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Research Article

Risk Assessment of Aquifer Salinization in a Large-Scale Coastal Irrigation Scheme, Italy

This paper describes a study conducted on a coastal agricultural area of southern Italy to assess the impending risk of aquifer degradation related to intensive groundwater pumping by farmers. It occurs that farmers rely on groundwater pumping to offset the inadequate irrigation delivery service provided by the local water management agency. The study area is intensively farmed by small land-holding growers with high-value horticultural crops, whose irrigation deliveries are supplied by a gravity-fed water distribution system operated by a local water users' organization. The soil and aquifer degradation hazards were appraised using a simplified environmental risk assessment procedure that allowed identifying the risk-generating processes, assessing the magnitude of impacts, and estimating the overall risks significance. The investigations revealed significant aquifer salinity increase during the past years. The stakeholders' perspective on agricultural water use was collected through field interviews, and was framed using a fuzzy cognitive map, which revealed the farmers' propensity to pump groundwater rather than rely on rotational deliveries from the surface distribution system. Finally, some preliminary risk mitigation options were appraised by exploring the growers' response to possible changes of irrigation deliveries by the water users' organization. The presented study consisted of multi-annual observations, data analysis, and modeling efforts, which jointly proved to be useful to analyze the main drivers to stakeholders' decisions and their long-term impacts on water resources use and management.

Keywords: Environmental risk assessment; Fuzzy cognitive maps; Groundwater degradation; Irrigation delivery systems; Seawater intrusion

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1 Introduction

Large irrigation schemes, especially those in Mediterranean areas continue to face growing challenges with regard to sustainable and resource-efficient agricultural water management. The European Environmental Agency pointed out that in the next few decades many southern Mediterranean areas will likely experience decreased water availability in summer periods, while frequency and intensity of droughts will most likely increase [1]. If these predictions of climatic variability materialize, the increased frequency and severity of droughts would decrease the reliability of irrigation water supply even beyond the uncertainties that are commonly considered today [2].

Besides the prospects of water shortage and uncertainty, inadequate delivery performance and poor agricultural water management at system scale often add environmental burdens to the current strain on fresh water resources [3, 4].

Stockle emphasized that the type of operation of irrigation water supply systems can affect the environmental performance of irrigated agriculture. Systems that deliver water continuously or by a fixed schedule are less efficient and/or limit management options available for irrigators as compared to on-demand water delivery operations [5]. Clemmens and Molden, and Giordano et al. pointed out that when irrigation deliveries by water agencies are unreliable, rigid, or untimely with respect to crops' and farms' needs, growers often rely on groundwater pumping as main source of irrigation water, provided that underlying aquifers are available and accessible [6, 7]. As documented by Merriam and Freeman [8], when growers control irrigation water deliveries from distribution infrastructures, salinity problems, as well as soil and aquifer degradation related to excess, inadequate, untimely, and improper irrigations, may be largely reduced or prevented. A great stimulus toward enhanced agricultural water management at project scale comes from this prospect of future increased uncertainty of fresh

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Abbreviations: **DEFRA**, Department of Environment Food and Rural Affairs; **DPSIR**, driving forces, pressures, state, impacts and responses; **EIA**, environmental impact assessment; **ERA**, environmental risk assessment; **ERA&M**, environmental risk assessment and management; **FAO**, Food and Agriculture Organization of the United Nations; **FCM**, fuzzy cognitive map; **FDS**, flexible delivery schedule; **RDS**, rotation delivery schedule; **SEA**, strategic environmental assessment; **SWB**, soil water balance; **WUO**, water users organization

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water supplies and from the general public perception that agricultural water use is often wasteful [9], and from environmental concerns.

According to the Food and Agriculture Organization of the United Nations (FAO), wise and resource-efficient management in large-scale irrigated areas requires the capability to forecast, monitor, and analyze the environmental trends and concerns, focusing the attention on impending risks of environmental degradation, while identifying the major risk-generating processes, and undertaking effective mitigation actions at the project scale [9]. Walshe et al. highlighted that the adoption of risk-based management approaches is crucial for the irrigation sector to achieve its goal of long-term economic and environmental sustainability [10]. In this perspective, the present paper describes a coordinated field investigation and modeling effort conducted on a coastal large-scale irrigated area of southern Italy with the aims of: (a) assessing the risk of soil and aquifer salinization; (b) identifying the main drivers to stakeholders' decisions about alternative water resources access and use; and (c) appraising viable risk management/mitigation options in view of upcoming environmental sustainability policies.

2 Materials and methods

This paper describes a methodological approach that was applied to assess the risk of groundwater and soil salinization in coastal irrigated areas, and to evaluate possible mitigations policies, based on a combination of field investigations and modeling efforts.

The work is based on the awareness of the role played by stakeholders' behavior in influencing implementation and effectiveness of mitigation policies. For this aim, a methodology based on the use of fuzzy cognitive map (FCM) concepts has been implemented to simulate farmers' decision-making processes concerning water resources management under limited supply. For a detailed description of the FCM methodology, the reader is referred to [11–14].

Figure 1 outlines the methodological steps and tools applied in the present study to:

a) characterize the environmental risks of aquifer degradation;
b) evaluate the irrigation delivery service by the water users' organization (WUO)-operated distribution system, and infer functional links with groundwater pumping by growers;
c) assess the growers' attitude to groundwater exploitation as opposed to withdrawals from the WUO-operated distribution system;
d) evaluate some viable risk mitigation options.

2.1 Study area and main environmental concerns

This study was conducted on the "Sinistra Bradano" irrigation scheme, an irrigated agricultural area of about 100 km^2 in southern Italy that extends over an alluvial plain facing the Ionian Sea, on the south-western side of the Apulia region (Fig. 2).

