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Irrigation Delivery Performance and Environmental Externalities from a Risk Assessment and Management Perspective

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1. Introduction

As a whole the Mediterranean region holds 3 % of the world's freshwater resources and hosts more than 50 % of the "water poor" population, i.e. people with less than 1000 m^3 per capita per year. In the Mediterranean countries access to water and irrigation is crucial for land productivity and stability of agricultural yields (Benoit and Comeau 2005). But the balance between water demand and availability in irrigated areas is reaching critical levels (EEA 2012) in parts of the Mediterranean region and is an increasingly difficult task to achieve, both in spatial and temporal terms. Fresh water supplies are in fact mostly limited and the national strategies of many countries are no longer addressed towards developing new water sources and storage infrastructures. On the other hand, water demand is progressively rising up, mainly due to population increase and to policies of agricultural development and farming intensification for food security goals. The European Environment Agency (EEA 2010) reported that climate change is likely to increase the current pressures on water resources and that increasingly much of the Mediterranean countries will face reduced water availability during summer months, while the frequency and intensity of drought is projected to increase in the southern areas.

The recurrent drought periods occurring under Mediterranean climatic conditions thus represent the major water scarcity issue for irrigated agriculture but, besides that, poor irrigation management and inappropriate delivery schedules are often the problems (Clemmens 2006; Hargreaves and Zaccaria 2007). Clemmens and Molden (2007) stressed the importance of flexibility and quality of delivery service on the economic and environmental viability of irrigation projects. Merriam and Freeman (2002) documented that accurate on-farm control of irrigation water deliveries can contribute to reducing

drainage and salinity problems on the project scale caused by excess, inadequate and non-uniform applications. Styles (1997) reported that in several areas of the world a significant increase in the number of farmers using irrigation wells has been observed during the last decades, even where less expensive irrigation water was available from the district, in response to the lack of flexible deliveries from the distribution networks. As pointed out by Umali (1993), poor water management by irrigation agencies is one of the leading grounds for irrigation-induced salinity in many agricultural areas. As a matter of fact, salinity problems in irrigated agriculture may often result from seawater intrusion into coastal areas where the water tables have been lowered due to mining of groundwater for irrigation purposes (Kijne et al. 1998). Zaccaria and Scimone (2008) refer that often times, when water distribution by the management authority is unreliable, inadequate in terms of delivery conditions, rigid or not timely matching crop water demand or growers' needs and practices, farmers tend to rely on aquifers as main water source for irrigation.

Sanaee-Jahromi et al. (2001) clarified that the delivery schedule performance relates to how well the water delivery schedule matches the crop irrigation requirements, whereas the operation performance refers to the ability of the system to supply water according to the schedule.

As for soil and aquifer degradation, Paniconi et al. (2001) and Capaccionia et al. (2005) pointed out that in coastal areas periods of intensive groundwater pumping for irrigation purposes can cause a drawdown of water levels in aquifers and give way to seawater intrusion, often leading to salt build-up in the cropped soils.

The present study was conducted on the Sinistra Bradano irrigation system managed by a local Water Users Association (WUA) to supply an irrigated agricultural area located in the western part of the province of Taranto (Apulia region, southern Italy) that stretches along the Ionian coast. Large reductions in the area serviced by the irrigation delivery networks operated by the WUA, and strong increases in the area irrigated by growers through groundwater pumping from farm tube wells occurred during the last 10 years, as documented by Zaccaria et al. (2010) on the basis of records provided by the WUA and by INEA (1999).

Under the perspective of responsible use of natural resources, a simplified Risk Assessment and Management procedure (RA&M) was thus applied to the study area for quantifying the risks of soils and aquifer degradation. Some feasible management options were also appraised for risk mitigation purposes on the basis of specific decision-making criteria.

2. Study area description

The "Sinistra Bradano" irrigation scheme (Fig. 1) covers a total command area of 9,651 ha and an irrigable area of 8,636 ha. This area was equipped for irrigation during the period from 1968 to 1974 and extends over an alluvial plain, with land elevation ranging between 24 and 54 m a.s.l. The irrigation system was designed for surface irrigation methods and is subdivided into 10 operational districts, each being composed by sub-units called sectors

that consist of a grouped number of farms. The system is managed by a local association of water users, namely the "Consorzio di bonifica Stornara e Tara" that distributes irrigation water to horticultural growers from mid April to late October by rotation delivery schedule. The rotation is fixed for the entire irrigation season with a flow rate of 20 l s^{-1} ha^{-1}, 5 hours of delivery duration to each user, and a delivery interval of 10 days.
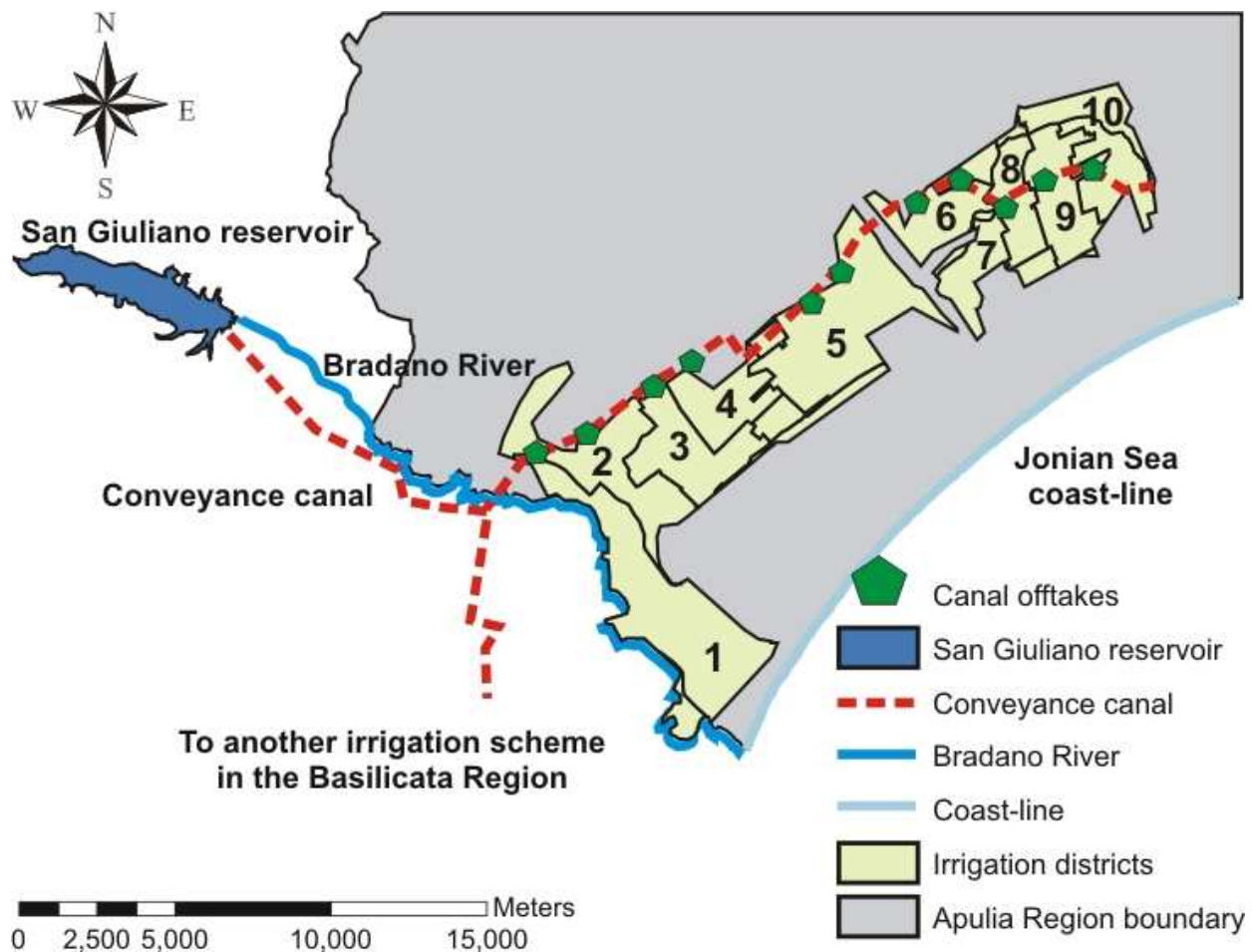

Figure 1. Overview of the Sinistra Bradano irrigation system.

