ASSESSMENT OF THE ENVIRONMENTAL SUSTAINABILITY OF IRRIGATED AGRICULTURE IN A LARGE-SCALE SCHEME — A CASE STUDY

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ABSTRACT

A study was conducted on a large-scale irrigated area located in southern Italy to analyze the cumulative effects of long-term water management practices on soils and aquifers. Assessing the environmental sustainability of irrigation systems operations was the main goal of the present research. This included envisaging feasible changes to "business-as-usual" in the study area with the aim of reducing pressures and of meeting current and future management objectives. The *Determinants-Pressure-State-Impact-Response* methodology suggested by the European Environmental Agency was applied to the case study to analyze cause-effect relationships between driving forces, pressures and potential impacts. Simulations of alternatives in water management and evaluation of resulting consequences were conducted by developing a spatial Decision Support System (DSS) on the study area. This basically involved development and ranking of alternatives by using a commercial software package (DEFINITE DSS).

Evaluation of the most likely resulting consequences was conducted by creating maps of environmental risk by means of two commercial GIS software packages (ArcGIS and IDRISI). The used approach showed its usefulness for achieving better understanding of relevant aspects related to management of irrigation water at regional scale, for designing strategic monitoring programs to be implemented and for envisaging feasible management alternatives on large-scale irrigation systems.

INTRODUCTION

In the arid and semi-arid regions of the Mediterranean irrigation projects, despite their promise as engines of agricultural growth, usually perform far below their potential (Small and Svendsen, 1992). In several cases, unrealistic designs, rigid water delivery schedules and operational problems are among the principal reasons for the poor performance of irrigation systems (Plusquellec et al., 1994).

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In others, system management often fails to respond to the needs of users, in particular to small holders carrying low social and political weight (UNESCO, 2003). In this geographic context irrigation agencies and farmers' associations are continuously asked to improve the efficiency of their irrigation networks and delivery systems by means of improved use of limited water resources (D'urso, 2001). For these reasons, assessment of actual performance and potential improvement of distribution systems are now receiving greater attention, not only from the usual efficiency-type stand-point but also from the environmental perspective. Existing irrigation systems need to be periodically evaluated for their performance achievements relative to current and future objectives. In this view, the proposed study focused on testing a methodology to conduct diagnostic analyses and simulate alternative management scenarios on large-scale pressurized irrigation systems. The approach used proved to work as an analytical basis to address modernization processes with greater accuracy than was done in the past.

OBJECTIVES AND APPROACH

The main objective of the present research was to develop the capability to perform diagnostic analyses on environmental effects resulting from management of irrigation water at regional scale. An analytical approach was proposed for achieving better understanding of major environmental effects of irrigation management to soils and aquifers. The analyses carried out allowed achieving the following specific objectives:

1. Mapping areas of environmental hazards caused by mis-management of water distribution
2. Simulating alternative water management scenarios
3. Evaluating the contribution of each alternative for maintaining environmental and economic sustainability of irrigated agriculture in the area
4. Supporting strategic planning and decision-making by using Decision Support Systems (DSS) and Spatial Decision Support Systems (SDSS)

The rationale followed within the present research is represented in the Figure 1. It involved several methodological steps, which are reported hereafter:

a) Data gathering and generation of basic GIS thematic layers on the study area
b) Processing of GIS thematic maps and standardization of environmental parameters
c) Impact assessment relative to the existing situation and preparation of environmental vulnerability maps
d) Identification of feasible water management alternatives with respect to "business-as-usual" in the study area
e) Setting decision rules and attributing weights for the DSS
f) Ranking the feasible alternatives and setting rules for selection of the most-suitable alternatives
g) Generation of impact maps related to the most-suitable alternatives

BACKGROUND ON THE STUDY AREA

The Sinistra Bradano Irrigation Scheme

The analyses were carried out on the areas served by the "Sinistra Bradano" large-scale irrigation system, which is located in the south-eastern part of the Italian peninsula (Apulia Region). This system covers a total topographic area of 9,500 ha. The physical boundaries of the study area as well as its location, shape, topographic conditions and extent are reported in Figures 2 and 3.

