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Research article

The role of interacting social and institutional norms in stressed groundwater systems

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ABSTRACT

Groundwater resources play an important role for irrigation, particularly in arid and semi-arid regions, where groundwater depletion poses a critical threat to agricultural production and associated local livelihoods. However, the relationship between groundwater use, farming, and poverty, particularly with regards to informal mechanisms of resources management, remains poorly understood. Here, we assess this relationship by developing a behavioural model of groundwater user groups, empirically grounded in the politically fragile context of Tunisia. The model integrates biophysical aquifer dynamics, institutional governance, and farmer decision-making, all of which are co-occurring under conditions of aquifer depletion and illicit groundwater extraction. The paper examines how community-level norms drive distributional outcomes of farmer behaviours and traces pathways of local system collapse — whether hydrogeological or financial. Through this model, we explore how varying levels of trust and leadership, ecological conditions, and agricultural strategies can delay or avoid collapse of the social-ecological system. Results indicate limits to collective action under path-dependent aquifer depletion, which ultimately leads to the hydrogeological collapse of groundwater user groups independent of social and institutional norms. Despite this inevitable hydrogeological collapse of user groups, the most common cause of water user group failure is bankruptcy, which is linked to the erosion of social norms regarding fee payment. Social and institutional norms, however, can serve to delay the financial collapse of user groups. In the politically fragile system of Tunisia, low levels of trust in government result in low social penalties for illicit water withdrawals. In the absence of alternative irrigation sources, this serves as a temporary buffer against income-poverty. These results highlight the need for polycentric coordination at the aquifer-level as well as income diversification beyond agriculture to sustain local livelihoods.

1. Introduction

Globally, around 70% of freshwater withdrawals and 90% of freshwater consumption (water withdrawals excluding return flows) are designated for irrigation use (Shiklomanov, 2000; Döll et al., 2009). Groundwater resources supply an estimated 43% of global total irrigation water use (Siebert et al., 2010). In semi-arid and arid regions, however, groundwater is often the predominant, if not the only, source of water for irrigation. Groundwater use in agriculture is increasing worldwide leading to widespread aquifer depletion (Siebert et al., 2010; Aeschbach-Hertig and Gleeson, 2012; Dalin et al., 2017; Schipanski et al., 2023), posing threats to food production systems and the sustainability of associated local livelihoods. Notably, small holder farmers, accounting for 84% of global farms and producing around 35% of the world's crops (Lowder et al., 2021) are at risk of losing their livelihoods. Despite these concerns, the complex relationship between (ground)water, agriculture, and poverty remains understudied and poorly understood (Balasubramanya and Stifel, 2020). Further

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research is particularly needed to better understand irrigation management and decision making processes in the context of arid regions as well as those experiencing rapid groundwater decline.

Groundwater, by its nature, is a non-excludable but rivalrous resource. Where individual decisions affect entire communities of water users, and where the same groundwater source is often used by multiple user groups/communities, centralised regulatory agencies are frequently put in charge of monitoring and setting withdrawal limits for respective water user groups (Lankford and Hepworth, 2010). However, due to the complexity of groundwater arising from its non-excludability, data availability, specific local hydrogeological characteristics and withdrawal behaviours, local institutions are often key to ensure the sustainability of withdrawals, at times together with central regulatory authorities, at times super-seeding them (Pahl-Wostl and Knieper, 2014; García et al., 2019; Pahl-Wostl, 2015). The failure of centralised regulation and enforcement mechanisms often leads to a rise in illicit groundwater withdrawals, i.e. unregulated water abstractions from unregistered wells (Molle and Closas, 2020). In areas where political systems are fragile and institutional trust is lacking, local communities may decouple from centralised institutions and assume a prominent role by promoting their own norms and rules independently (or on top) of the ones developed by a central government (van Steenbergen et al., 2015; García et al., 2019). This implies that communities are able and willing to self-regulate, and thus monitor, sanction and mediate potential conflicts. At the same time, this poses a collective action problem. Specifically, individuals are faced both with inter-temporal and social dilemmas by which increasing withdrawals today can lead to a future system collapse, and by which increasing withdrawals for one individual can be detrimental for the entire system. In this research, we contribute to the current literature on agricultural groundwater governance in arid regions in several key dimensions, listed in the following paragraphs.

Groundwater users in the semi-arid context of Central Tunisia depend on underlying aquifer systems to irrigate livelihood-sustaining crops (such as olives, citrus fruits, and garden vegetables, etc.). The social and political context of Post-Authoritarian and Post-Arab Spring Tunisia is marked by the erosion of institutional trust and the reliance on local informal mechanisms above formal rules or institutions. We explore dynamics of water user decision-making within this fragile political setting, defined broadly as an environment that is exposed to frequent or chronic disturbances or stressors to social-ecological resilience and institutional robustness (Schoon and Cox, 2012). The reliance on dwindling groundwater resources for irrigation (MARHP, 2017) can be characterised as a "take-some dilemma", where benefits from extraction (often in the short term) are individual, while negative outcomes (often long-term) are collective (Cumming, 2018). In the case of groundwater over-exploitation, this dilemma can turn into a "lose-lose trap" over time, where outcomes are negative both for individuals and the wider community (i.e. groundwater-dependent farmers end up depleting their aquifers). These traps are reinforced by social-ecological feedbacks and may be difficult if not impossible to reverse (Cinner, 2011). For instance, lower groundwater levels lead to higher extraction costs, which farmers are increasingly unable to cover, which in turn leads to decreasing revenues from irrigated agriculture, which further impacts the ability to cover rising costs.

The coupling of Social-Ecological Systems (SESs) (Folke, 2006) has represented the major advance in collective action research in the past 15 years (Filatova et al., 2016; McGinnis and Ostrom, 2014). SESs represent complex adaptive systems composed of interactions between humans and the environment (Berkes et al., 1998; Folke et al., 2016). Modelling these interactions sheds light on inherent dynamics, patterns, and feedbacks within the coupled SES (Levin et al., 2013). SES research acknowledges the need to include governance, behavioural social and psychological processes to assess management adaptability in SESs (Peng et al., 2021; Kimmich et al., 2023; Mathias et al., 2020; Baggio et al., 2022; Freeman et al., 2020). While some advances have been made in this regard, e.g. in the developments of methods for polycentric governance (Oberlack et al., 2018; Kimmich and Tomas, 2019) or experimental studies aimed at understanding the interaction between individuals and collective behaviours (Baggio et al., 2019; Janssen et al., 2010; Ostrom, 2009a), methods to operationalise individual and collective structures of decision-making in complex common-pool resource (CPR) settings remain limited (Kimmich et al., 2023). Collective action theory underlines the importance of stable institutions — a reliable set of rules that streamline decisions on resource allocation and use (North, 1990; Ostrom, 1990). Studying collective action dynamics in the context of political fragility, this study contributes to the collective action literature by considering bottom-up decision-making in the absence of stable institutions and formal mechanisms of water governance.

In addition to these formal characteristics, SES research on groundwater systems has largely been limited to settings where informal local monitoring and enforcement of rules are in place and assumed to be functioning, e.g. Castilla-Rho et al. (2017). In fragile political settings, however, where formal as well as informal rules are subject to considerable uncertainty, water users are likely to make decisions on water withdrawals based on alternative sets of rules. In contrast to rational-choice theory, which sees resource users as proactive maximisers of private preferences and beliefs (Shepsle, 1989), theories of institutionalism in CPR theory portray resource users as fallible learners of bounded rationality (Ostrom, 2011). Choices are made based on incomplete information and imperfect information-processing capabilities and are affected by shared norms, rules, and incentives. Shared internalised norms of behaviour, both formal and informal, influence the subjective mental constructs that resources users use to interpret a specific decision situation and attain individual and collective goals (Siddiki et al., 2019). This paper explores the role of leadership (Von Rueden et al., 2014; Glowacki and Von Rueden, 2015; Meinzen-Dick, 2007) and trust (Levi and Stoker, 2000; Fafchamps, 2006) within the path-dependent context of fragile political systems. We bear on notions of social psychology to integrate social and institutional norms into the SES, which reflect commonly shared standards of behaviour within the community. Compliance with norms depends on existing social preferences, the ability to generate shared understanding and visions, and the desire to retain a prosocial self-image and avoid judgement or disapproval from peers (Fehr and Schurtenberger, 2018). Resource users attach a positive or negative internal valuation to given action situations, e.g. groundwater withdrawal, fee payment, etc. Ostrom (2009a), Boix and Stokes (2007).

Given the particular characteristics of stationarity and storage of groundwater resources as compared to other CPR systems (Baggio et al., 2016), SES models of groundwater systems need to pay specific attention to the biophysical characteristics of the underlying aquifer (Schlager et al., 1994). This paper will explore ecological drivers and limits to collective action within the chosen aquifer system. Previous research suggests that collective action is highest under relative resource scarcity, where water users see the value of participating in allocation and management activities (Uphoff et al., 1990; Ostrom and NRC, 2002; Rutte et al., 1987). In contrast to coupled social-ecological groundwater systems that model closed-loop feedbacks between water user behaviour and the aquifer, this SES simulates groundwater levels as a largely exogenous process with weak feedback links between local withdrawals and groundwater levels. By shifting the boundary of endogenous water withdrawals from the aquifer scale to individual water user groups, we believe it is possible to construct a more realistic model-world that represents the CPR context from the perspective of water users. Most commonly, local collective action of water withdrawals will hold weak feedback links with the state of the aquifer. Resource users will be bounded by their biophysical environment, where neighbouring withdrawals are outside of their own control.