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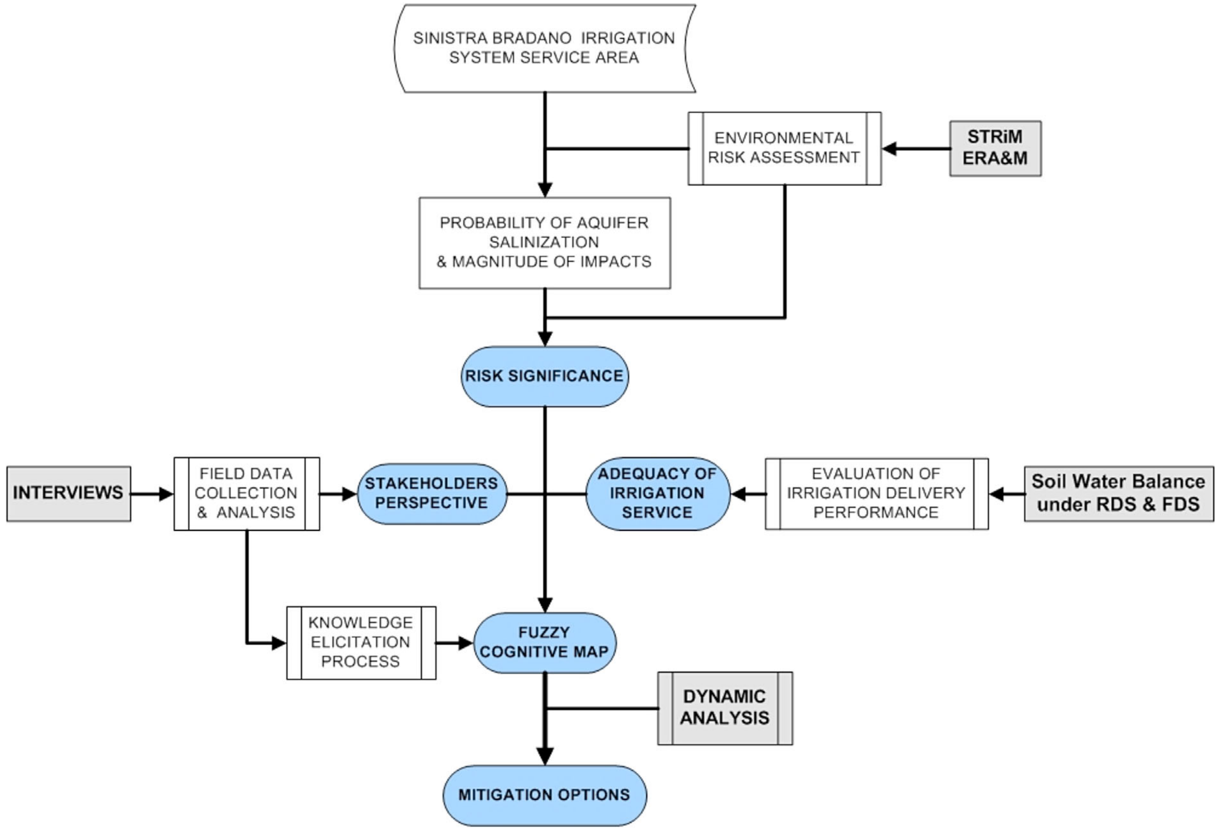

Figure 1. Sequence of methodological steps applied within the present study.

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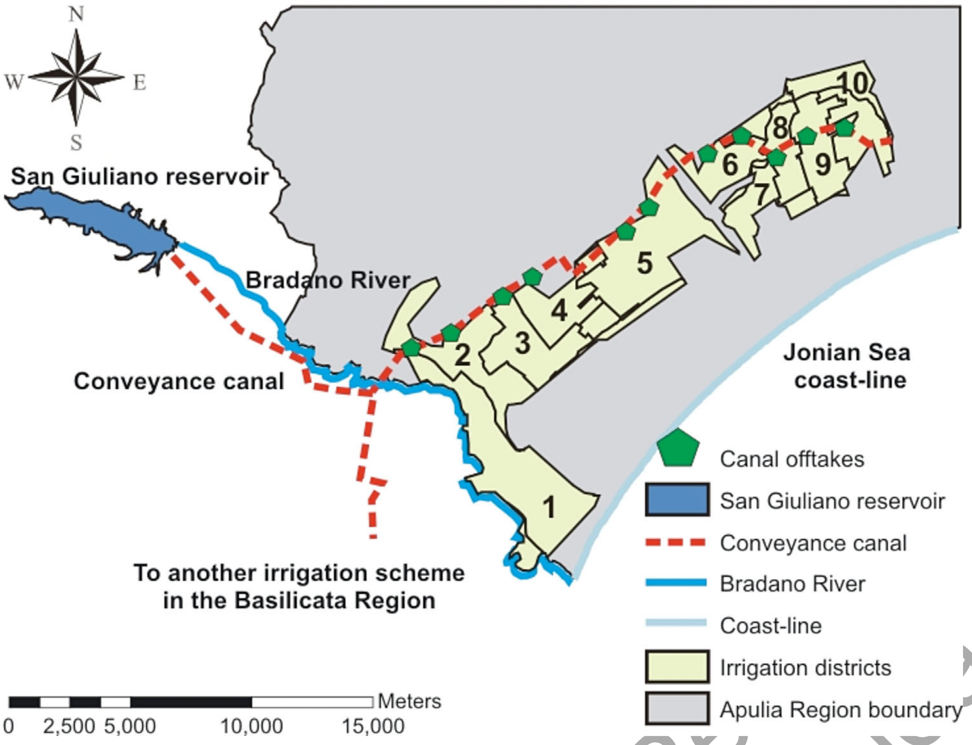

Figure 2. Overview of the study area (source [17]).

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The irrigation system commands an overall area of 9651 ha, with the main network gradually put into operation during the period from 1968 to 1974 and designed to provide irrigation delivery service to a total irrigable area of 8636 ha. The entire system is operated by the "Consorzio di bonifica Stornara e Tara", a water users' organization (WUO) that supplies service water to growers by rotation delivery schedule through a gravity-fed distribution network.

Figure 2 shows the main water supply chain, which starts from the San Giuliano reservoir and proceeds with a conveyance canal, along which ten off-takes are located that divert water to as many district pipe delivery networks distributing water to farm gates. More details on the irrigation infrastructure, the operational procedures of the distribution network, the crop irrigation management practices commonly followed by farmers, and resulting impacts to groundwater quality can be found here [15–17].

Officers from the WUO reported a progressive decrease of the total area requesting irrigation delivery service from the collective distribution system in the period from 1997 to 2007. In contrast, a sharp increase of the area irrigated with groundwater through farm wells during the same period was reported by farmers and system's operators during the interviews. Farmers described such trends as due to inadequate water delivery service provided by the WUO. Many growers pointed out that their reliance partly or fully on groundwater pumping to irrigate their fields was necessary to offset constraints imposed by the fixed rotation deliveries. Several growers reported to be dissatisfied with the irrigation service provided by the WUO, and indicated that deliveries often do not enable to meet irrigation needs because of inadequate timing and delivery conditions.

The cropping pattern in the study area comprises table grapes (43%), citrus (25%), and summer vegetables (25%), with the majority of farmers using micro-irrigation methods. Both sprinkler and surface irrigation are no longer used in the study area due to limited water supply, and to high labor and energy costs.