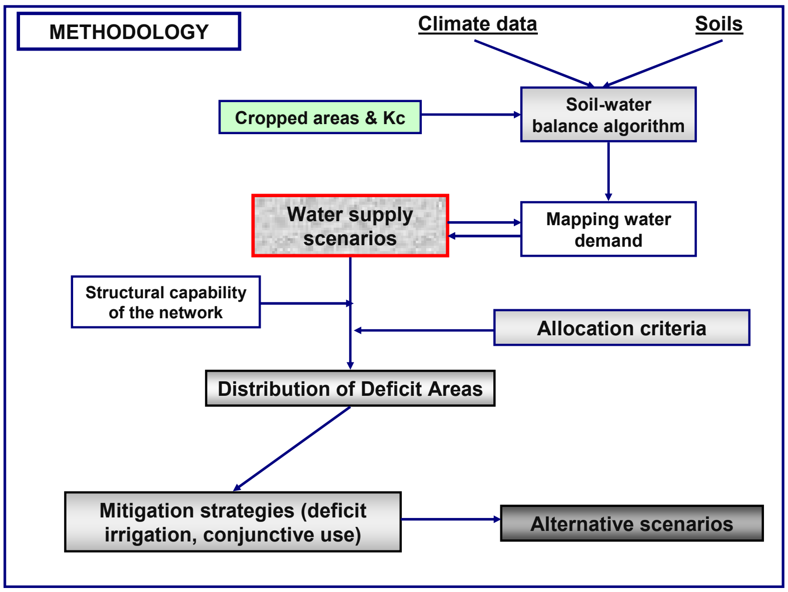


Figure 1. Rationale of the methodology adopted in the study area.

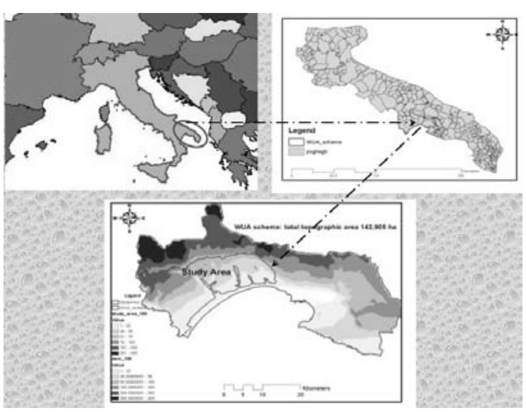


Figure 2. Location and extent of the area of interest

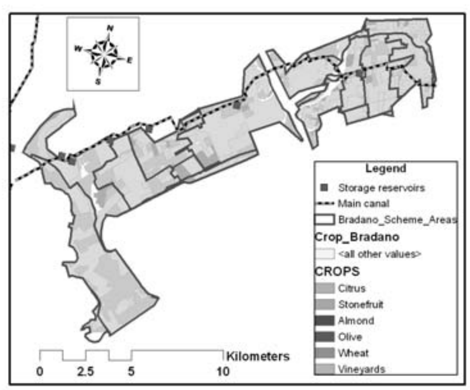


Figure 3. Representation of the "Sinistra Bradano" irrigation scheme

The main irrigated crops are table grapes, citrus, olive and summer vegetables. Most of the farms utilize trickle irrigation as predominant method, while in some limited areas sprinkler irrigation is still utilized for citrus and summer vegetables.

Due to favorable agro-climatic conditions, agriculture in the area is intensive and highly market-oriented. Climate is semi-arid with an average yearly precipitation of about 550 mm, which are poorly distributed along the months. Therefore profitable farming in the area is strongly dependent upon irrigation. The typical irrigation season lasts from the beginning of April to mid November. The hydraulic scheme is composed of a main canal conveying water from a regional dam to four storage and compensation reservoirs, which serve ten irrigation districts. From each of these reservoirs, district pressurized distribution networks originate for delivering irrigation water to the farms. The Figure 3 shows the main features of the irrigation scheme.

