MODELLING THE IMPACTS OF VOLUMETRIC WATER PRICING IN IRRIGATION DISTRICTS WITH CONJUNCTIVE USE OF SURFACE AND GROUNDWATER RESOURCES

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Abstract. Water pricing has been identified as a generally valid water supply policy to help solve problems of water scarcity and competition. As for the non-agricultural sectors, in the last three decades water pricing has been widely discussed in and promoted with regard to the irrigation management, though in the actual practice its effectiveness is quite controversial. This is particularly true in semi-arid regions, where conjunctive use of collective facilities and on-farm groundwater pumps may cause conflicts and mismanagement of water resources. Under such circumstances, irrigation water pricing policies are not easy to deploy and implement effectively, due to potential occurrence of side and unintended effects. In this framework, the present work aims at investigating the impact at the district scale of water pricing policies, on both surface water (SW) and groundwater (GW) resources. In this regard, a model which deals with the analysis of farmers' decision concerning water source selection is proposed. The analysis is carried out keeping capital asset as given, also with the aim to elicit the relevance of on-farm irrigation water cost on resources use during the irrigation season. Reference is made to an intensive agricultural district in Southern Italy, conjunctively supplied by collective schemes managed by the local irrigation board and on-farm individual groundwater pumping systems. The proposed model was built along with local stakeholders, in order to (i) underline the relationship between the water tariff applied for collective supply service and the irrigation source selection during the irrigation season; and (ii) the relevance of the conjunctive use of GW based on pumping cost convenience and service standards needed to fulfil the irrigation requirements. The results have been then integrated into a quantitative water balance model, and a scenario analysis used to show the potential side impacts that a restrictive SW tariff policy applied during drought periods may have on the GW state, in different hydrological conditions.

***Keywords**:* water pricing strategies, water allocation criteria, integrated water management for irrigation, groundwater exploitation.

1 INTRODUCTION

Sustainable water resources management is a complex environmental policy issue and requires taking into account interests related to using, sharing and preserving an increasingly limited resource (Portoghese et al. 2013). The role of irrigated agriculture is highly relevant in this direction, since it is crucial for the socio-economic welfare but, at the same time, it represents the largest exploiter of water resources (FAO 2014). An increasing level of conflict between different water users and uses is observed, particularly in the Mediterranean area (Jury and Vaux, 2007), due to the growing pressures such as water scarcity, climatic conditions, poor governance and socio-economic needs (Portoghese et al. 2015, Pluchinotta et al. 2018).

Integrated water resource management (IWRM) methods and tools are often invoked to understand how different water managers and users perceive water resources issues and behave consequently (Giordano et al. 2013), and to predict potential long-term impacts on water resources (Bouwer 2000). In fact, purely technical criteria are no longer sufficient to address the challenges related to water management in a given system (Pahl-Wostl 2007). Specifically, for irrigation systems, the existence of interconnections among several different issues (e.g. economic, social, and environmental) and among multiple actors, strongly affect its dynamic evolution (Giordano et al. 2015). Traditional processes to support water resources management are based on a merely technical approach and rely on a limited knowledge of system complexity (e.g. the individual behavior of actors), thus often resulting in highly uncertain and potentially ineffective options (e.g. Portoghese et al. 2013, de Vito et al. 2017, Giannoccaro et al. 2013).

The key issue to consider in policy-and decision-making processes related to water resources management is that water is a natural resource, linked to basic human needs and distributed from a spatial point of view, used by several different actors and owned by no one. Furthermore, the use of common resource such as groundwater, without a complete awareness of the multidimensional implications of individual actions and decisions, is typically responsible for problems of overexploitation and free-riding (Pluchinotta et al. 2018). Water cannot be considered as a traditional marketable good and therefore poor designing processes can lead to poor allocations (Momeni et al. 2019). Though water saving in agriculture is among the objectives of the succeeding CAP reforms, Giannoccaro and Berbel (2011) found that farmer's decision on the extent of irrigation water use across Mediterranean EU Members is only slightly influenced by the CAP reform, also considering the extreme NO-CAP support scenario.

