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An integrated modelling tool to evaluate the acceptability of irrigation constraint measures for groundwater protection

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ABSTRACT

In many arid and semi-arid regions agriculture is the main user of GW, causing problems with the quantity and quality of water, but there are few institutional policies and regulations governing sustainable GW exploitation. The authors suggest an integrated methodology for enabling local GW management, capable of combining the need for GW protection with socio-economic and behavioural determinants of GW use. In the proposed tool, integration is reinforced by the inclusion of multiple stakeholders, and the use of Bayesian Belief Networks (BBN) to simulate and explore these stakeholders' attitude to GW exploitation and their responses to the introduction of new protection policies. BBNs and hydrological system properties are integrated in a GIS-based decision support system – GeSAP – which can elaborate and analyse scenarios concerning the pressure on GW due to exploitation for irrigation, and the effectiveness of protection policies, taking into account the level of consensus. In addition, the GIS interface makes it possible to spatialize the information and to investigate model results.

The paper presents the results of an experimental application of the GeSAP tool to support GW planning and management in the Apulia Region (Southern Italy). To evaluate the actual usability of the GeSAP tool, case study applications were performed involving the main experts in GW protection and the regional decision-makers. Results showed that GeSAP can simulate farmers' behaviour concerning the selection of water sources for irrigation, allowing evaluation of the effectiveness of a wide range of strategies which impact water demand and consumption.

1. Introduction

In many arid and semi-arid regions, the overexploitation of groundwater (GW) impoverishes water quantity and quality, requiring more stringent regulations of GW use. Irrigated agriculture produces almost half of the world required food and fibres (United Nations, 2003), and is the main user of GW in many parts of the world, especially in arid and semi-arid regions, where it accounts for up to over 80% of GW use (Llamas and Martínez-Santos, 2005). The key water management challenge in these areas is to develop strategies aiming at finding a compromise between water resource sustainability and agricultural income (Molina et al., 2010).

Achieving sustainable use of GW will require changes that go beyond improving efficiency of water use, and implies a radical change in water policy and the implementation of innovative governance (Holtz and Pahl-Wostl, 2011). A key challenge for achieving GW sustainability is to frame the hydrological implications of various alternative management strategies in such a way that they can be evaluated properly and then effectively enforced. Assessment of the ability of GW to support water use is a fundamental issue and appropriate resource management must definitely assume GW as a common resource (Llamas and Martínez-Santos, 2005).

On the other hand, it is clear that any improvement in the efficiency/sustainability of GW use, given the continuing global trend towards GW exploitation, will have implications on water demand management, and also on the generally accepted world view of agriculture (Gleeson et al., 2010).

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Many times, the best attempts to solve GW management problems actually worsen the situation, because the policies selected create unexpected side effects. These unexpected dynamics often create resistance to policies, with the tendency for an intervention to be delayed, diluted, or defeated by the system's response to the intervention itself (Sterman, 2000). The increasing awareness of the uncertainty and complexity of water resources management is challenging the traditional management regimes based on a top–down approach and is decreasing the trust of decision-makers regarding the usefulness of simulation models to support decision-making (Knűppe and Pahl-Wostl, 2011; Borowski and Hare, 2007).

Avoidance of policy resistance requires expansion of the boundaries of the model used as the basis for decisions, so that decision-makers become aware of and understand the implications of the feedbacks created by their decisions (Sterman, 2000). Therefore, integrated models are required to take the complexity of the world into account as a response to the challenges of integration in water management itself (Borowski and Hare, 2007; Sterman, 2000).

Integration takes place broadly across sectors, and is basically a process of knowledge integration and integration across scales. This integration is reinforced by the inclusion of a divergent group of stakeholders as part of the modelling process. Modelling becomes a process of co-production of knowledge, based on the awareness that there may simultaneously be many different and equally valid ways of understanding a problem and finding solutions (Brugnach and Ingram, 2012). In scientific literature, these approaches are named participatory modelling.

According to Voinov and Bousquet (2010), two main objectives may be achieved through the integration of stakeholders in the modelling process: i.e. development of a shared understanding of a system and its dynamics, and support for identification of the most suitable course of action, thus reducing the level of conflict among the different stakeholders (Gaddis et al., 2010). In several cases, the collective learning process aimed at achieving shared understanding also leads to a better decision-making process (e.g. Metcalf et al., 2010; Lynam et al., 2010). During these processes, stakeholders and scientists are involved in a debate in which assumptions are teased out, challenged, tested and discussed (Checkland, 2001). Participants become aware of each other's perspectives and key interests (Henriksen et al., 2007), and are required to negotiate a credible and legitimate knowledge base to inform and support the decision-making process (Vogel et al., 2007). Independently of the approach adopted, participatory modelling aims to explore options and enrich the debate (Sandker et al., 2010). It can help participants to confront the real drivers of changes and to recognize non-linearities (Garcia-Barrios et al., 2008).

As a consequence, the role of decision supports tools in the context of environmental decision-making processes is changing, and these can play a twofold role. On the one hand, decision support tools should support the elicitation of preferences, values and knowledge held by the different actors, and make knowledge accessible to inform the debate. On the other hand, models are also a shared platform through which this debate is organized and structured, and through which different sources of knowledge are integrated, including what emerges throughout the process (Guimãres Pereira et al., 2005).

Several models exist which are based on the integration between scientific and stakeholder knowledge, and a wide range of modelling methodologies have been used, including the Bayesian Belief Networks, agent-based modelling and system dynamic modelling (Stave, 2002).

The Bayesian Belief Network is largely considered a modelling tool suitable for eliciting and communicating the differences in understanding problems and for supporting the social learning process. According to the most recent findings, the construction of the network of nodes (i.e. variables), links between nodes, and the definition of the conditional probability of their occurrence, allowed participants to become aware of the interests and concerns of others (Henriksen et al., 2007; Molina et al., 2010; Castelletti and Soncini-Sessa, 2007).

Several examples of BBN implementation for GW management can be found in the scientific literature (e.g. Farmani et al., 2009). Most of them are based on stakeholders involvement (Martin de Santa Olalla et al., 2005; Henriksen and Barlebo, 2008; Henriksen et al., 2007; Molina et al., 2010). Among them, Martinez-Santos et al. (2010) proposed a BBN-based approach to support stakeholders involvement in conflicting water management situations. Their approach is based on the assumption that a conflict between different parties may simply reflect different knowledge frames, interests, and beliefs among the participants, that is, it could be based on ambiguity (Brugnach and Ingram, 2012). Thus, BBNs were used in their work to structure these different knowledge frames.

In line with the most recent researches, our work incorporates stakeholders and behavioural models of actors as a way of capturing the necessary socio-psychological elements which must be considered when testing policy options (Borowski and Hare, 2007; Hare and Deadman, 2004; Bousquet and Le Page, 2004; Giordano et al., 2007; Moss et al., 2001; Becu et al., 2003; Barreteau et al., 2003). BBNs have been innovatively used in this work to investigate differences in stakeholders' understanding of a problem, and to analyse and measure emerging conflicts due to the implementation of GW protection policies. We mainly refer to Object-oriented Bayesian Belief Network (OOBBN), which are defined in scientific literature as a special family of Bayesian Belief Networks which allow a structuring of the model domain into sub-domains, and with linkages from variables in one sub-domain to other sub-domains (Molina et al., 2010). Hereby, OOBBNs were developed in this work to provide a description of real-world GW management domain, characterized by different decision agents, each with her/his own decision model. The links between the sub-domains represent the impact of an action on others' decision model.

BBNs and hydrological system features were integrated in a GIS-based decision support system – GeSAP – able to elaborate and analyze scenarios concerning the pressure on GW due to exploitation for irrigation purposes and the effectiveness of protection policies, taking into account the level of consensus.

The GeSAP system was applied experimentally to support GW planning and management in the Apulia Region (Southern Italy).

The paper is organized as follows: Section 2 provides the description of the methodologies adopted to assess the pressures on GW and to evaluate the effectiveness of GW protection policies; Section 3 is dedicated to the description of the results obtained in the study area and to the discussion of the feedbacks collected with local decision makers concerning the application of the GeSAP GIS-based Decision Support System to the Apulia region; Section 4 presents summarizing and concluding remarks.

2. Materials and methods

In the absence of detailed hydrological and hydro-geological studies aimed at determining the amounts of percolation on local and regional scales, a simple but effective approach to investigate the sustainability of GW resources has to consider at least the first order controls of aquifer exploitation. These are: i) the average percolation amount, R, corresponding to the natural GW recharge per year; and ii) the volume of GW pumped per year, P, where the difference between R and P is assumed as a sustainability index for GW use. To be sustainable, GW use should ensure that a certain percentage of R is left for the remaining GW services such as feeding the baseflow of streams, preventing seawater intrusion, conserving wetlands, and so on. Defining GW sustainability strategies is an urgent need in many regions around the world where aquifer exploitation was developed far above the natural renewal rates (Gleeson et al., 2010). Moreover, beyond hydrological evaluations, GW sustainability strategies should be assessed from an interdisciplinary perspective, where ecology, geomorphology, climatology and socio-economic issues play an important role (Alley and Leake, 2004). Community involvement is essential for the success of long-term GW management strategies in which setting specific goals for GW use requires a shared understanding of the fragility of the resource (Sophocleous, 2010).

With this aim, our work develops an integrated methodology able to combine hydro-geological, socio-economical and behavioural determinants of GW use to support GW resource protection. A series of three indices was therefore designed to assess the degree of GW exploitation before and after the definition of protection policies (Fig. 1). All the three indices were developed and implemented through a GIS platform enabling to account for the spatial dimension of GW exploitation due to the variability in agricultural water demands, hydro-geological features and farmers' behaviour across the investigated area.