The main source is the Bradano River, whose water gets partially diverted and stored in the "San Giuliano" reservoir of a total capacity of 70 Mm^3, which is located in in the nearby region of Basilicata. Water is then conveyed from the San Giuliano reservoir to the study area by a main canal along which 10 open-branched district distribution networks originate that divert water to the district distribution networks. Water diversion from the main canal occurs through cross-regulators and undershot gates, which are manually operated by the WUA's staff on a regular basis for implementing the planned delivery schedule. Water is finally distributed to users through gravity-fed branched delivery networks consisting of buried pipelines, and pressure at farm hydrants ranges between 0.3 and 0.6 bars depending on their ground elevation relative to the canal off-takes, thus resulting from the difference in elevation between the inlets of the distribution networks and the lower-elevation irrigated areas.

Climate of the area is semi-arid to sub-humid and referred to as "Maritime-Mediterranean", which is typical of the coastal areas of the Mediterranean region. Precipitation ranges between a minimum of 400 mm, in south-eastern part of the scheme, and a maximum of 730 mm in the northern part of the scheme. The average yearly rainfall is around 550 mm, 35 % of which occurring during the winter months, 32 % during fall and 33 % during spring and summer. There is typically very little summer precipitation, thus summer droughts are frequent, and irrigation is usually needed from April to September. Because of semi-arid climatic conditions, profitable farming in the area depends largely on irrigation.

The main crops grown in the area are citrus, table grapes, olive trees and summer vegetables, whose relative distribution is reported in Table 1 and Figure 2 as referred to the year 2006. Soils are mainly of alluvial type, resulting from deposits onto flat clayey plains that were afterwards subjected to a long period of carbonate leaching. For the purposes of the present study the cropped soils were grouped into five classes, according to the USDA soil textural classification, as shown in the soil map reported in Fig. 3, with most of the cropped areas being on loamy-sand. The electrical conductivity (EC) of soils, measured during a survey campaign in 2006, resulted in a range of values between 0.064 and 0.635 dS m^{-1}.

CROP	AREA (Ha)	Area (%)
Table-grapes	3,753	43.5
Citrus	2,208	25.6
Vegetables	2,184	25.3
Olives	432	5,0
Almonds	14	0.1
Orchards	44	0.5
TOTAL	8,635	100

Table 1. Cropping pattern and relative distribution in the Study Area

At farm level, micro-irrigation methods are currently used by growers in the majority of cropped areas, whereas sprinkler irrigation covers only 20% of the citrus acreage. Surface irrigation is no longer practiced due to high labour costs. In a few larger farms, small storage reservoirs were constructed by farmers with the aim of buffering the delivery timing and discharge to achieve higher flexibility in crop irrigation management.

As for the service area, even though the cropped area has not changed over the years, the area irrigated with water supplied by the WUA's networks progressively decreased since 1990 and onward, with no significant changes in the cropping distribution. Based on WUA's records reported in Table 2, the area requesting irrigation delivery service from the WUA passed from 2,128 ha in 1997 to only 921 ha in 2007, out of a total cropped and irrigable area of 8,636 ha.

Several farmers and extension officers from the study area were interviewed and reported that the irrigation delivery schedule enforced by the WUA is too restrictive with respect to the prevailing farming conditions, and not often timely to match the actual crop water

requirements and farmers' irrigation needs (Zaccaria et al. 2006). The rigid rotation supply may in fact cause wasteful water use due to improper timing, over-irrigation and runoff, and may inhibit good farm management, as documented by some authors (e.g. Merriam et al. 2007).
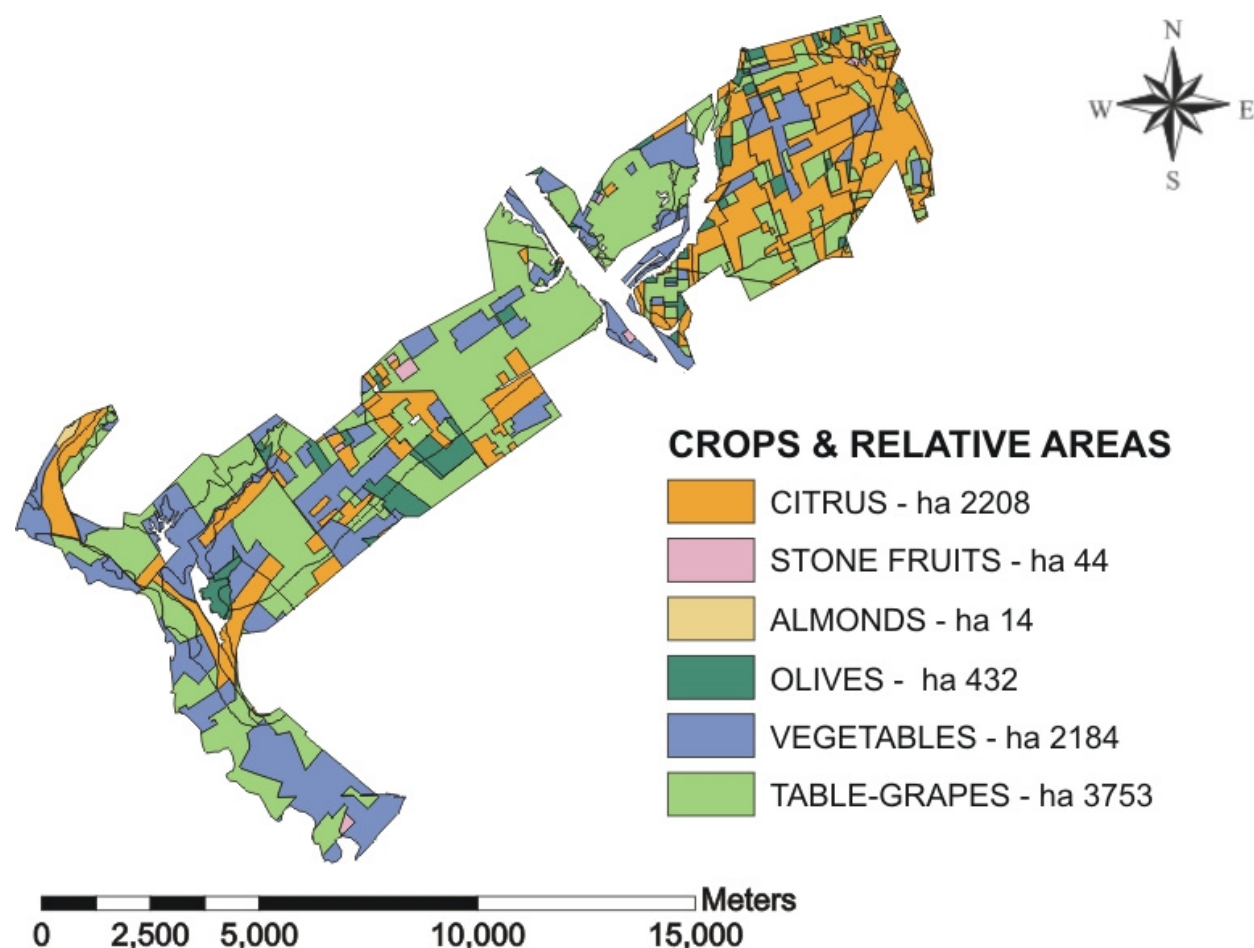

CROPS & RELATIVE AREAS

CITRUS - ha 2208

STONE FRUITS - ha 44

ALMONDS - ha 14

OLIVES - ha 432

VEGETABLES - ha 2184

TABLE-GRAPES - ha 3753

Figure 2. Cropping pattern of the Sinistra Bradano irrigation systems for 2006

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Area (ha)	2,128	2,046	2,026	2,044	1,815	-	1,354	1,183	1,004	987	921
Area (% of irrigable)	24.6	23.7	23.4	23.7	21.0	-	15.7	13.7	11.6	11.4	10.7

Table 2. Areas serviced by the WUA in the years 1997-2007 in the Sinistra Bradano irrigation system (Source: Stornara e Tara Water Users Association, 2008)