Although water is not regarded as a market good, one of the most widely used policies to decrease water consumption is water pricing, as experienced in different studies which focus on the potential effects in terms of farmers' awareness raising and support for shifting towards different cropping patterns (Berbel et al. 2019, Momeni et al. 2019). Additionally, specific water pricing strategies could be a valuable solution to deal with extreme conditions (e.g. in drought periods) to attain an efficient water consumption. However, water pricing is a complex problem related to the definition of the actual value of water for irrigation that intertwines with economic, social and environmental factors (e.g. Ziolkowska 2015). Assuming a competitive and unregulated water extraction regime, the temporal and spatial variability of external drivers results in inefficient pricing and misallocation of resources (Katic and Grafton 2012). Consequently, it is necessary to build a solid knowledge base on the multidimensional implications of water pricing strategies, to support an adequate design of economic instruments and policies to help limit water overexploitation (de Vito et al. 2017, Dono et al. 2010).

Focusing on domestic, industrial and energy uses, water pricing policies mainly aim to affect the behavior of users, ensuring that they pay for the service, that the available water fulfils their demand, and that the resources are used appropriately and sustainably as required also by the Water Framework Directive (EC 2000). Concerning the agricultural sector, Molle and Berkoff (2007) reviewed the history of ideas and experiences in irrigation water pricing, thus identifying the striking gaps between theory and practice, and analyzing constraints on the effectiveness of irrigation pricing policies. The overall picture that emerges is that too often stated policy objectives are based on analogy with water supply and energy sectors, making this extrapolation very misleading given the particular characteristic of the irrigation sector. Despite the theoretical advantages that could be achieved (e.g. efficient water use, sustainable financial management), pricing irrigation water is not easy to deploy effectively. In fact, water authorities need a clear identification of the results to achieve, the performance (and potential impacts) that different pricing instruments have and the preconditions that enable them to work. Additionally, pricing instruments are built under assumptions that often do not hold in reality, and their introduction may lead to a number of adverse behaviors, unintended consequences and side effects that are often neglected (Davidson et al. 2019). Among these, if water is distributed through collective facilities managed by a central authority, uncontrolled extractions of groundwater may result where this resource is available (Dono et al., 2010), and negative impacts on incomes may occur (e.g. Giannoccaro et al., 2010). Despite these effects clearly depend on the specific water pricing scheme adopted, a general evidence is that fulfilling the environmental objectives while limiting intense social and economic negative impacts is not straightforward (Cortignani et al. 2018).

In this regard, adequately understanding and representing the behaviour of farmers in terms of water use and allocation, may help assessing the impacts of potential adaptation measures implemented in reaction to policies and/or changes in water availability (Graveline 2016). Within this framework, the present work is focused on the analysis of an intensive agricultural district in the southern Italy (the Capitanata district), where irrigation demand is jointly fulfilled by on-farm groundwater (GW) wells and a collective network supplied by surface water (SW). The objective of the study is threefold: i) to describe, in a structured way, the effect of different tariffs of collective service on farmers' decisions related water source selection (WSS) during the irrigation season; ii) to quantitatively describe the potential impacts of the WSS on both collective SW and on-farm GW withdrawals, through a global water balance model; iii) to understand the implications on system sustainability (specifically in terms of groundwater overexploitation), analyzing the effects of different SW pricing policies.

Going further into details, the selection process of a specific irrigation source by farmers (i) is quantitatively described in the present work as a function of some key drivers (e.g. water pricing, quality of the irrigation service, etc.). From the methodological point of view, starting from the evidences of individual interviews, a model capable to simulate farmers' decisions regarding WSS and to describe water allocation patterns is developed, and validated using data series. The model is then integrated in a quantitative water balance model (ii) with the purpose of informing policy- and decision-makers about (iii) the multiple potential impacts of different water pricing strategies, due to the strong interconnectedness between SW and GW systems.