The Groundwater Exploitation Index (*GEI*) is defined by combining an estimation of the expected GW exploitation with the GW recharge. The groundwater regulated-exploitation index (GEI_R) aims to assess the effectiveness of protection policy in terms of reducing pressure on GW, and represents the decision-makers' target. Finally, the groundwater exploitation index under acceptable regulation (GEI_{AR}) is defined to account for the farmers' reaction to the implementation of the GW protection policies. To this aim, a degree of acceptability is calculated.

To achieve GW sustainability objectives, the proposed index-based methodology sets up a comparison between GW recharge and expected GW exploitation, evaluated considering both the crop water requirements (*CWR*) and the farmers' behavioural model (propensity to GW exploitation). If exploitation is not sustainable, then a protection policy is required. Farmers' reactions can have an impact on the effectiveness of GW protection policy: if farmers do not consider the protection policy acceptable (i.e. a high degree of conflict), there will be strong opposition to the policy implementation (e.g. illegal pumping), leading to reduced effectiveness of the policy itself (i.e. lower than the planned target of GW exploitation). In the methodology, the actual impact of protection policy is assessed integrating the regulated GW exploitation index with the farmers' acceptability degree. The decision-making process ends when the selected policy makes it possible to meet the sustainability criteria.

The three indices – *GEI*, GEI_R, and GEI_{AR} – have been implemented using a spatialized information base and GIS tools. This allows the decision-makers to define different protection policies according to the local degree of GW pressure. Moreover, the degree of acceptability allows identification of the areas where strong conflicts with farmers are likely to emerge. Hence, decision-makers can focus their negotiation strategy on such areas.

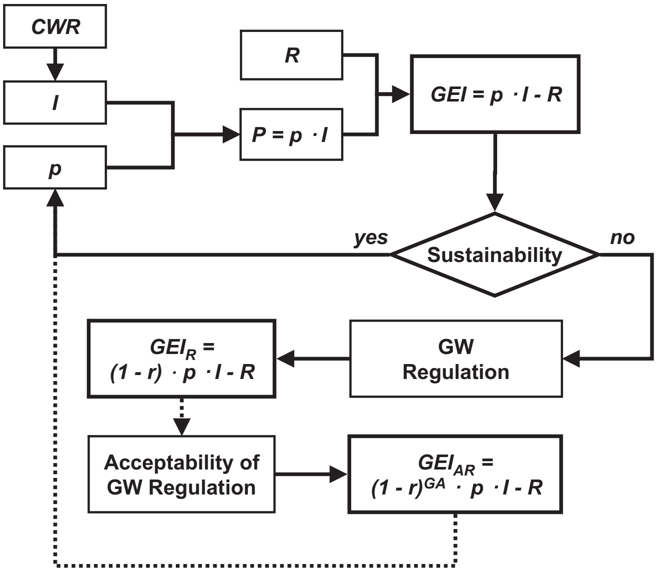


Fig. 1. Synthetic indices adopted for the integration between quantitative and behavioural aspects regulating groundwater exploitation for irrigation. Accordingly, the input variables are the crop water requirement, *CWR*, of the interested area, the potential volume of groundwater exploitation for agriculture, *I*, the propensity of farmers to groundwater exploitation, *p*, with respect to other water resources, the natural groundwater recharge per year, *R*, while the output indices are the groundwater exploitation index, *GEI*, the groundwater regulated-exploitation index, GEI_R, and the groundwater exploitation index under acceptable regulation, GEI_{AR}. Dotted connectors in the scheme refer to farmers' behavioural and probabilistic interaction while continuous lines regard deterministic processes.

The following sections describe how the three indices are defined and evaluated.

2.1. The GW exploitation index GEI

The *GEI* is calculated according to the following equation and expressed in mm/year:

$$GEI = p \cdot I - R \tag{1}$$

where *I* represents the potential GW withdrawal volume, *p* is the propensity to GW exploitation in the year of the analysis, and *R* is the mean annual GW recharge.

The *GEI* allows to represent those areas where GW use for irrigation is not sustainable and the implementation of an effective protection policy is necessary.

2.1.1. Potential withdrawal volume

In our methodology the potential GW withdrawal volume *I* is the annual overall GW withdrawal capacity of a given area as a result of hydro-geological (i.e. aquifer storage and yield) and structural (i.e. number and specifications of pumping facilities, licenced annual volumes) constraints. Of course the assessment of such term, though crucial, is often difficult at least over large regions (due to limited data availability), and therefore indirect methods such as those based on *CWR* can be very helpful. In fact, it can be assumed that in shortage of surface water resources, irrigation requirements are satisfied through GW exploitation. Consequently, mean annual *CWR* estimations can be assimilated to the potential GW withdrawal volume *I*, provided that other sources of irrigation supply are taken into account in the overall water balance of a given agricultural land area. The *CWR* approach can indeed be adopted to evaluate other cropping scenarios in terms of GW exploitation policies.

2.1.2. Propensity to GW exploitation

The propensity to GW exploitation *p* can be defined as the probability that a farmer uses GW for irrigation in a given year. It assumes values included in the interval [0, 1] and it is estimated through a multi-step approach based on farmers' behavioural models.

The first step is to structure the farmers' knowledge (acquired via direct interviews) into Cognitive Maps (CMs) (Kosko, 1986; Ozesmi and Ozesmi, 2004). A CM can be defined as a qualitative model of the decision-making, in which the nodes represent variables and the arrows represent causal assertions. The links may be positive or negative. The existence of a positive link between the variables "A" and "B" means that if "A" increases then "B" increases. If the link is negative, then an increase in A implies a decrease in B. The links are also characterized by a weight, which represents the strength of the connection, that is, how strong the influence one variable has on the another one.

The "ends-means" approach is adopted for CMs development (Eden and Ackermann, 2001). CMs are constructed firstly through their value system, that is, actors' main objectives and, secondly, by the main courses of action considered suitable to achieve those objectives. CM development process is based on the analysis of individual semi-structured interviews.

Although CM's capabilities to reflect the way actors are accustomed to talking and thinking about decision-making situations, they only allow representation of limited forms of causal inference, and are not able to take into account the uncertainty due to limited knowledge of the system (Montibeller et al., 2007). The CMs are subsequently used as the basis for the development of the BBNs. Giordano et al. (2013) discussed the issues to be addressed when using CM to develop BBN. A methodology to derive the conditional probability tables (CPTs) from the strength of links in the CM is described in that work.

The developed BBNs are capable to simulate farmers' choice of the main source of water for irrigation.

The GW irrigation costs, which strongly influence farmers' behaviour, are calculated referring mainly to energy costs for pumping.

Direct costs of GW use have been considered. Direct costs were divided into fixed costs and variable costs and refer to the costs of capturing and delivering irrigation water. Fixed or capital costs include all investments in irrigation infrastructures, such as building wells and installing pumps, and concerning equipment, plus depreciation and interest payments on the investment. Variable or running costs include pump energy costs, operation and maintenance of water delivery devices and personnel costs.

To take into account the spatial differences in terms of water table elevation and water piezometric head of irrigation systems among the different cadastral units, all costs have been estimated on a spatial scale. In addition, capital costs have been annualized considering their useful life.

In practical terms, the average cost per cubic meter of water C_{T1} in each cadastral unit is given in Equation (2):

$$C_{T1} = \frac{C_{Dr\_An}(H_{Dr}, n) + C_{Eq\_An}(H_T, n, Q) + C_P(n) + C_M(n)}{V} + L_1 \ C_{kWh} \tag{2}$$

where: C_{Dr_An} is the annualised cost for drilling the *n* wells in a cadastral unit, each with an average depth of H_{Dr}, *n* is the number of wells in each cadastral unit, C_{Eq_An} is the annualized cost for pumps and other electrical equipment, which is a function of

H_T, n and the flow rate Q, C_P is the annual cost of labour required to operate GW pumping stations and water supply systems, C_M is the annual cost for the maintenance of well infrastructure, V is the annual amount of water extracted in the cadastral unit in m^3, L_1 is the work required in kWh to pump 1 m^3 of GW up to the total H_T head according to the expression reported below, C_{kWh} is the unit cost per kWh.

The estimation of the unit energy cost L_1 to raise water from below ground to the required height is given by the water pump formula. For a hypothetical irrigation supply network it can be expressed as in Equation (3):

$$L_1 = \frac{H_T}{102 \ \eta \ 3.6} \tag{3}$$

where the total head $H_T = H_g + H_p + H_e$ – in metres – is the sum of geodetic head H_g given by the water table depth, rising main head loss H_p, and the standard pressure for irrigation networks H_e, while η is the standard notation for pumping efficiency.

In the case of deep carbonate aquifers, the spatial evaluation of H_g was computed from the digital elevation model (DEM), assuming a balance between water table elevation above sea level (ranging from less than 1 m close to the sea to a few dozen metres inland) and rising main losses. For the alluvial aquifers, the water table was assumed to follow the topography at depths derived from the analysis of available data. In both cases, H_e was set at 30 m, while a pumping efficiency equal to 0.7 was considered to account for other localized head losses and for the ageing of pumping components.

The pumping energy cost per cubic meter of water has been estimated by combining the obtained unit energy consumption with the spatial analysis of irrigation volumes, thus marking the determining role of landscape elevation in controlling GW exploitation costs. It was found that the areas with higher energy costs for water correspond to those areas of the region with a higher water demand due to the *CWR* and disadvantaged GW depths. The average energy consumption per hectare is about 340 kWh per year considering all cadastral elements with at least one recorded well, but average energy consumption in intensively irrigated areas is about 1500 kWh/ha.