The reduction in the area serviced by the WUA indicates that the area irrigated by groundwater pumping has tremendously increased over the years, most likely as a consequence of inadequate water delivery conditions with respect to the actual farmers' requirements. In other words, during the different years farmers irrigated larger areas exclusively relying on groundwater pumping, most likely for avoiding the limitations imposed by the rotation delivery schedule. Major changes, instead, occurred to the farm

irrigation methods, as the majority of growers passed from surface methods to pressurized high-frequency irrigation. As reported by the extension agents and farmers' representatives interviewed, when the water supply is flexible and shows no delivery constraints (i.e. storage reservoirs, holding ponds or groundwater pumping), growers usually tend to distribute small amounts of water to cropped fields by means of micro-irrigation systems with high frequency, which also varies during the irrigation season in response to perceived crop water needs.
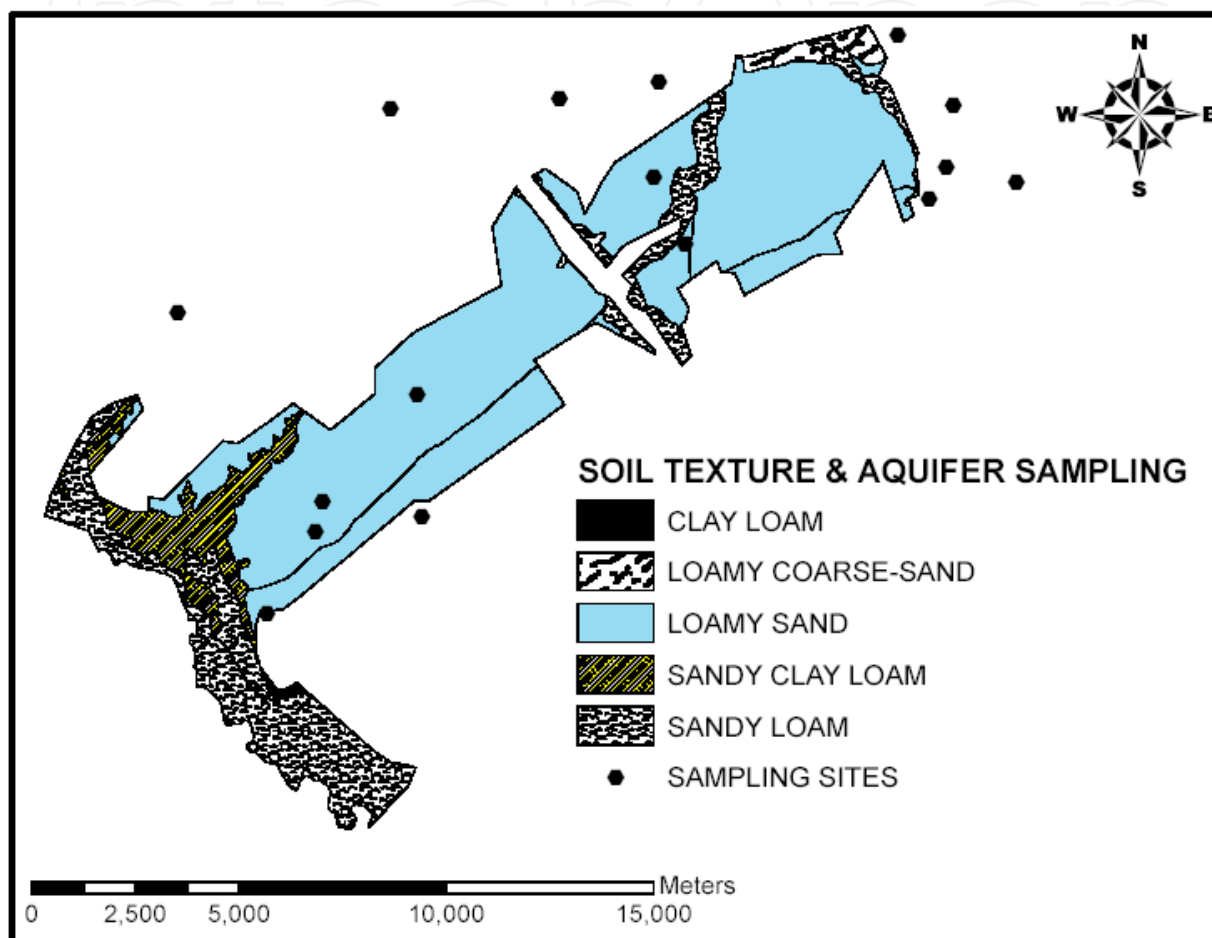

Figure 3. Soil map of the Sinistra Bradano irrigation system (textural classification according to the USDA soil classification), and sites of groundwater sampling conducted in 2006

According to extension service agents and growers' representatives, the majority of farmers consider the water distribution conducted by the WUA as not matching the actual crops' needs and farmers' requirements, both in terms of timing and of conditions of delivery. Delivery intervals, flow rates and pressure heads available at hydrants are found to be inadequate by farmers for the prevailing farming practices. As a result, during the last 10 years many growers relied nearly exclusively on groundwater pumping for irrigating their crops for large part of the irrigation season in order to achieve the desired flexibility.

As such, a concentration of groundwater pumping is found to occur during the peak water demand periods (July and August). This has progressively led to high antropogenic pressure on groundwater resources and has started originating aquifer contamination and

soil degradation, namely due to seawater intrusion in the groundwater and salt build-up in the agricultural soils, which are considered as the major causes of environmental degradation in the study area.

Some research works conducted in areas bordering the system under study (Polemio and Ricchetti 1991; Polemio and Mitolo 1999; Polemio et al. 2002) revealed that seawater intrusion is progressively increasing in the whole Ionian coastal aquifer. A strong increase in the area subjected to seawater intrusion was also documented by Zaccaria et al. (2010) based on a comparison between two subsequent Regional Water Plans, namely the "Piano Regionale di Risanamento delle Acque" (Regione Puglia 1983) and the "Piano di Tutela delle Acque della Regione Puglia" (Regione Puglia 2007). This increase was found to be consistent with the strong increment in the number of agricultural wells drilled during the last decades throughout the whole area.
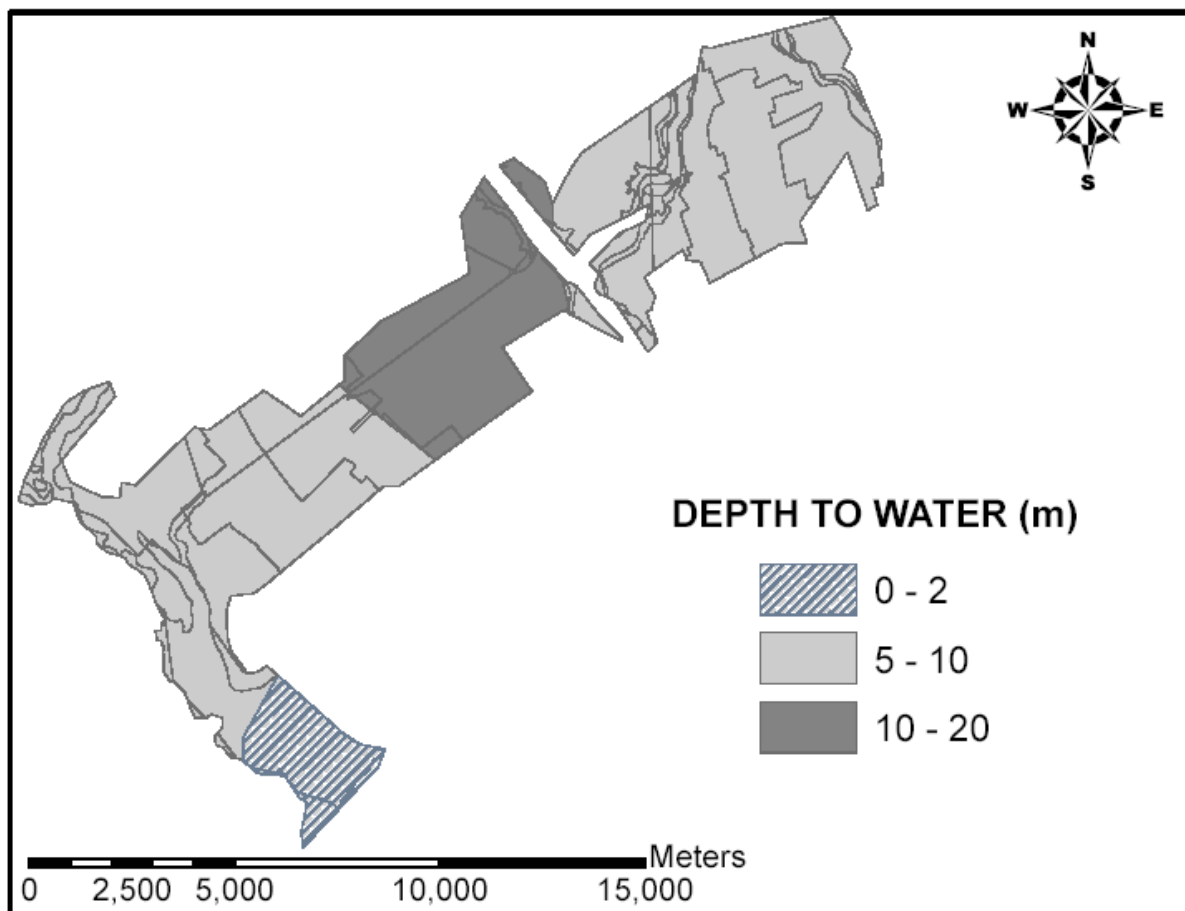