Zaccaria et al. provided a description of the groundwater hydrological set-up in the study area [15] on the basis of findings from previous investigations [18–20], which reported the existence of abundant groundwater resources in the shallow unconfined upper aquifer as well as in the deeper confined aquifer. Additional investigations carried out in bordering areas found that seawater intrusion is progressively increasing throughout the Ionian coastal aquifer, due to the shallow aquifer being subjected to heavy pumping [21–23]. This trend was also described after comparing two consecutive regional water plans [24, 25]. A monitoring program conducted between 2006 and 2011 by regional water agencies collected hydro-geological, chemical and physical data, and confirmed the qualitative degradation of groundwater in the coastal plain caused by seawater intrusion in the shallow aquifer [26, 27].

From a quantitative standpoint, the above-described monitoring showed a seasonal fluctuation of the groundwater table, with a decreasing trend during dry seasons and an increasing one during the rainy periods, which were related to the precipitation pattern and to groundwater abstractions for irrigation purposes occurring over the study area.

During interviews with farmers and WUO's technical staff it was found that groundwater pumping usually peaks in July and August and increases the risk of aquifer contamination owing to seawater intrusion. Soil degradation results from salt build-up in the agricultural lands due to irrigation with saline groundwater not coupled with sufficient salt-leaching practices. Soil salinization is among the major causes of irrigated land being lost to production and is one of the most prolific adverse environmental impacts associated with irrigation [9], and as such represents a major

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concern in the study area, urgently in need of careful risk assessment and management. Such conditions and hazards are very common in many large-scale irrigated systems located in coastal zones where groundwater resources are often over-drafted, allowing seawater intrusion and resource degradation. FAO reports that such environmental effects could often approach harmful levels, and reversing the movement of a salt water wedge is usually both difficult and very expensive [9].

2.2 Methodological steps

This section describes methods and tools used in the present work to assess the environmental risks impending in the study area, evaluate the irrigation delivery service provided by the WUO, and model the farmers' decisions on alternative irrigation water supplies.

2.2.1 Environmental risk assessment

Environmental/Ecologic risk assessment (ERA) is the process of estimating likelihoods and consequences of the effects of human actions or natural events on plants, animals, and ecosystems of ecological value [28]. According to Kibria, the concept of ERA as defined by Wilson and Crouch is "a way of examining risks so that they may be better avoided, reduced, or otherwise managed" [29, 30]. Thus, the process of risk assessment allows informed decision-making when uncertainty concerning future events or actions prevails [31].

Walshe et al. emphasized that although ERA procedures can provide a basis for making the vague tenets of sustainability operationally meaningful, the broad adoption among stakeholders in irrigated areas is still unproven [10].

The present study utilized a simplified framework for environmental risk assessment and management (ERA&M) that is based on the environmental risk management guidelines issued by the Department of Environment Food and Rural Affairs (DEFRA) [32] of the United Kingdom. Application of this analytical tool enabled the characterization of environmental risks of aquifer degradation, the identification of risk generating processes, and the assessment of risk probability and significance to the study area. This ERA&M framework is linked to other environmental protection procedures, such as the environmental impact assessment (EIA), the strategic environmental assessment (SEA) and the framework on driving forces, pressures, state, impacts, and responses (DPSIR) conceived by the European Environmental Agency [33].

Figure 3 illustrates the five main iterative steps of the ERA&M framework that enable: (1) problem formulation; (2) generic (qualitative) and detailed (quantitative) risk assessment process; (3) development of risk management and monitoring strategy; (4) reporting and communicating results from the risk assessment and management strategy; and (5) implementing risk management strategy and monitoring.

The framework links the DPSIR indicators and monitoring framework to risk assessment and risk management, with focus on key emerging aspects, such as: (a) the importance of accurately defining the actual environmental problem; (b) the need to prioritize all relevant risks prior to their quantification and proceeding with the data collection; (c) the need to consider the risks from the initial stages, taking into account feasible management solutions using options appraisal; (d) the iterative nature of the process.

Within the present study, the ERA&M framework was applied to the "Sinistra Bradano" service area for detailed risk assessment, with attention given to: (i) identification of primary and secondary environmental hazards; (ii) characterization of sources, pathways, receptors, and impacts for each identified hazard; (iii) determination of the main risk generating processes; (iv) estimation of impacts of the hazardous phenomena; and (v) assessment of risk probabilities and significance. A preliminary appraisal of feasible risk mitigation measures was carried out involving local farmers and system operators.

2.2.2 Assessment of irrigation delivery performance

Irrigation deliveries by the water distribution system under the current operational mode were reproduced through simulations and compared to irrigation practices typically followed by growers to maximize farming income for the different crops grown. Specifically, daily root-zone soil water balances (SWB) were simulated using an Excel application where the methodology proposed by Allen et al. [34] was used for the different crop-soil-climate combinations found in the study area. The simulated SWBs were used to compare water applications, crop evapotranspiration, and resulting water excess and deficits when farmers irrigate according to the rotational delivery schedule (RDS) currently adopted by the WUO, or if they follow an alternative and flexible delivery schedule (FDS). In details, simulations of RDS are based upon fixed irrigation dates and time durations to reproduce the delivery service currently enforced by the WUO, which consists of ten days irrigation intervals, flow rate of $20\,\mathrm{L\,s^{-1}\,ha^{-1}}$ and 5 h duration of delivery for each serviced farmer. In contrast, simulations under FDS reproduced the irrigation scheduling plans that farmers commonly follow when they rely on flexible and unconstrained water source, such as groundwater pumping.

2.2.3 Reproducing farmers' decision-making on alternative irrigation supplies

A model capable of simulating farmers' decisions about alternative irrigation sources was developed and used for validating results stemming from the risk assessment procedure, and to provide information for preliminary evaluation of viable risk management options. To this aim, local stakeholders were involved in a cognitive modeling exercise to develop the FCM, which is a graphical representation of their mental models and drivers to decisions [11].

FCM is a conceptual model that includes fuzzy logic to define the strength of relationships between concepts as close as possible to the cognitive representation made by stakeholders. As described elsewhere, the model can be considered as a "mirror" of the cause and effect relationships in the mind of decision makers [14]. The causal links in FCM can be either positive or negative and may be characterized by weights representing the strength intensity of relationships between concepts. The analysis of FCMs allows identifying the causal concepts, or variables, and the causal connections, or links [35].