2.1.3. GW recharge estimation

The G-MAT (Portoghese et al., 2005) model is adopted to estimate natural GW recharge. G-MAT is a semi-distributed GIS-based hydrological model and was originally developed for the sustainability assessment of water resources with particular emphasis on GW-dependent regions and irrigation requirements. It considers the major landscape features that determine the soil water balance, such as vegetation and soil moisture storage and water flux processes. G-MAT yields natural GW recharge on a monthly basis, through the distributed application of the soil water balance equation, evaluated as the difference between the inflows (rainfall, irrigation) and outflows (evapotranspiration, surface runoff), assuming the monthly irrigation amounts equal to the soil moisture deficit (Allen et al., 1998). The spatial resolution of the implemented model is 1 km^2, thus assuring a feasible representation of the spatial heterogeneity of soil and sub-soil, as well as a realistic description of catchment morphology. Accordingly, vegetation patterns are spatially-averaged thus assuming that field scale heterogeneities are compensated by the time-variation of crops. This coarse representation of vegetation was proved adequate to investigate regional scale patterns of water use for irrigation.

2.2. GEI_R: GEI due to GW regulation policy

The GEI_R index is expressed in the Equation (4):

$$GEI_R = (1 - r) \cdot p \cdot I - R \tag{4}$$

where r is the percentage reduction in GW use according to the protection policy. This index represents the level of exploitation under full enforcement of the GW regulation targets. If the protection policy impedes the achievement of farmers' main goals – i.e. quantity and quality of crop production – then their strong opposition may cause drastic limitations to the implementation of protection measures. Their opposition may result in illegal GW use and it will hamper the achievement of the policy's goal. Therefore the actual reduction of GW pressure will be lower than planned, as described in the following section.

2.3. GEI_{AR}: GEI under acceptable GW regulation

The degree of acceptability (*GA*) may vary between 0 and 1 and is the output of the BBN simulating the farmers' behaviour after the implementation of the protection policy.

$$GEI_{AR} = (1 - r)^{GA} \cdot p \cdot I - R \tag{5}$$

The exponential form in Equation (5) operates an increase in the abstraction term in the exploitation index compared with the reduction targets established by the regulation measures. Considering the extremes of *GA*, it can be noted that, for $GA = 1$, i.e. when there is unanimous consensus, $GEI_{AR} = GEI_R$ and the expected goal is fully achieved; while if $GA = 0$, i.e. a high level of conflict, $GEI_{AR} = GEI$, meaning that the policy completely fails in reducing the pressure on GW due to the strong opposition by farmers. For all other intermediate values of *GA* and for reduction factors r ranging from 0 to about 0.3 (i.e. −30%), the exponential form in Equation (5) operates an almost linear reduction of r by a factor equal to *GA*. For higher values of r, the exponential term deviates from the linear approximation, thus yielding a higher deviation from the target GW regulation.

The adopted formulation has the advantage of simply integrating the acceptability degree into the previously defined target exploitation index GEI_R, while at the same time reproducing the social reluctance to accept drastic reduction policies (i.e. high r values) as a non-linear function of the parameter r.

2.3.1. Acceptability of GW regulations

GA is defined as a function of the interference between actors, that is, the impacts of the actions of one actor on the set of objectives of the other one, and of the importance of the objectives influenced by the actions (Zeleny, 2008; Obeidi et al., 2005).

Let d_i and d_{i+1} be two decision agents involved in GW management. The impacts of the action a_j^i of the agent d_i on the k-th objective of the agent d_{i+1} is calculated according to Equation (6):

$$IM\left(a_j^i, o_k^{i+1}\right) = \left(o_k^{i+1} - O_k^{i+1}\right) \tag{6}$$

In which, $IM(a_j^i, o_k^{(i+1)})$ is the impact of the j-th action of the i-th agent on the k-th objective of the agent $i+1$; $O_k^{(i+1)}$ is the ideal value of the k-th objective; $o_k^{(i+1)}$ is the actual value the k-th objective of the agent d_{i+1} due to the implementation of the action a_j^i.

Therefore, the acceptability degree is assessed according to Equation (7) (Giordano et al., 2013)

$$GA = f\left(o_k^{i+1} - O_k^{i+1}\right) \tag{7}$$

The spatialization of the *GA* allows the identification of those areas with the highest degree of conflict. In such areas, the implementation of any GW protection strategy could be limited by strong opposition of farmers. The objectives of the strategy would not be achieved and the pressure on GW resources would not actually be reduced. In such areas, it is essential to introduce conflict mitigation measures to support the effective implementation of the GW protection strategy.

2.4. GeSAP tool

The methodology described above is implemented into a GIS-based Decision Support System adopting the conceptual architecture reported in Fig. 2. The geographically-based data (hydro-meteorological, land use, wells distribution, GW properties) are stored in the GIS database. This database provides inputs to the BBNs (simulating behavioural models). These two modules are then integrated to spatially evaluate the propensity to GW exploitation and the acceptability degree. The output indicators (*GEI*, GEI_R, GEI_{AR}) are then shown through the GIS interface.

The GeSAP interface implements a hierarchical structure, divided in three elaborative levels, in which the output of every step is the input for the next one, together with other data predefined by the system or by the user. The three elaboration levels coincide with the three GW exploitation indices, explained in the previous sections. The comparison between the three elaborative levels allows to evaluate the efficiency of the GW protection strategies, in terms of withdrawals reduction. The tool is entirely developed as an extension of the ESRI ArcGis Desktop 9.3.1 and can be loaded and operated through a specific toolbar. It is able to integrate

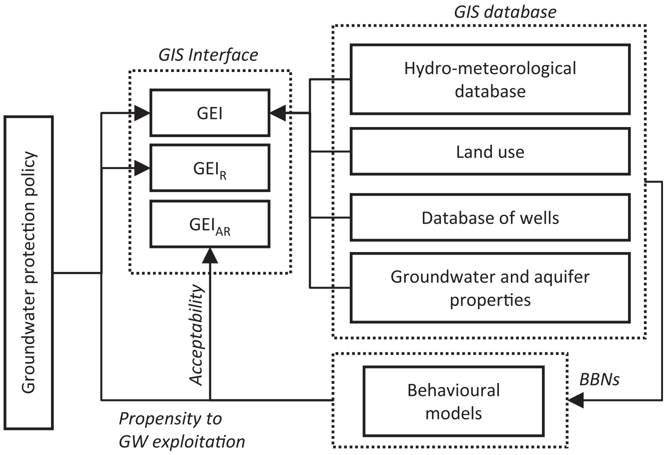


Fig. 2. Conceptual architecture of the GeSAP decision support system.

grid maps in ASCII format containing the spatial information, and the output of the BBN related to the farmers' behaviour.

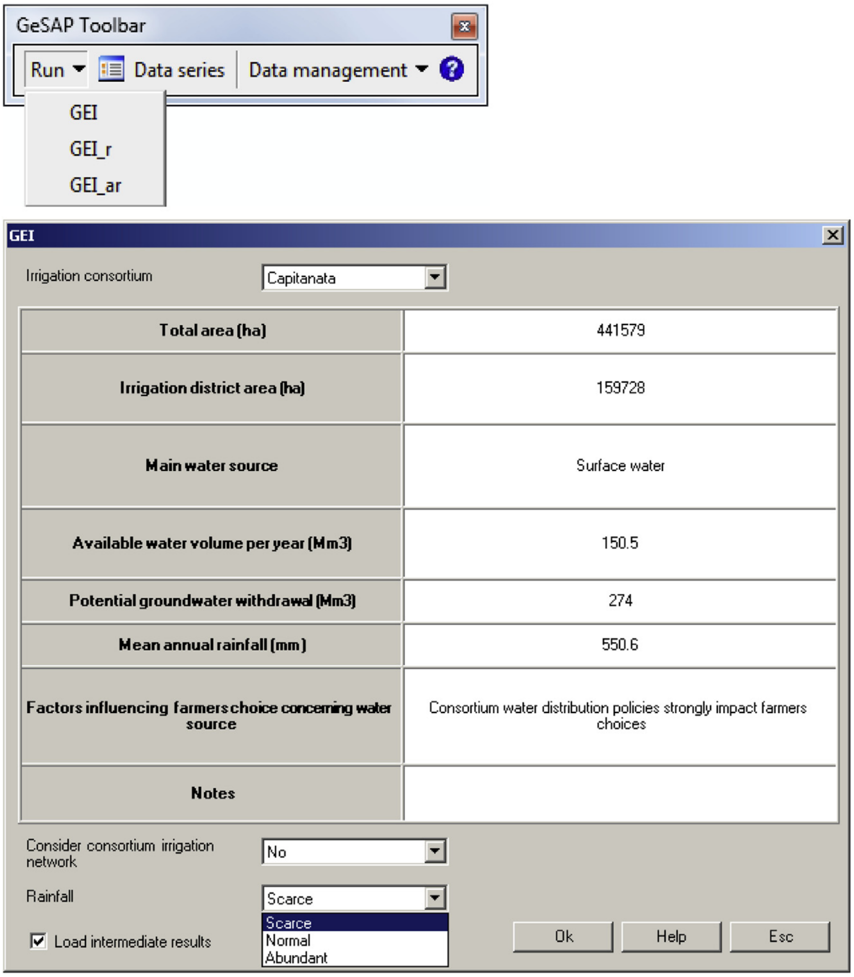
The GeSAP interface allows the user to select the information to be elaborated by way of the three GW exploitation indices. The analysis is carried out for each of the irrigation consortia. The interface provides fundamental characteristics of the selected consortium, which are used during the calculation phases in the GIS environment. Users are required to select the mean rainfall and the presence of irrigated areas. The interface requires other specific input to describe the farmers' choice. GeSAP can be used to simulate different GW management scenarios under different climatic conditions. An example of the GeSAP graphical interface is represented in Fig. 3 for one of the consortia investigated in the study region.