Figure 4. Depth-to-water map of the aquifer in the Sinistra Bradano area

The area under study is characterized by abundant groundwater resources coming from both a shallow upper unconfined aquifer and a deeper confined aquifer, whose hydrological set-up was described by Zaccaria et al. (2010) based on the outcomes of previous investigations (Cotecchia and Magri 1967; Cotecchia et al. 1971; Piccirillo 2000). According to Polemio et al. (2002) the shallow aquifer is subjected to heavy utilization and therefore to seawater intrusion. Observations of the water table depth were conducted in 2004 (Regione

Puglia 2007) and led to the development of the depth-to-water map (Fig. 4), which shows that the water table lies at depths ranging from 2 m (in the south-western part) to 20 m (in the north-eastern part) from the ground surface, confirming the easy access to the aquifer by farmers for irrigation purposes.

Seawater intrusion upon coastal groundwater was reported by Polemio et al. (2002) as a real problem for the social and economic development of this area, as results from the analysis of hydro-geological, chemical and physical data collected at boreholes in areas near the study site that revealed quality degradation of coastal plain groundwater, owing to seawater intrusion in the shallow aquifer. This evidence was also supported by data collected in the period 2006-2007 during a research project aiming at monitoring groundwater parameters at regional level (Regione Puglia 2006).

Detailed information on the operational procedures of the distribution networks, on the resulting effects on crop irrigation management by farmers, on the poor performance in water delivery, and on the impending need of system modernization were documented by previous research works and were all described in details by Zaccaria and Lamaddalena (2005), Zaccaria et al. (2010), and Zaccaria and Neale (2012).

3. Materials and methods

3.1. Soil water balance modeling

Simulations of daily soil water balance in the root zone were performed for forty-two unique crop-soil-climate combinations to compare the amounts of water applied, crop evapotranspiration, delivery schedule performance and the related yield impacts when irrigation is conducted under the current rotational delivery schedule (RDS) or if an alternative flexible delivery schedule is adopted (FDS). The crop-soil-climate combinations were identified by intersecting the cropping pattern map with the soil map and with the areas of influence of three meteorological stations (Ginosa Marina, Castellaneta and Massafra) located within or surrounding the study area, using commercial GIS software (ArcGIS). The procedure, models and data utilized for the above sets of water balance simulations are described in details in Zaccaria et al. (2010) and followed the methodology proposed by Allen et al. (1998). The delivery schedule performance was used as an indicator of potential room for water conservation.

Figure 5 presents the simulation results for the three main crops grown in the study area (vegetables, table-grapes and citrus) under the RDS and FDS scenarios.

For the simulations under rotation delivery scheduling (RDS), fixed irrigation dates and volumes were adopted to reproduce the current deliveries conducted by the WUA, i.e. irrigation intervals of 10 days, flow rate of 20 l s^{-1}ha^{-1} with 5 hours of delivery duration. For the simulations under flexible delivery (FDS), the irrigation schedules reproduced those that are commonly used by farmers when they rely on flexible or unconstrained water supply i.e. on-farm storage reservoirs, holding ponds, or groundwater pumping, and according to the irrigation methods and practices commonly utilized in the study area for each crop.
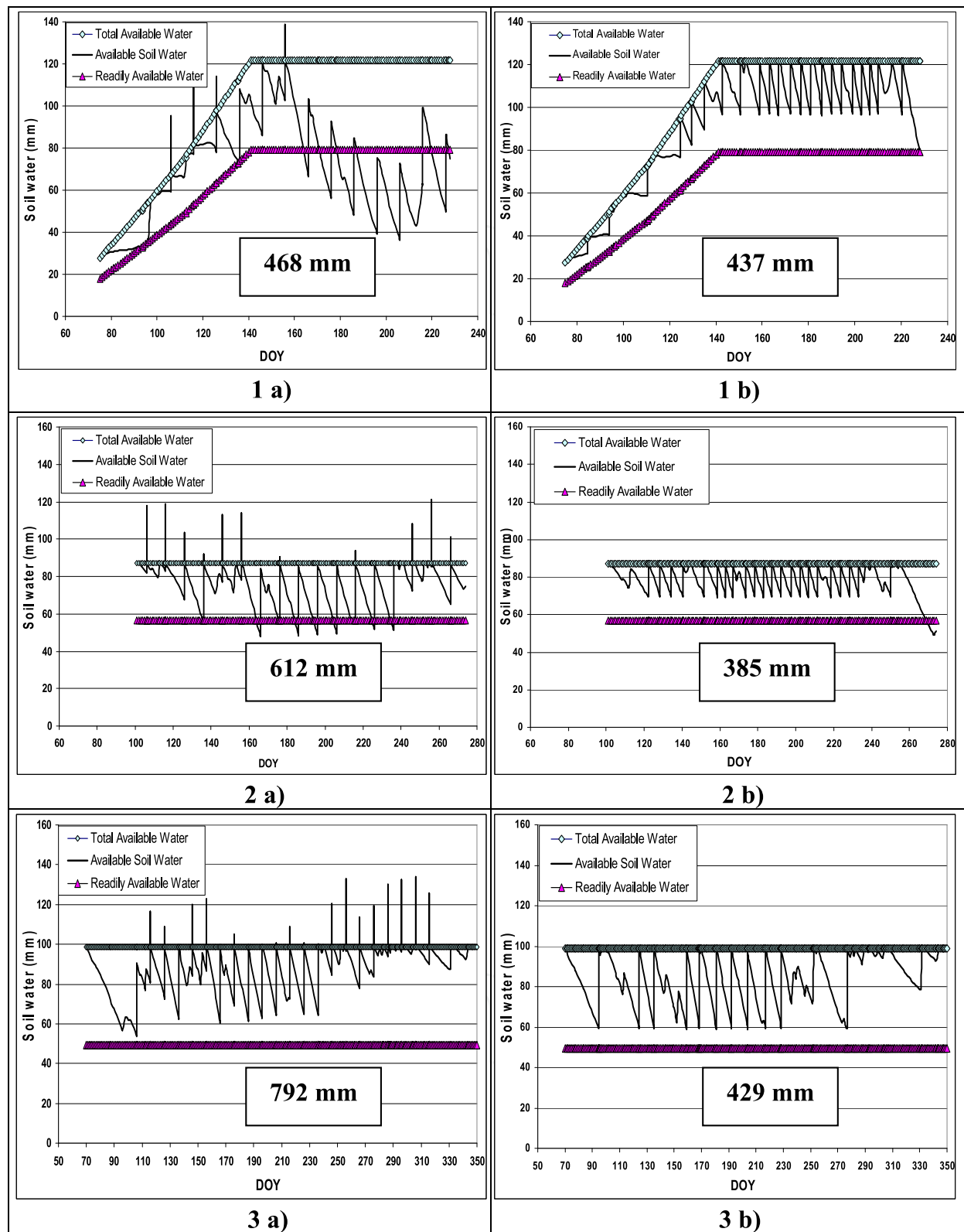
Figure 5. Simulated soil water balance for units consisting of 1) vegetables grown on sandy-loam soil in the area of Ginosa Marina, 2) table-grapes grown on loamy-coarse sandy soil in the area of Castellaneta, and 3) citrus grown on loamy-sand soil in the area of Massafra, under the RDS (sections a) and FDS (sections b).