The irrigation distribution network is operated by rotation delivery schedule. The usual rotation is based on a 10-day shift. At present, distribution of irrigation water to farms, as reported by many farmers, is too restrictive and not timely matching the actual crop water requirements and farmers' needs. As a result of all the above issues, during the last 10 years a large number of water users started drilling on-farm irrigation wells (nearly 6,000 wells are reported to be existing in the area and most of them are unlicensed). This led to over-pumping from the aquifers, to saline intrusion in groundwater and to an increasing process of salt build-up in the soils. The major environmental concerns in the area can be reported as follows:

1. Climatic conditions, intensive management of agricultural systems and non-optimal allocation of water supplies make *"business-as-usual"* not sustainable in the area on the long run
2. There is high pressure on groundwater resources that resulted in soil degradation and aquifer contamination

Lack of accurate understanding of cause-effect relationships and trends complicate the search for effective solutions. All the above factors are progressively leading the area to environmental unbalances, which likely result in high vulnerability of the study site to further degradations on the medium run, such as salinization of soils and aquifer and potential desertification risk.

THE D.P.S.I.R. MODEL

The **D**eterminants-**P**ressures-**S**tatus-**I**mpacts-**R**esponses Model (D.P.S.I.R.) is a methodology proposed by the European Environmental Agency (EEA) in 1999 and developed on the basis of the Pressure-Status-Responses (PSR) and Determinants-Status-Responses (DSR). The D.P.S.I.R. model represents the scheme utilized by EEA for developing reports on the state of environment in Europe. It enables the description of current environmental problems by identifying the different cause-effect relationships and makes them comparable at the European scale. The model is composed by five stages which allow evaluating the causal process leading to environmental alterations. Besides being a useful approach to frame a problem, the D.P.S.I.R. model represents a sound tool to develop the decision-making process, thus allowing identifying the most promising correction measures to be conducted on a site-specific situation. The comprehensive outlines of the model and of its methodological phases, as applied to the Sinistra Bradano irrigation scheme, are reported in the Figure 4.

The following pressure indicators were identified for the present study area:

1)Salt build-up in the irrigated soils; 2) Salinity level and salinity distribution in aquifer; 3) Magnitudes of water deficits (water withdrawals from aquifer)

As for the State and Impact stages, the following impacts were pointed out for the area served by the Sinistra Bradano irrigation scheme:

- Increase of soil and groundwater salinity
- Decrease of productivity for soils, crops and for agricultural systems
- Soils and water degradation beyond natural recovery capabilities
- Risk of desertification

