water resource use. The model's strengths lay in its ability to represent the heterogeneity of agents, incorporate survey data for parameterisation, and explore multiple climate and policy scenarios. This approach allowed for a more realistic representation of the socio-hydrological system and its inherent complexities. The findings reveal that (1) expanding groundwater access through abstraction authorizations can boost short-term productivity but risks long-term soil salinisation and land abandonment; (2) mixed irrigation strategies mitigate immediate water scarcity but become less effective as salinity accumulates; and (3) climate change, with a projected 12 % reduction in dam replenishment, exacerbates water scarcity and reinforces the need for integrated resource management. Furthermore, (4) policy measures such as groundwater extraction quotas and financial incentives for sustainable practices are critical not only for encouraging the adoption of sustainable behaviours but also for aligning individual decision-making with broader collective goals. By considering the dynamic interactions between agents, their environment, and the broader socio-hydrological context, the ABM framework contributes to a better understanding of the challenges and opportunities associated with managing shared irrigation water resources in arid regions.

Funding

This project is funded by Office Chérifien des Phosphate (OCP group) through the collaboration between Cranfield University (CU), Rothamsted Research (RRes) and Mohammed VI Polytechnic University (UM6P).

CRediT authorship contribution statement

Imane El Fartassi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Alice E. Milne**: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data Curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Helen Metcalfe**: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Rafiq El Alami**: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Alhousseine Diarra**: Software, Formal analysis. **Vasthi Alonso-Chavez**: Validation, Investigation, Writing – review & editing. **Toby W. Waine**: Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Joanna Zawadzka**: Software, Formal analysis. **Ron Corstanje**: Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Rothamsted Research receives strategic support from the UKRI-BBSRC (UK Research and Innovation-Biotechnology and Biological Sciences Research Council).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109357.

Data availability

The supplementary data to this article is available and attached

References

Acemoglu, D., Ozdaglar, A., 2011. Opinion dynamics and learning in social networks. Dyn. Games Appl. 1 (1). https://doi.org/10.1007/s13235-010-0004-1.

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5 (12), 853–861. https://doi.org/10.1038/ngeo1617.

Amrouk, E.M., 2021. Price Dyn. Interact. Int. Cash. Crop Staple Food Mark. ⟨https://bonndoc.ulb.uni-bonn.de/xmlui/handle/20.500.11811/8960⟩.

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecol. Model. 229, 25–36. https://doi.org/10.1016/j.ecolmodel.2011.07.010.

Ayers, R.S., Westcot, D.W., Food and Agriculture Organization of the United Nations, 1985. Water quality for agriculture. Food and Agriculture Organization of the United Nations.

Bouaziz, A., Belabbes, K., 2002. Effic. Product. De. l'eau En. irrigué au Maroc.

Bouchaou, L., Alfy, M. El, Shanafield, M., Siffeddine, A., & Sharp, J. (2024). *Groundwater in Arid and Semi-Arid Areas*. 1–5.

Bulatewicz, T., Yang, X., Peterson, J.M., Staggenborg, S., Welch, S.M., Steward, D.R., 2010. Accessible integration of agriculture, groundwater, and economic models using the Open Modeling Interface (OpenMI): methodology and initial results. Hydrol. Earth Syst. Sci. 14 (3), 521–534. https://doi.org/10.5194/hess-14-521-2010.

Castellano, C., Fortunato, S., Loreto, V., 2007. Statistical physics of social dynamics. Rev. Mod. Phys. 81. https://doi.org/10.1103/RevModPhys.81.591.

Crooks, A.T., Heppenstall, A.J., 2012. Introduction to Agent-Based Modelling BT - Agent-Based. In: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Models of Geographical Systems. Springer Netherlands, pp. 85–105. https://doi.org/10.1007/978-90-481-8927-4_5.

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., Ritsema, C.J., 2016. The threat of soil salinity: A European scale review. Sci. Total Environ. 573, 727–739. https://doi.org/10.1016/j.scitotenv.2016.08.177.