2.5. Study region

The Apulia region is a peninsula of about 20,000 km^2, and may be considered a typical example of GW overexploitation due to the limited availability of surface water resources (concentrated in the north-western part of the region, named Capitanata plain) contrasting with valuable GW bodies extending from the carbonate ridge to the sea shoreline (Masciale et al., 2011). The main GW reservoirs in Apulia are represented by the Mesozoic carbonate successions of the foreland, forming the Gargano (North-East of the region, corresponding to the homonymous irrigation consortium), Murge (central peninsula, corresponding to the Terre d'Apulia consortium) and Salento limestone outcrops (southern peninsula, partly covering the Arneo and Ugento li Foggi consortia). Less extensive and thick, but nevertheless important, aquifers of the region are located in the clastic sediments of Quaternary age outcropping in the Capitanata plain (corresponding to the homonymous irrigation consortium), in the Brindisi plain facing the Adriatic Sea (corresponding to part of the Arneo consortium) and in the plain surrounding the western limit on the Ionian gulf (corresponding to the Stornara e Tara consortium). Groundwater, fed by seasonal rainfalls, mixes with sea water from continental intrusion. Hydrogeological conditions, such as permeability, depth of water, specific discharge of wells, as well as natural water quality, are influenced by factors related to the stratigraphic and structural features of the aquifers and, in limestone formations, by the irregularly distributed occurrence of karst phenomena. Broadly speaking the aquifer's base level for carbonate formations corresponds to sea level and freshwater overlays saltwater while the water table depth ranges from few tens of meters in the coastal zones to 300–500 m in the inland of the region. Quaternary aquifers of Capitanata, though with a low specific discharge of wells, have quite shallow GW and are therefore affordably exploitable. Hydrogeological equilibrium of GW systems in Apulia, mainly governed by the fresh – sea water balance, may be altered by uncontrolled withdrawals and occasional decrease of rainfall alimentation.

Over many centuries, gentle orographic features and high population density have led to the intensification of farming, accompanied by the replacement of existing natural vegetation with agricultural crops (more than 76% of the total area is used for agriculture). Starting from the 1960s, traditional rain-fed agriculture has been replaced by irrigated farming and water-intensive crops (irrigated crops now occupy about 17% of the region's agricultural land). Besides the development of some multipurpose artificial reservoirs (from the 1950s to the 1980s), the main drivers of irrigated farming have been innovations in pumping and irrigation technologies and the implementation of policies favouring irrigated agriculture.

Specialized agriculture is a vital economic resource for Apulia, with cereals and vegetables mainly grown in the fertile central northern zone, and olive trees and vineyards dominating the central and southern areas of the region. Agricultural development in the region has been responsible for several interconnected environmental pressures involving water resources (water table depletion and seawater intrusion in GW), landscape management (extensive changes in land use, monocultures) and biodiversity (loss of soil fertility, replacement of natural species).



Irrigation consortium: Capitanata

Total area (ha)	441579
Irrigation district area (ha)	159728
Main water source	Surface water
Available water volume per year (Mm3)	150.5
Potential groundwater withdrawal (Mm3)	274
Mean annual rainfall (mm)	550.6
Factors influencing farmers choice concerning water source	Consortium water distribution policies strongly impact farmers choices
Notes	

Consider consortium irrigation network: No

Rainfall: Scarce

☑ Load intermediate results

Fig. 3. GeSAP graphical interface, where the user selects the consortium in which the groundwater exploitation indices (*GEI*) are computed in three steps under different conditions. The selection from the list box retrieves the main features of the consortium in which the *GEI* computation is launched in the next step including the retrieval of the consortium spatial domain. In practice, the user is asked to set whether to consider the existent irrigation network or not and to select the level of the annual rainfall in the year of interest (compared to the mean annual rainfall) in order to customize the subsequent *GEI* computational steps.

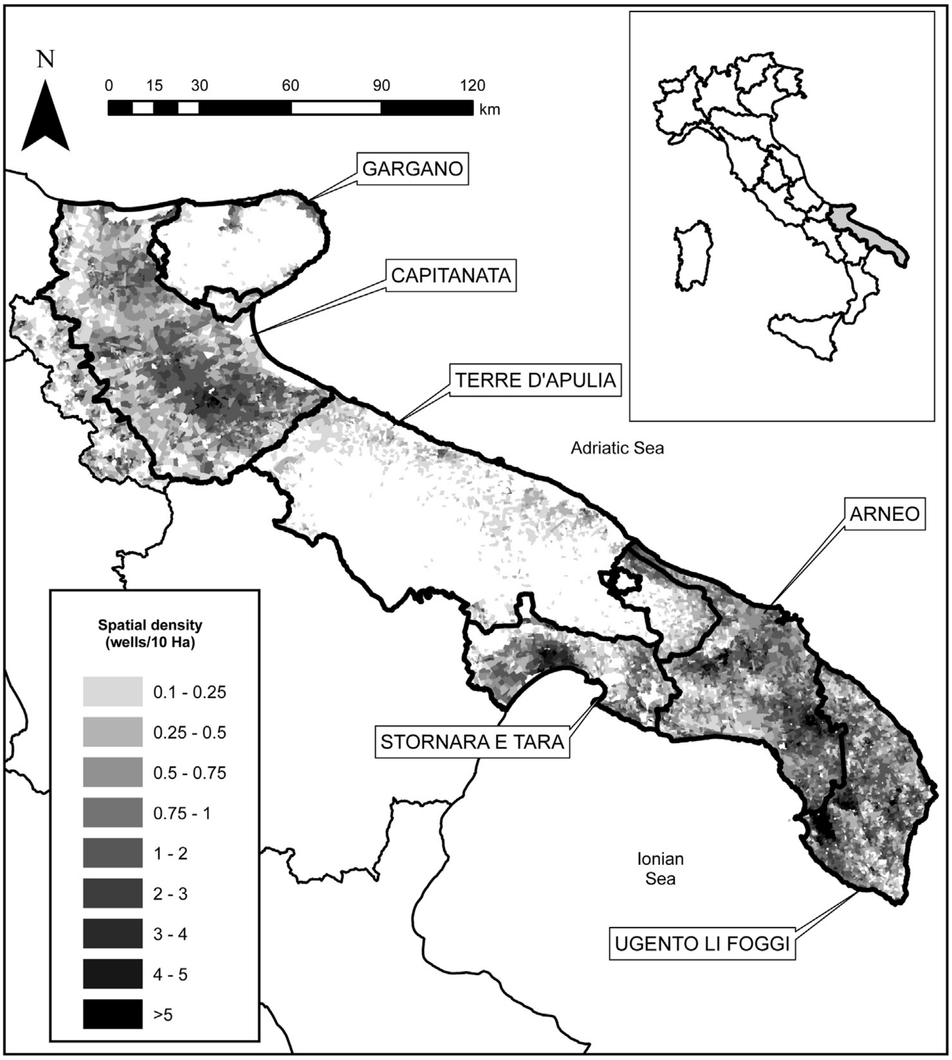


Fig. 4. Spatial representation of groundwater well distribution in the study region at a resolution corresponding to the cadastral map elements. The map also represents the geographical layout of the irrigation consortia.

In the Apulia region 6 irrigation consortia are present (Fig. 4). They are public entities that provide for the land protection and water resources management, for the soil conservation, for the irrigation, for the preservation of the natural environment and for ensuring an adequate technical and administrative assistance to farmers.

In the following Table 1 a few basic features about each consortium are reported.

The scarcity of water has always been a major constraint to the social and economic development of the region, due to climatic conditions and the low water supply capacity of surface water bodies. To overcome this problem, huge water systems were built between 1970 and 1980 to transfer water from the bordering regions on the Apennines, mainly to drinking water supplies but also for uses in agriculture. Besides the critical dependency on these external water resources, the available water supply was not enough to satisfy the entire demand for water. During the last three decades, there has been a continuous increase in GW withdrawal by farmers (as single farm and as irrigation consortia) without appropriate legislation for sustainable resource management, resulting in lowering of GW levels in many places.

Considering the serious effects of seawater intrusion (already observed) and the consequent reduction of the irrigated surfaces along the coast, the regional water authority proposed the enforcement of restrictions on the use of GW. In agreement with the Water Framework Directive (EEC 2000/60), a Water Protection Plan was approved in 2009 which established a 20–40% reduction in the current amount of GW extracted. However, the new legislation caused great conflicts between farmers and the regional authority due to the expected economic damage to an agricultural sector highly dependent on irrigation. It is also difficult to enforce new regulations concerning pumping licences, because the amount of water extracted in the region is unknown.

Table 1
Description of irrigation consortia with their main water sources.