The simulated irrigation scheduling shows that under RDS over-irrigation occurs at different times for the three main crops, whereas soil water deficits take place only for vegetables and table-grapes in the second half of the season. Alternatively, if farmers could rely on FDS, the irrigation management would be more effective at farm level and both water stress and excess applications could be easily avoided.

The results reported in Fig. 5 clearly show that farmers are heavily bounded by the present mode of operation of the water delivery system. If farmers irrigate in compliance with the fixed delivery currently scheduled by the WUA, the crops are likely to experience both situations of water deficit and excess waterings. The comparison between RDS and FDS schedules explains why many growers prefer to irrigate using groundwater pumping rather than rely on deliveries from the irrigation distribution networks. By managing farm irrigation under FDS growers can easily prevent water deficit and water excess to their crops by applying a lower amount of water than that under RDS. The simulation results are supported by information provided by the growers interviewed who reported that, in order to offset the restrictions imposed by rigid rotation delivery and to achieve more effective irrigation timing, many farmers pump water from the aquifer, which in their perception represents an unconstrained and flexible water supply.

3.2. Groundwater quality

Groundwater quality was sampled at eighteen sites throughout the Sinistra Bradano area in 2006 (Fig. 3), with two samples collected per each site, the first in February and the second in July. Measurements of total dissolved solids (TDS) and electrical conductivity (EC) were conducted on the groundwater samples, with TDS values determined by means of laboratory measurements using the gravimetric method, whereas EC values were obtained using a conductivity meter (Hanna Instruments, mod. HI 9835). Winter and summer salinity maps were developed based on the spatial interpolation of point-measured values of the TDS and EC, using the inverse weighted distance method embedded in the GIS software package. These maps are presented in Fig. 6 and seasonal changes in groundwater quality were assessed by comparing the aquifer salinity in winter with that of summer. The comparison showed that groundwater salinity increased in 2006 from winter (Fig. 6 – section a) to summer (Fig.6 – section b). The increase in groundwater salinity mainly concerned the eastern part of the study area. From Fig. 6 it can be inferred that the groundwater salinity in winter for the eastern part ranged between TDS values of 1.5 and 1.8 g l^{-1}, whereas it reached TDS values between 1.9 and 3.1 g l^{-1} in summer, which is most likely related to the intensive groundwater pumping during period of peak demand, specifically from May to August. The western-most part of the study area showed no significant increment of groundwater salinity. This can be reported as the main consequence of the inadequate delivery schedule enforced in the area.

3.3. Crop evapotranspiration and crop performance under saline irrigation

Salts brought into the soil water solution through irrigation with saline water can reduce crop evapotranspiration by making soil water less available to root extraction by plants,

thus creating low osmotic potential in the root zone. In other words, the total potential energy of soil water solution can be reduced due to the presence of salts. Some salts can even have toxic effects on plants or induce nutrient deficiencies, thus reducing plants metabolism and growth. Many plants can make physiologic adjustments and reduce the negative effects of low osmotic potential of soil water by adsorbing ions from soil solution and by synthesizing organic osmolytes. Both processes involve the use of metabolic energy by plants that often results in reducing growth and canopy development under saline conditions.

The response of different crops to salinity may vary, according to their different tolerances and to the physiologic capability to make the required osmotic adjustments, with some crops being able to yield acceptable productions at higher soil salinity than others. Keller and Bliesner (2000) developed a widely practiced approach for predicting the crop yield reductions due to salinity based on a yield-salinity equation adapted from Ayers and Westcott (1985), which is reported hereafter.

$$Y_r = \frac{Y_a}{Y_m} = \frac{\max EC_e - EC_w}{\max EC_e - \min EC_e}$$

where:
Y_r = relative yield
Y_a = actual crop yield
Y_m = maximum expected crop yield when $EC_e < \min EC_e$
max EC_e = electrical conductivity of the saturated soil extract that will reduce the yield to zero (dS m^{-1})
min EC_e = electrical conductivity of the saturated soil extract that will not decrease crop yield (dS m^{-1})
EC_w = electrical conductivity of the irrigation water (dS m^{-1})

Values for min EC_e and max EC_e for the main crops grown in the study area were taken from Keller and Bliesner, as adapted from Ayers and Westcott, and are listed in the Table 3.

CROP	min EC_e (dS m^{-1})	max EC_e (dS m^{-1})	Sensitivity to salinity
Table-grapes	1.5	12.0	Medium Sensitive
Citrus	1.7	8.0	Sensitive
Vegetables	1.5-2.5	10.0-14.0	Medium Sensitive
Olives	2.7	14.0	Medium Tolerant
Almonds	1.5	7.0	Sensitive
Orchards	1.5	6.5	Sensitive

Table 3. Salt tolerance of agricultural crops commonly grown in the study area

Provided that the impact of salinity on plants is a time-integrated process, generally only the seasonal effects are considered to predict the reduction in crops evapotraspiration, growth and yield as occurring over an extended period of time. The above equation is thus not expected to be accurate for predicting salinity effects on crop evapotranspiration and yield for short periods.

Within the present research the likely crop yield reductions due to the use of saline irrigation water were not estimated, as this process requires the collection of multi-annual data on soil and aquifer salinity at short intervals with the aim of assessing the time of crop exposure to different levels of salinity in the soil water and to determine the evolution of soil water salinity along the year as resulting from seasonal rainfall leaching salts from the root zones.

3.4. The ERA&M procedure

The local climatic conditions, as well as the intensive farming of agricultural areas together with the inadequate distribution of water supplies make "business-as-usual" not environmentally-viable in the area on the long run. In view of a strategic change to the existing situation, a simplified Risk Assessment and Management (RA&M) procedure was applied to the study area through a new framework to identify viable counter-measures and mitigation of the existing environmental concerns and risks.

