Assessment and Management of Environmental Risks Resulting from Operation of Large-scale Irrigation Delivery Systems: a Case Study in Southern Italy

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Abstract: The cumulative effects of irrigation delivery schedule on aquifer and on agricultural soils were analysed in a study conducted on a large-scale irrigated area located in southern Italy. These effects likely result from the inadequate operation of the large-scale irrigation delivery system. Agriculture in the study area is market-oriented and tightly dependant on irrigation, due to hot and dry climatic conditions and to the poor distribution of seasonal rainfall. The study area is characterized by fairly high levels of groundwater salinity likely due to intensive exploitation of the aquifer by farmers especially during peak irrigation demand periods. The concentration of groundwater pumping during these periods results most likely in seawater intrusion. Rising of salinity levels are in fact noted in the groundwater from the start of irrigation season up to the months of July and August. The effects of alternative irrigation distribution schedules to groundwater salinity were assessed in a previous study by simulating water deliveries through a soil-water budget approach under different combinations among crops, soils and climatic conditions. The water distribution currently carried out by the local managing authority poses risks both to the aquifer and to agricultural soils. The present work aimed at conducting a generic Risk Assessment and Risk Management of the soils and aquifer degradation in the study area. Risk generating processes for the major environmental hazards were clearly identified and risks significance was also estimated. Some feasible management options were tentatively evaluated by using different criteria such as the social acceptability, the effectiveness in risk alleviation and the necessary costs for implementation. The Risk Assessment and Risk Management procedures were carried out in view of eventual new agricultural/territorial planning as well as of potential counter-measures for mitigating the existing environmental problems and for reducing the potential risks.

Keywords: Irrigation delivery systems, Environmental Risk Assessment, Seawater intrusion.

1. INTRODUCTION

In many Mediterranean irrigation schemes distribution of water to farms is conducted by means of large-scale delivery networks. In the past, these systems played a significant role in developing, stabilizing and diversifying agricultural production. At present, the major focus is on the effective distribution of limited water resources that otherwise would be accessible only to few users (Lamaddalena and Sagardoy, 2000). Under scarcity conditions, water allocation and distribution to farms usually follows a supply-driven approach

Despite their promise as engines of agricultural growth, in many areas of the world irrigation delivery systems perform far below their potential (see Small and Svendsen, 1992). As pointed out by Plusquellec et al. (1994) and by Lamaddalena et al. (1995), this may be due to unrealistic designs, to inadequate water delivery schedules and to operational constraints. When crop production is strongly dependant on irrigation, the effective and responsible water delivery to farms is critical for maintaining economic and environmental sustainability of agricultural areas. If water delivery by the management authority is unreliable, inadequate in terms of the conditions of delivery, rigid or not timely matching crop water demand or growers' practices, farmers tend to rely on groundwater resources as main source of irrigation.

Many researches have proved that the over-exploitation of groundwater for agricultural purposes causes a drawdown of water levels and gives way to the seawater intrusion in coastal areas, consequently resulting in the deterioration of quality of the irrigation water pumped from wells (Paniconi et al., 2001). Seawater intrusion into the groundwater (Capaccionia et al., 2005) occurs during periods of intensive pumping, also leading to the subsequent salt build-up in the cropped soils.

Under the perspective of responsible use of natural resources, there is a specific need for providing land-use managers with reliable tools and techniques for assessing environmental man-induced risks. This can generate the opportunity of evaluating the reliability of mitigation and management options on a sound scientific basis.

This paper describes the work for conducting the generic Risk Assessment and Risk Management (RA&M) of the soils and aquifer degradation in a large-scale irrigation scheme located in southern Italy and managed by a local Water User Organization (WUO). Some management options, which represent alternatives to the "business-as-usual", were identified and evaluated for mitigating existing environmental problems in the area.