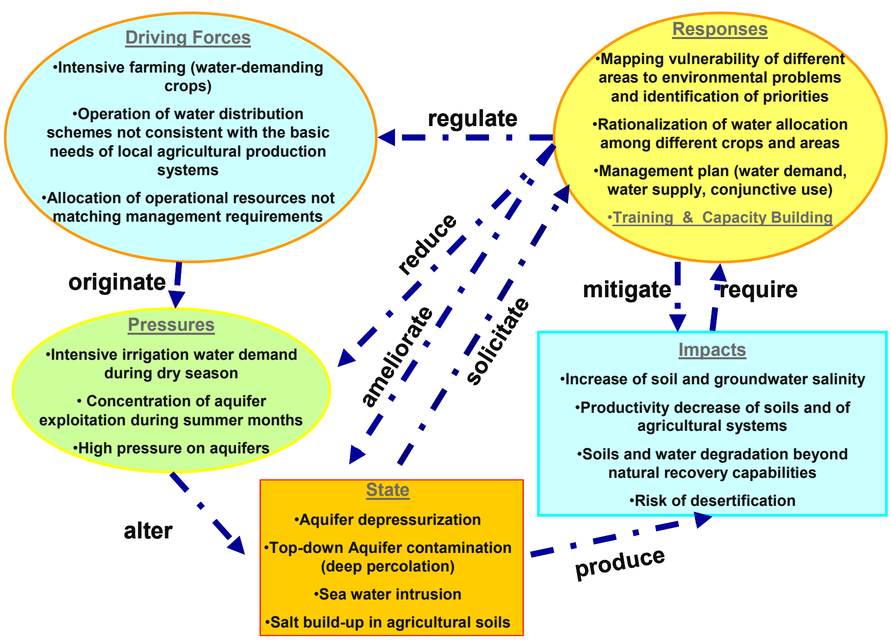


Figure 4. The D.P.S.I.R. model applied to the study area

IMPACT ASSESSMENT, DEVELOPMENT AND EVALUATION OF ALTERNATIVE SCENARIOS

After data collection and processing, the impact assessment relative to the current situation involved the generation of maps of environmental vulnerability over the study area under three different climatic scenarios (Average, High-demanding, Very-high demanding). Those vulnerability maps were produced by combining the following distributed GIS datasets:

1. Standardized maps of pressure exerted to underground aquifer (water pumping from aquifer) under the three specified climatic scenarios
2. Standardized map of salinity distribution in the underground aquifer over the whole study area
3. Standardized map of aquifer recharge over the whole study area

In order to evaluate the spatially-distributed pressure exerted to aquifer, maps of distributed irrigation demand over the study area were first generated under the three different climatic scenarios. Following the indications obtained by the technical staff of the local WUA, a total water supply of 20 Mm^3 was considered. This amount corresponds nearly to 50 % of the total water demand calculated under the three different climatic scenarios. This total available water supply was allocated to the different cropped areas by using an optimization model, which was developed on purpose for the present research. The model basically finds the optimal allocation of limited water supply over the multi-cropped irrigated area. Based upon the model results, distributed maps of water deficit were generated. These water deficit situations refer to the share of water deliverable to cropped areas based upon results from the optimization model and upon the total available water supply. As an example, the maps of water deficit under the very-high demand climatic situations are reported in Figure 5. Given that water deficit situations imply pumping from the aquifer the necessary volumes for full satisfaction of crop irrigation requirements, the water deficit maps were considered as distributed maps of potential water withdrawals from aquifer. These water withdrawals correspond to the amounts of water that farmers are likely to be pumping from aquifer during the irrigation season in the different irrigation districts all over the cropped areas.