The applied ERA&M procedure (Fig. 7) was developed within the STRiM project (www.strim.eu) funded by the EU under the INTERREG IIIB CADSES Programme. It is a simplified framework for conducting environmental risk assessment and management, predominantly based on the Environmental Risk Management guidelines issued by the Department of Environment Food and Rural Affairs (DEFRA, 2002) of United Kingdom, which focus on risk management and applicability to any type of environmental risk. The STRiM RA&M framework consists of 5 iterative steps and is linked to other key environmental protection decision-making procedures such as the Environmental Impact Assessment (EIA), the Strategic Environmental Assessment (SEA) and the framework conceived by the European Environmental Agency (EEA) on Driving Forces, Pressures, State, Impacts and Responses (DPSIR). Both the Risk Assessment (RA) and Risk Management (RM) phases require datasets to support decision-making, often in the form of indicators. In order to harmonize environmental protection management, the STRiM framework has the novelty of linking the DPSIR indicators and monitoring framework with RA and RM, something that was not attempted before. The framework embeds risk assessment into the risk management process and, as such, includes a number of key aspects emerging throughout the various steps of the process. Among these issues, the most relevant are: a) the importance of accurately defining the actual hazards or environmental problems; b) the need to prioritize all relevant risks prior to proceeding with their quantification through the data collection; c) the need to consider the risks while taking into account feasible management solutions through the use of option-appraisal from the initial stages; d) the iterative nature of the process.
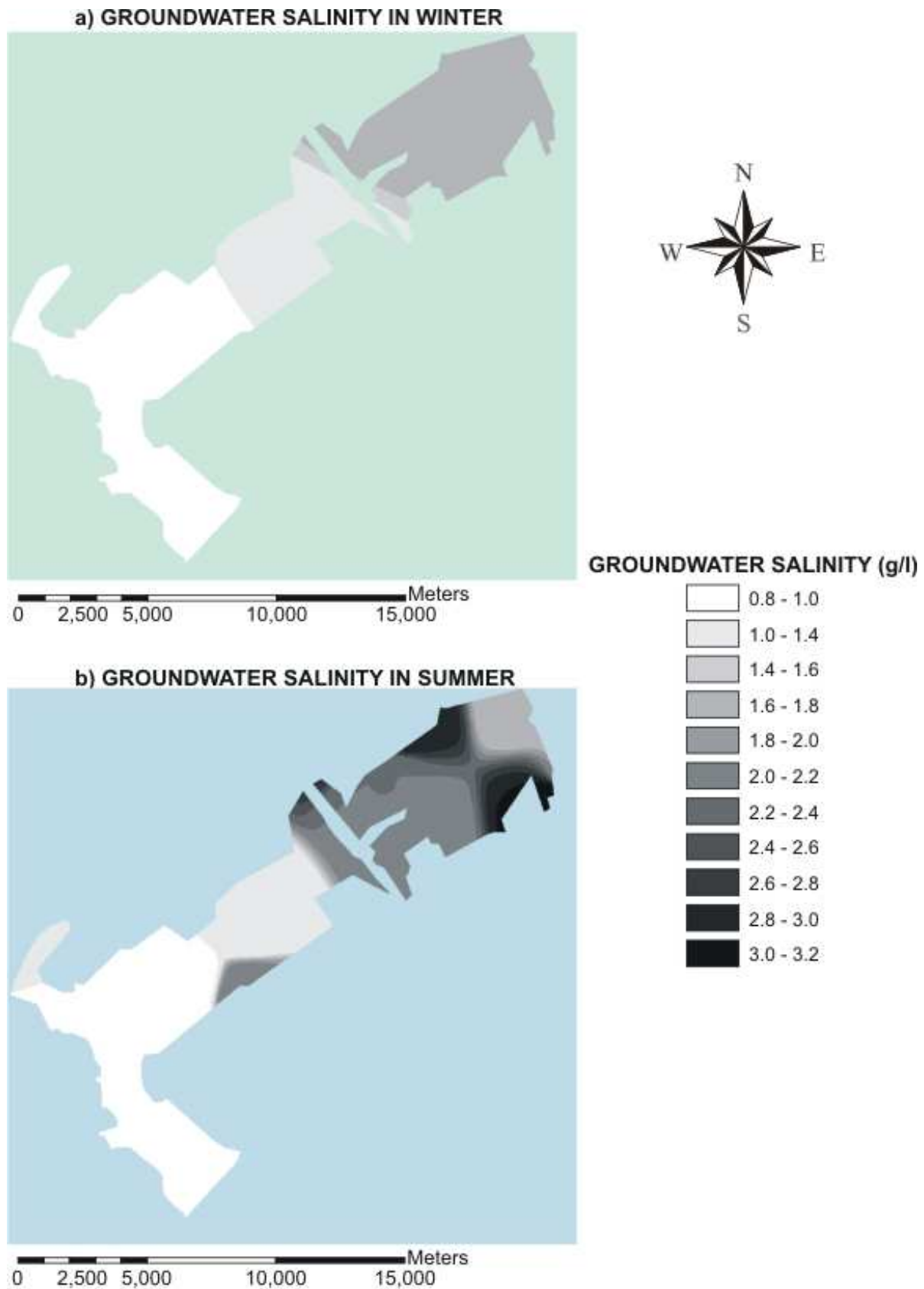
Figure 6. Map of groundwater salinity in the study area during winter (February) (a) and summer (July) (b) for the year 2006
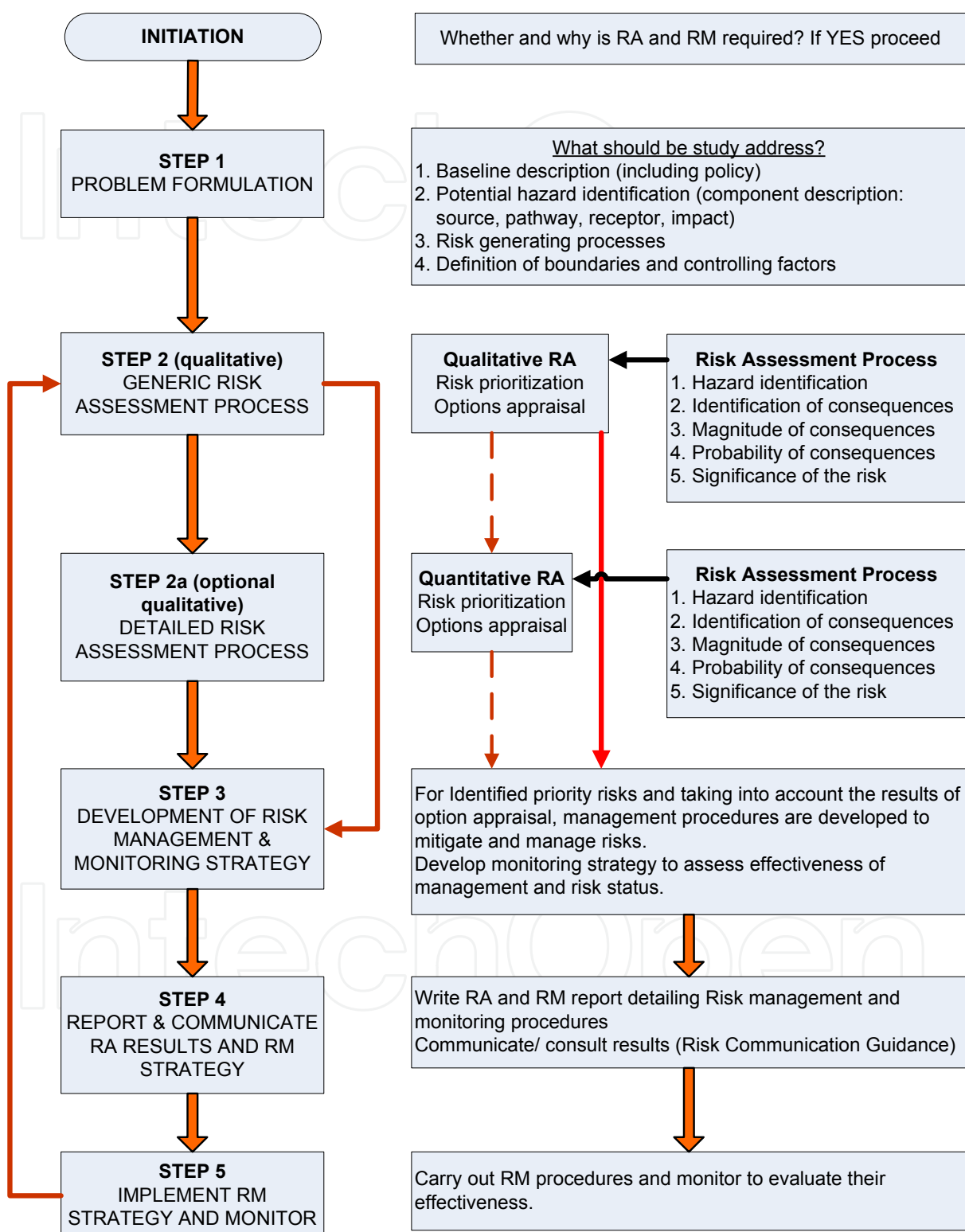
INITIATION — Whether and why is RA and RM required? If YES proceed

STEP 1
PROBLEM FORMULATION

What should be study address?
1. Baseline description (including policy)
2. Potential hazard identification (component description: source, pathway, receptor, impact)
3. Risk generating processes
4. Definition of boundaries and controlling factors

STEP 2 (qualitative)
GENERIC RISK ASSESSMENT PROCESS

Qualitative RA
Risk prioritization
Options appraisal

Risk Assessment Process
1. Hazard identification
2. Identification of consequences
3. Magnitude of consequences
4. Probability of consequences
5. Significance of the risk

STEP 2a (optional qualitative)
DETAILED RISK ASSESSMENT PROCESS

Quantitative RA
Risk prioritization
Options appraisal

Risk Assessment Process
1. Hazard identification
2. Identification of consequences
3. Magnitude of consequences
4. Probability of consequences
5. Significance of the risk

STEP 3
DEVELOPMENT OF RISK MANAGEMENT & MONITORING STRATEGY

For Identified priority risks and taking into account the results of option appraisal, management procedures are developed to mitigate and manage risks.
Develop monitoring strategy to assess effectiveness of management and risk status.