Dao, P.U., Heuzard, A.G., Le, T.X.H., Zhao, J., Yin, R., Shang, C., Fan, C., 2024. The impacts of climate change on groundwater quality: A review. Sci. Total Environ. 912, 169241. https://doi.org/10.1016/J.SCITOTENV.2023.169241.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., Blöschl, G., 2015. Debates - Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. Water Resour. Res. 51 (6), 4770–4781. https://doi.org/10.1002/2014WR016416.

Duchemin, B., Benhadj, I., Hadria, R., Hagolle, O., Kharrou, M.H., Mougenot, B., Courault, D., Chehbouni, A., 2009. Evaluation of irrigation water amount in semi-arid croplands using time series of formosat-2 images (January). Int. Geosci. Remote Sens. Symp. . (IGARSS) 3, 10–14. https://doi.org/10.1109/IGARSS.2009.5418295.

El Fartassi, I.El, Metcalfe, H., Milne, A.E., Alami, R.El, Diarra, A., Waine, T.W., Zawadzka, J., Corstanje, R., 2024. Adapt. Agric. Water Manag. Arid Reg.: Model. Farmer Behav. Coop. Irrig. Sustain. 19852.

Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environ. Model. Softw. 45, 1–7.

Ng, T.L., Wayland Eheart, J., Cai, X., Braden, J.B., 2011. An agent-based model of farmer decision-making and water quality impacts at the watershed scale under markets for carbon allowances and a second-generation biofuel crop. Water Resour. Res. 47, W09519.

Foster, S., Garduño, H., 2013. Groundwater-resource governance: Are governments and stakeholders responding to the challenge? Hydrogeol. J. 21 (2), 317–320. https://doi.org/10.1007/s10040-012-0904-9.

Foster, T., Brozović, N., Butler, A.P., Neale, C.M.U., Raes, D., Steduto, P., Fereres, E., Hsiao, T.C., 2017. AquaCrop-OS: An open source version of FAO's crop water productivity model. Agric. Water Manag. 181, 18–22. https://doi.org/10.1016/j.agwat.2016.11.015.

Ghoreishi, M., Razavi, S., Elshorbagy, A., 2021. Understanding human adaptation to drought: agent-based agricultural water demand modeling in the Bow River Basin, Canada. Hydrol. Sci. J. 66 (3), 389–407. https://doi.org/10.1080/02626667.2021.1873344.

Gleeson, T., Richter, B., 2018. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. River Res. Appl. 34 (1), 83–92. https://doi.org/10.1002/rra.3185.

Grafton, R.Q., Libecap, G., McGlennon, S., Landry, C., O'Brien, B., 2011. An integrated assessment of water markets: A cross-country comparison. Rev. Environ. Econ. Policy 5 (2), 219–239. https://doi.org/10.1093/reep/rer002.

Gurmessa, S.K., MacAllister, D.J., White, D., Ourdraog, I., Lapworth, D., MacDonald, A., 2022. Assessing groundwater salinity across Africa. Sci. Total Environ. 828, 154283. https://doi.org/10.1016/j.scitotenv.2022.154283.

IPCC. (2022). Fact Sheets | Climate Change 2022: Impacts, Adaptation and Vulnerability. In Fact Sheet. ⟨https://www.ipcc.ch/report/ar6/wg2/about/factsheets/%0Ahttps://www.ipcc.ch/report/ar6/wg2/about/factsheets⟩.

IPCC. (2023). *Summary for Policymakers of the Intergovernmental Panel on Climate Change*.

Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.D., Ross, A., 2016. Integrated groundwater management: Concepts, approaches and challenges. *Integr. Groundw. Manag.: Concepts, Approaches Chall.* https://doi.org/10.1007/978-3-319-23576-9.

Kamal, S., Sefiani, S., Laftouhi, N.E., El Mandour, A., Moustadraf, J., Elgettafi, M., Himi, M., Casas, A., 2021. Hydrochemical and isotopic assessment for characterizing groundwater quality and recharge processes under a semi arid area: Case of the Haouz plain aquifer (Central Morocco). J. Afr. Earth Sci. 174. https://doi.org/10.1016/j.jafrearsci.2020.104077.

Kharrou, M.A., Simonneaux, V., Er-Raki, S., Page, M.L., Khabba, S., Chehbouni, A., 2021. Assessing Irrigation Water Use with Remote Sensing-Based Soil Water Balance at an Irrigation Scheme Level in a Semi-Arid Region of Morocco. remote sensing 13, 1133.