In summary, the key aspects through which we contribute to the current body of literature can be listed as follows. First, we link groundwater user behaviour, aquifer dynamics, and governance together in an SES framework (Fig. 1), consisting of a social decision-making module for water use, a hydrogeological module, and an institutional governance module, as well as feedback loops between and within these modules. We track the erosion of social norms and the resulting impact on system sustainability or collapse (Richter et al., 2013) and identify scenarios that can delay system collapse. Second, while collective action theory hypothesises that self-governing resource users have the ability to successfully overcome resource problems, here we provide nuance to this capacity to self-govern in the face of chronic water scarcity and institutional fragility. We study the role of overlapping social and institutional norms in highly stressed CPR settings and shed light on social-ecological complexity of the coupled groundwater system. Third, we contextualise our model by leveraging both quantitative and qualitative data collected on the ground. The qualitative data for the decision-making and institutional modules is based on interviews performed by the authors in the governorate of Kairouan, Tunisia in May 2022 (Erfurth et al., 2023). The quantitative data includes simulated groundwater data for the hydrogeological module related to the same area. The paper thereby addresses critical knowledge gaps on the causal processes that transform local decision-making and ecological processes to emergent SES phenomena (Schlüter et al., 2019).

The developed SES is used to investigate the following research questions: (a) In the absence of formal legal frameworks and informal structures of monitoring and compliance, which community-level norms drive collective outcomes under conditions of aquifer decline? (b) What are potential root causes of the erosion of social norms? (c) Under what ecological and institutional scenarios can groundwater user groups avoid or delay system collapse?

2. Methods

2.1. Social-Ecological system model

We present here a modelling framework to analyse the viability of sustainable water governance in the absence of a centralised regulatory framework, formal monitoring, and compliance mechanisms. Instead, the governance of the common-pool resource emerges only through local leadership and informal peer monitoring. The model simulates distributional outcomes of individual farmer behaviour with collective effects on the success or failure of the water user group as well as individual effects on livelihoods. The model will simulate two types of system collapses: (i) a hydrogeological collapse, where hydraulic heads go below critical threshold levels, and (ii) a financial collapse, where the water user group (also referred to as *groupements de développement agricole* (GDAs) in the Tunisian context) is unable to cover pumping costs and has to terminate its service of water provision. In the latter case, the GDA is blocked by the central electricity provider. These two types of crashes represent two collective action problems, i.e., the overexploitation of groundwater resources and the unwillingness of farmers to pay groundwater fees. The model considers threshold levels for groundwater hydraulic heads and financial debt, and the groundwater user group collapses if one of these thresholds is exceeded. Similarly to these thresholds, the model establishes a poverty threshold to the user profit function to understand livelihood dynamics. While exceeding this threshold will not crash the system of groundwater extraction, it is an indicator of social sustainability within the system. Linked to these thresholds, the model observes three types of sustainability: “Social sustainability” defined as the percentage of farmers living below the poverty threshold, “financial sustainability” as a measure of the financial budget of water user groups, and “ecological sustainability” as a function of groundwater withdrawals (N.B. local decisions only have a minimal impact on groundwater depletion in this model, which is mostly driven by the combined groundwater use by all water users in the aquifer). We identify scenarios that delay surpassing the poverty and financial thresholds. The model was constructed using Python software and will simulate 20 years of water user behaviour in the study area.

2.1.1. Dynamic resource module

Hydrogeological dynamics of the aquifer are represented by a surrogate of an established MODFLOW model (Harbaugh, 2005). Based on 45 years (1971–2016) of observed and modelled data (see SES calibration in Section 2.2 for more detail), regional responses of hydraulic heads are linked to the volume of water pumped from the aquifer using an auto-regressive approach (coefficient of determination: 0.96). The change in hydraulic head, $\Delta hh(t)$, is predicted using previous changes in hydraulic head and groundwater withdrawals at time t.

$$\Delta hh(t) = \alpha + \beta_1 \Delta hh(t-1) + \beta_2 V^{\mathrm{p}}(t) + \epsilon \,. \tag{1}$$

$V^{\mathrm{p}}(t)$ refers to the total volume of groundwater pumped within a given aquifer, and can be expressed as follows:

$$V^{\mathrm{p}}(t) = V^{\mathrm{ext}}(t) + W^{\mathrm{alloc}}(t) + W^{\mathrm{ill}}(t)\,, \tag{2}$$

where W^{alloc} is the total allocated water in the GDA, and W^{ill} the total amount of illicitly extracted groundwater by the GDA. The water extracted outside the GDA is represented by $V^{\mathrm{ext}}(t)$ and stands for the fraction of pumped water outside the GDA at t_0, calculated based on rescaled pumping rates. The variable values of $V^{\mathrm{ext}}(t)$ are outside the control of the GDA and are predicted based on the pumping trend of the last twenty years of the MODFLOW simulation (1996–2016) yielding a growth rate of 4.2% per year. It follows, that groundwater depletion is a largely exogenous model process, where water users only contribute marginally to overall withdrawal rates.

2.1.2. Governance module

Water user groups (GDAs) are managed by a leadership council that decides how much water will be pumped in a given year, and consequently how much water will be allocated to each farmer in the GDA. Groundwater is made available to water users as determined by institutional decision rules. These decisions are a function of GDA decision-making: a. how much water to extract, b. how to distribute it among users, and c. at what price. Volume and price are determined by the ability of leaders to long-term plan (binary parameter $sust$) and distribution is based on equity (binary parameter equ), both derived from qualitative interview data. Under high $sust$, price is calculated each year based on extraction and operation costs and the expectation of fee recovery, while total withdrawals by the GDA stay static. Under low $sust$, price is static (based on an initial (low) price-setting of 0.15 Tunisian Dinar (TND) per m^3 based on interview data), while withdrawals increase at the same rate as withdrawals outside the GDA (based on MODFLOW data). Under high equ, water will be allocated equitably among all water users. Under low equ, one-fifth of GDA members receive twice as much water than they would have, had the water been allocated equitably. The price and allocated volume will influence whether farmers choose to withdraw additional water from illicit sources or settle for official allocations.

The financial state of the GDA is determined by

$$S(t) = S(t-1) - W^{\mathrm{alloc}}(t-1)\cdot c_{\mathrm{E}} - c_{\mathrm{op}} + \sum_i D_i(t-1)\cdot c_{\mathrm{w}}(t-1)\cdot w_i^{\mathrm{alloc}}(t-1)\,, \tag{3}$$

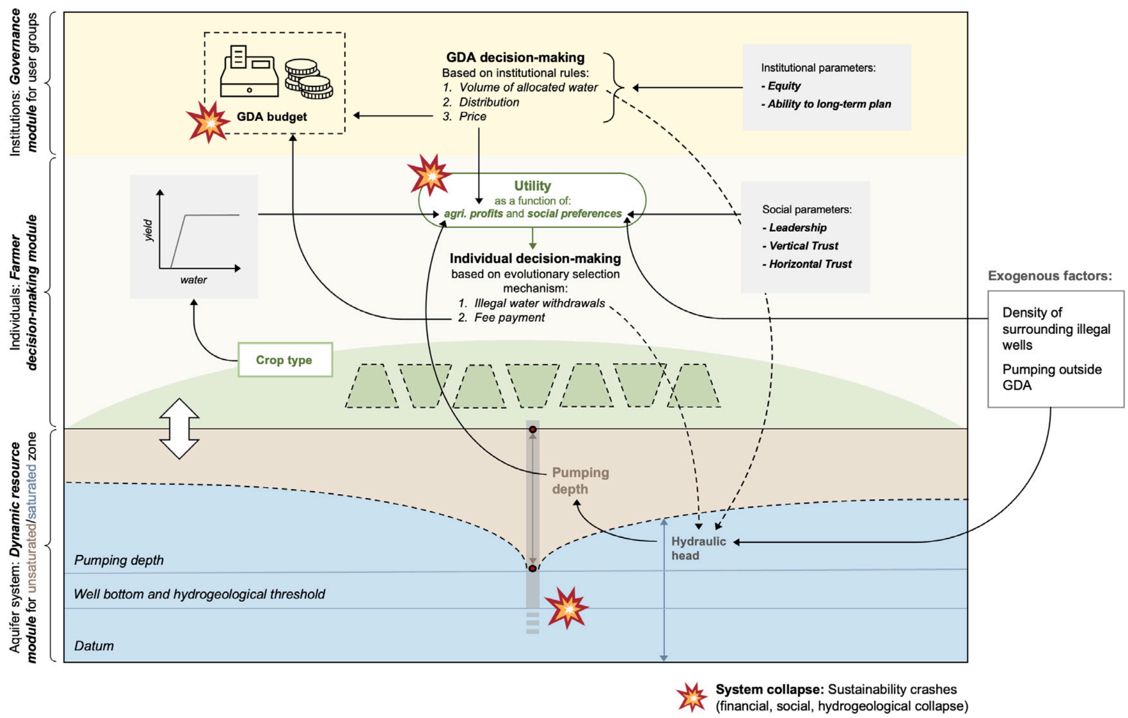


Fig. 1. SES Model schematic. Interacting, co-evolving resource, farmer decision-making, and governance modules and types of system collapse.

where S stands for the financial budget of the GDA at a given time, c_E stands for the GDA's groundwater extraction cost, c_{op} for additional operational costs (e.g. maintenance, labour, etc.), D_i for the decision of individual farmers to pay their fees, c_w for the price at which groundwater is sold to farmers, and w_i^{alloc} is the water allocated to user i. Once the GDA surpasses its debt threshold, the user group is frozen by the local electricity provider and can no longer supply GDA members with water. In this case, farmers can only resume agricultural activities by drawing on water from illicit sources. Extraction costs are calculated using a linear regression approach based on collected well data on extraction costs and associated hydraulic heads from the year 2012. Based on the regression results, we determine an increase in extraction cost of 0.050 TND for every metre of groundwater decline. This includes electricity prices, which for the purpose of this model are assumed to be constant.