Consortium	Total area (ha)	Equipped area (ha)	Irrigated area (ha)	Dominant land use	Main water source
Gargano	150,337	570	428	Pasture, followed by grains and forests	Spring water
Capitanata	441,579	140,378	53,667	Grains, vineyards, orchards and olive trees	Surface water
Terre d'Apulia	569,807	17,645	4972	In the coastal area predominate olive trees and vineyards, while in the inland predominate grains and pasture	GW
Stornara e Tara	142,949	43,705	13,203	Vineyards, followed by citrus, vegetables and olive trees	Surface water
Arneo	249,425	18,659	1127	Vegetables and olive trees, followed by vineyards	GW
Ugento li Foggi	189,494	15,055	2120	Olive trees followed by vegetables	Spring water GW

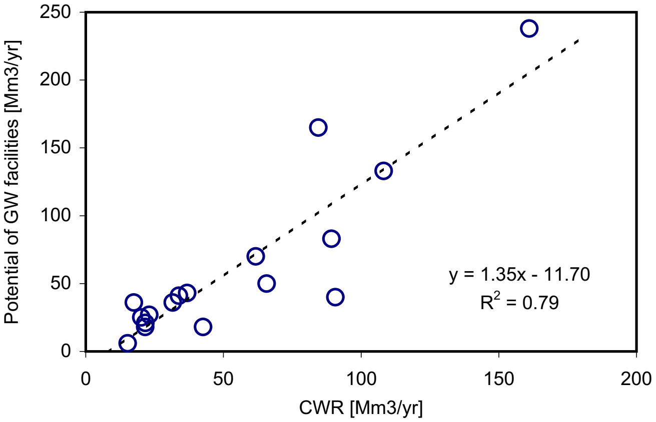


Fig. 5. Correlation between mean annual crop water requirement (*CWR*) average irrigation amounts estimated for each aquifer with the G-MAT model and withdrawals resulting from analysis of the database of pumping licences.

3. Results and discussion

The GeSAP tool has been implemented to support the definition of an effective and acceptable GW protection policy in the Apulia region.

3.1. Pressure level on GW in the study region

The GW pressure level *GEI* has been calculated using Equation (1) and the evaluation of the considered factors is described in the following sub-sections.

3.1.1. Potential withdrawal volume (I) and GW recharge (R) estimation

Recently, the regional water authority has launched a campaign to create a centralized database of the existing abstraction licences. A preliminary result of this activity is an estimate of more than 150,000 wells, although it is likely that there is also an unknown but consistent number of illegal wells. Furthermore, very little is known about the construction, installation, and operational conditions of these wells, thus increasing the potential damage caused by intense and uncontrolled aquifer exploitation.

Given the well documented situation of GW pumping facilities, we adopted a direct estimate of the potential GW withdrawal obtained from the areal summarizing of the regional database of GW licences. A few characteristics describing the intensity of GW exploitation were drawn from this database using the spatial resolution of cadastral map elements with an average dimension of 130 ha (Fig. 4). This analysis made it possible to estimate an average of 0.89 wells every 10 ha and a standard deviation of 1.23 for those cadastral elements where at least one pumping licence was recorded.

Moreover we correlated the direct estimates of potential GW withdrawals extended over the main aquifers in the region with the mean annual *CWR* estimated on the same areas (Fig. 5) through the soil water balance module of the G-MAT distributed hydrological model (Portoghese et al., 2005). In particular we referred to the irrigation districts where farmers conjunctively use common facilities supplied by surface water and GW pumping facilities at farm-scale. Consequently, though all district areas are plotted in Fig. 5, the regression line was estimated using those areas where only GW is used for irrigation. (The point falling below the regression line refers to those areas in which surface water with common irrigation facilities).

Other water balance estimates for Apulia's main aquifers are reported in Table 2 together with the mean water table depths and corresponding irrigation consortia. Mean annual water balance components are computed as average values over the period 1951–2000.

Good agreement was found between modelled irrigation volumes (*CWR*) and potential withdrawal volumes (Fig. 5). In particular, the over-estimation of GW potential compared to modelled irrigation requirements (+35%) can be explained with irrigation efficiency issues that were not considered in the *CWR* estimation. Moreover, some misfits in withdrawal estimations (Fig. 5) were justified by specific aquifer features such as an incomplete wells' data record (Murgia Nord), the abundance of drinking wells in scattered households (Salento Ion, Salento Adr) and the presence of a surface water supply in irrigation districts (Fortore, Tavoliere B, Ofanto).

Overall, an estimate of about 960 Mm^3 per year was evaluated for the entire region (about 3700 km^2 of irrigated land) corresponding to an average annual GW supply of 0.25–0.30 Mm^3 per km^2 of irrigated land.

Table 2

Modelled water balance components of main regional aquifers going from North to South and groundwater potential withdrawal from the existing facilities. In the table, the mean water table depths and the correspondence between aquifers and irrigation consortia are also reported. Aquifers where irrigation supply is based on joint use of surface and groundwater resources are marked with an asterisk (*) while outputs from the adopted water balance model are marked with a double asterisk (**).

Aquifer name	Area [km^2]	Irrigated area [km^2]	Rainfall [mm/yr]	Runoff** [mm/yr]	Recharge** [mm/yr]	Unit CWR** [m^3/ha/yr]	CWR** [Mm^3/yr]	Potential of GW facilities [Mm^3/yr]	Mean water table depth [m]	Corresponding consortium/a
Fortore*	186	67	694	204	54	2272	15	6	125	Capitanata
Gargano	1832	78	682	125	89	2240	17	36	173	Gargano and Capitanata
Tavoliere AP	271	75	680	202	48	2694	20	25	75	Gargano and Capitanata
Tavoliere A	856	272	678	198	54	2270	62	70	118	Capitanata
Intermed A	548	87	690	227	41	2486	22	18	288	Capitanata
Tavoliere BP	496	133	660	220	41	2772	37	43	51	Capitanata
Tavoliere B*	1202	372	665	217	54	2909	108	133	130	Capitanata
Intermedio B	591	89	683	219	44	2433	22	21	326	Capitanata
Ofanto*	398	142	666	217	59	3003	43	18	158	Capitanata and Terre d'Apulia
Murgia Nord	1709	356	654	84	169	2546	91	40	184	Capitanata and Terre d'Apulia
Murgia Sud	2932	338	651	50	188	2641	89	83	194	Arneo and Terre d'Apulia
Alta Murgia	1446	83	652	79	135	2780	23	27	282	Terre d'Apulia and Stornara e Tara
Arco Ionico	465	208	648	183	69	3159	66	50	90	Stornara e Tara
Murgia Tar	755	106	632	77	132	3195	34	41	149	Arneo, Terre d'Apulia and Stornara e Tara
Brindisi	409	117	657	175	65	2702	32	36	72	Arneo
Salento Ion	2138	647	661	50	205	2490	161	238	100	Ugento li Foggi, Arneo and Stornara e Tara
Salento Adr	1669	389	663	62	189	2172	84	165	92	Ugento li Foggi and Arneo
Apulia region	19,337	3662	665	119	124	2586	947	960	155	–

3.1.2. Propensity to GW exploitation (p)

Given the different behaviour of farmers in the different areas, a CM was developed specifically for each consortium. As an example, Fig. 6 shows the CM developed using the results of the farmers interviews in the Capitanata consortium.

In the CM the variables are connected with arrows of different thickness, according to the strength of causal relationships, that can be strong, medium or weak. The sign "–" is used for negative links. The CM contains variables and causal connection influencing the farmers' behaviour and, particularly, the selection of the main source of water for irrigation. Two feasible alternatives of water sources were considered: i.e. water supplied by the irrigation consortium and water supplied by GW withdrawal.

After the development stage of the CMs, a validation phase was carried out involving different groups of experienced farmers to assess the ability of the CMs to describe farmers' behaviour. To guarantee a high level of reliability, farmers groups were selected in areas with different characteristics and required to validate both the variables included in the CM and the network of links.

A sequential implementation of CMs and BBNs made it possible to elicit and structure farmers' mental models and to evaluate spatial maps of the propensity of farmers to use GW as the primary source for irrigation. The driving factors adopted for BBN implementation are climatic conditions, consortium management policies, GW salinity, cost of GW exploitation, market conditions, and type of crop. The timescale of the BBN is one year.

As an example, Fig. 7 shows the BBN developed starting from the CM shown in Fig. 6.

The BBNs were used to assess how likely GW is the primary source of water for irrigation. Two main groups of variables were included in the BBN, that is, the exogenous nodes and the endogenous nodes. The former referred to both physical conditions of the system – i.e. precipitation, type of crops – and to the results of decision making processes of other actors – i.e. the price of water distributed from the consortium, market conditions. The endogenous variables are those influencing the farmers' decision which were part of the system perceived by the farmers – i.e. water demand, irrigated areas, etc. The states of the variables were defined according to farmers knowledge. The basic assumption is that the higher is the probability of GW withdrawal *p*, the stronger is the pressure on GW caused by irrigation.

After developing the BBN and estimating the CPTs, an evaluation of BBN capabilities to simulate farmers' decision process concerning irrigation management was needed. To this aim, water managers and farmers were involved in the BBN validation phase. They were required to indicate whether the BBN results were acceptable or, on the contrary, changes were needed concerning relationships among variables, their states or their probabilities. Moreover, data concerning water distributed by the consortia in the previous years were collected and analysed.

BBN analysis identified the two most important elements influencing farmers' decisions: water availability and GW irrigation cost. The total cost per cubic meter of extracted water has been estimated using the methodology described in Section 2.1.2 (Fig. 8). We considered all cost categories and a cost per kWh of 0.15 Euro. As a result, the GW cost for 7% of the irrigated area is between 0 and 0.12 Euro/m^3, for 33% of this area it is between 0.13 and 0.24, and for 49% it is between 0.25 and 0.50 Euro/m^3.

3.1.3. The GW exploitation index GEI

Fig. 9 shows the regional map of the GW exploitation index *GEI* in a scarce-rainfall year, corresponding to an accumulated annual precipitation of less than 80–% of the annual long-term mean (conversely, abundant-rainfall years correspond to annual precipitation over 120% of the long-term mean, while normal precipitation years fall between 80% and 120%).

The *GEI* values are representative of the hydro-geological disturbance caused by GW use. As such, they are expressed in mm per year, although 11 discretized class intervals were also introduced to enhance the meaning of the proposed index-based GW pressure assessment. The class intervals were set according to the empirical distribution of values in the study region and their characteristic values are reported in Table 3.