A representative sample of farmers and irrigation system operators from the "Sinistra Bradano" service area participated in a set of semi-structured interviews conducted in 2012 and 2013. Growers were selected according to the farm size, accessibility to the WUO-operated irrigation delivery system, access to groundwater, and crops grown. Farmers were required to describe the main elements influencing their decision concerning the management of the available water supply under drought conditions. The collected

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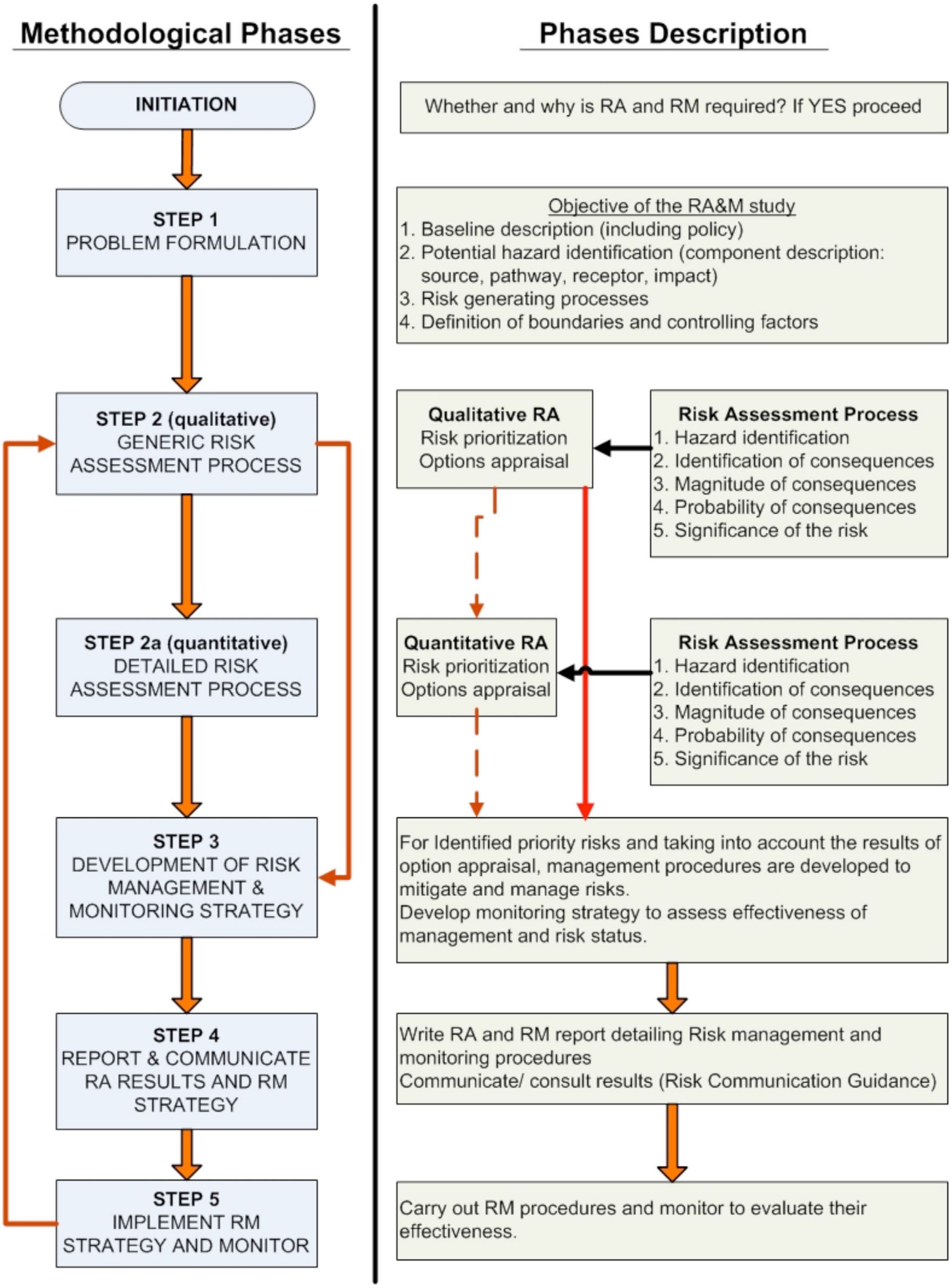

Figure 3. Main steps of the ERA&M framework (modified from [32]).

responses were analyzed and coded into a causal diagram showing connections among the variables. Participants were then asked to specify the strength and the polarity of those causal links, which assumed values ranging in the interval between -1 and $+1$, whereas the weight of each link was described using the linguistic statements "high," "medium," and "low" [36]. A fuzzy linguistic function was developed to utilize these linguistic variables in mathematically sound manner [37]. These variables can be

Table 1. Example of adjacency matrix for a fuzzy cognitive map with six variables

Vector		Adjacency matrix					
		C1	**C2**	**C3**	**C4**	**C5**	**C6**
0	**C1**	**0.0**	1.0	0.0	0.0	0.0	0.0
1	**C2**	1.0	**1.0**	0.0	1.0	1.0	0.3
0	**C3**	0.0	0.0	**0.0**	0.0	0.0	0.0
0	**C4**	0.0	0.0	0.0	**0.0**	0.0	0.0
0	**C5**	0.0	0.0	0.0	0.0	**0.0**	0.7
1	**C6**	0.0	0.0	0.0	0.0	0.0	**1.0**

physically measurable quantities, complex aggregate and/or abstract concepts. Once defined, FCM can be used to simulate the effects of possible actions, taking into account the perceived cause-effect relationships between the elements of the considered system.

To this aim, the so called "adjacency matrix" was developed, that according to Özesmi and Özesmi represents the relationship information from a FCM, and shows the existing connections between each couple of variables in the map [38]. The number in the cell, C_{ij}, represents the weights assigned by the stakeholders to the linkage connecting C_j and C_i. The fuzzy linguistic function was used to determine the numerical value to assign in the table, expressed in real numbers between -1 and $+1$. The vector contains the value of the variables before the FCM simulation. In order to simulate the impacts of one variable on the others, its value is set to "1" in the vector, meaning that the variable under study is turned on. To reiterate the impulse given by this variable to the system state, the corresponding value in the diagonal is changed to 1. No concept causes itself, for this reason the diagonal of the matrix consists of a series of zeros, except in correspondence of the guiding variables.

In addition, the matrix allows storing and manipulating the causal influence values of a FCM. Table 1 is an example of adjacency matrix obtained by a generic FCM constituted by six variables, where numbers represent weights and polarities of the relations between concepts. The causality relationships between couples of concepts are represented by real numbers between -1 and $+1$. The diagonal of the matrix is called vector, (indicated with bold characters in Table 1) and it is constituted by a series of zeros, except in correspondence of the guiding variables. By examining the adjacency matrix it can be determined how stakeholders view the system. Once the cognitive maps are drawn and the adjacency matrix coded, different simulations can be run and "what/if" questions may be asked (http://arxiv.org/abs/q-bio/0603022) [39], identifying the effects that various drivers have on the whole system. These drivers are external elements not under the farmers' control, which influence the state of the system.