2.1.3. Farmer decision-making module

We model the strategic decisions that individual farmers make, the collective outcomes that result from these decisions, and the distributional effects on their livelihoods. Farmers create agricultural profits by cultivating crops and using the CPR to irrigate. The utility of farmers is however affected by vertical and horizontal institutional arrangements. We consider farmers within a water user group (GDA) that can observe the irrigation practices within as well as outside of the GDA (both private farmers and farmers belonging to other GDAs). Farmers get water allocated by the GDA, and make decisions to pay their fees for allocated water, and to extract groundwater illicitly. Agricultural land is assumed to be uniformly distributed among farmers (23500 m^2 per farming household based on administrative datasets). Based on the presence of vertical and horizontal trust, households make decisions about additional, illicit water extractions. Under strong leadership, farmers are more likely to be encouraged to pay fees for allocated water.

Utilities of farmers are driven by individual household profit functions. The output (kg/ha) generated for a representative hectare is given by

$$y_i(t) = \begin{cases} 0 & \text{if } w_i(t) < ET_{\min} \\ y_{\max} - \left(y_{\max} \cdot K_y \cdot \left(1 - \frac{ET_i(t)}{ET_{\max}} \right) \right) & \text{if } w_i(t) \in [ET_{\min}, ET_{\max}] \\ y_{\max} & \text{if } w_i(t) > ET_{\max}, \end{cases} \tag{4}$$

where w_i is the total water used by household i for irrigation, y_{max} and y_i are the maximum and actual yields, ET_{max}, ET_{min} and ET_i are the maximum, minimum, and actual evapotranspiration ($ET = (p + w_i) \cdot k_c$, where p is precipitation and k_c is the crop coefficient), and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses (Table A.4). These water-yield relationships are defined by the water production function of the Food and Agriculture Organisation of the United Nations (FAO) (Steduto et al., 2012).

The total amount of water used by farmer i is given by

$$w_i(t) = w_i^{alloc}(t) + w_i^{ill}(t), \tag{5}$$

while total allocated water and total illicit extraction are given by $W^{alloc}(t) = \sum_i w_i^{alloc}(t)$ and $W^{ill} = \sum_i w_i^{ill}(t)$, respectively. The profit of household i in the GDA at time t is given by

$$\pi_i(t_s) = \sum_{t=t_s}^{t_s+h} \left(p^c \cdot y_i(t) \cdot a_i - c_i^{alloc}(t) - c_i^{ill}(t) - c_i^c(t) \right), \tag{6}$$

with p^c the price the crop is sold at (TND/kg), a_i the average size of agricultural land per farmer, $c_i^{alloc}(t)$ the cost for the allocated water, $c_i^{ill}(t)$ the cost for illicit water extraction, and $c_i^c(t)$ stands for the cultivation costs. The cost for the allocated water is given by

$$c_i^{alloc}(t) = D_i(t) \cdot c_w(t) \cdot w_i^{alloc}(t), \tag{7}$$

where $D_i(t) \in \{0, 1\}$ is the decision of household i to pay the water fee at time t and $c_w(t)$ is the cost per unit of allocated water. If farmers do not manage to make sufficient profits, they cannot pay for water resources.

Utilities are not solely driven by profits but also by norm-based dynamics in the water user group community. Internal valuations of actions are subtracted from the individual profit of a given action, which translate to collective outcomes for the groundwater user group (Ostrom, 2009a; Fehr and Schurtenberger, 2018; Fischbacher and Gächter, 2010). Vertical and horizontal mechanisms generate these penalties (r^V and r^H respectively) of not adhering to rules and norms. The vertical mechanism is driven by social parameters of trust in government rules and GDA leadership, and the psychological cost of deviating from vertical norms is given by

$$\begin{aligned} r_i^{\mathrm{V}}(t) &= \alpha^{\mathrm{V_T}} \cdot V_{\mathrm{T}} \cdot (w_i(t) - w_i^{\mathrm{alloc}}(t)) + \alpha^{\mathrm{V_L}} \cdot V_{\mathrm{L}} \cdot (1 - D_i(t)) \\ &= \alpha^{\mathrm{V_T}} \cdot V_{\mathrm{T}} \cdot w_i^{\mathrm{ill}}(t) + \alpha^{\mathrm{V_L}} \cdot V_{\mathrm{L}} \cdot (1 - D_i(t)), \end{aligned} \tag{8}$$

where $\alpha^{\mathrm{V_T}}$ and $\alpha^{\mathrm{V_L}}$ represent penalty weights for observed levels of vertical trust (V_T) and leadership (V_L). These weights, as opposed to the parameters of trust and leadership themselves, indicate how receptive water users are to the specific social characteristic. For example, even high leadership efforts can be nullified by unresponsive water users (i.e. low leadership weight). Vertical trust refers to trust in government rules and institutions (Kaasa and Andriani, 2022; Lubell, 2007). Based on interview data, we assume that higher levels of trust in government rules reduce the likelihood of farmers to withdraw water illicitly. Leadership refers to the ability of the GDA administrative council to long-term plan (with regards to the financial budget of the GDA and the volume of groundwater withdrawals) and in part to motivate users to support these plans (Meinzen-Dick, 2007; Fafchamps, 2006; Von Rueden et al., 2014; Glowacki and Von Rueden, 2015). In our model, this is captured by the norm to pay for allocated water. The horizontal mechanism is driven by social trust within the GDA and social pressures from outside the GDA related to the surrounding density of illicit wells, and the psychological cost of deviating from horizontal norms is given by

$$r_i^{\mathrm{H}}(t) = \alpha^{\mathrm{H,int}} \cdot H_{\mathrm{T}} \cdot |(w_i(t) - \bar{w}^{\mathrm{int}}(t))| + \alpha^{\mathrm{H,ext}} \cdot \left(c^{\lambda_0} - c^{\mathrm{den}} \cdot \lambda\right) \cdot w_i^{\mathrm{ill}}(t), \tag{9}$$

where $\alpha^{\mathrm{H,int}}$ and $\alpha^{\mathrm{H,ext}}$ represent penalty weights for observed levels of horizontal/social trust (H_T) and the tolerance for illicit extractions determined by the density of surrounding illicit wells. The variable $\bar{w}^{int}(t)$ stands for the average water use within the GDA. Ostrom (1990) argues that 'individuals have shared a past and expect to share a future. It is important for individuals to maintain their reputations as reliable members of the community' (88). It follows that social trust, the expectation that other members of the GDA comply with rules, influences individual judgements of performing an action (Levi, 1988; Gambetta, 2000). In the first term, deviations from the average use, both positive and negative, are penalised and reflect the pressure towards conformism. The second term captures how illegal wells in the neighbourhood of the GDA shape the norm of illegal extraction. The penalty incurred per unit of illegally extracted water depends on the density λ of the illegal wells in a range of 3 km from the GDA, assumed to represent the most commonly frequented radius by GDA water users. The cost is proportional to the extracted volume from illicit wells. Values of trust and leadership stem from qualitative interview data (more detail on parameter calibration can be found in Section 2.2).

The utility of a household i in the GDA at time t is therefore given by

$$u_i(t) = \pi_i(t) - r_i^{\mathrm{V}}(t) - r_i^{\mathrm{H}}(t), \tag{10}$$

as we assume that households are myopic in the context of stressed groundwater systems (Ostrom, 2009b).

An evolutionary selection mechanism is established to simulate the ability of water users to switch to utility-enhancing strategies. In each year, all households have on average a chance to change their strategy on illicit withdrawals and fee payment. They do so by comparing their own utility with the utility of one of the best performing members of the GDA. This selection mechanism represents the asynchronous decision-making of farmers. Specifically, one of the five best performing households is selected uniformally, reflecting the influence of high-status GDA members. Strong horizontal mechanisms can lead to the erosion of norms - a new normal is defined as water user compare themselves to others, while strong vertical mechanisms reinforce the norms. At each time t, the probability of household k changing strategy to the strategy of household l (both for payment decision and illicit water withdrawals) is a function of the relative utility differential between the matching partners, according to the logistic function:

$$p_{kl}(t) = \frac{1}{1 + \exp\left(-\zeta \cdot \frac{u_l(t) - u_k(t)}{u_k(t)}\right)}, \tag{11}$$

where ζ represents the responsiveness to relative utility differentials. Since illicit water extraction is not perfectly observable, there is an imitation error captured as follows

$$w_i(t) \to w_k(t) + \varepsilon, \tag{12}$$

where $\varepsilon \sim \mathcal{U}[0.8\, w_k(t), 1.2\, w_k(t)]$ and $\mathcal{U}[\cdot,\cdot]$ represents the uniform distribution over the specified interval. When the water allocation is uniform over the GDA members, this imitation mechanism means that only illicit water withdrawals are imitated. In case of unequal water allocation, the illicit water extraction can compensate for lower levels of allocated water.