Kremmydas, D., Athanasiadis, I.N., Rozakis, S., 2018. A review of Agent Based Modeling for agricultural policy evaluation. Agric. Syst. 164 (October 2017), 95–106. https://doi.org/10.1016/j.agsy.2018.03.010.

Letcher, R., Jakeman, A.J., Barreteau, O., Borsuk, M., Elsawah, S., Hamilton, S., Henriksen, H., Kuikka, S., Maier, H., Rizzoli, A.-E., van Delden, H., Voinov, A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ. Model. Softw. 47, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005.

Mabhaudhi, T., Chibarabada, T., Modi, A., 2016. Water-Food-Nutrition-Health Nexus: Linking water to improving food, nutrition and health in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 13 (1). https://doi.org/10.3390/ijerph13010107.

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É .Ó., Taylor, R.G., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7 (2). https://doi.org/10.1088/1748-9326/7/2/024009.

Malek, Ž., Douw, B., Vliet, J.Van, Zanden, E.H. Van Der, & Verburg, P.H. (2019). *Local land-use decision-making in a global context*.

Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P., 2014. A review of droughts on the African continent: A geospatial and long-term perspective. Hydrol. Earth Syst. Sci. 18 (9), 3635–3649. https://doi.org/10.5194/hess-18-3635-2014.

Meinzen-Dick, R., 2014. Property rights and sustainable irrigation: A developing country perspective. Agric. Water Manag. 145, 23–31. https://doi.org/10.1016/j.agwat.2014.03.017.

Michael, D., 2009. Economies of size in production agriculture. J. Hunger Environ. Nutr. 4 (3–4), 375–392. https://doi.org/10.1080/19320240903321292.

Milne, A.E., Gottwald, T., Parnell, S.R., Chavez, V.A., van den Bosch, F., 2020. What makes or breaks a campaign to stop an invading plant pathogen? PLoS Comput. Biol. 16 (2), 1–20. https://doi.org/10.1371/journal.pcbi.1007570.

Mkilima, T., 2023. Groundwater salinity and irrigation suitability in low-lying coastal areas. A case of Dar es Salaam, Tanzania. Watershed Ecol. Environ. 5 (March), 173–185. https://doi.org/10.1016/j.wsee.2023.07.002.

Nguyen, B.Q., Van Binh, D., Tran, T.N.D., Kantoush, S.A., Sumi, T., 2024. Response of streamflow and sediment variability to cascade dam development and climate change in the Sai Gon Dong Nai River basin. Clim. Dyn. 62 (8), 8283–8298. https://doi.org/10.1007/s00382-024-07319-7.

Nguyen, Q., Kantoush, S.A., Tran, T.N.D., Van Binh, D., Vo, N.D., Saber, M., Sumi, T., 2023. Response of hydrological to anthropogenic activities in a tropical basin Binh. Proc. IAHR World Congr. 269–278. https://doi.org/10.3850/978-90-833476-1-5_iahr40wc-p1339-cd.

NIC, 2009. North Africa: The Impact of Climate Change to 2030 (selected Countries), 60. National Intelligence Council.

Noël, P.H., Cai, X., 2017. On the role of individuals in models of coupled human and natural systems: Lessons from a case study in the Republican River Basin. Environ. Model. Softw. 92 (March 1993), 1–16. https://doi.org/10.1016/j.envsoft.2017.02.010.

Osumba, J.J.L., Recha, J.W., Oroma, G.W., 2021. Transforming agricultural extension service delivery through innovative bottom-up climate-resilient agribusiness farmer field schools. Sustain. (Switz.) 13 (7). https://doi.org/10.3390/su13073938.

Otoo, M., Lefore, N., Schmitter, P., Barron, J., Gebregziabher, G., IWMI, 2018. *Bus. Model Scenar. Suitabil.: Smallhold. Sol. Pump. -Based Irrig. Ethiop.* (Issue March). https://doi.org/10.5337/2018.207.