2. THE STUDY AREA

The "Sinistra Bradano" large-scale irrigation scheme is an agricultural area located in the western part of the province of Taranto, (Apulia Region, southern Italy) covering a total topographic area of 9651 ha. The whole scheme is subdivided into 10 operational districts that include an overall irrigated area of 8636 ha. The water source is the San Giuliano dam located on the Bradano River in the nearby region of Basilicata. The dam has a total capacity of 70 Mm^3, out of which 35 Mm^3 are usually available for irrigation of the Sinistra Bradano scheme. Water is conveyed from the San Giuliano dam to the study area by means of a main canal for about 30 Km. The water conveyance and distribution systems are managed and operated by a local WUO. The area is characterized by a hot and dry climate, which is typical for the Mediterranean region. The precipitation is scarce, averaging around 550 mm $year^{-1}$, and occurs mainly in the period between November and March. Summer droughts are frequent. Irrigation water is supplied to farms through a pressurized distribution system. The distribution network is operated by rotation delivery schedule with a fix delivery interval of 10 days. The rotation is fixed for the entire irrigation season (April through October) with a flow rate of 20 l s^{-1} and 5 hours of delivery of to each user.

The main crops are citrus, table grapes, olive trees and summer vegetables. Soils are mainly of alluvial type and the applied water gets drained in 2 or 3 days. Because of semi-arid climatic conditions, profitable farming in the area strongly depends on irrigation. Nevertheless, farmers report that usually the water distribution conducted by the WUO is not matching the actual crops' needs nor the 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. Consequently, during the last 10 years many farmers have utilized groundwater pumping as main source of irrigation for large part of the irrigation season. A concentration of groundwater pumping occurs during the peak water demand periods (July and August). This progressively led to high pressure on groundwater resources and started originating aquifer contamination and soil degradation. In details, seawater intrusion in the groundwater and salt build-up in the agricultural soils are the major causes of environmental degradation in the study area.

Seasonal changes in the groundwater quality were assessed in a previous study by comparing the groundwater salinity in winter versus that in summer. Summer and winter salinity maps were in fact developed based on the spatial interpolation of point-measured values of the Total Dissolved Solids (TDS) and Electrical Conductivity (EC) of samples collected from the groundwater in the Sinistra Bradano area during the irrigation season of 2006. The comparison between winter and summer maps showed a relevant increase in salinity from winter to summer, from EC of 1.5 - 1.8 g l^{-1} in winter to 3.1 g l^{-1} measured in summer. This salinity increase is most likely related to the intensive pumping from the aquifer during period of peak demand, specifically from May to August. This can be reported as the main resulting consequence of the inadequate delivery schedule enforced in the area. Several interviews with local operators and growers revealed that many water users rely exclusively on groundwater pumping for irrigating their crops in order to achieve the desired flexibility. The rigid rotation supply may in fact cause wasteful water use such as improper timing, over- irrigation and runoff, and may inhibit good farm management (e.g. Merriam et al. 2007).

The local climatic conditions as well as the intensive farming of agricultural areas and non-optimal distribution of water supplies make "business-as-usual" not sustainable in the area on the long run.

Given the above hazardous phenomena and the need for a strategic change with respect to the existing situation in the study area, a generic Risk Assessment and Management (RA&M) procedure was conducted through a new framework in view of possible counter-measures for mitigation of existing environmental problems and risks. The RA&M framework was conceived under an EU-funded project named *"Remotely Accessed Decision Support System for Transnational Environmental Risk Management* (Project STRiM), within the Interreg III B - CADSES Program, and is outlined hereafter.

3. THE STRiM RA AND RM FRAMEWORK

The STRiM RA&M framework (Figure 1) consists of 5 iterative steps and is 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 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). Environmental Risk Assessment (RA) and Risk Management (RM) require datasets to support decision-making, often in the form of indicators. In order to harmonise environmental protection management, the STRiM framework links the DPSIR indicator and monitoring framework with RA and RM, something 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 problem; **b)** the need to prioritize all relevant risks prior to quantify them and proceed with the data collection; **c)** the need to consider the risks taking into account feasible management solutions by using options appraisal from the initial stages; **d)** the iterative nature of the process.

4. POTENTIAL HAZARD IDENTIFICATION

The potential hazard occurring in the study area is the aquifer over-exploitation. Under the specific situation of the study area, the intention (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*") for which the RA&M is required is the management of business-as-usual, which corresponds to the intensive farming along with the adopted irrigation delivery schedule by the water management authority. The secondary hazards resulting from the aquifer over-exploitation are those reported in the Figure 2, whereas the sources, pathways, receptors and impacts are indicated in the Table 1 for each hazard.

The potential sources for aquifer over-exploitation are the intensive pumping (S1) by farmers during peak irrigation demand periods (July and August) and the inadequate water distribution through the irrigation networks (S2). This situation occurs due to the existing

market-oriented agriculture based on water-demanding crops and to the current operation of the irrigation distribution system, which is not matching crops and farmers' water requirements. The primary pathway (P1) is 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 salinization by seawater is thus the aquifer itself.