2.2. SES calibration

The governorate of Kairouan presents a particularly interesting case study to investigate social-ecological dynamics in a complex groundwater dilemma. First, groundwater plays a critical role for irrigation and associated livelihoods in Kairouan and has witnessed severe depletion in the last decades (Snoussi et al., 2022). Second, the hydrogeological diversity of the area, with mixed unconfined–confined aquifer characteristics at varying depths, enables us to study farmer behaviour under different aquifer conditions (Hamdi et al., 2018). Third, with close proximity to the city of Sidi Bouzid, the birthplace of the Arab Spring, the region holds a fraught relationship with social unrest and institutional fragility.

The SES is calibrated using empirical evidence from qualitative interviews with water user groups (GDA), hydrogeological models, local inventories, and the wider literature. Semi-structured interviews with farmers and water user group officials from 15 GDAs were conducted in the Tunisian governorate of Kairouan in May 2022 by the authors (Erfurth et al., 2023). Guiding questions concerned variables of generalised trust in government, social trust, perceptions of equity, discounting and the ability to long-term plan, leadership, etc. Interviews followed ethics protocol of the School of Geography and the Environment, University of Oxford [approval number: SOGE 1A2020-183]. The interviews were conducted in Tunisian Arabic and translated to French by a local expert. These informal interviews ranged from 1–7 interviewees depending on respondents' availability and interest in joining the study. Qualitative interview data were translated into gradients of 0–1 based on protocol rules developed by Basurto and Speer (2012). Anchor points were iteratively developed based on empirical and theoretical knowledge of the case setting (Table A.1). Specific parameter value ranges (for Monte Carlo simulations), variable values, and their data sources can be found in the annex (Tables A.3 and A.5).

Hydrogeological diversity is captured by an established MODFLOW groundwater model of the aquifers Sisseb, AinJloula, AinBoumorra, and Chougafia elaborated by the National Agronomic Institute of Tunisia (INAT) (Hamdi et al., 2018). Hydrogeological data were extracted from the model using the Python package FloPy and analysed with the geospatial software QGIS (QGIS.org, 2022). Hydrogeological thresholds were defined based on empirical accounts of water users and GDA officials in water user groups, where wells have run dry. We assume that if groundwater levels fall below a given change in depth, GDAs are unable to continue pumping and farmers can no longer rely on official GDA groundwater (only illicit sources). For the purpose of this model, illicit water is assumed to be 50% more expensive than water from legal sources (average measure based on literature and interviews) and continuously available to water user independent of the pumping depth of the GDA (e.g. illicit water can be purchased from deeper wells beyond the perimeter of the GDA). Initial pumping rates, hydraulic heads, pumping depths, and extraction costs are calibrated based on observed and modelled data from the year 2012. Hydrogeological processes largely serve as input to the model — with limited feedback of simulated water user behaviour on the underlying aquifer due to the chosen model boundary.

The inventory of illicit wells used in this analysis stems from a field campaign conducted by INAT in 2016 and was analysed using QGIS. All agricultural water user groups covered by the model and inventory were investigated in the study (in total 15 water user groups distributed across 15 villages). Agricultural data from Water Evaluation And Planning (WEAP) models (Sieber, 2019) include information on cultivation costs, crop price, extraction and maintenance costs based on data collected between 2003 and 2017.

2.3. Definition of scenarios

Four scenarios are defined to model decision-making under different hydrogeological conditions and agricultural strategies. Given the hydrogeological diversity in the chosen study area, two representative GDAs, one for "unfavourable" and one for "favourable resource settings", were chosen to represent the breadth of aquifer dynamics (Table A.2). In "unfavourable" resource settings, hydraulic heads are considerably lower than in the "favourable" counterpart. Lower hydraulic heads translate to higher risks of hydrogeological collapse and extraction costs that will influence farmers' utilities. GDAs in unfavourable resource settings are subject to higher aquifer extraction rates and higher densities of surrounding illicit wells, which translate to lower penalties regarding illicit withdrawals for farmers in the GDA. Based on empirical evidence from water user interviews, we assume hydrogeological thresholds are lower under unfavourable conditions. Regarding agricultural strategies, we model two types of crops: a low-value/low-water crop and a high-value/high-water crop. Crop types are stylised to represent crops with different water inputs/requirements and cash outputs. Water-yield relationships are calibrated based on data on representative crops in the region (olive and tomato for low-value/low-water and high-value/high-water crop respectively). In the model, all farmers cultivate the same crop within a given simulation to enable stylised comparisons between the agricultural strategies. We assume that farmers cannot switch to the other crop type within a single simulation (reflecting practical difficulties farmers face when switching between crops in the real world, e.g. sunk investment, social rules). Further information on the calibration of resource settings and crop types can be found in the annex. To summarise, four scenarios emerge:

1. FAV+LOW: Favourable resource setting combined with low-value/low-water crop
2. FAV+HIGH: Favourable resource setting combined with high-value/high-water crop
3. UNFAV+LOW: Unfavourable resource setting combined with low-value/low-water crop
4. UNFAV+HIGH: Unfavourable resource setting combined with high-value/high-water crop

3. Results

3.1. User group collapse and declining agricultural revenues are unavoidable in the long-term

For each scenario defined in Section 2.3, we employ Monte Carlo (MC) simulations of key social parameters. Social parameter ranges consistent across all scenarios represent the range of social and institutional characteristics under fixed ecological resource conditions and agricultural strategies (see Table A.3 for an overview of the parameters). Social parameter values are sampled from a random uniform distribution (10,000 MC simulations for each of the four scenarios). The results represent the range of possible collective action outcomes given variable social characteristics of water user groups. MC simulations reveal two pathways leading to system collapse of water user groups: Hydrogeological collapse and financial collapse (Fig. 2). While water user groups under unfavourable resource conditions (UNFAV) experience hydrogeological collapse after 8 years and after 17 years under favourable conditions (FAV) (Fig. 3.B and 3.C), pathway 2 of financial collapse most often precedes pathway 1 of hydrogeological collapse (Fig. 3.A).

Results from the model reveal a common trend of early bankruptcy within the first five years of the simulation across all four scenarios (Fig. 3.A). Under scenario FAV+LOW, groundwater user groups have the highest chance to avoid bankruptcy, although after ten years there is approximately an 80% likelihood of collapse. Under the same ecological scenario but combined with the high-value/high-water crop choice (FAV+HIGH), all water user group run bankrupt after 4 years independent of social and institutional characteristics. User groups that experience a rapid erosion of the norm of fee payments will run bankrupt prior to hydrogeological collapse (Fig. 4).

In terms of individual livelihoods, we compare the average percentage of farmers living below the poverty threshold across the four scenarios (Fig. 5). Overall, income-poverty from agricultural activity cannot be avoided in the long term. Notably, water users under unfavourable resource settings are generally better capable to avoid a lose-lose poverty trap. Among the four scenarios, the scenario UNFAV+LOW is the best performing scenario in terms of individual livelihoods. Unfavourable resource settings yield better income-poverty results than favourable resource settings due to the higher concentration of illicit wells and associated lower social penalties for GDA members when withdrawing water from illicit sources (defined in Eq. (9)). Choosing to cultivate low-value/low-water crops leads to consistently better outcomes than the high-value/high-water equivalent due to early adaptation to water scarcity. This means that user groups that employ water-efficient agricultural strategies (LOW) under unfavourable water availability (UNFAV) are better equipped to buffer the effects of path-dependent aquifer depletion. Under diminishing water supply, lower water demands enable more sustained agricultural profits. When high-value crops are cultivated, 100% of farmers live below the poverty threshold after 12 years independent of social and institutional rules. For FAV+HIGH, poverty levels increase drastically within the first year of the simulation due to water-intensive crops and high penalties for illicit withdrawals. Low-value crops can postpone the point in time when the poverty threshold is surpassed by several years. We also observe that although GDAs stop functioning after hydrogeological collapse, farmers are able to sustain their livelihoods for several years beyond the hydrogeological collapse by means of illicit water extraction. The social and institutional parameters that explain these outcomes will be further explored in the subsequent section, where single scenario simulations unpack the social and institutional dynamics that can prevent or delay bankruptcy and poverty outcomes.

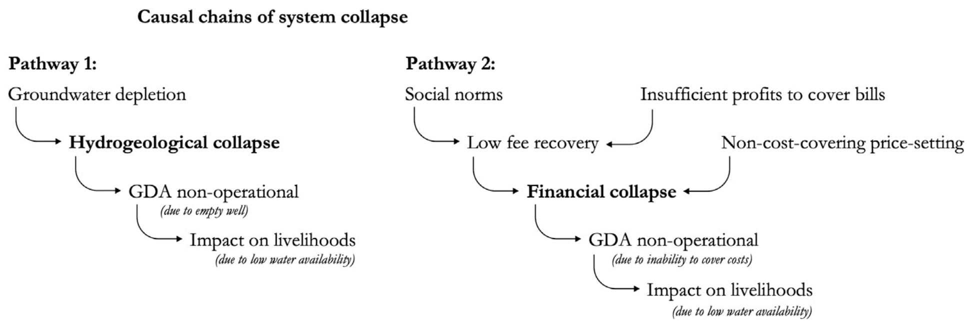


Fig. 2. Causal chains for system collapse. Pathways of water user group collapse as a result of hydrogeological collapse (pathway 1) or financial collapse (pathway 2).