STEP 4
REPORT & COMMUNICATE RA RESULTS AND RM STRATEGY

Write RA and RM report detailing Risk management and monitoring procedures
Communicate/ consult results (Risk Communication Guidance)

STEP 5
IMPLEMENT RM STRATEGY AND MONITOR

Carry out RM procedures and monitor to evaluate their effectiveness.

Figure 7. The STRiM Risk Assessment and Management Framework (modified from DEFRA, 2002)

4. Hazard identification and Risk-generating processes

The aquifer over-exploitation is the primary environmental hazard impending in the study area. In view of this hazard, managing "business-as-usual" represents the intention for which the RA&M is required, the intention being defined as "*any course of action, intentional or otherwise, which by its nature may pose a risk to the environment - natural or built - and the life it sustains*". The "business-as-usual" or baseline scenario in the study area consists in maintaining the intensive farming practices along with the irrigation delivery schedule enforced by the water management authority. The secondary hazards resulting from the aquifer over-exploitation are those indicated in Fig. 8, whereas the sources, pathways, receptors and impacts are indicated in the Table 4 for the primary hazard.

The potential causes concurring to aquifer over-exploitation are the intensive groundwater pumping (S1) by farmers during peak irrigation demand periods (July and August) and the inadequate water distribution through the irrigation networks (S2). This situation is driven by the existing market-oriented agriculture that is based on water-demanding crops, and by the current operation of the irrigation distribution system that does not match with crops and farmers' water requirements. The primary pathway (P1) goes through groundwater pumping, which in some periods may occur beyond the safe yield of aquifer due to concentration of withdrawals. This has the effect of depressurizing the aquifer, giving way to seawater intrusion and to aquifer contamination by saline water. The receptor of salination by seawater intrusion is thus the aquifer itself.
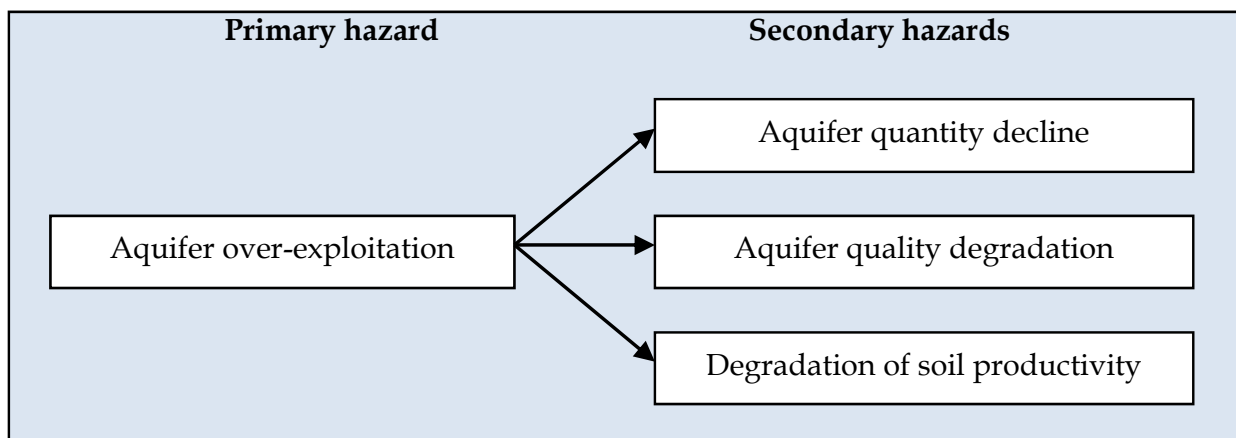

Figure 8. Primary and secondary hazards identified in the study area

The secondary pathway (P2) is again through groundwater pumping by farmers and through the distribution of saline water onto irrigated fields. The major potential impact is the salts build-up in the irrigated soil (I2.1) resulting from the distribution of saline irrigation water and from the water evaporation and transpiration processes.

As for the identification of risk-generating processes, the current water distribution and the conditions of water delivery (discharge and pressure head at hydrants) being not adequate for proper farm irrigation management both concur to the environmental hazard. The extensive use of groundwater pumping throughout the study area results in drawdown and qualitative

deterioration of aquifer, as well as in salts loads being progressively brought onto cropped plots through saline irrigation water. If leaching is not properly conducted on a regular basis, or in case salts are not flushed away from the root zones by the action of seasonal rainfalls, soils are progressively subjected to salts build-up, which may negatively affect their productivity. The soil and aquifer salination thus represent the main risk-generating processes.

Hazard	Source	Pathway	Receptor	Impact
H1 Aquifer over-exploitation	S1 - Intensive pumping by farmers during peak demand periods	P1-Aquifer	R1-Aquifer	I1.1 - Aquifer Depletion
				I1.2 - Salination by seawater intrusion
	S2 - Poor water distribution through the irrigation networks	P2-Aquifer	R2– Soils	I 2.1 - Salt build-up in the soils

Table 4. Hazards sources pathways receptors and impacts

5. Controlling factors of hazards and magnitude of impacts

The aquifer over-exploitation is tightly dependent upon the following factors:

- **Crop water demand**, which is driven by evapo-transpirative demand, growth stage of crops, prevailing farming and irrigation practices, and by effective rainfall. A peak concentration of crop water demand in the study area is usually observed during the months of July and August, and the majority of farms are not equipped with water storage facilities (holding ponds) that could help them buffering the irrigation demand with the water delivery by WUA.
- **The adopted delivery schedule** depends on the available flow rate, on the design and capacity of the existing distribution network, as well as on operational resources and skills provided by the technical staff of the WUA. In the study area the rotation delivery is not agreed upon with farmers, but is instead dictated by the WUA following a supply-driven approach. More flexible arranged deliveries would allow partially overcoming the rigid water distribution.
- **On-farm irrigation practices**, can range from full replenishment of soil water depletion from the root zone to different levels of deficit irrigation, on the basis of the crops grown, the specific sensitivity of the different growth stages to water deficits, the target yields, and the farmers' skills and capability in field water management. Full irrigation is the most common irrigation practice in the study area. Micro-irrigation methods allow maximizing crop yields even when using saline water. Leaching of salts from top soil layers is usually not carried out by the majority of farmers, but flushing of salts mainly occurs due to fall and winter rains.

- **Natural leaching and aquifer recharge** mainly depends on rainfall intensity and distribution, vegetation cover, soils' hydraulic features, and slope. In the study area natural leaching and partial aquifer recharge usually occur during fall and winter months but, as pointed out by previous investigations, those are not sufficient to avoid aquifer salinity increase and salts build-up in the soils on the long run.

The overall magnitude of impacts was estimated based on three criteria, namely a) the spatial distribution of impacts, b) their time-duration, and c) the time necessary to onset the impacts. These impacts were assigned a partial score for each criteria based on a scale ranging from 1 to 4. For instance, the scale related to the spatial distribution of impacts assigned scores according to the following ratings:

Nowhere (0%): score = 0;

Localized (< 5%): score = 1;

Scattered (5-15%): score = 2;

Widespread (15-50%): score = 3;

Throughout (> 50%): score = 4.

The overall magnitude of impacts resulted by multiplying the partial scores assigned for the three criteria, thus on a scoring scale ranging from 0 to 64, then classified from "negligible" (score 0) to "mild" (score 1-22) to "moderate" (score 23-43) to "severe (score 44-64). The calculated values for the magnitude of impacts are reported in Table 5.

Hazard	Receptor	Impact	Spatial scale	Temporal scale	Time of onset to impact	Overall magnitude
H1 Aquifer over-exploitation	R1 Aquifer	I1.1.1 Aquifer depletion	Throughout (> 50%) 4	Medium term (5-20 years) 2	Medium (1-10 years) 3	Moderate 24
		I1.1.2 Salination by seawater intrusion	Throughout (> 50%) 4	Medium term (5-20 years) 2	Medium (1-10 years) 3	Moderate 24
	R2 Agricultural soils	I1.2.1 Salts build-up	Throughout (> 50%) 4	Medium term (5-20 years) 2	Immediate (0-1 year) 4	Moderate 32

Table 5. Estimated magnitude of impacts

6. Estimation of risk probabilities

The estimation of the overall probability of hazards is also based upon three criteria, respectively the probabilities of hazard occurring, of the receptors being exposed, and of harm resulting to the receptor. Within each criteria, the probabilities were assessed and classified on a High (score 3) to Negligible (score 0) scale. The overall probabilities of hazards were finally obtained by combining the partial scores assigned in each criterion and afterwards classifying the overall scores based on the following probability scale:

Negligible (when score ~ 0);

Low (when score = 1-9);

Medium (when score = 10-18);

High (when score = 19-27).