After a short overview of the case study, the adopted modelling approach is described in the following Section. The application of the model in the case study is then described in Section 3 together with the results on the SW and GW volumes allocated for irrigation throughout the investigated period, including the effects on GW stock under different water pricing and groundwater recharge scenarios. Some remarks on the presented model and its potential use for basin scale water management are reported in the Discussion (Section 4), followed by the Conclusions.

2 MATERIALS AND METHODS

2.1 Study area

The case study concerns the Capitanata area, which represents a highly-developed agricultural area and is the largest irrigated area of Puglia (Southern Italy). The agricultural area is approximately 500,000 ha in which wheat, olives, vegetables, and grapes are widely cultivated. The annual irrigation requirement is fulfilled through both a collective network managed by the local irrigation board and on-farm individual groundwater pumping systems. Surface water uptake and distribution in the irrigation district is managed by the Reclamation and Irrigation Board of Capitanata (CBC) which is a governing and technical body ruled by farmers' representatives. Nowadays, the CBC manages 441,579 ha of the whole agricultural area, and comprises two main irrigation districts, one in the northern part (Fortore irrigation district), and one in the southern part (Sinistra-Ofanto irrigation district), both equipped with modern pressurized pipe networks. As far as concerns the Fortore district, the area currently equipped with the water distribution network is about 110,000 ha. Approximately 40% (an average of 45,500 ha) of this area is irrigated annually through the SW distribution network, while the remaining part within the CBC irrigation supply domain is irrigated directly by the farmers using the private wells as usually happens for the rest of the CBC domain outside the SW supply area (Lamaddalena 2004, Levidow et al. 2014). The total irrigation need over this area is on average 171,000 Mm^3, corresponding to a unit irrigation of 3,800 m^3/ha, while the allocation guaranteed by the CBC is only 2,050 m^3/ha which is given by the average SW stock in ordinary years (103 Mm^3) divided by the average irrigated area in the CBC irrigation census (including water losses).

In such context, the underperformance of CBC supply system is mainly due to a) water shortage and limited water supply through the CBC water distribution network; b) high irrigation water demand due to adopted cropping patterns over the greatest part of the CBC; c) inadequate performances of the water distribution network during the periods of higher water demand; d) incomplete water distribution network. The CBC board is aware that the SW supply allows an average satisfaction degree below 50% and that GW extractions are operated by the associated farmers (30,800 associates) as a complementary supply source. Farmers are allowed to pump GW even in the CBC supply area, provided that they have a legal license issued by Regional Government. As a result, there are growing concerns on the state of GW (Guyennon et al. 2016).

A volumetric water tariff scheme is applied in the CBC district in which irrigation water charges aim to support a cost recovery for system operation and management. A mixed payment scheme is adopted and specifically: 24% of CBC revenue comes from the fixed component related to the farm irrigated area (reported in the CBC irrigation census), while the remaining 76% comes from the applied volumetric block tariff (with an average unit payment of 0.14 €/m^3 according to recent financial reports).

2.2 Conceptual model of water allocation dynamics

The model proposed in the present paper is one of the main results of a multi-step approach that has been implemented by the same research group in the study area, with the general objective of analyzing irrigation practices through the involvement of relevant stakeholders, trying to get a deep insight into the multidimensional impacts related to water use (e.g. environmental, economic, social, etc.). The whole process is summarized in the following Figure 1.