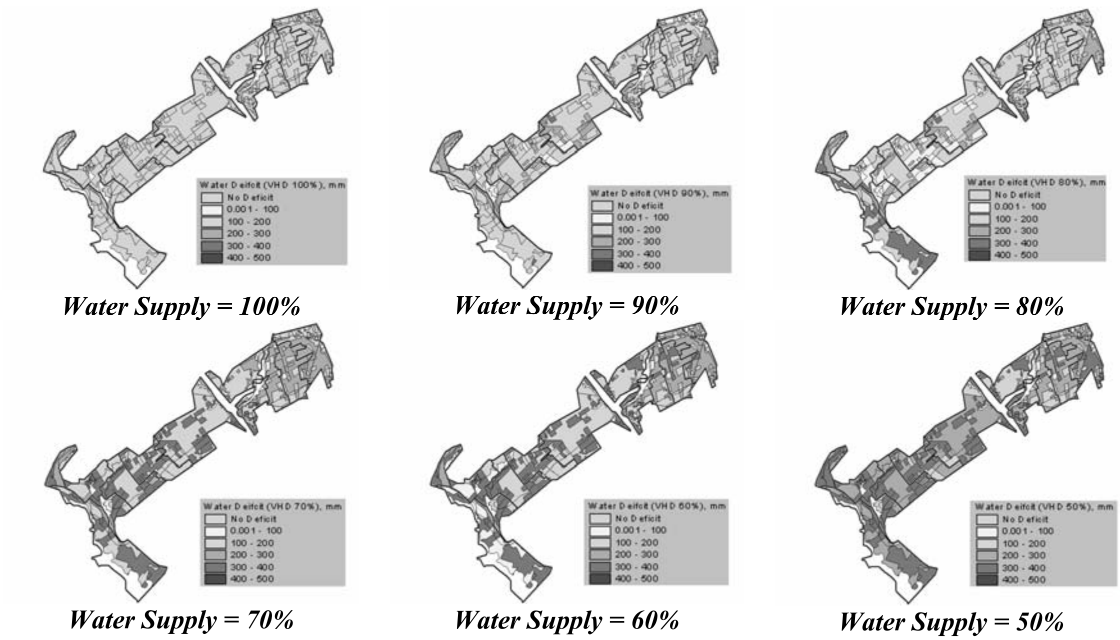


Figure 5. Optimal allocation of water from WUA and
resulting deficit areas for the Very-High Demand scenario

DEVELOPMENT OF THE SPATIAL DSS

The maps of potential water pumping, salinity distribution and aquifer recharge were generated using ArcView and ArcGIS software packages and then imported into the commercial software IDRISI, which is a Spatial DSS working on geo-referenced files.

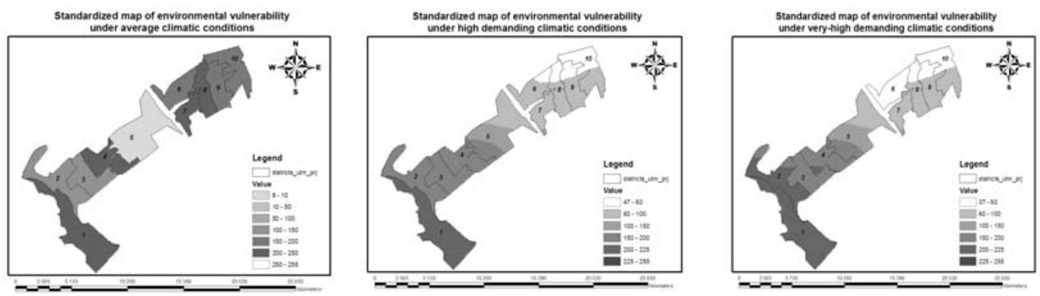
The standardization procedure was performed in IDRISI in order to homogenize maps having different units and to combine them into environmental vulnerability maps.

The standardized maps of pressure, salinity and aquifer recharge were combined into IDRISI by using *Decision Support* functionality calling for *Multi Criteria Evaluation* (MCE) through a *Weighted Linear Combination*, thus attributing the weights reported in the following Table 1 to the different factors.

Table 1. Weights allocation to the different factors used in the Multi Criteria Evaluation to generate maps of environmental vulnerability for the study area

Factor	Factor	Weight
1	Pressure exerted to aquifer	0.3
2	Aquifer salinity	0.5
3	Aquifer recharge	0.2

Following the above-described approach, three different maps of environmental vulnerability, one for each climatic scenario, were generated and are presented in the Figures 6.



Average climatic conditions ***High-demanding climatic conditions*** ***Very-high-demanding conditions***

Figure 6. Standardized maps of environmental vulnerability under different conditions