The FCM obtained was used to simulate farmers' behavior and decision-making about alternative irrigation sources and about the choice of farming or fallowing their croplands.

3 Results and discussion

High environmental risks of aquifer and soil degradation were found in the study area, as mostly related to stakeholders' water management decisions and farmers' propensity to groundwater pumping rather than using service water. The most relevant findings of the present work, both from the interview survey and the modeling effort are presented and discussed hereafter.

3.1 Assessment of environmental risk

This section focuses on the identification of main environmental hazards in the study area and on the quantitative appraisal of impacts, both in terms of magnitude and probability of occurrence.

3.1.1 Hazard identification and risk-generating processes

The intensive aquifer exploitation by growers is the primary environmental hazard affecting the study area in the baseline scenario (business-as-usual). Secondary hazards, such as decline in aquifer quantity and quality, as well as soil salinization may occur as consequences.

Table 2 shows pathways, receptors, and impacts identified for the primary hazard, from which it can be observed that intensive groundwater pumping (S1) by growers during peak irrigation periods (July and August) and inadequate water deliveries provided by the irrigation distribution system (S2) are primary causes of uncontrolled aquifer exploitation. The given existing market-oriented farming and the current water delivery service not matching farmers' water needs represent the main drivers underlying the current situation.

S1 is somewhat independent from S2 for different reasons: (a) groundwater pumping was the main irrigation supply before the "Sinistra Bradano" scheme was constructed and equipped for surface water delivery service by the WUO, thus farmers are well accustomed to this water source, also as a drought-mitigation supply; (b) whenever possible and economically viable, farmers prefer to have full control of their on-farm irrigation decisions; and (c) many farmers still perceive groundwater pumping as somewhat cheaper than service water, even though the contrary was shown by economic analyses on several instances.

The primary pathway (P1) goes through groundwater pumping, which in some peak-demand periods may exceed the natural recharge of the aquifer, causing groundwater overdraft (I1.1) and giving way to seawater intrusion and to saline contamination of aquifers (I1.2). The secondary pathway (P2) refers to the inadequate irrigation delivery service by the collective water distribution network, which encourages many farmers to pump groundwater, and also results in the use of saline water on fields causing salts build-up (I2.1). The inadequate water delivery service provided by the

Table 2. Sources pathways receptors and impacts of the primary hazard

Hazard	Source	Pathway	Receptor	Impact
H1 Aquifer uncontrolled exploitation	**S1** – Intensive pumping by farmers during peak demand periods	**P1** – Aquifer	**R1** – Aquifer	**I 1.1** – Aquifer depletion **I 1.2** – Salinization by seawater intrusion
	S2 – Inadequate water delivery through the irrigation distribution system	**P2** – Aquifer	**R2** – Soils	**I 2.1** – Salt build-up in cropped soils

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WUO-operated distribution system includes delayed start of irrigation delivery relative to timing of crop irrigation demand, fixed rotation schedule, long irrigation intervals, large discharges, and insufficient pressure at hydrants. These factors contribute to a heavy dependence on groundwater pumping throughout the study area, which in turn results in aquifer drawdown and water quality degradation, as salts from seawater intrusion are progressively deposited onto fields. If salt leaching is not regularly conducted by farmers during irrigations, or the seasonal rainfalls are not sufficient to flush salts beyond the root zone, salt build-up will eventually have adverse impact on soil productivity.

3.1.2 Controlling factors of hazards and magnitude of impacts

The aquifer exploitation by farmers indirectly depends upon the following factors: (a) crop water use; (b) irrigation delivery schedule enforced by the WUO; (c) on-farm irrigation practices; and (d) natural salt leaching and aquifer recharge.

The overall magnitude of impacts was estimated based on three criteria, namely: (1) the spatial distribution of impacts; (2) their duration over time; and (3) the time necessary to realize impacts. Consultation with environmental experts allowed assigning partial scores to such impacts for each criterion on a scale ranging from 1 to 4. Score assignment was thus based on expert opinion and led to the ratings shown in Table 3.

The overall magnitude of impacts was computed through a weighted average of the partial scores assigned to the three criteria. Such scores were based on equal weight of each criterion relative to the overall score, following consultation with experts, as suggested by Gwartney et al. [40].

The magnitude of impacts was then classified based on a scale between 0 and 4, ranging from "negligible" (score 0–1) to "mild" (score 1–2), to "moderate" (score 2–3) to "severe" (score 3–4), as shown in Table 4.

3.1.3 Estimation of risk probabilities and risk significance

The overall probability of hazards was also estimated on the basis of three criteria: (1) the likelihood of hazard occurring; (2) the probability that receptors could be exposed to hazards; and (3) the probability that harms could result to the receptors. Similarly as in the previous case, such probabilities were assessed on the basis of expert opinion and then classified on a scale from 0 to 3, *i.e.*, "not occurring" (score = 0), "low" (score = 1), "moderate" (score = 2), and "high" (score = 3), as shown in Table 5.

To assess the overall probabilities of hazards, the partial scores assigned to each criterion were multiplied, considering equal weights for each of them, and afterwards the resulting scores were classified, as reported in Table 6.

Table 4. Estimated magnitude of impacts

			Criterion			Overall magnitude	
Hazard	Receptor	Impact	1	2	3	Average score	Classification
H1	R1	I 1.1	4	2	3	3.0	Moderate
		I 1.2	4	2	3	3.0	Moderate
	R2	I 2.1	4	2	4	3.3	Severe

Figure 4 shows a simple matrix with two-ways entry that was created to provide an analytical and consistent basis to make decision while assessing the environmental risks. The risk significance was estimated combining the magnitude of impacts and risk probability, and yielded results shown in Table 7, which clearly shows high risk significance resulting from high magnitude of impacts and high probability of occurrence of aquifer depletion and salinization, as well as salinity build-up in cropped soils.

The values of Table 7 were finally displayed in the matrix of Fig. 4, which clearly shows that the three above-mentioned impacts generated by the uncontrolled groundwater pumping are located in an area of the graph of high magnitude and high probability of occurrence, thus their risk significance is high.