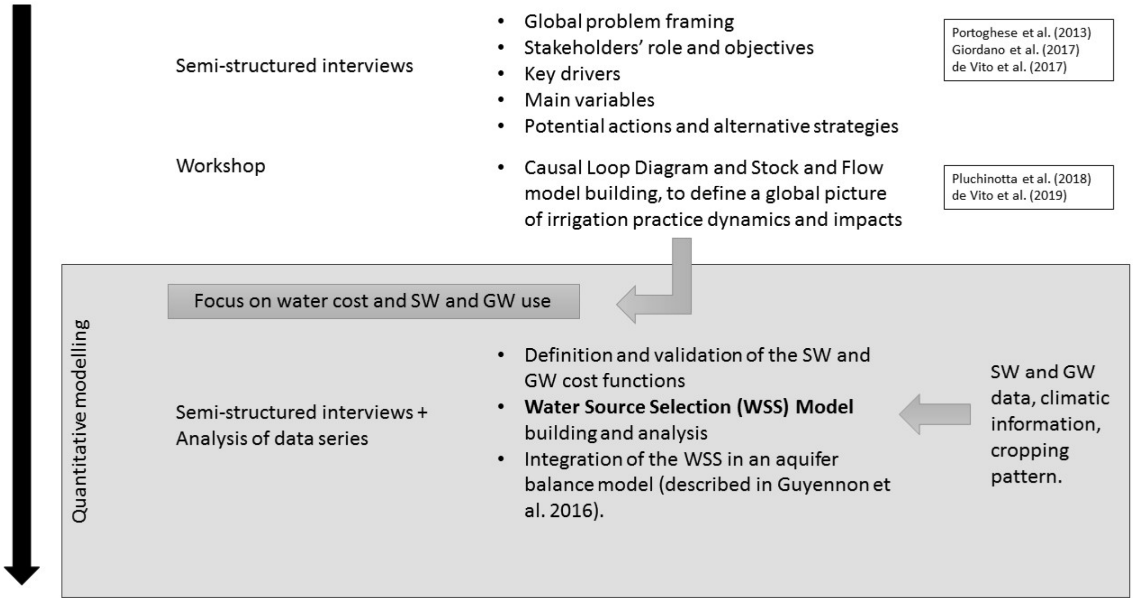


Figure 1. Overview of the modelling process in the study area

An interview-based approach was adopted with the key actors involved in the problem of water resources management for irrigation in the study area. The main objective of the interviews was to describe the district-scale dynamics related to irrigation practices. More specifically, semi-structured interviews involving both local farmers and decision makers from the CBC were performed between 2011 and 2017 in order to define their main objectives and concerns related to irrigation practices, the key drivers of system evolution, the current strategies and alternatives to act on the state of the system (Giordano et al. 2013; Giordano et al. 2015, de Vito et al. 2019). The approach was used to identify and formalize the general rules of behavior for the stakeholders. The results of the interviews have been then structured using qualitative/semi-quantitative System Dynamics tools (i.e. Causal Loop Diagrams and Stock and Flows Models) as discussed in Pluchinotta et al. (2018), Pluchinotta et. al (2019), de Vito et al. (2019). A workshop with the same stakeholders was also organized to contribute to model building and validation.

This first phase of the modelling process was specifically oriented to support understanding and unravelling the high complexity of the system, which is affected by a dense network of relationships among different stakeholders, having different roles and interests, but all strongly influencing the evolution of the system. This helped building a global picture of the system, taking jointly into account the environmental, agricultural, social and economic implications of irrigation practices, but revealing that water pricing strategies have a crucial role in driving system evolution and need further investigation.

Starting from the global model, the present work provides a quantitative analysis of one of the key dynamics that were identified and discussed more in detail in the system, i.e. the impact of water pricing policies on the water source selection by the farmers. The irrigation source selection depends on multiple factors, such as mainly: i) the irrigation demand, the climate variability, the tariff scheme of the collective supply service, the standard of irrigation service (i.e. the accessibility to the irrigation supply points, the level and stability of pipe pressure, the flow rate and its stability at each point of delivery, the on-demand of irrigation, the quality of supplied water, the guarantee of supply), the pumping cost of on-farm groundwater wells. For instance, the access to the SW collective facilities is provided by about 30,000 delivery points operating with on-demand water supply during the irrigation season (April-September) making the CBC service more efficient than on-farm GW irrigation and therefore preferable as long as SW is available and affordable during the season.

However, the SW collective service is strongly affected by the winter rainfall pattern before every irrigation season, whereas the use on-farm groundwater wells is perceived as less variable.