The overall probabilities for the study area are those reported in Table 6

		H1	
Probability of hazard occurring	receptor independent	High (3)	
Probability of receptors being exposed	R1	High (3)	
	R2	High (3)	
Probability of harm occurring to receptor	R1	High (3)	
	R2	High (3)	
Overall probability		H1.R1=27 (high)	H1.R2=27 (high)

Table 6. Probability estimation

7. Risk significance

Risk significance is assessed considering the magnitude of consequences and the probability of effects occurring. In case of qualitative risk assessment, a simple two-ways entry matrix that considers simultaneously the probability and magnitude of consequences, such as the one reported in Table 7 can provide a consistent basis for decision-making.

Evaluation of the risk significances for the 3 impacts that were analyzed in the present case study led to results reported in Table 8. The results from the evaluation were then used to prioritize the most relevant risks and conduct options appraisal to identify viable and consistent management solutions.

As for risk communication process, the results from the risk prioritization should be communicated to the technical staff and to the decision-makers of the WUA through thematic meetings. Also, outcomes from the evaluation of magnitude and probability and

from the risk prioritization stage should be disseminated to farmers' groups and to opinion leaders by means of extension service activities and through specific field focus meetings.

Increasing acceptability	Consequences			
	Severe	Moderate	Mild	Negligible
Probability				
High	high	high	medium/low	near zero
Medium	high	medium	low	near zero
Low	high/medium	medium/low	low	near zero
Negligible	high/medium/low	medium/low	low	near zero

Table 7. Risk significance evaluation matrix.

Risk	Significance score
Risk (H1. R1.I1.1)	Moderate x High = **High**
Risk (H1. R1. I1.2)	Moderate x High = **High**
Risk (H1. R2. I2.1)	Moderate x High = **High**

Table 8. Risk Significance for the study area

8. Appraisal of risk management options

Options appraisal consists in the identification of the most suitable risk-management techniques. This entails scoring, weighting and reporting the different risk management options, and comparing alternatives prior to selection. Viable options can be appraised on the basis of various criteria. For the present study, alternative risk management techniques were evaluated according to: a) social risk acceptability by stakeholders; b) technical feasibility; c) effectiveness in risk alleviation; d) duration of effects; e) costs for implementing the risk management options. The results from options appraisal for the three major risks, namely aquifer quantitative depletion, aquifer degradation, and salts build-up in the agricultural soils are shown in Table 9a, 9b and 9c.

Risk 1 Aquifer depletion	Timing Instant result to progressive	Social acceptability (-- to ++)	Feasibility (-- to ++)	Effectiveness in risk alleviation (-- to ++)	Duration	Cost Low to high
Business as usual (zero option)	Never --	Acceptable +	Very feasible ++	Very ineffective --	Never --	Very affordable ++
Limit water pumping from Groundwater	Immediate +	Unacceptable -	Feasible +	Very effective ++	Short term -	Unaffordable -
Improved rotation in water delivery	Medium +/-	Acceptable +	Feasible +	Effective +	Medium term +/-	Very affordable ++
Decrease water tariffs by WUO to compensate for pumping costs	Long term -	Very Acceptable ++	Feasible +	Effective +	Short term -	Unaffordable -
Water delivery on-demand	Medium +/-	Acceptable +	Feasible +	Very Effective ++	Medium term +/-	Affordable +

a)

Risk II Aquifer salination	Timing Short term to permanent solution	Social acceptability (-- to ++)	Feasibility (-- to ++)	Effectiveness in risk alleviation (-- to ++)	Duration Instant result to progressive	Cost Low to high
Business as usual (zero option)	Never --	Acceptable +	Very feasible ++	Very ineffective --	Never --	Very affordable ++
Stop groundwater pumping	Medium +/-	Very unacceptable --	Feasible +	Very effective ++	Medium +/-	Unaffordable -
Limit groundwater pumping to safe yield of aquifer	Medium +/-	Unacceptable -	Feasible +	Effective +	Medium +/-	Unaffordable -

Rotation irrigation delivery + conjunctive use	Medium +/-	Acceptable +/-	Feasible +	Effective +	Medium +/-	Affordable +
Irrigation delivery on-demand	Medium +/-	Acceptable +	Feasible +	Effective +	Medium +/-	Affordable +
Artificial aquifer recharge	Immediate ++	Neither unacceptable nor acceptable +/-	Feasible +	Very effective ++	Medium +/-	Affrodable +

b)

Risk III Salts build-up in the agri-cultural soils	Timing Instant result to progressive	Social acceptability (-- to ++)	Feasibility (-- to ++)	Effectiveness in risk alleviation (-- to ++)	Duration	Cost Low to high
Business as usual (zero option)	Never - -	Acceptable +	Very feasible ++	Very ineffective - -	Never - -	Very affordable ++
Improved rotation delivery	Long term -	Acceptable ++	Very feasible ++	Effective +	Medium Term +	Affordable +
Improved rotation delivery + conjunctive use	Medium +/-	Very acceptable ++	Feasible +	Effective +	Medium Term +	Affordable +
Irrigation delivery on-demand	Medium +/-	Very acceptable ++	Feasible +	Very effective ++	Long term ++	Affordable +
Improved on-farm irrigation practices (leaching)	Medium +/-	Neither unacceptable nor acceptable +/-	Feasible +	Very effective ++	Long term +	Very affordable ++
On-demand delivery + leaching	Immediate +	Acceptable +	Feasible +	Very effective ++	Long term +	Affordable +

c)

Table 9. Risk Management option selection matrices for: a) aquifer depletion (Risk 1), b) aquifer
salination (Risk 2), c) salts build-up in the agricultural soils (Risk 3)

9. Conclusive remarks

Selecting a suitable risk management option strongly depends on the weights attributed by the evaluator to the decision criteria for the different options with respect to the zero-alternative (business-as-usual). Some of the identified management options pertain to alternative operation of the large-scale distribution network, whereas some others entail improved water management practices at the farm scale or mixed options.

As for the risk related to aquifer quantitative depletion, the preferred option could be to operate the distribution network by an improved rotation delivery, which could better match crop water requirements in terms of timing of delivery. This would require some accurate estimation of irrigation requirements and improved irrigation scheduling plans, as well as some extension service activities to assist farmers in the effective use of available water.

As for the risk of aquifer salination, since it is tightly linked to the amount and concentration of groundwater pumping during the irrigation season, conducting artificial aquifer recharge would be very effective in reducing the pressure over the groundwater. For mitigating the existing effects on aquifer salinity, a strong reduction in groundwater pumping should also be enforced along with artificial aquifer recharge. These two measures in conjunction would most likely allow decreasing the existing level of salinity and inverting the trend of progressive salinity increase in the whole study area.

As for the risk of salts build-up in the agricultural soils, the on-demand delivery in conjunction with improved irrigation practices (leaching) at the farm level would result as the best management options. These techniques would entail some modernization works to the irrigation distribution network as well as extension service activities to train farmers on aspects related to soil-water balance and salinity balance for the major crops grown in the area, and for the prevailing farming practices and irrigation methods.

Overall, selecting the most suitable and viable risk management option would be a matter of strategic planning by the Regional Administration and by the WUA, as well as of the available financial resources, human resources and skills available and required for implementing the options.

Combining the risk management options for the above three risks would result in bringing together conflicting objectives for different stakeholders that may be involved in the land planning and land use. Land users may in fact primarily or exclusively be interested in mitigating the risk of salts build-up in the cropped soils, whereas land planners, and the actors responsible for sustainable use of natural resources, would be inclined to address broader objectives with high priority, such as the reduction of aquifer depletion and salination.

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