The results from the risk assessment methodology were then validated by implementing two models aimed at simulating farmers' decisions regarding irrigation sources and management. The first model simulates the root-zone daily soil water balances for the cropped fields, and was used to evaluate the adequacy of irrigation delivery service provided by the WUO-operated distribution system. The second model reproduces farmers' propensity to utilize different sources of water, and the reactions to different external drivers.

3.2 Irrigation delivery performance

Results from simulated soil–water balance for vegetables, table-grapes, and citrus, under the RDS and FDS scenarios are shown in Fig. 5. The figure shows that over-irrigation may occur under RDS at different times for all the three crops, whereas only vegetables and table-grapes may incur water deficits along the second half of the irrigation season. From the figure it can also be inferred that if growers irrigate following the FDS, irrigation management can be more efficient and allow avoiding both water deficits and excessive applications. It is worth emphasizing that the FDS is a stand-alone scenario, thus not complementing the RDS. In fact, when relying on groundwater pumping, farmers usually do not enroll and request

Table 3. Criteria and ratings utilized for estimating the magnitude of impacts

Spatial distribution on impacts			Duration over time			Time to onset the impacts		
Score	Range	Description	Score	Range	Description	Score	Range	Description
0	0%	Nowhere	0	0 years	None	0	>20 years	Not likely occurring
1	<5%	Localized	1	<5 years	Short term	1	10–20 years	Long term
2	5–15%	Scattered	2	5–20 years	Medium term	2	5–10 years	Medium term
3	15–50%	Widespread	3	20–30 years	Long term	3	1–5 years	Short term
4	>50%	Throughout	4	>30 years	Forever	4	<1 years	Immediate

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Table 5. Criteria and ratings utilized for estimating the risk probability

1) Probability of hazard occurring			2) Probability of receptor being exposed			3) Probability of harm to the receptor		
Score	Range	Description	Score	Range	Description	Score	Range	Description
0	0–10%	Not occurring	0	0–10%	Not occurring	0	0–10%	Not occurring
1	10–30%	Low	1	10–30%	Low	1	10–30%	Low
2	30–50%	Moderate	2	30–50%	Moderate	2	30–50%	Moderate
3	>50%	High	3	>50%	High	3	>50%	High

irrigation delivery service from the WUO, not to incur in water fees in addition to their on-farm irrigation cost.

3.3 Reproducing farmers' decision-making on alternative irrigation supplies

Figure 6 shows the FCM, which graphically represents the models and drivers of irrigation decisions derived from the interviews. The three levels of thickness of the causal arcs on the map represent the strength of the connections that are "high," "medium," and "low," while the "+" and "−" signs represent positive and negative nature of the links. Such a cognitive map is the result of aggregating individual farmers' FCMs in this specific study area, and comprises nodes representing the main variables influencing farmers' behavior, and arrows that represent causal assertions.

Table 6. Estimated risk probability

			Criterion			Overall probability	
Hazard	Receptor	Impact	1	2	3	Average score	Classification
H1	R1	I 1.1	3	3	3	3.0	High
		I 1.2	3	3	3	3.0	High
	R2	I 2.1	3	3	3	3.0	High

Negligible (score = 0), low (score = 0–1), medium (score = 1–2), high (score = 2–3).

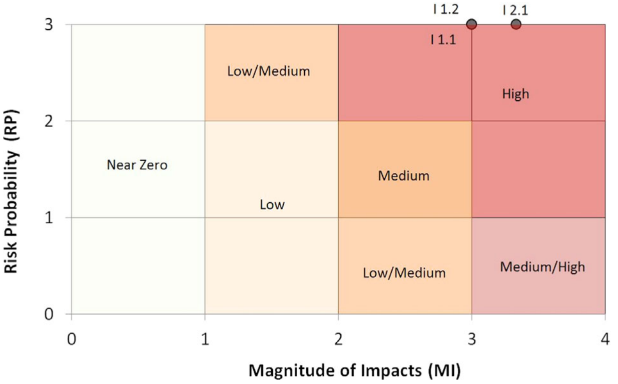

Figure 4. Estimated significance of aquifer degradation risk in the "Sinistra Bradano" area.

Table 7. Estimated risk significance

Hazard	Receptor	Impact	Magnitude of impacts	Risk probability	Risk significance
H1	R1	I 1.1	3.0	3.0	High
		I 1.2	3.0	3.0	High
	R2	I 2.1	3.3	3.0	High

As shown in Fig. 6, growers can alternatively decide to rely on water delivered by the WUO-operated distribution system or on groundwater pumping. Another relevant decision concerns either continuing in the farming business or laying fallow lands. The FCM shows that both groundwater withdrawals and climatic conditions have a direct impact on groundwater depth: if groundwater abstractions increase and drought occurs, the aquifer level is lowered and the salinity increased. The map also shows the main farmers' objective, *i.e.*, maximizing the income from farming activities, which is directly dependent on crops yield. If sufficient irrigation water is timely available and the overall irrigation costs are bearable, growers will achieve profitable income and continue farming. Market conditions represent another important driver influencing the economic profitability of farming activities: favorable market encourages growers maintaining or increasing the cropped acreage and agricultural production, whereas unfavorable conditions will lead them to fallow croplands.

For the "Sinistra Bradano" area, external drivers of the system can be grouped as follows:

a. *Weather conditions*: These are mainly due to temperature and rainfall. In the FCM, this variable measures to what extent temperature and rainfall are favorable to farming. A fuzzy linguistic function was defined, with increasing values as "strongly unfavorable," "unfavorable," "favorable," and "strongly favorable."
b. *WUO's regulations*: These are related to water pricing, timing of irrigation season start, relative to timing of crop irrigation needs, and the rotational intervals between irrigations within the enforced delivery schedule. For this driver, fuzzy linguistic functions were defined with reference to values of revenue: (a) water pricing: "high," "medium," and "low"; (b) delay in irrigation season start: "significantly delayed," "delayed," and "not-delayed"; and (c) rotational interval: "significantly long," "long," "short," "significantly short."
c. *Market conditions*: Many farming decisions are strongly influenced by the market price of the agricultural products, in which possible values of market conditions could be defined as "strongly favorable," "favorable," "unfavorable," "strongly unfavorable."