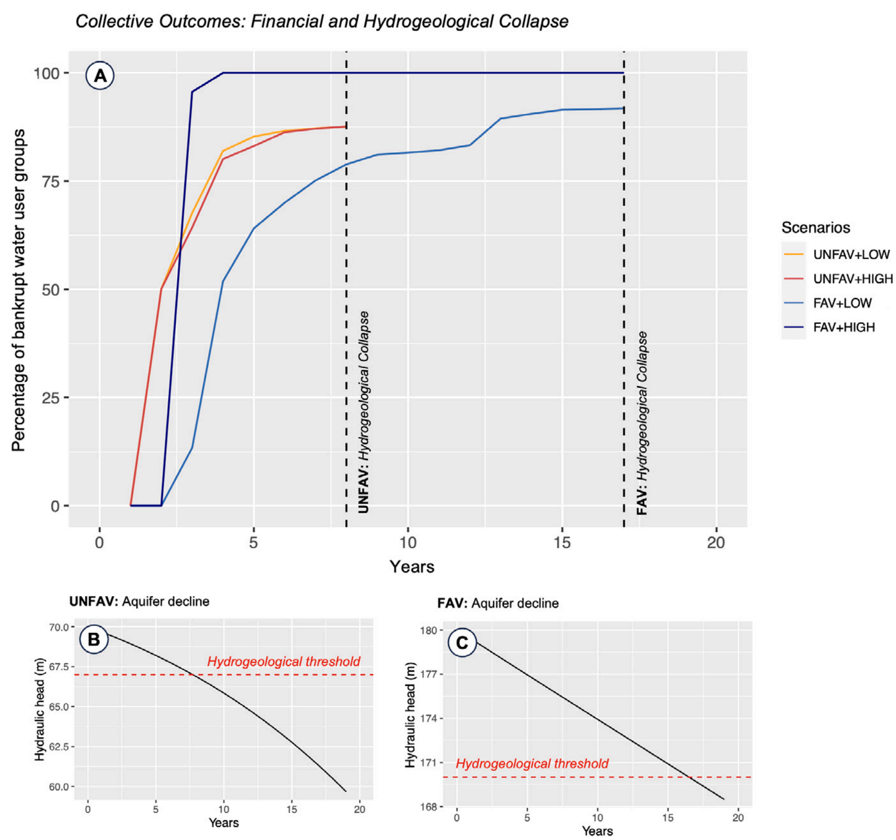


Fig. 3. Sustainability of the user group. Monte Carlo simulations of bankruptcy among user groups (10,000 simulations) under four key scenarios including hydrogeological thresholds for system collapse. (a) Percentage of bankrupt water user groups and fee payment in operational water user groups, (b–c) Aquifer decline under unfavourable and favourable conditions, respectively.

3.2. *Strong leadership, sustainable water pricing, and low levels of vertical trust serve as delay mechanisms for system collapse*

Feature importance analyses serve the identification of specific scenarios that illustrate system dynamics and there-embedded causal chains. We have employed boosted decision trees to examine the relative impact of social characteristics on the likelihood of collective action outcomes (i.e. fee recovery, illicit withdrawals, poverty etc.). In order to identify key drivers of these outcomes, individual feature importance of these parameters is assessed by XGBoost, which stands for Extreme Gradient Boosting, a scalable, distributed gradient-boosted decision trees machine learning library (Chen and Guestrin, 2016). These iterative decision tree algorithms are trained on multiple iterations to find patterns within features of a dataset. XGBoost hyper-parameters were optimised using k-fold cross-validation in combination with randomised grid search. Machine learning tools such as XGBoost hold several advantages over more traditional statistical approaches such as identifying complex non-linear relationships in large modelled datasets. Subsequently, we employed Shapley values (Lundberg and Lee, 2017; Shapley, 1953; Dubey, 1975; Cohen et al., 2005) to assess the contribution of specific features to the outcomes predicted via XG-Boost. Shapley values are rooted in cooperative game theory (Shapley, 1953) and represent the average marginal contribution of a feature across all possible feature combinations. By computing the Shapley values for each feature, one can assess their relative importance in the model's predictions (Table 1). Features with higher Shapley values have a larger impact on the model outcome predictions, while features with lower values have lesser influence.

Under the scenario FAV+LOW, leadership (defined in Eq. (8)) is consistently ranked the most important feature for all independent variables, followed by price setting (defined in Eq. (7)) and equity (Table 1). Contrarily, under unfavourable resource settings, the importance

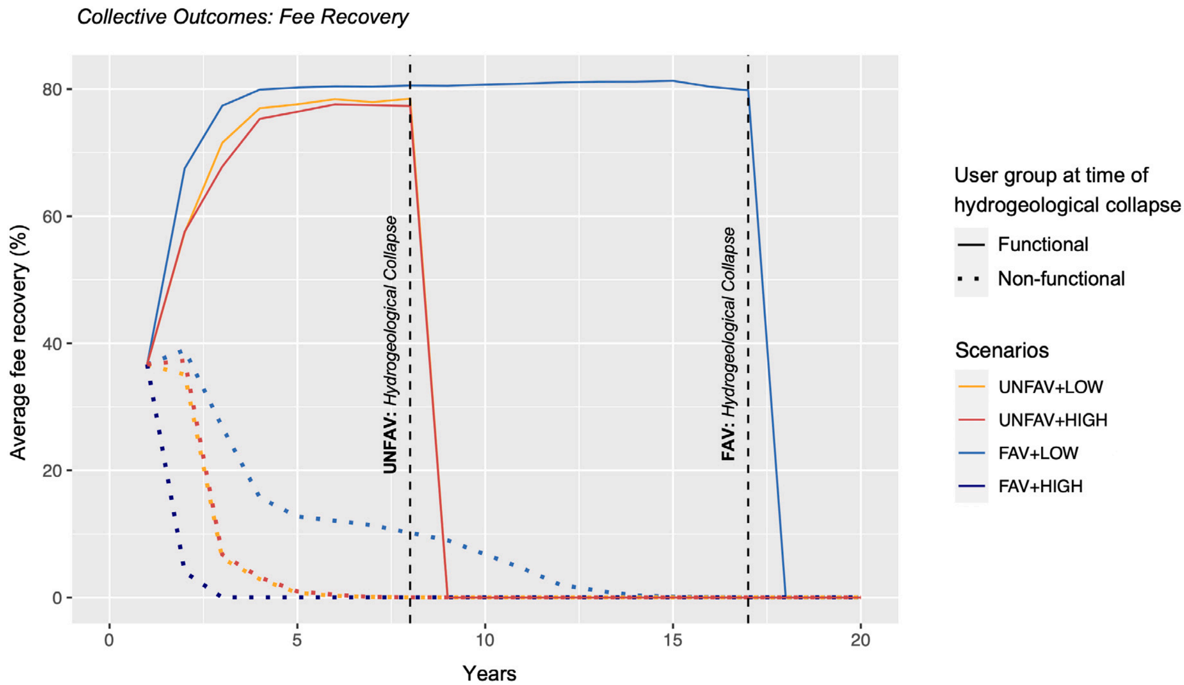


Fig. 4. Fee recovery in functional versus non-functional water user groups. Percentage of fee payments by water users in user groups that are functional and non-functional at the time of hydrogeological collapse — averaged across Monte Carlo simulations (10,000 per scenario). GDAs that are functional at the time of hydrogeological collapse (solid lines) show an increasing trend of fee recovery over time, while GDAs that are non-functional at the time of hydrogeological collapse experience norm erosion through time (dotted lines).

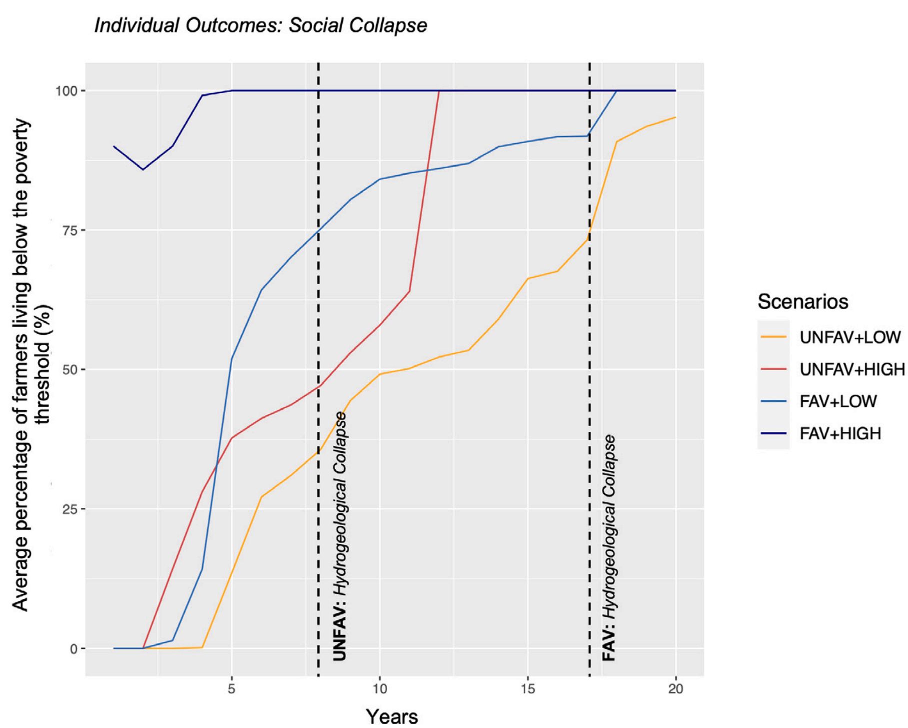


Fig. 5. Social Sustainability. Percentage of water users living under the poverty threshold (World Bank Group, 2019) averaged across Monte Carlo simulations (10,000 per scenario). Among scenarios, GDAs under UNFAV+LOW conditions are best able to delay poverty impacts.

of parameters varies across outcomes. Choosing low-value/low-water crops, the key parameters for fee recovery and the budget of the user group (in order of importance) are price setting, leadership, and equity. Regarding poverty and illicit withdrawals, the key parameters are vertical trust, horizontal trust (defined in Eqs. (8) and (9) respectively), and price setting. Choosing high-water/high-value crops, fee recovery and GDA budget were most influenced by price setting, leadership, and vertical trust.