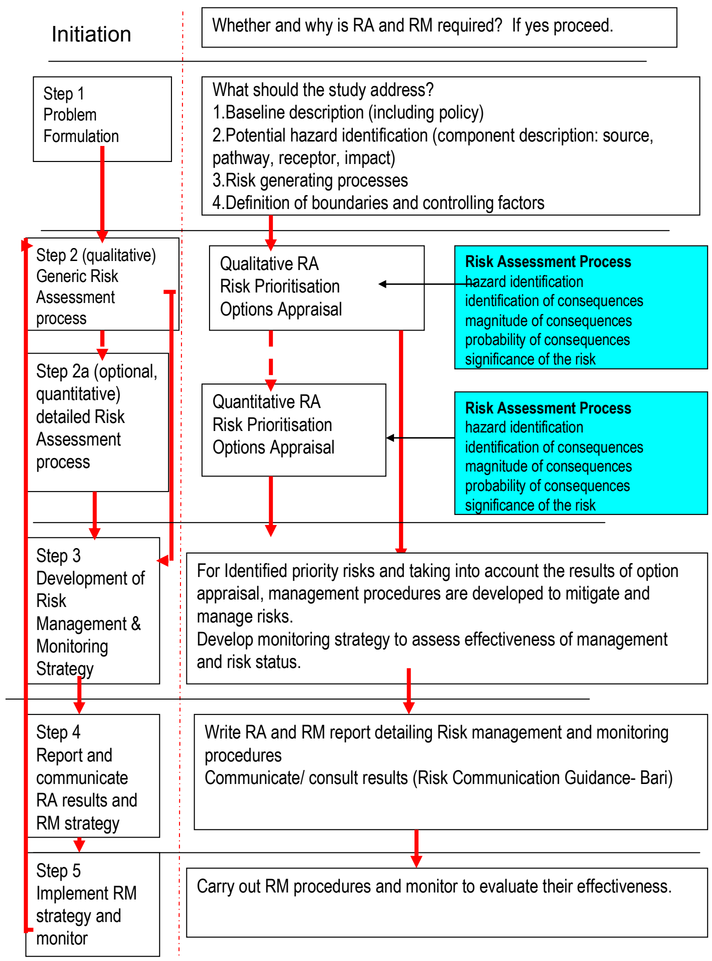

Figure 1. STRiM Risk Assessment and Management Framework (modified from DEFRA, 2002)

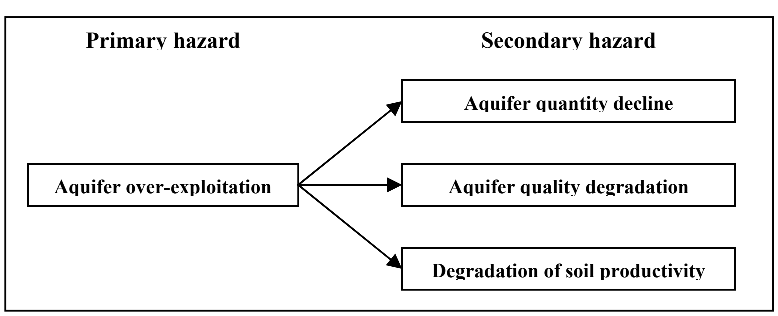

Figure 2. Primary and secondary hazards identified in the study area

Table 1. Hazards sources pathways receptors and impacts

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 - Salinization by seawater intrusion
	S2 - Poor water distribution through the irrigation networks	**P2**-Aquifer	**R2**– Soils	**I 2.1 -** Salt build-up in the soils

The standardized map of salinity distribution within the aquifer is reported in Figure 3. Figure 4 represents the spatial distribution of environmental vulnerability as related to aquifer pumping, to salinity distribution within the aquifer and to aquifer recharge.