Although the adopted class intervals did not allow any objective assessment of potential aquifer damage due to the recognized level of exploitation, the practical application proved the usefulness of this metric in the evaluation of the impact of GW protection policies.

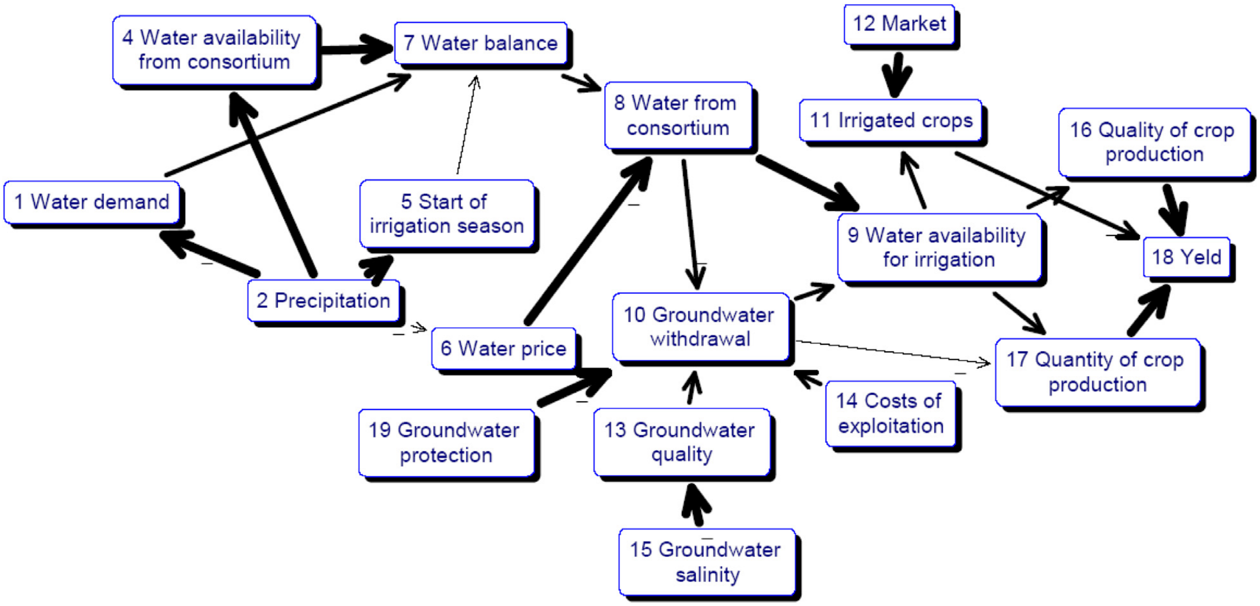


Fig. 6. Cognitive map developed using the results of the farmers interviews in the Consortium of Capitanata.

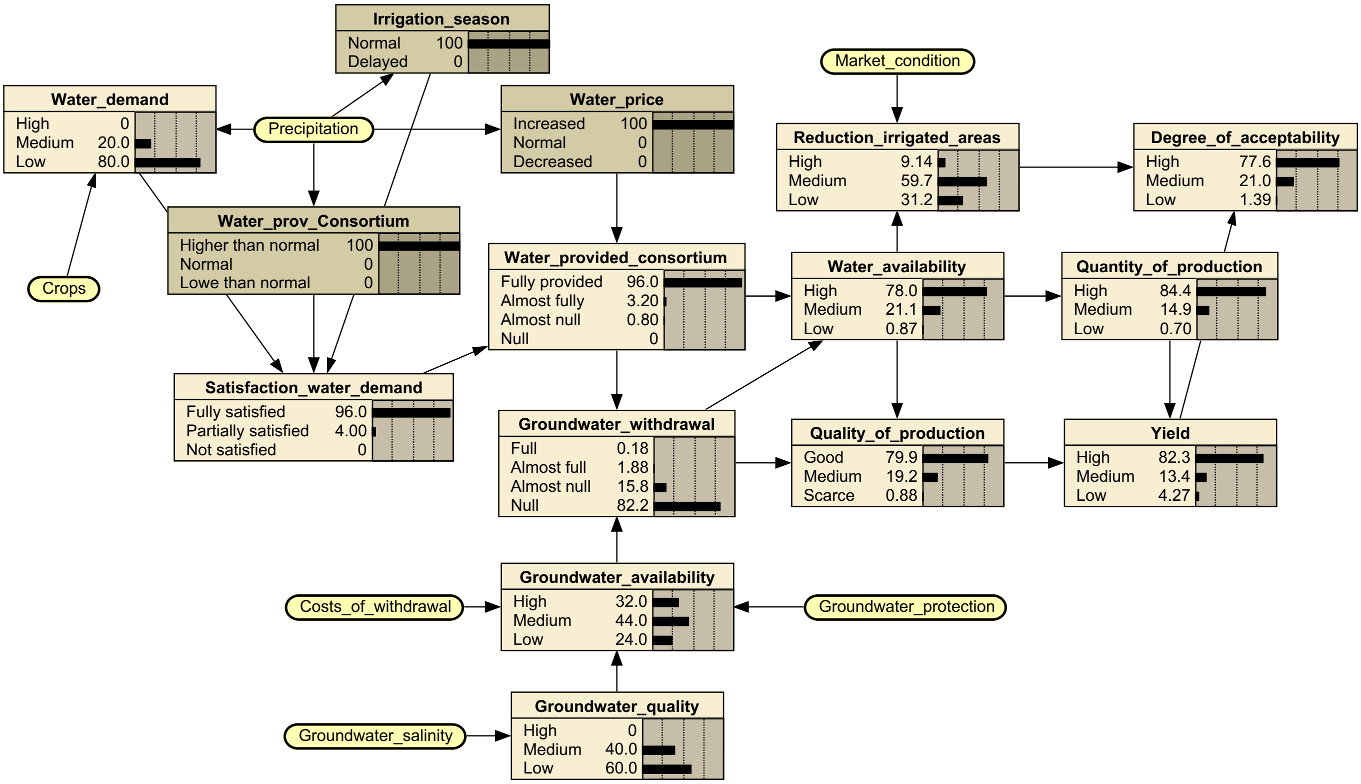


Fig. 7. Bayesian Belief Network (BBN) based on the cognitive map of farmers operating in the Capitanata Consortium. Three different kinds of elements are defined in the BBN. The elements in the rounded boxes are constants. The darker boxes represent variables for which an initial finding was defined. In this case, the findings were defined considering the consortium decisions concerning the water price, the start of the irrigation season and the amount of water to be distributed. The remaining variables are those whose values were assessed according to the conditional probability table (CPT) and the parent nodes values.

As shown in Fig. 9, three areas are characterized by widespread pressure on GW, i.e. Capitanata plain, part of the Ionian gulf and part of the southern peninsula. The high pressure in Capitanata is mainly due to the high water requirements of the crops grown there and to the consortium's water distribution policy (water price in scarce-rainfall years). The other two critical areas have very limited public water supply networks, so that GW is the only source of irrigation water in dry years.

An interesting result of the proposed approach regards the low spatial coherence between the boundaries of the protected areas set by the regional authority, and the pressure on GW as reported by the *GEI* mapping in the Capitanata plain (Fig. 9, detail). According to such results, the established extent of the protected areas was proved insufficient to effectively achieve the GW protection objectives across the whole area.

3.2. Impact of GW protection strategies (GEI_R and GEI_{AR})

The proposed GIS-tool was used to assess the actual impacts of a GW protection strategy setting a fixed GW reduction rate (different reduction rates can be set through the GeSAP interface in user-specified areas). A reduction of 40% of the exploited volume was established as a target.

The acceptability of this GW regulation was calculated referring to farmers' BBN (Fig. 7). The aim is to assess the interference between the regional authority (i.e. the actor implementing the GW regulation) and the farmers. The value of the parameter "groundwater protection" in the farmers BBN was set as "high". If we consider the Equation (5), then $O_k^{(i+1)}$ represents the expected farmers "yield", while $o_k^{(i+1)}$ is the yield due to the implementation of GW regulation. Both values are assessed considering the value of "yield" in the farmers' BBN. The stronger is the negative impact of the policy and the lower is the degree of acceptability.

In the BBN, two different scenarios were defined: the first was characterized by favourable market conditions (an attractive price for the irrigated crop products); while in the second, market conditions were unfavourable (a reduced margin between production costs and the price of products).

The estimated *GA* was implemented in the equation used to calculate GEI_{AR} according to Equation (5) as a raster map calculation. This index allows evaluation of the pressure on GW after protection policy implementation, taking the farmers' reaction into account.

For the sake of simplicity, the results from two important irrigation consortia – i.e. Capitanata and Ugento li Foggi – were used to analyse the effectiveness of GW protection strategies. These areas were selected because they represent the two extreme conditions concerning GW protection. On the one hand, most of the Ugento li Foggi consortium falls within a GW protection area due to seawater intrusion, while irrigation water is basically supplied by GW resources. This means that the GW protection policies should be extensively implemented in the Ugento li Foggi area to effectively achieve GW remediation targets. On the other hand, only a few areas in the Capitanata consortium are GW protection areas, and most of the irrigation water supply is guaranteed by artificial reservoirs supplying an on-demand irrigation network of about 54,000 ha.