Three different scenarios were simulated by means of an Excel application by modifying the values of the external drivers. First, the worst case scenario was simulated; "strongly unfavorable" climatic conditions, "high" water pricing; "significantly delayed" irrigation season start, and "strongly unfavorable" market conditions. The initial values of these variables in the vector were changed

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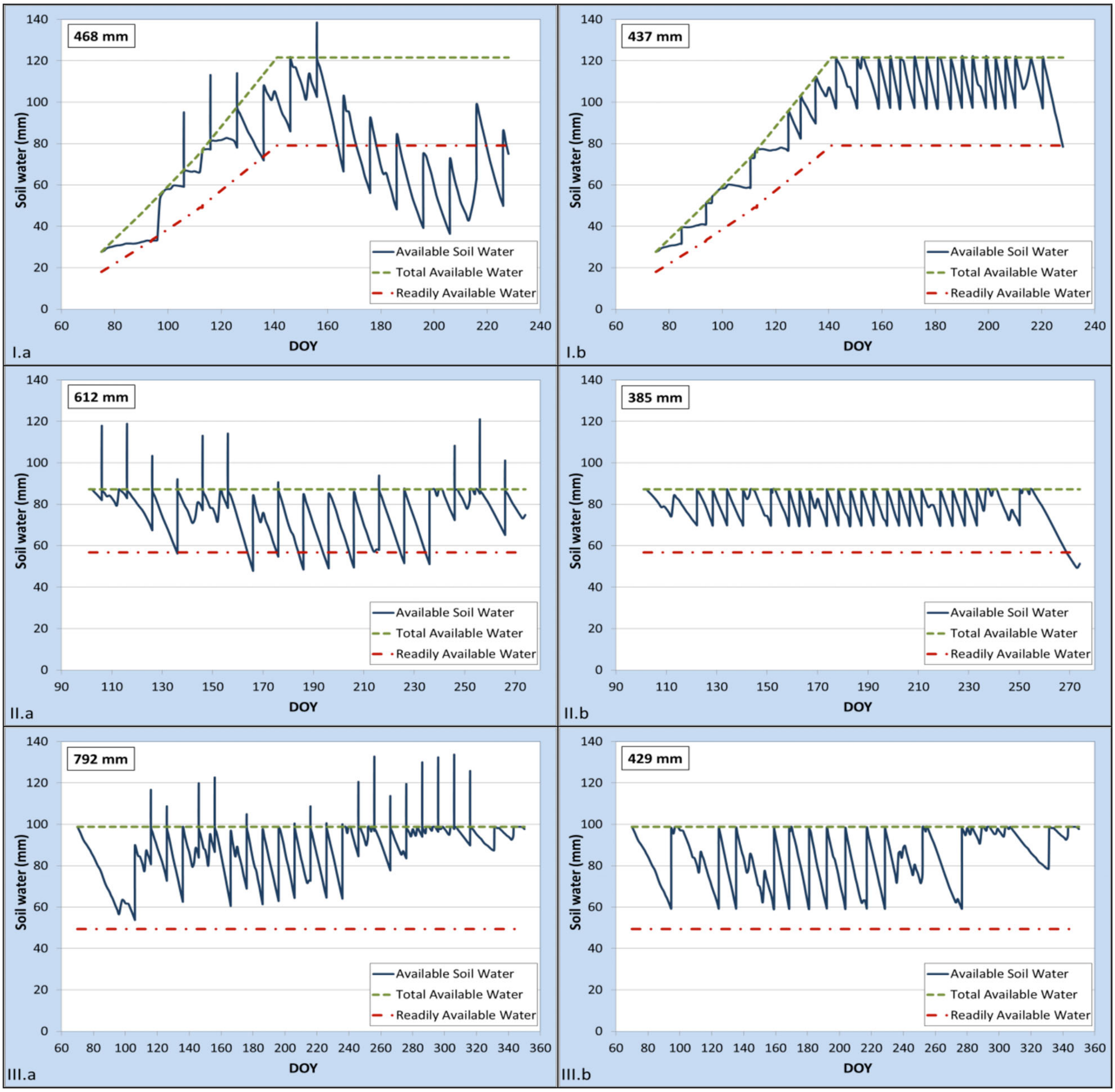

Figure 5. Simulated soil water balance (modified from [15]) for: (I) vegetables grown on sandy-loam soil; (II) table-grapes grown on loamy-coarse sandy soil; and (III) citrus grown on loamy-sand soil, under the RDS (sections a) and FDS (sections b).

accordingly. The equation reported below was used to simulate the impacts of these variables on the state of the system

$$C_1^{t+1} = \sum_{j=1, j\neq i}^{n} C_j^t W_{ji} \qquad (1)$$

where C_{t+1} is the value of the concept C_i at time $t+1$; C_{jt} the value of the interconnected concept Cj at step t; and W_{ji} is the weighted arc from C_j to C_i. The initial running of the FCM starts assigning the value 1 to the above mentioned variables. Then, Eq. (1) is iteratively implemented to change the values of the variables, which are reported on the vertical axis of Figs. 7–9 until they reach the steady state. The steady states are thus used as basis to compare the values of the variables in each scenario.

The conditions shown in the Fig. 7 describe the current state of farming, as reported by several farmers and irrigation system operators during interviews.

The analysis of this diagram allows drawing some important conclusions concerning the farmers' behavior under drought conditions. The negative market and the high water pricing may lead to fallow lands, adversely impacting farm income. In some instances, the tendency to quit farming has the effect of reducing groundwater abstractions. Therefore, under this scenario the impact on the groundwater use decreases, but a strong social conflict could emerge.

Under strongly favorable market conditions (Fig. 8), growers will continue farming their lands, *i.e.*, the "fallow lands" variable does not increase. The WUO's regulations about water pricing and timing

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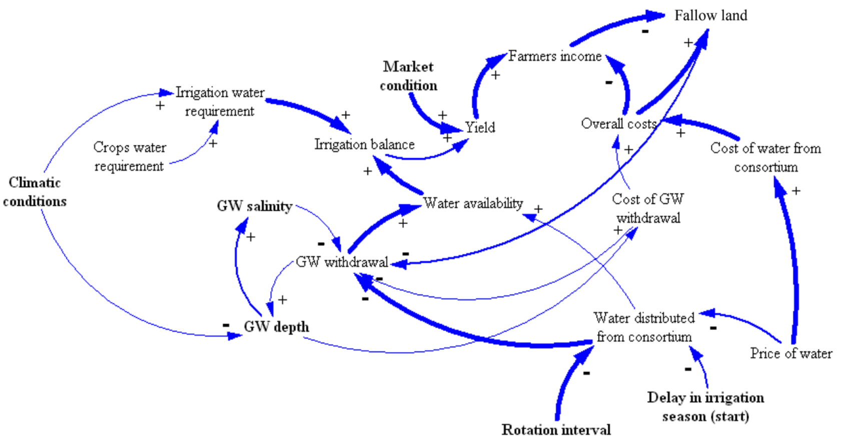

Figure 6. FCM describing the farmers' behavior regarding selection of alternative irrigation sources.