Afterwards, several alternative scenarios with respect to the "business-as-usual" (Zero-Alternative) were developed with the aim of reducing the pressure over the aquifer by means of a better water distribution to farms. These water management alternatives were generated and defined by using the DEFINITE DSS software package (Janssen et al., 2003) and are reported in the Table 2. Once the feasible water management alternatives were defined, the decision rules (effects) and attribution of weights for the Multi Criteria Analysis were also determined as presented in the following Table 3. The subsequent step to the definition of effects and attribution of weights was the determination of decision-making criteria. Two separate simulations of Multi Criteria Analysis (MCA) were run, the first one mainly addressed at achieving *Environmental Sustainability* in the area, whereas the other was mostly oriented to achieving *Economic Feasibility*. The two simulations are based upon different decision-making criteria, which were developed by assessing weights effects through pair-wise comparisons between the different effects, taken two at a time. Assessing the relative importance weight of each effect with respect to the other ones allowed setting the decision-rule on which to base the alternative ranking. The eight alternatives, including the "business-as-usual" (Zero Alternative) were ranked applying the Multi Criteria Analysis (MCA) in the DEFINITE software package.

Table 2. Water management alternatives generated in DEFINITE DSS for the area

Alternative	Description
1	Modernization of the irrigation distribution network to allow for on-demand delivery schedule
2	Optimal combination of supplementary water from other irrigation schemes, rehabilitation and modernization of the irrigation distribution network
3	Combination of centralized water pumping from aquifer and modernization of irrigation distribution network
4	Combination of conveyance of supplementary water from other water schemes and modernization of irrigation distribution network
5	Business as usual (Zero Alternative)
6	Optimal combination of centralized water pumping from aquifer and rehab. and modernization of the irrigation distribution network
7	Combination of rehabilitation and modernization of the irrigation distribution network
8	Rehabilitation of the irrigation distribution network

Table 3. Decision rules and units to be used in the Multi Criteria Analysis for the study area

Effect	Effect description	Unit
1	Overall monetary cost for physical works necessary to implement the alternative	(----/++++)
2	Time necessary for implementing the alternative	(----/++++)
3	Efficacy in reducing water deficit	(%)
4	Required engineering & management skills and capacity-building for implementing the alternative	(----/++++)
5	Efficacy in reducing pressure to aquifer	(%)

RESULTS AND DISCUSSION

The results are presented in the Figures from 7 to 12. These results show that under the High-Environmental Sustainability decision scenario the most advisable alternative is the optimal combination of supplementary water from other irrigation schemes, rehabilitation and modernization of the irrigation distribution network (Alternative 2). Alternative 4 (Combination of conveyance of supplementary water from other water schemes and modernization of irrigation distribution network) is ranked as second-best, right after the Alternative 2. The Business-as-usual alternative, which corresponds to the actual asset in the study area, is ranked as last, due to the fact that its environmental sustainability is very poor. Under the High-Economic Feasibility scenario, ranking of alternatives is almost opposite, as the main purpose here was to find fast and cheap alternative solutions to the current situation. Therefore, cost and time necessary for implementing alternatives are in this case the most relevant factors in the decision-making.