As shown in Fig. 10(a), in the Ugento Li Foggi consortium the actual effectiveness of the GW protection policy is less than expected for many reasons. In this consortium, GW is the only source of water for irrigation, therefore, under favourable market conditions and scarce rainfall, farmers would not reduce GW exploitation

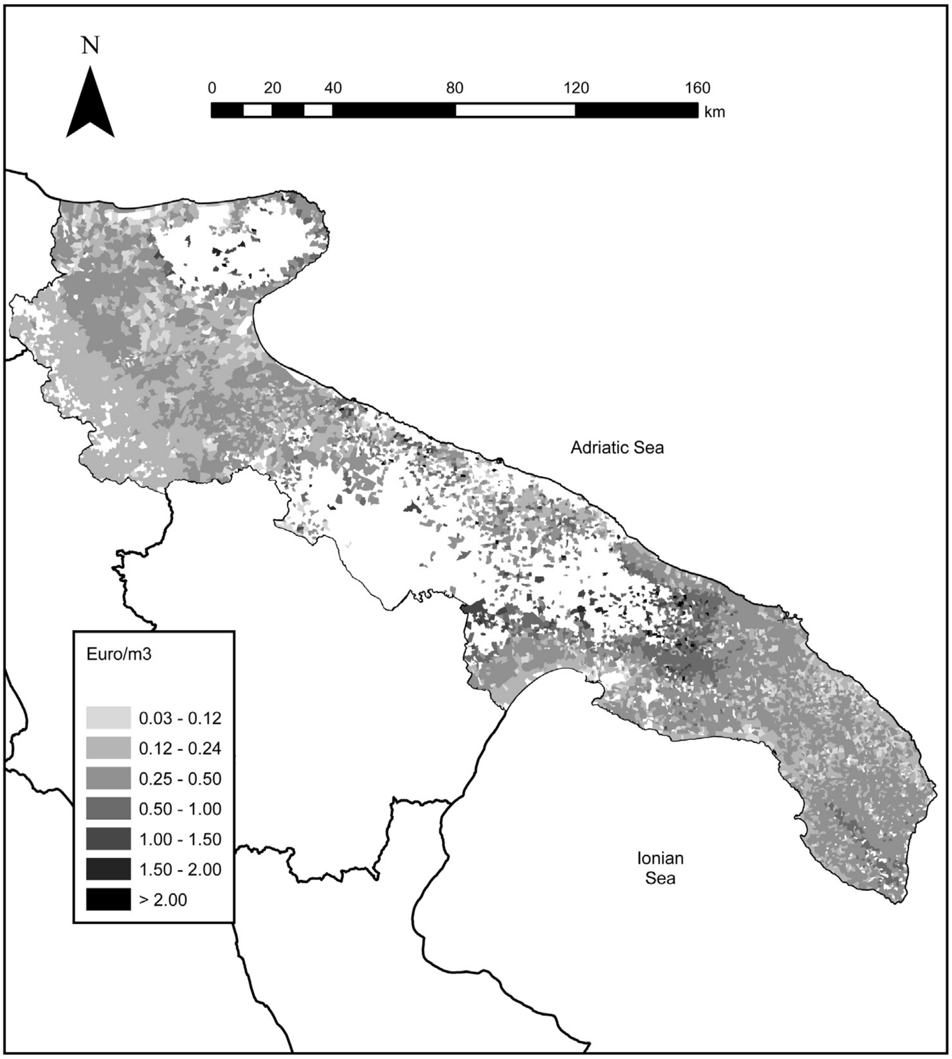


Fig. 8. Map of unit cost in Euro/m^3 according to Equation (2) and for a cost per kWh of 0.15 Euro.

because this would lead to severe reductions in crop yield, with an unsustainable economic loss. The black columns in Fig. 10(a) represent the areal distribution of the GEI_{AR} classes due to protection strategy implementation, taking the farmers' behaviour into account. The number of spatial units in the high pressure classes for the GEI_{AR} (6–10) is higher than expected according to the reduction targets, whereas the units in the low pressure classes (0–3) show only a slight decrease compared to the expected target. This means that if decision-makers do not take farmers' opposition into account, they will not achieve GW protection objectives. Consequently, if farmers' opposition is considered, the decision makers may identify conflict mitigation strategies and so increase the policy's effectiveness.

Under the same background conditions, in the Capitanata area, Fig. 10(b), the strong pressure on GW is reflected by spatial class distribution of *GEI* values (with represented classes from 6 to 10) and the very low effectiveness of the protection policy. The low effectiveness of protection measures can be related to the minimal extension of GW protected areas and to the farmers' reluctance to reducing GW exploitation adopting less water-demanding crops. Most areas with a high level of pressure are in fact outside the protected areas (Fig. 9). Moreover, under limited water availability from the reservoirs (scarce-rainfall years) the consortium policy responds with a higher price of water distributed by the irrigation network, and this drives farmers to exploit GW to keep their production costs affordable.

3.3. Supporting decision making process for GW protection

To evaluate the actual usability of the GeSAP tool in supporting decision making process, a test was organized involving the main regional experts in GW protection and the regional decision-makers to simulate a real process. The collected feedbacks allowed the authors to critically evaluate the tool and to identify its main benefits and drawbacks.

According to the collected opinions, one of the most interesting results of GeSAP is the enlargement of the set of alternatives for GW protection. This is mainly because of GeSAP's ability to simulate farmers behaviour regarding the selection of the sources of water for irrigation. The existing studies on GW pressure at the regional level were mainly based on assessment of the recharge rate and of GW exploitation in relation to the climatic conditions. Thus, farmers' behaviour was not taken into account in most cases, and this made it impossible to evaluate the effectiveness of a wide range of strategies impacting on the water consumption.

During the experimentation, decision-makers became aware of the complex set of elements influencing farmers' behaviour.

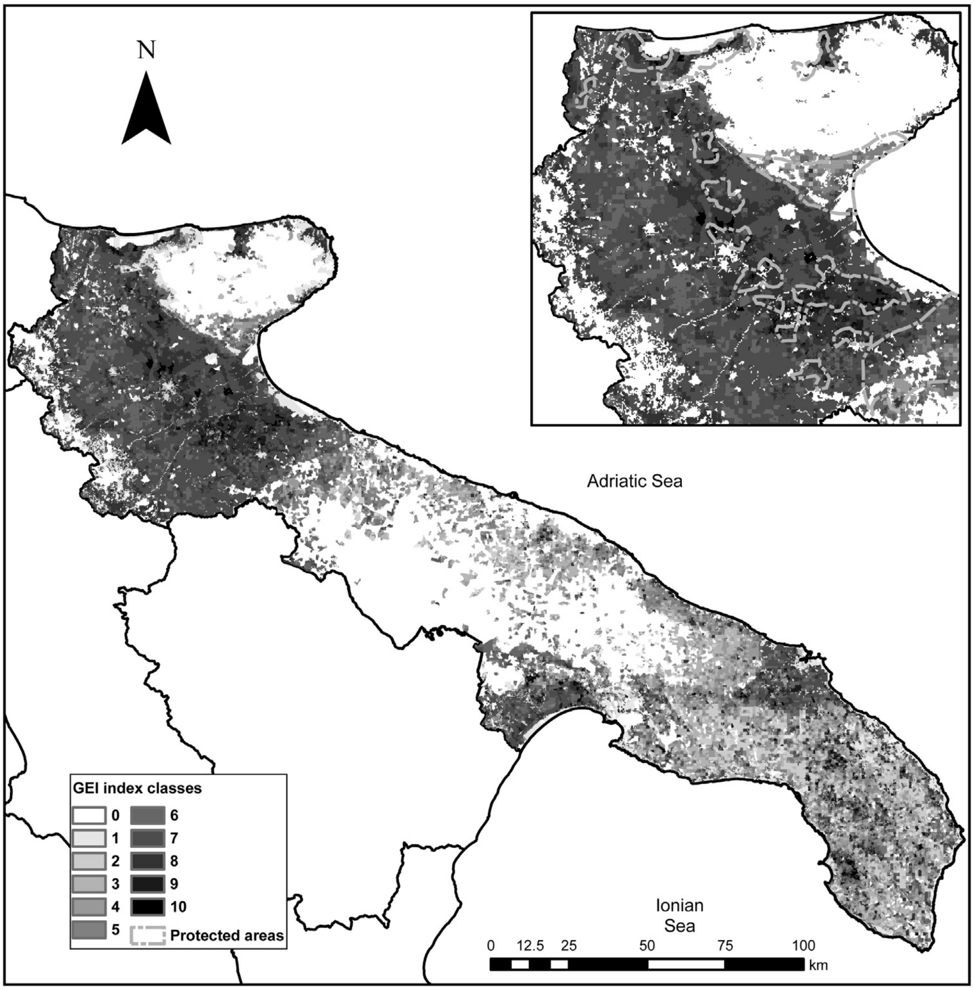


Fig. 9. Groundwater exploitation index (*GEI*) map across the entire region for a scarce-rainfall year and favourable market conditions. The detail in the upper right corner shows the overlay map of the groundwater protection areas defined by the regional water authority and the *GEI* in the Capitanata Consortium.

According to their previous knowledge, farmers were supposed to select the main source of water basically according to the climatic conditions and to their crops' water requirements. The GeSAP simulations made it possible to capture the impacts of the irrigation management policies on farmers' behaviour. Through the model application, decision-makers learnt how to quantitatively assess the impacts of developing new water projects, such as extending irrigation networks or introducing alternative water sources, in terms of GW sustainability. Moreover, although the water price is usually defined at the beginning of the irrigation season by each consortium according to its own rules, decision-makers became aware that an intervention by the regional authority to keep the price as low as possible would have a positive impact on GW protection.

Table 4 shows the impacts of irrigation management policies in terms of degree of acceptability and actual reduction of GW exploitation.

Three different scenarios were simulated. The first one was characterized by the absence of irrigation network. Thus, GW was the only source of water for irrigation. The second one was characterized by a low availability of water provided by the consortium and high price of water. In the third one, plenty of water was available from the consortium and at a low price.