Since water user groups most frequently collapse due to bankruptcy (pathway 2 in Fig. 2), we explore how leadership and vertical trust interact to motivate farmers to pay their fees. In other words, which social and institutional characteristics drive community norms of fee

Table 1
Feature importance analyses. Different feature subsets (starting from column 2) are driving the output variables (column 1) under different scenarios. Features are ranked by importance for each output variable (dark grey indicating the most important feature, followed by second and third most important features with diminished grey intensity respectively)

	Sust. price-setting	Equity	Leadership (abs.)	(alpha)	Vertical Trust (abs.)	(alpha)	Horizontal Trust (abs.)	(alpha)	External pressure (alpha)
FAV+LOW									
Fee recovery	1.19	0.45	1.81	1.76	0.12	0.10	0.05	0.03	0.24
Poverty	0.99	0.37	2.02	1.95	0.16	0.14	0.05	0.04	0.28
Illicit withdrawals	0.98	0.37	2.01	1.95	0.15	0.14	0.06	0.05	0.27
GDA budget	1.27	0.69	2.28	2.20	0.18	0.17	0.07	0.05	0.33
UNFAV+LOW									
Fee recovery	1.3	0.12	0.55	0.54	0.08	0.08	0.03	0.03	0.02
Poverty	0.00	0.00	0.00	0.00	0.03	0.03	0.01	0.01	0.00
Illicit withdrawals	711.70	387.37	247.17	503.82	8525.51	7539.02	815.95	712.67	90.83
GDA budget	2.81	0.39	1.89	1.88	0.32	0.34	0.06	0.09	0.04
UNFAV+HIGH[a]									
Fee recovery	1.30	0.12	0.55	0.54	0.08	0.08	0.03	0.03	0.02
GDA budget	2.85	0.17	1.94	1.90	0.25	0.31	0.13	0.11	0.03

[a] Feature importance for poverty and illicit withdrawals could not be tested since there was no variation between values at terminal time t or times of system collapse ("poverty crash" after 12 years). Feature importance was also not analysed for the scenario FAV+HIGH due to the lack of variability in outcomes (i.e. systems collapse independent of social and institutional conditions).

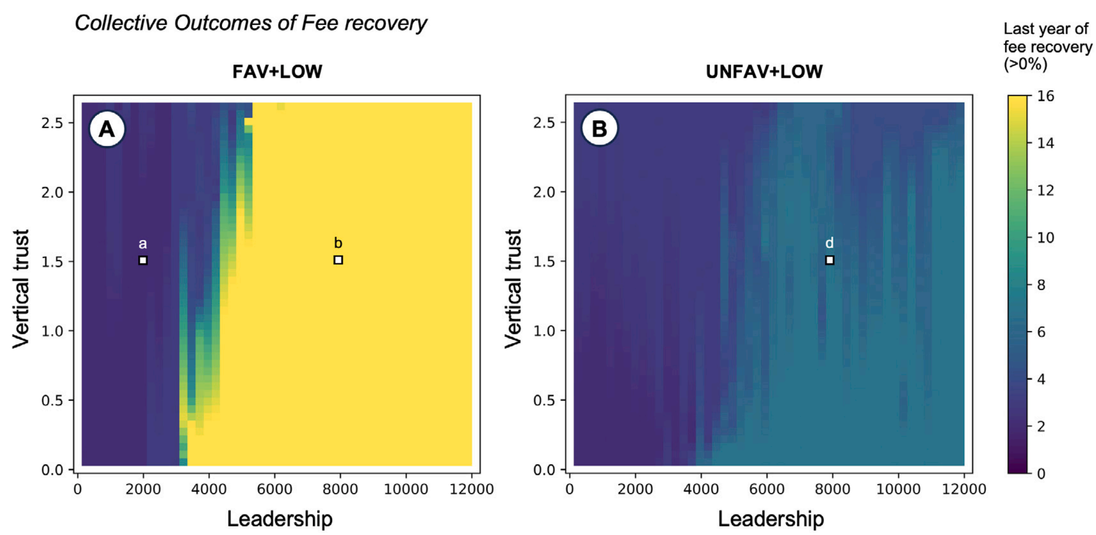


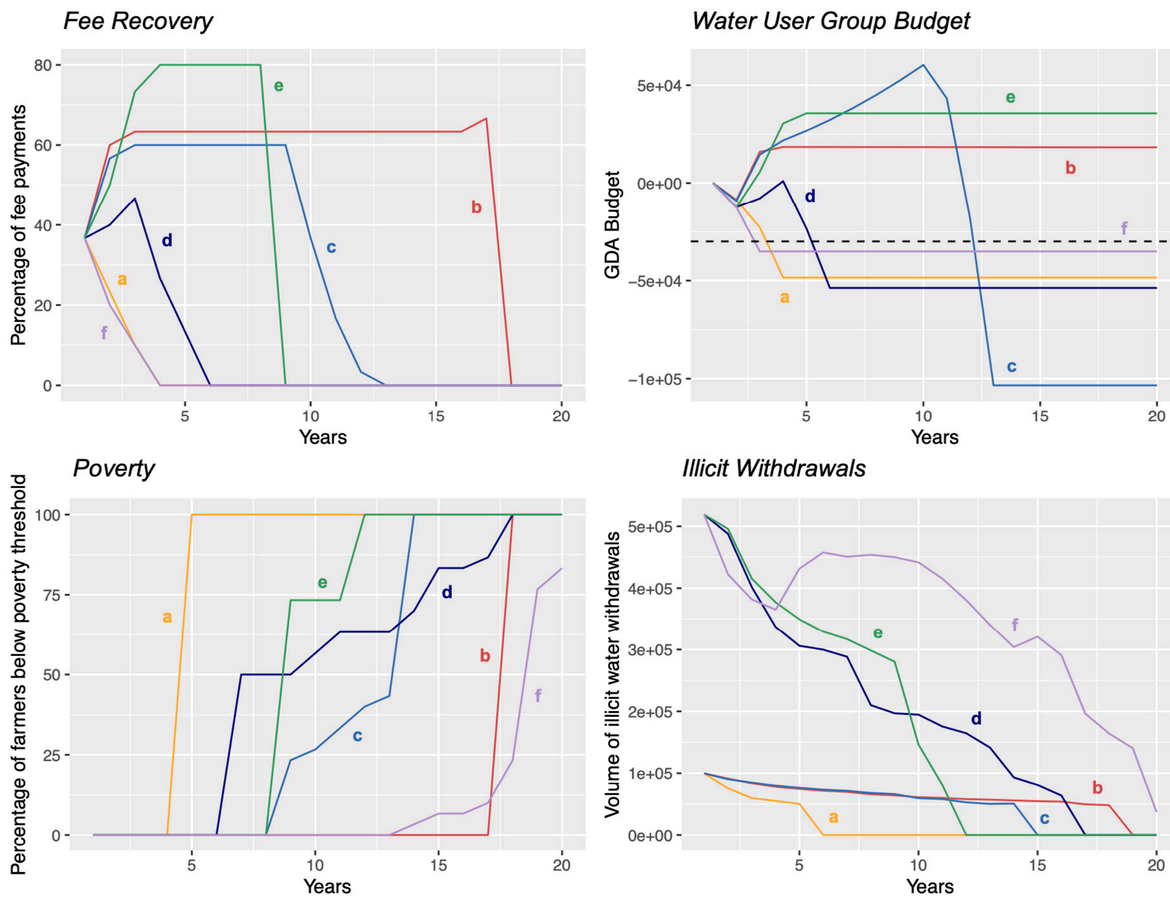
Fig. 6. Heatmaps of fee recovery. Drivers of individual fee payments under varying scenarios. Colours correspond to the last year before fee recovery reaches 0%. Lower-case letters correspond to single-simulation scenarios in Fig. 7. High leadership and low vertical trust serve as positive predictors of fee recovery. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recovery (Fig. 4)? What are the individual and combined effects of these characteristics? To this purpose, we show the combined effects of leadership and vertical trust on the time of collapse for fee recovery (Fig. 6). "Measures of good governance", i.e. social and institutional rules, can delay the collapse of water user groups until wells run dry (until year 17 in FAV resource settings). Scenario FAV+LOW combined with high equity and sustainable price setting (Fig. 6.A) yields the best results for fee recovery. High leadership is a positive predictor of fee recovery across scenarios.

Leadership, the parameter determining penalties regarding fee payments (as formulated in Eq. (8)), is a key driver of farmer behaviour with cascading effects across all collective action outcomes. Under high leadership, price-setting, and equity, water user groups are most likely to avoid financial collapse and high poverty outcomes (scenario b in Fig. 7). Lower leadership scores reduce the ability of water user groups to prevent collective outcomes of user group bankruptcy and individual outcomes of poverty (scenario a in Fig. 7). Equity only has a positive effect on fee recovery and bankruptcy under conditions of sustainable price-setting. Under low equity conditions and sustainable pricing, the time of collapse occurs several years earlier than under high-equity conditions (scenario c versus b in Fig. 7). Sustainable price-setting, i.e. the ability of water user groups to recover their costs, serves as a *conditio sine qua non* for the GDA to avoid bankruptcy independent of high leadership and equity scores.