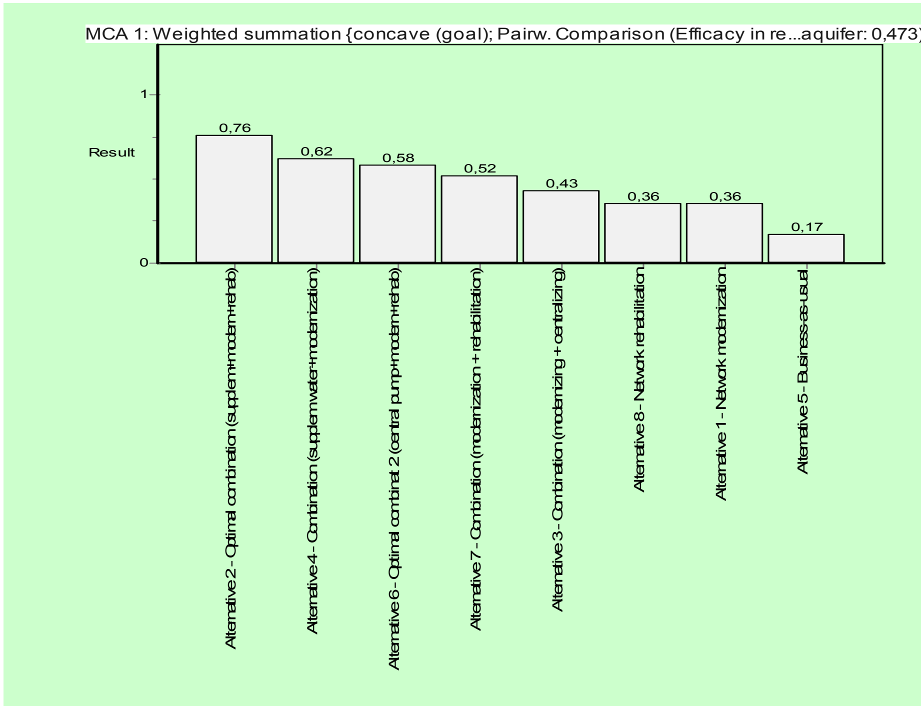


Figure 7. Ranking of alternatives from the MCA under High-Environmental Sustainability

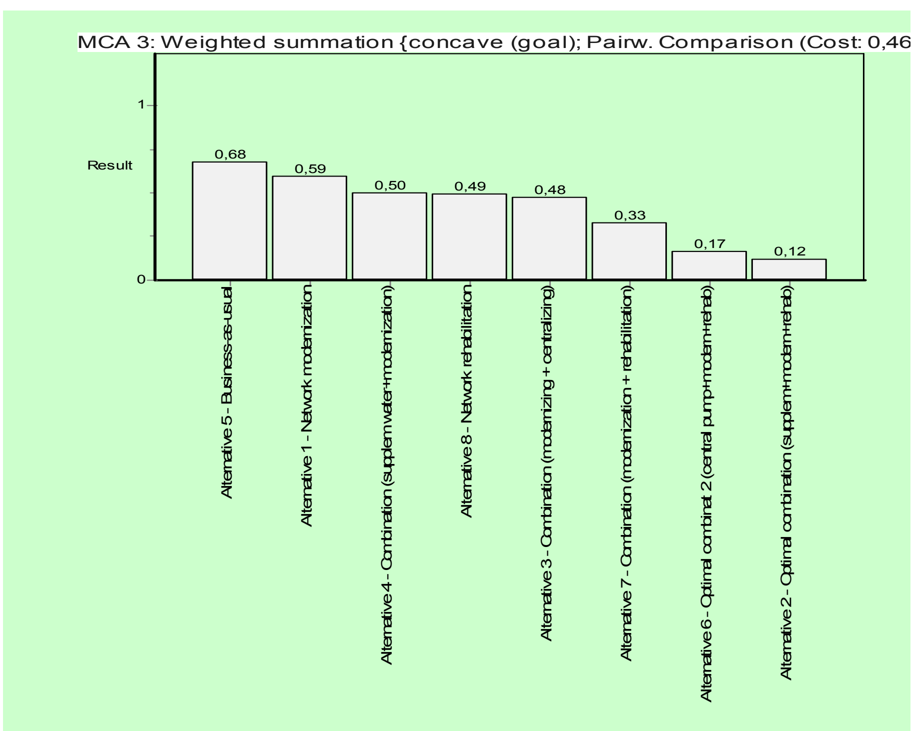


Figure 8. Ranking of alternative from the MCA under High-Economic Feasibility

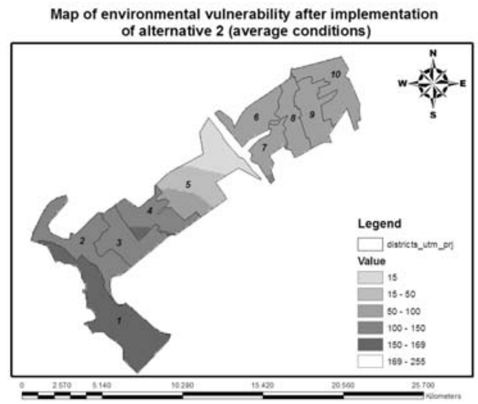


Figure 9. Map of environmental vulnerability after implementing the Alternative 2