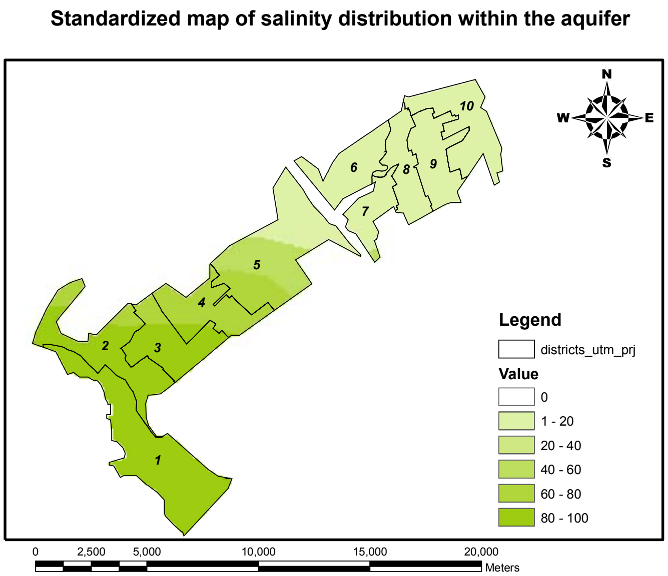

Figure 3. Standardized map of salinity distribution within the aquifer

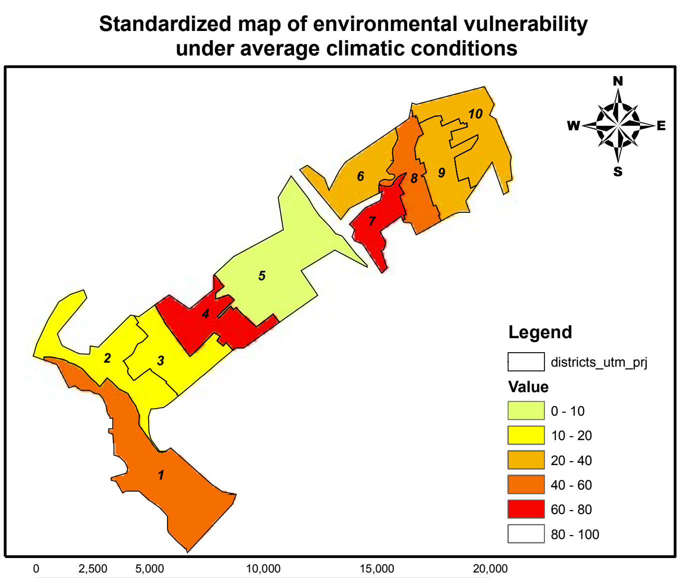

Figure 4. Standardized map of environmental vulnerability under average climatic conditions

The secondary pathway (P2) is again through groundwater pumping by farmers and through the distribution of saline water onto irrigated fields. The main potential impacts are: the quantitative depletion of aquifer (I1.1), which occurs beyond the safe yield and/or beyond the natural recharge capability; the aquifer salinization due to seawater intrusion (I1.2); the accumulation of salts in the irrigated soil (I2.1) resulting from the distribution of saline irrigation water and from the water evaporation and transpiration processes.

5. IDENTIFICATION OF RISK GENERATING PROCESSES

<u>Risk generating processes for the over-exploitation of aquifer.</u>

As pointed out in previous sections, many growers report that the rotation delivery schedule operated by the water management organization is too restrictive and not timely matching the actual crop water needs for the whole study area. Also the conditions of water delivery, namely the flow rate and pressure heads at hydrants, are not those required at farm level for proper operation of the on-farm irrigation systems. Thus, the current irrigation deliveries are not adequate for the existing farming conditions. Being the aquifer relatively shallow in the whole study area, a large number of farmers in the last ten years started drilling on-farm tube-wells and using them for irrigation purposes. This led to a very large number of irrigation wells, either licensed or unlicensed, which pump irrigation water from the aquifer during large part of the irrigation season, with the highest concentration of withdrawals occurring during the months of July and August. As in many other coastal areas, the over-exploitation of groundwater resources causes drawdown of water levels and gives a way to intrusion of seawater. Besides the aquifer depletion beyond the safe yield, this also results in the qualitative deterioration of groundwater due to salinization. This also results in an increasing process of salt build-up in the soils, as farmers utilize salinized groundwater to irrigate their cropped fields. Salts loads are thus progressively brought onto cropped soils through the 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 means of winter rainfalls, soils are progressively subjected to salts build-up, which may negatively affect their productivity.