While under unfavourable resource settings (as opposed to FAV), high-value/high-water crops can achieve positive individual and collective outcomes under favourable leadership and trust conditions (scenario e in Fig. 7), poverty rates will always reach 100% sooner than in scenarios where lower water demands can continue to generate yields and incomes for longer (scenario d in Fig. 7). In all scenarios, farmers cannot avoid high poverty rates at terminal time, where either user groups have collapsed or/and the cost of illicit withdrawals becomes too expensive to cover.

High leadership, low vertical trust, sustainable pricing, and high equity lead to the best possible collective outcomes for the water user group in terms of fee recovery and financial sustainability. The



Scenario	Name	Resource Setting	Crop	Sustainability of price-setting and allocation	Equity	Leadership	Vertical Trust	Horizontal trust	External pressure
a	"Low leadership"				High	2000			
b	"High leadership (FAV)"	Favourable	Low						
c	"Low equity"			High	Low	8000	1.5	0.27*	1.34*
d	"High leadership (UNFAV)"								
e	"High-water/value crop"	Unfavourable	High		High				
f	"Low trust"		Low			2000	0.01	0.15	0

*representing median values for the respective parameter

Fig. 7. Single simulations of user behaviour. Outcomes of fee recovery, user group budget, poverty, and illicit withdrawals.

results suggest, however, that the best outcomes in terms of individual livelihoods can be achieved under low leadership and vertical trust (scenario f in Fig. 7), due to low penalties regarding illicit withdrawals — particularly in unfavourable resource settings, where farmers rely more heavily on illicit water sources. In this scenario, we can track the erosion of norms both in terms of a rapid decline in fee payments (in years 1-4) as well as an increase of illicit withdrawals (in years 4-6). The model thereby suggests that water user groups that disregard formal government rules perform better in terms of poverty outcomes due to higher cash flows from illicit withdrawals. Generally, illicit withdrawals serve as a buffer and coping strategy for water users under increasing water scarcity. In contrast to previous simulations, cost-covering price-setting by the GDA in these scenarios is not an advantage for farmers with respect to poverty outcomes as the ability to easily access groundwater from illicit sources is more relevant for farmers than a functioning GDA. Under scenario f that sees low penalties for illicit withdrawals (as defined in equations (8) and (9)), levels of poverty are initially low despite (or rather because of) the early financial collapse of the water user group. The decline of illicit withdrawals (due to rising extraction cost with increasing extraction depth) and the sharp increase of poverty levels in the last years of simulations indicate, however, that this serves only as a temporary coping strategy for water users.

4. Discussion and conclusion

This study explored the impact of aquifer depletion and illicit groundwater withdrawals on agricultural systems and associated local livelihoods using the fragile political system of Tunisia as a case study. We assessed the influence of interacting social and institutional norms on decision-making of small-holder farmers in the absence of formal monitoring and enforcement rules. Our results revealed practical limits of self-governing institutional arrangements under given social-ecological conditions and provide critical insights into collective action dynamics in stressed groundwater SESs. With a focus on vertical and horizontal mechanisms of trust and leadership and associated norm-driven behaviour, we developed a modelling framework that captures the behaviour of individual farmers, and that integrates the interactions with their peers and the water user group by means of social and institutional norms. The SES model thereby contributes to the commons and SES literature and addresses critical knowledge gaps in the water-agriculture-poverty nexus (Schlüter et al., 2019; Balasubramanya and Stifel, 2020).

The model showcased that under simulated scenarios of aquifer decline, low-value/low-water crops lead to better long-term livelihood outcomes for farmers than high-value/high-water crops. Vertical mechanisms of leadership served as key drivers for collective action in water user groups (particularly under favourable conditions) with cascading effects across all collective action outcomes. Horizontal mechanisms of social trust on the other hand were found inadequate to overcome practical hurdles that can prevent financial collapse of water user groups. This finding aligns well with qualitative interviews conducted with GDA members. As one water user states: "Social peace is important when there is water. When there is no water, social peace goes out the window" (Erfurth et al., 2023). Most frequently, financial collapse (pathway 2 in Fig. 2) precedes hydrogeological collapse (pathway 1 in Fig. 2). It follows that farmers and their water user groups are not able to prevent the type of collapse that is directly caused by their own collective action (as an endogenous process of the simulation). Financial collapse is triggered either by inadequate price-setting (by the GDA administrative council) or user behaviour (inadequate fee recovery due to inherent payment preferences or insufficient profits to cover water costs) (Fig. 2). We find that water user groups can only avoid bankruptcy by setting cost-covering prices but even that may be insufficient under water scarcity or norms that are lenient towards non-compliance (i.e. payment avoidance).

Generally, water user groups are more likely to delay rather than avoid system collapse. Decreasing groundwater supplies and high levels of poverty at terminal time indicate that agriculture alone struggles to provide long-term livelihoods for farmers in the case region (even under best-case conditions, see Fig. 5). Water economising measures such as switching to low-water crops or improving water use efficiency could delay or prevent collapse but only if these measures are implemented in a well-concerted manner across the aquifer and are accompanied by socially-accepted regulatory limits to extraction (Sears et al., 2018). Given the limited success (i.e. low uptake) of such regulatory limits at the local level, it is likely that scaling these solutions across polycentric governance levels would prove difficult (i.e. basin-wide uptake of these withdrawal limits). Global research on groundwater overexploitation has shown that design and coordination of polycentric groundwater governance frameworks often fails due to an overestimation of the role of the state (Molle and Closas, 2020; Molle et al., 2018). Shall indeed polycentric coordination fail, farmers will be faced with the collapse of agricultural production system and the need to diversify their income sources beyond agriculture.

Further, our model highlights the limits of individual and community-level action in the face of extensive aquifer-level groundwater depletion, and provides practical considerations of livelihood-generating agricultural strategies. Against common policy advice that seeks the rapid closing of illicit wells, under unfavourable resource conditions, water users may find it advantageous to turn to illicit groundwater sources that are independent of the collective action risks associated with regulated withdrawals in official water user groups. By drawing from reliable (albeit more expensive) illicit groundwater sources, farmers can generate a temporary income by cultivating crops. Groundwater from illicit wells thereby serves as an important buffer for farmers to avoid the poverty trap and could help to transition away from agriculture in a region set on a path of long-term aquifer depletion. Due to the key importance of reliable groundwater sources, lower levels of trust in government (that discourage illicit extraction) thereby lead to better outcomes for farmers and their water user groups as social penalties for illicit withdrawals decline. Given the historic context of political fragility and the general lack of trust in government and government rules, illicit welling turns into a coping strategy for water users. In a regulatory framework that offers no formal means of enforcement of rules, and under given conditions of water scarcity and associated risks for agricultural livelihoods, communities that disregard formal rules perform better than rule-conforming GDAs.

It is important to reiterate, however, that illicit withdrawals accelerate the process of aquifer depletion and do not serve as a long-term coping strategies for farmers. The system simulated here has taken a realistic stance on the low probability of rapid concerted action on the scale of the aquifer that would put a halt to decade-long groundwater depletion. In the absence of a functioning regulatory system and formal support for local water user groups, farmers are likely to be left to their own devises to generate livelihoods from agricultural activities for as long as possible. The social-ecological take-some dilemma of continued or even accelerated groundwater overextraction from largely illicit sources translates to higher likelihoods for poverty traps (Cumming, 2018), i.e. the higher the overextraction levels, the earlier farmers will be unable to withdraw sufficient water to irrigate their crops.

Finally, our simulations reveal strong patterns of path dependence. Farmers generally rely on known "tried-and-tested" cultivation and water withdrawal strategies and will only change their own strategies if they see an opportunity to improve their utilities by imitating a well-performing peer (Baggio and Hillis, 2018). While this phenomenon has been observed in the study area, the simple social network chosen for the model neglects the possibility of external interventions e.g. policy implementation or individual ingenuity. There are multiple opportunities to expand the current version of the model. They range from more complex social networks, forward-looking preferences of farmers, more diverse and dynamic crop choices, to aquifer-level (rather than GDA-level) agent-based groundwater withdrawals, market volatility, as well as climate change scenarios.

Finally, the paper has demonstrated that in settings of gradual aquifer decline, a continuation of the status quo results in the eventual collapse of agricultural production systems with deleterious effects on associated livelihoods. The model facilitated a greater insight into the poorly-studied relationship between groundwater, agriculture, and poverty (Balasubramanya and Stifel, 2020) by modelling water user groups that, decoupled from centralised institutions, construct their own set of social and institutional norms (van Steenbergen et al., 2015; García et al., 2019). The paper has contributed to new research on the importance of fit of groundwater governance systems (Marston et al., 2022) by modelling context-specific user dynamics using ground-level empirical evidence. A better understanding of these context-specific dynamics can inform future water management strategies that are realistic given systemic limits and opportunities (Mollinga et al., 2007; Meinzen-Dick et al., 2018). Results of this paper suggest that policy efforts should strengthen the institutional capacity of collective action groups including practical guidance regarding a transition to less water-intensive crops. A reconsideration of the feasibility of irrigated agriculture under given water constraints is necessary and should be accompanied by providing farmers with the opportunity to diversify incomes beyond agriculture. Regardless of policy interventions, irrigated agriculture will decrease due to falling groundwater tables and limited water supplies — either accompanied by appropriated policy measures or unaccompanied (with potentially devastating effects on farmers'

Table A.1
Interview questions and corresponding variables and anchor points.