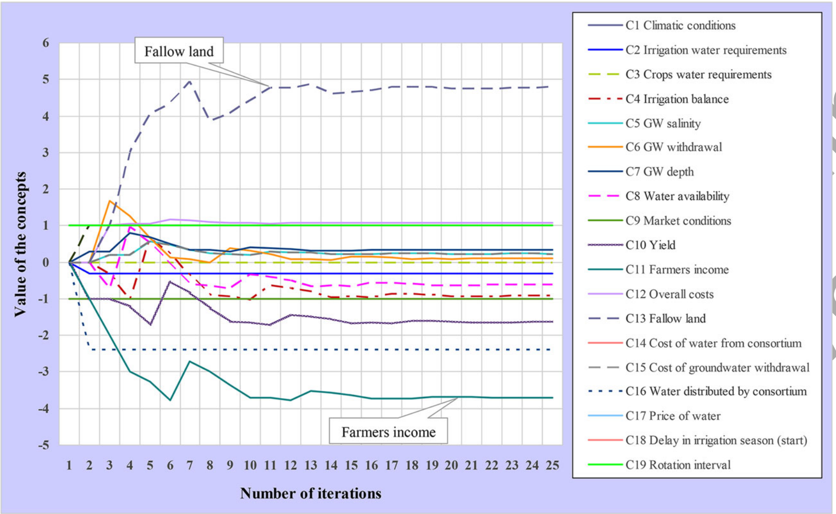

Figure 7. State of the system in the worst case scenario.

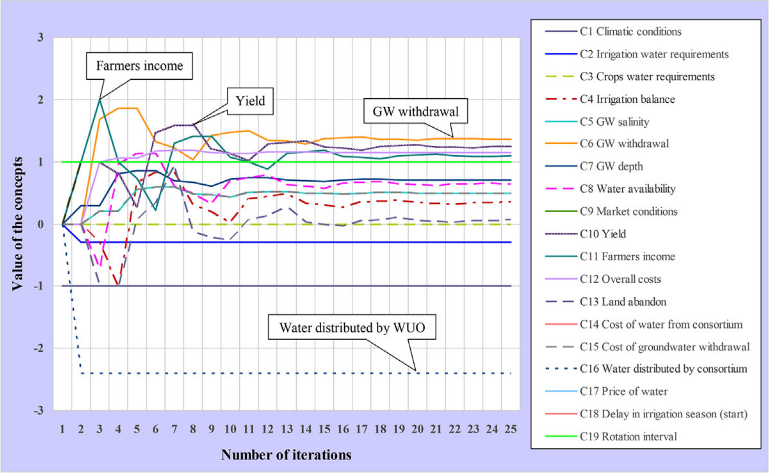

Figure 8. State of the system under favorable market conditions.

of irrigation season starts have the effect of encouraging to using groundwater as primary irrigation source in order to achieve profitability, leading to increased pressure on groundwater resources.

Figure 9 shows how better informed decisions and improved delivery service by WUO, *i.e.*, relatively low water pricing, shorter rotation delivery intervals, and timely irrigation season start, could positively impact farmers' decisions. Such improved WUO regulations would lead farmers to prefer water delivered by the distribution systems as primary irrigation source. This would also reduce land fallowing, decrease groundwater abstractions, and stabilize or even increase farmers' income.

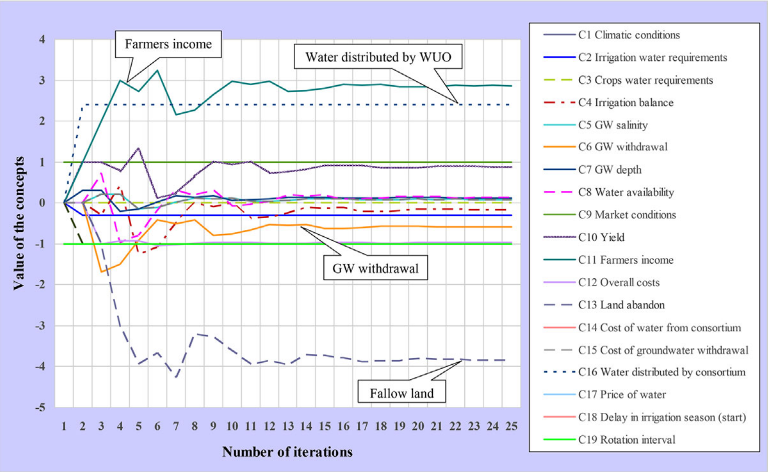

Figure 9. System state under favorable market conditions, unfavorable climatic conditions, and enhanced WUO's policies.

The FCM analysis allowed validating the results from the risk assessment. The simulations clearly showed the impacts of farmers' decisions to groundwater abstraction and quality. Importantly, FCM analysis demonstrated the role played by the WUO's water management policies on farmers' behavior. The current situation, characterized by high water price, delayed start of the irrigation season, and unsatisfactory rotational schedule of water distribution has resulted in an unsustainable use of groundwater. Moreover, these conditions are encouraging farmers to fallow lands, thus leading to an increasing level of social conflict. It could be inferred that the two pathways of risk described in Section 3.1 are tightly interconnected.

Furthermore, FCM analysis provides some preliminary indications about possible risk mitigation measures and demonstrated how an ineffective water management strategy by WUO led to farmers' decisions on groundwater dependency and over-use. The risk of groundwater depletion cannot be effectively managed without fostering a significant change in the WUO's regulations and water management strategy. Currently, water pricing and the fixed rotational schedule is not acceptable to the majority of farmers.

Future investigations and data analysis are necessary to better define and appraise a set of detailed and cost-effective risk mitigation options with broader involvement of local stakeholders.

4 Conclusions

In the present study, information collected from farmers and delivery system's operators, and groundwater observations were coupled with a modeling effort, which jointly illustrated the growers' dependency on pumping groundwater, as well as the long-term environmental impacts. Analyses also showed that the inclination of farmers to depend on groundwater is more influenced by the unreliable irrigation delivery service than by groundwater salinity and cost of groundwater pumping.

Reductions in the risk of soil and aquifer degradation could be achieved through enhanced irrigation delivery service to farmers. Further field investigations and data analysis are yet necessary to better define and prioritize cost-effectiveness and social acceptability of risk management measures.

Overall, the present work showed that a detailed elaboration of environmental risks as well as communication between all parties are essential to the development of informed and responsible decisions. Integration of field investigations and modeling tools proved to be useful in analyzing complex water management scenarios. Public participation is a key factor in making informed decisions about water resources access and use.

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