According to these results, if the availability and affordability (low price) of the water supplied by the consortia would increase, farmers would prefer this water source because of its better quality. In the third scenario the variable "water provided by consortium" was high, allowing farmers to get to a good "yield" even in case of GW protection policy. This resulted in a high acceptability degree and, in turn, in a good efficiency of policy implementation.

Modelling farmers' and decision-makers' behaviour regarding the management of water resources for irrigation shed light on some crucial issues for arid regions. The access to timely information concerning the availability of water for irrigation is crucial to reduce the conflict level. At the beginning of the cropping period, farmers do not have information on the actual quantity of water that will be distributed by the consortium. Therefore, their cropping decisions are taken according to assumptions based on the quantity of water obtained the previous year. When the

Table 3
Class intervals adopted to describe levels of groundwater pressure.

Class of GW pressure	Interval of values [mm/yr]	Class of GW pressure	Interval of values [mm/yr]
0	$x \le -450$	6	$-100 < x \le -50$
1	$-450 < x \le -350$	7	$-50 < x \le 0$
2	$-350 < x \le -250$	8	$0 < x \le 100$
3	$-250 < x \le -200$	9	$100 < x \le 200$
4	$-200 < x \le -150$	10	$x \ge 200$
5	$-150 < x \le -100$		

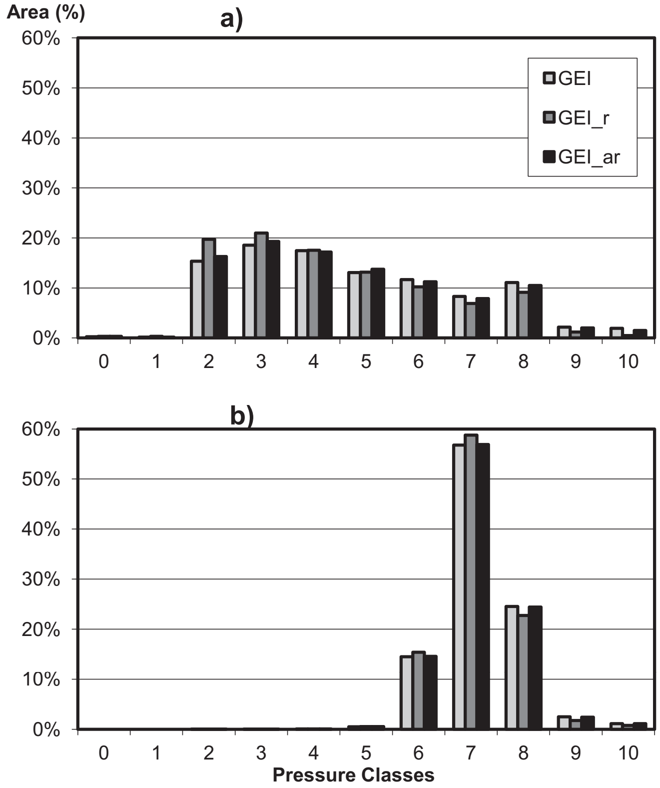


Fig. 10. Histogram of the three application levels of the groundwater exploitation index applied to Ugento li Foggi consortium (a) and to the Capitanata consortium (b) to diagnose groundwater pressure (Groundwater Exploitation Index – *GEI*), to evaluate pressure under the target reduction according to groundwater regulation (Groundwater Regulated Exploitation Index – GEI_R), and to evaluate pressure under the acceptable reduction of groundwater use by farmers (Groundwater Exploitation Index under Acceptable Regulation – GEI_{AR}).

information becomes available, often farmers cannot react immediately changing their crops in order to reduce the water requirement. This leads to a high level of conflict. During the trial, decision-makers and experts began to discuss the possibility of developing a more effective early warning system for drought, capable to seasonal forecast to provide farmers with reliable information at the beginning of the season, supporting them in the selection of the most suitable crops for the climatic conditions. To this purpose, the index-based approach undertaken by the European Drought Observatory (European Commission – JRC, 2011) could be helpful to the timely and objective classification of ongoing climate anomalies and their consequences on soil and vegetation response. Further advance for drought risk management and early warning will be possible in the near future when seasonal climate forecasts will have a concrete development (Xia et al., 2012) and be compliant to farmers and water managers needs.

Decision makers were also genuinely interested in the analysis and spatialization of the degree of conflict. According to their opinion, visualizing the results of conflicts analysis through the GIS-based tool has a twofold positive effect. On the one hand, the GIS map enhances the comprehensibility of the results for the decision makers, reducing the gaps between scientists and practitioners (Bäcklund et al., 2010; Cutts et al., 2011; Smith et al., 2012). On the other hand, the GIS interface allowed identification of the areas with the highest degree of conflict. This information may effectively support decision-makers in defining measures for conflict mitigation. Hence, the economical and political efforts to solve conflicts should focus on such areas. Moreover, the visualization of impacts of GW protection policies could enhance the communication between the different stakeholders and could be used as a basis for discussion and negotiation (Griffon et al., 2010).

Table 4
Expected vs. actual reduction of groundwater exploitation under different policy scenarios.

Scenario	Water price	Water distributed by consortium	Expected reduction (*r*)	Degree of acceptability (*GA*)	Actual reduction
1	–	None	40%	0.11	5.45%
2	High	Low	40%	0.25	12%
3	Low	High	40%	0.88	36.2%

One of the drawbacks highlighted during analysis of the results concerned the qualitative nature of the results of BBN simulation. This represented a weakness in the methodology for most of the experts involved, who was more familiar with quantitative assessments. Thus, the experts, considered qualitative results insufficiently reliable, and suggested improving the methodology by combining the BBN with some quantitative information to increase overall confidence in the results. For example, the experts suggested to integrate the information collected by the monitoring system – i.e. climatic data, GW level and quality, etc – in the developed tool.

Moreover, the experimentation highlighted the role played by farmers' decision models in the assessment of both GW pressure and conflict analysis. These mental models are dynamic rather than static, and their changes are the results of complex learning processes concerning irrigation management and agricultural practices, but are also due to exogenous elements such as climate trends and market situations. Therefore, to take the learning process into account, farmers' decision models have to be updated by combining them with a learning model, to better understand changes in social learning, preferences and behaviour.

Finally, both experts and decision-makers pointed out that the boundaries of the system at the basis of the model should be enlarged to take external economic drivers – e.g. EU agricultural policies – into account. EU agricultural policies can in fact heavily affect market conditions and economic performance of agricultural farms, acting both on cost and price sides as well as on support mechanisms. Recent reforms in the Common Agricultural Policy, notably in 2003 and in 2008, aiming at modernising the sector and making it more market-oriented, exposes farmers to higher price volatility, as the instability on world commodity markets may permeate to EU markets more easily due to reduced market intervention and more open markets (European Commission, 2011).

4. Conclusions

The sustainability of GW resources is a function of many factors, including reduction in GW storage, saltwater intrusion, reductions in stream flow and lake levels, loss of wetland and riparian ecosystems, land subsidence, and changes in GW quality. The GW sustainability criterion is clearly stated in the definition of good quantitative status set out in the Water Framework Directive (WFD) in the Annex V 2.1.2. (European Union, 2000) according to which the anthropogenic alterations must secure that "the level of GW in the GW body is such that the available GW resource is not exceeded by the long term annual average rate of abstraction." A specific test for the assessment of the quantitative status at the scale of GW body is suggested in the guidance document No. 18 of the WFD Common Implementation Strategy (European Commission, 2009) where the available GW resource is evaluated as the difference between groundwater recharge and environmental flow requirements. In practice, this assessment should take into account that each GW system and development situation is unique, and has to be analysed in detail with regard to the nature of the water issues involved, including the social, economic, and legal constraints that must be taken into account. However, as recently remarked in the Blueprint to Safeguard Europe's Water Resources (European Commission, 2012), "there is no European regulation defining the ecological flow, nor a common understanding of how it should be calculated".

This contribution addresses GW protection issues by developing an integrated and multidisciplinary approach. In particular, it investigates the integration of scientific information and farmers' knowledge with regard to the assessment of GW exploitation and proposes the use of synthetic indices of GW exploitation by locally comparing natural recharge estimations with annual average rate of GW abstraction. The *GEI* is a quantitative index that relates to the GW quantitative status as far as the issue of the environmental flow requirements can be neglected (e.g. when GW levels and salinity clearly indicate a long-term decline of the available resource) or treated in a second step. The GEI_R is the target of a regulated GW exploitation given by the reduction rate of abstraction needed to meet the GW sustainability criterion by assuring the environmental GW requirements anyway calculated. The developed integrated model was proved capable of assessing the actual effectiveness of GW protection strategy by taking farmers' responses into account (i.e. the GEI_{AR}). The use of the GIS-based interface made it possible to map policy effectiveness, and consequently to identify the areas requiring further policies to achieve a sustainable use of GW. In the environmental and institutional framework here presented, the proposed methodological approach provided new insights in the integrated management of scarce water resources in a highly water demanding region.

A drawback in the proposed methodology could be eventually for cases where indicators that simply relate the GW quantitative status to the long-term average recharge and abstraction rates are not representative of the hydrogeological response and therefore changes in GW level and discharges to rivers, lakes and wetlands become important. For such cases there is a need for supplementary tools to the proposed integrated modelling tool, like environmental flow assessment approaches, integrated groundwater and surface water flow models that can describe changes in groundwater level and discharges to surface water systems (e.g. hydraulic/habitat models that can describe conditions for fish in river reaches etc.) in order to complete a full, and proper assessment of sustainable groundwater abstraction both at regional and local scales. For some more complex cases there could even be a need for more advanced tools like solute transport/salt water intrusion or ecological models.

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