Oulaid, B., Milne, A.E., Waine, T., El Alami, R., Rafiqi, M., Corstanje, R., 2024. Stepwise model parametrisation using satellite imagery and hemispherical photography: Tuning AquaCrop sensitive parameters for improved winter wheat yield predictions in semi-arid regions. Field Crops Res. 309 (May 2023), 109327. https://doi.org/10.1016/j.fcr.2024.109327.

Purvis, B., Mao, Y., Robinson, D., 2019. Three pillars of sustainability: in search of conceptual origins. Sustain. Sci. 14 (3), 681–695. https://doi.org/10.1007/s11625-018-0627-5.

Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R.J., Drechsel, P., Noble, A.D., 2014. Economics of salt-induced land degradation and restoration. Nat. Resour. Forum 38 (4), 282–295. https://doi.org/10.1111/1477-8947.12054.

Railsback, S.F., Grimm, V., 2011. Agent-Based and Individual-Based Modeling. Princeton University Press. ⟨http://www.jstor.org/stable/j.ctt7sns7⟩.

Reidsma, P., Janssen, S., Jansen, J., van Ittersum, M.K., 2018. On the development and use of farm models for policy impact assessment in the European Union – A review. Agric. Syst. 159 (October 2017), 111–125. https://doi.org/10.1016/j.agsy.2017.10.012.

Sadath, P.V.R., Kartheeshwari, M.R., Elango, L., 2023. *Sustainable Groundwater Management Under Global Climate Change: Mitigation and Adaptation Measures* (Issue November). Springer International Publishing. https://doi.org/10.1007/978-3-031-34783-2_10.

Salman, M., Pek, E., Lamaddalena, N., & Food and Agriculture Organization of the United Nations. (2019). *Policy guide to improve water use efficiency in small-scale agriculture: the case of Burkina Faso, Morocco and Uganda* (Issue November).

Sanderson, M.R., Bergtold, J.S., Heier Stamm, J.L., Caldas, M.M., Ramsey, S.M., 2017. Bringing the “social” into sociohydrology: Conservation policy support in the Central Great Plains of Kansas, USA. Water Resour. Res. 53 (8), 6725–6743. https://doi.org/10.1002/2017WR020659.

Schlüter, M., Müller, B., Frank, K., 2019. The potential of models and modeling for social-ecological systems research. Ecol. Soc. 24 (1). ⟨https://www.jstor.org/stable/26796919⟩.

Tran, T.N.D., Nguyen, B.Q., Grodzka-Łukaszewska, M., Sinicyn, G., Lakshmi, V., 2023. The role of reservoirs under the impacts of climate change on the Srepok River basin, Central Highlands of Vietnam. Front. Environ. Sci. 11 (ember), 1–17. https://doi.org/10.3389/fenvs.2023.1304845.

Tran, T.N.D., Do, S.K., Nguyen, B.Q., Tran, V.N., Grodzka-ŁUkaszewska, M., Sinicyn, G., Lakshmi, V., 2024. Investigating the Future Flood and Drought Shifts in the Transboundary Srepok River Basin Using CMIP6 Projections (January). IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 17, 7516–7529. https://doi.org/10.1109/JSTARS.2024.3380514.

Tran, T.N.D., Tapas, M.R., Do, S.K., Etheridge, R., Lakshmi, V., 2024. Investigating the impacts of climate change on hydroclimatic extremes in the Tar-Pamlico River basin, North Carolina. J. Environ. Manag. 363 (June), 121375. https://doi.org/10.1016/j.jenvman.2024.121375.

Van Genuchten, M.T., Hoffman, G.J., 1984. Analysis of crop salt intolerance data. Springer.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw. 25 (11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.

Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: Past reconstruction and future projections. Environ. Res. Lett. 9 (10). https://doi.org/10.1088/1748-9326/9/10/104003.

Wada, Y., Van Beek, L.P.H., Van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37 (20). https://doi.org/10.1029/2010GL044571.

Yazdanpanah, M., Hayati, D., Hochrainer-Stigler, S., Zamani, G.H., 2014. Understanding farmers' intention and behavior regarding water conservation in the Middle-East and North Africa: A case study in Iran. J. Environ. Manag. 135, 63–72. https://doi.org/10.1016/j.jenvman.2014.01.016.