6. CONTROLLING FACTORS OF THE HAZARDOUS PHENOMENA AND MAGNITUDE OF IMPACTS

The aquifer over-exploitation depends upon the following factors:

- <u>Crop water demand</u>, which is tightly dependant on the evapo-transpiration demand, on water-holding capacity of soils, on the growth stage of crops, on the prevailing farming and irrigation practices, and on the effective rainfall (amount of rainfall stored in the depth of the root zone). In the study area a concentration of crop water demand is observed for the months of July and August. Also most of farms are not equipped with storage facilities (holding ponds) which may allow buffering crop demand with the actual water delivery.

- <u>The adopted delivery schedule,</u> which basically depends on the available flow rate, on the water demand, 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 WUO. In the study area irrigation water is distributed to farms by a fix 10-day rotation. The rotation is not agreed with farmers and is dictated by a supply-driven approach by the WUO. More flexible arranged deliveries would allow partially overcoming the rigidity of the water distribution.

- <u>On-farm irrigation practices,</u> which can range from full satisfaction of irrigation requirements to different levels of deficit irrigation, based on the crops grown, on the specific sensitivity of the different growth stages to water deficit, on the target yield, as well as on the farmers' ability in water management at field level. In the study area full irrigation is the most common irrigation practice. Crops are mainly irrigated by micro-irrigation methods, which allow maximizing crop yields even with the use of saline water. Leaching of salts from soil top layers is usually not carried out by the majority of farmers, but salts flushing mainly occur due to fall and winter rains.

- Natural leaching and aquifer recharge, which depends mainly on rainfall (intensity and distribution), on vegetation cover, on soils' hydraulic features, and on slope. Natural leaching and partial aquifer recharge usually occur in the study area during fall and winter months but, as resulted from previous investigations, are not capable of avoiding the progressive salinity increase in the aquifer and salts build-up in the soil on the long run.

The overall magnitude of impacts was estimated based on three criteria, namely the spatial spread of impacts, the time-duration of impacts and the time necessary for the impacts to be onset. Within each of the above criteria, the impacts were assigned a partial score based on a scale ranging from 1 to 4. For instance, the scale related to the spatial spread of impacts assigns scores based on 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 2.

Table 2. Impact magnitude estimates

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 Salinization 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**

7. ESTIMATION OF 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. In each criteria, the probabilities were assessed and classified on a High (score 3) to Negligible (score 0) scale. The overall probabilities of hazards were obtained by combining the partial scores assigned in each criterion and then 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 3

Table 3. Probability estimation

		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)**

8. EVALUATION OF RISK SIGNIFICANCE

Risk significance is evaluated accounting for both the magnitude of consequences as well as the probability of effects occurring. In case of qualitative risk assessment, a simple two-ways entry matrix considering simultaneously probability and magnitude of consequences, such as the one reported in Table 4 can provide a consistent basis for decision-making.
The evaluated risk significances of the 3 analysed impacts for the case study are presented in Table 5. The results from the evaluation are then used to prioritize the most relevant risks and conduct options appraisal to identify feasible 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 WUO 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 specific field focus meetings.

9. OPTIONS APPRAISAL

Options appraisal consists in the identification of the most suitable risk management technique. This involves scoring, weighting and reporting the different risk management options, and comparing alternatives. There are various criteria for appraising the potential options. For the present study, the aspects considered in evaluating the risk management techniques are: 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 conducting the options appraisal for the three major risks, namely aquifer quantitative depletion, aquifer degradation, and salts build-up in the agricultural soils are reported in Table 6a, 6b and 6c.

Table 4. Risk significance evaluation matrix.

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 5. Risk Significance for the study area

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 6a. Risk Management option selection matrix for aquifer depletion (Risk 1)

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 +

Table 6b. Risk Management option selection matrix for aquifer salinization (Risk 2)

Risk II Aquifer salinization	**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 +

Table 6c. Risk Management option selection matrix for salts build-up in the agricultural soils (Risk 3)

Risk III Salts build-up in the agricultural 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 +

10. CONCLUSIONS

Selecting a preferred 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 relate 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 plan, as well as some extension service activities.

As for the risk of aquifer salinization, 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 pressure over the aquifer. 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 will allow decreasing the existing level of salinity and inverting the trend of salinity increase in the whole study area.

Concerning 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 would entail some modernization works to the irrigation distribution network as well as intensive extension service activities for training farmers on the field on issues 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.

The selection of the most suitable risk management option would be a matter of strategic planning by the Regional Administration and by the Water User Organization as well as of the available funds, human resources and skills available and required for implementing the options.

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

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