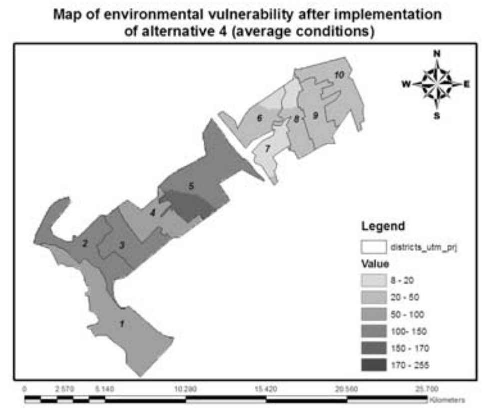


Figure 10. Map of environmental vulnerability after implementing Alternative 4

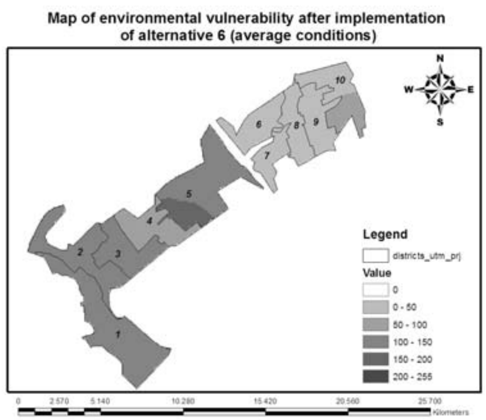


Figure 11. Map of environmental vulnerability after implementing Alternative 6

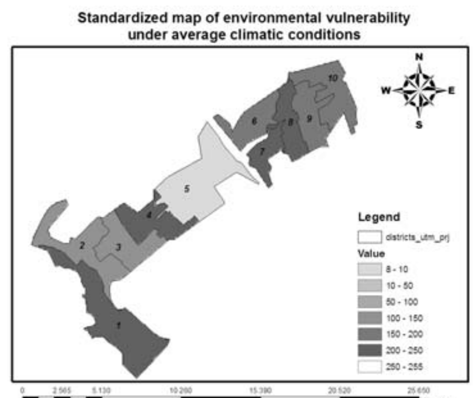


Figure 12. Map of environmental vulnerability after implementing Alternative 5

GENERATION OF IMPACT MAPS OF THE ALTERNATIVES

The impact on environment resulting from the different proposed alternatives was evaluated by considering the contribution of each alternative to reduce the pressure exerted on the aquifer and to decrease the water deficit. Both criteria are inter-related and therefore each water management solution will result in a different level of pressure exerted over the aquifer, which in turn will determine a mitigated environmental vulnerability with respect to the Zero Alternative (business-as-usual). The complete impact attribution of the different alternatives, necessary for running the MCA, can be observed from the Table 5.

Table 5. Complete impact attribution of the different alternatives

Effect	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8
Cost	+	++++	++	++	0	++++	+++	++
Time for implementation	+	++++	++	++	0	+++	+++	++
Efficacy in reducing water deficit (%)	30	100	70	70	0	100	60	30
Required capacity building	++	++++	+++	+++	0	++++	+++	+
Efficacy in reducing pressure to aquifer (%)	30	100	30	70	0	60	60	30

CONCLUSIONS AND RECOMMENDATIONS

The results from the development of a Decision Support System on the area served by the Sinistra Bradano irrigation scheme show that sound decision-making involves the availability of accurate datasets and the consideration of a number of economic and environmental aspects from the standpoints of different stakeholders. Such complex problems can be framed by using Spatial Decision Support tools and feasible alternative solutions can be more addressed to environmental sustainability or to economic feasibility. In order to improve the whole decision process, adequate decision guidelines could be elaborated and suggested within a Water Management Plan to be implemented for each large-scale irrigated area.

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