Variable	Interview questions	Anchor points
Trust in government	Generally speaking, can you trust the government to do what is right? Do you think the government understands the challenges the GDA faces? Does the government help your GDA? What do you think of current water policies? Do you think they adequately address your needs?	0: The GDA "can never trust the government to do what is right". Policies are counterproductive (the government works against the will of the people). The government could not care less about farmers. 0.33: The GDA "can rarely/sometimes trust the government to do what is right". Policies are neither helpful nor hurtful. The government has a poor understanding of farmers' needs. 0.67: The GDA "can mostly trust the government to do what is right". Policies are imperfect but somewhat address needs. The tries to help but not very successfully. 1: The GDA "can always trust the government to do what is right". Policies adequately address water users' needs. The government supports the GDA.
Social cohesion/ reputation	Do you think members care about the profits of the other members? Do you think it is important for users what other users think of them? Is social peace important (in relation to other targets)?	0: There is no social cohesion. Members do not care about their reputation or other water users' profits. Social peace is not a priority. 0.5: There is some social cohesion. Members generally care about each other, but they care more about their own livelihoods than their reputation and other water users' profits. Social peace is not a priority. 1: There is social cohesion. Members care about their reputation and about the profits of others. Social peace is a priority.
Expectation of rule-following	Without monitoring, if a member says they will withdraw a specific volume and pay the agreed upon price, do you expect that they will do just that? Do you have a sense of whether members follow rules?	If a GDA member says they will do x, e.g. pay their fees, you expect that without monitoring … 0: the member will not do x. 0.33: the member will only sometimes do x. 0.67: the member will mostly do x. 1: The member will do exactly what they say.
Discounting/ ability to long-term planning	Would GDA members be willing to use less groundwater this year if you were promised more/stable groundwater in the future? What is the price per m^3 that water is sold to farmers? Do you think farmers should pay less, the same, or more for water than right now?	0: Leaders only consider present benefits and do not consider over-extraction, and fees that do not cover costs a problem. 0.33: Leaders have some but little understanding of the need for sustainable groundwater extraction and fee setting. "There is little that can be done about these problems". 0.67: Leaders understand the need for sustainable groundwater extraction and fee setting but largely see their hands tied. There have been efforts to increase fees/limit water use but not sufficiently. 1: Leaders understand the need for sustainable groundwater extraction and fee setting. Efforts to increase fees/limit water use are effective.
Leadership	What motivates you/the CA to do their job? Do you think this motivation influences other members? In your own words, what is the purpose/mission of the GDA? Whose responsibility should it be to ensure that the GDA is functioning well? What was the role of the CA in solving conflicts?	0: Leaders are unmotivated and uninterested in managing the GDA. They see responsibility of managing the GDA, and guaranteeing its functioning, elsewhere. The CA does not engage in conflict resolution. 0.33: Leaders are somewhat motivated but struggle to translate this motivation to members of the GDA. There is some understanding of CA responsibility (e.g. responsibility lies with the entire GDA) but not in action. CA does not effectively engage in conflict resolution. 0.67: Leaders are motivated but struggle to translate this motivation to members of the GDA. There is an understanding of CA responsibility and some limited success in managing the GDA. Involvement but limited success in conflict resolution. 1: Leaders are very motivated and translate this motivation to members of the GDA. CA assumes full responsibility in managing the GDA and guaranteeing its functioning. The CA successfully resolves conflicts. "
Fee recovery	What is the percentage of fees recovered from farmers?	0: <= 40% of farmers pay 1: 100% of farmers pay (continuous scale based on data)

livelihoods). Results thereby reiterate the necessity of basin-wide collective action in stressed groundwater systems while acknowledging associated implementation challenges, particularly in fragile political contexts.

CRediT authorship contribution statement

Sophie Bhalla: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jacopo A. Baggio:** Writing – review & editing, Software, Methodology, Conceptualization. **Reetik-Kumar Sahu:** Writing – review & editing, Software, Methodology, Data curation. **Taher Kahil:** Writing – review & editing, Project administration. **Jamila Tarhouni:** Validation, Software, Resources, Investigation. **Rahma Brini:** Resources, Project administration, Investigation. **Matthias Wildemeersch:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix. Annex

See Tables A.1–A.5

Table A.2
Calibration and data sources of scenarios of unfavourable and favourable resource settings.

	Description	Unfavourable	Favourable	Source
loc	Location of the GDA (required for surrogate hydrogeological model)	Loc. of repres. GDA in Sisseb aquifer	Loc. of repres. GDA in AinBoumorra aquifer	MODFLOW model
$hh_{(t0)}$	Initial hydraulic head (m)	70	180	MODFLOW model (in 2012)
λ	Density of illicit wells (number of illicit wells in 3 km radius)	175	10	Inventory of illicit wells
den^{1km}	Density of illicit wells (number of illicit wells in 1 km radius)	26	5	Inventory of illicit wells
$will_{(t0)}$	Initial annual illicit withdrawals by water users (m^3)	525 252.53	101 010.10	Literature (MARHP, 2017) and inventory of illicit wells[a]
$Vp_{(t0)}$	Total pumping at time 0 (m^3 s^{-1})	1	0.8	MODFLOW model
thr_{hyd}	Hydrogeological threshold (decline in m when well is assumed to run dry)	3	10	Empiric accounts from informal interviews

[a] It is estimated that on average half of all groundwater wells in Tunisia are illegal. We assume that withdrawals whether legal or illicit are the same/similar for a given well. Using data from the illicit well inventory (number of illicit wells in 1 km radius), we further assume a linear relationship where 0 illicit wells = 0 illicit water, and average illicit wells = allocated water = illicit water.

Table A.3
Ranges of social and institutional parameters.

Parameter	Description	Minimum	Maximum	Type
V_T	Vertical trust	0	1	continuous
H_T	Horizontal trust	0	1	continuous
V_L	Leadership	0	1	continuous
$alpha^{V_T}$	Vertical trust penalty weight	0	2.670763282[a]	continuous
$alpha^{H,int}$	Horizontal trust penalty weight	0	1.082790324[a]	continuous
$alpha^{V_L}$	Leadership penalty weight	0	12130.5[a]	continuous
$alpha^{H,ext}$	Social pressure from outside GDA weight	0	2.670763282[a]	continuous
equ	Equity	0[b]	1[b]	binary
sust	Sustainability of price-setting and allocation	0[c]	1[c]	binary

[a] We assume that penalties range from around 0 to maximum 50% of individual profits per norm. 50% represents the highest possible penalty, e.g. highest $will_{(t)}$ and highest V_T values in MC simulations (modelled on scenarios of unfavourable ecological and low value/low water crop).
[b] 0 = one-fifth of GDA members receive twice as much water than they would have had the water been allocated equitably; 1 = equitable distribution.
[c] 0 = static price of 0.15 TND per m3 (source: interviews) and increasing withdrawals (based on MODFLOW defined growth rate); 1 = price calculated based on extraction and operation costs, and the expectation of fee recovery; withdrawals remain static.

Table A.4
Calibration of crop parameters for high-water/high value (HIGH) and low-water/low-value (LOW) crops respectively.

Parameter	Description	HIGH	LOW	Source
k_c	Crop coefficient	0.8	0.54	Steduto et al. (2012), Vermeiren et al. (1980), Ahmed et al. (2007), Saadi et al. (2015)
K_y	Yield coefficient	0.8	0.6	Steduto et al. (2012), Vermeiren et al. (1980), Ahmed et al. (2007), Zairi et al. (2003)
ET_{min}	Min evapotranspiration needed to generate yield (m/year)	0.624	0.3	Steduto et al. (2012), Vermeiren et al. (1980), Ahmed et al. (2007), Zairi et al. (2003)
ET_{max}	Evapotranspiration for given max yield (m/year)	1.264	0.6	Steduto et al. (2012), Vermeiren et al. (1980), Ahmed et al. (2007), Zairi et al. (2003)
y_{max}	Maximum yield possible (kg/ha)	75 000	22 750	Steduto et al. (2012), Vermeiren et al. (1980), Ahmed et al. (2007), Soethoudt et al. (2018) (assuming maximum yield based on average yield)
c^c	Cultivation cost (TND/y)	8500	1600	Data collection (WEAP)
P^c	Price of crop sold on the free market (TND/kg)	0.47	1.19	Data collection (WEAP)

Table A.5
Calibration and data sources of model variables.

Variable	Description	Value	Source
n	Number of farmers in GDA	30	Interview data
$w_{alloc}(t_0)$	Initial groundwater allocated annually to water users (m^3)	200 000	Interview data and administrative records; averaged based on representative GDA in the given resource setting
fee_{perc}	Expectation of initial percentage of GDA member paying their fees	0.5	Interview data
ζ	Zeta parameter of logistic function	1	Assumption based on interviews
p_{pre}	Cash at start (TND)	15 000	Assumption based on poverty threshold; tested during calibration
a	Average size of agricultural land per farmer (m^2)	23 500	Administrative records
thr_{fin}	Threshold for GDA bankruptcy (TND)	−30000	Based on data from administrative records indicated operational status and financial debt of GDAs
thr_{pov}	Poverty threshold for farmers (TND)	7505	WBG (2019); assuming 1 household consists of 5 people
c_{op}	Annual GDA costs for maintenance, personnel, etc. (TND)	20 000	Assumption based on interviews
c^{ill}	Cost of groundwater from illicit sources	c_E * 1.5	Assumption based on the literature and interviews
ϵ	Error when copying illegal water withdrawals	0.2	Assumption
c^{den}	Density effect (rate at which penalty declines)	1/max. density (= 0.0057)	Inventory of illicit wells
$c^{\lambda 0}$	Maximum possible penalty (when lambda_den = 0)	1	Assumption
c^{alloc}	Initial price of allocated water (TND per m^3)	0.15	Interview data

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