The behavior of CBC managers concerning their yearly decisions on the irrigation tariff plans was analyzed, with specific reference to the water availability in the reservoirs at the beginning of the irrigation season and on other key variables (e.g. expected irrigation water demand, seasonal climate pattern). An increasing block tariff is established so that, during the irrigation season, each farmer pays an increasing unit price, SW_{cost} (€/m^3), according to specific volume thresholds of cumulated unit irrigation (m^3/ha) during the season, with a minimum tariff corresponding to the first threshold which guarantees almost all seasons the basic water allotment (BWA) for most users. The other volume thresholds are meant to gradually decrease accessibility to SW use. The consequence of the block tariff scheme applied by the CBC leads farmers to use CBC waters at lower allotment (2,050 m^3/ha), in general without overcoming the lowest tariff threshold, and then to use on-farm GW wells to fulfill the further irrigation needs. This is in line with the CBC policy, which aims at allocating all the available water to most of the associated farmers (Giannoccaro et al. 2010). The CBC decision rules were derived from the analysis of the available irrigation tariff plans (2000-2012) and afterwards were applied to extrapolate the tariff plans for the years between 1993 and 1999 based on hydrological conditions in the reservoirs, since the tariff plans were not available in those years.

As already pointed out, the CBC irrigation board is aware both of the medium-term irrigation needs (resulting from the updates of irrigation census) and of the expected seasonal irrigation needs (derived farmers' communication before the beginning of each irrigation season). Moreover, the CBC performs a continuous monitoring of the key meteorological and hydrological variables (including water levels in the reservoir) during the year to support matching the seasonal trends of irrigation demand and the SW availability. Therefore, the irrigation managing board is timely updated on the situation and hence on the degree of demand fulfilment. Consequently, in regular hydrologic seasons the CBC board recognizes a 50% water demand fulfilment through collective systems, which is in good agreement with the average demand fulfilment around 47% from SW supply, estimated from the combination of data on the SW availability with modelled irrigation needs during the study period 1993-2012 (with a standard deviation of 22%).

The above reported conditions have brought farmers to increase groundwater exploitation to meet the irrigation demand causing a serious depletion of GW stock. This is related to the large number of licensed wells for irrigation reported in the database of the regional water authority (~3,700 wells with an average discharge of 5.7 l/s). The indirect effect of SW tariff on GW use is investigated through the quantitative hydrological model proposed in the following.

2.3 Water-Source-Selection model (WSS)

As far as the irrigation service is concerned, the interviews with farmers highlighted that the SW supply is by far preferred thanks to the high density of the CBC network, the availability of a pressurized on-demand service and the good water quality (Pluchinotta et al., 2018). Conversely, on-farm wells have in most cases poor water quality and limited discharge, with additional operations needed for water filtering, irrigation tanks filling and pressurization of irrigation systems. Most of the interviewed farmers declared the use of GW pumping only after the cumulated irrigation reaches the first tariff threshold, in case of ordinary SW supply. However, some farmers declared the use of GW extraction as complementary source even before reaching the volume threshold of 2,050 m^3/ha.

Therefore, though the SW supply was identified as the preferred option under fair conditions of SW availability, GW withdrawals are perceived as a means to fulfil the irrigation demand, thus suggesting the hypothesis that the CBC pricing policy may exert an impact on groundwater resources exploitation that needs careful investigation.

The proposed WSS model attempts to estimate, in a given irrigation district and time of the irrigation season, the degree of irrigation demand that is satisfied from the collective irrigation network (%SW) and the complementary irrigation supply satisfied by on-farm groundwater pumping (%GW). The WSS model aims at simulating farmers' choices for the irrigation water sources under different hydrologic, economic and agricultural constraints, though some simplifying assumptions are needed for model implementation. In particular: i) both SW and GW resources are considered fully available to all farmers in the whole study area, ii) farmers are assumed to provide irrigation water when needed for an optimal agronomic response, iii) GW resource is virtually unlimited during the irrigation season, though an increase of pumping cost due to the water table lowering is considered, iv) GW quality with reference to salt content is also invariant. In such a context, our hypothesis is that farmer's decision on source selection relies on operational cost minimization pursue for water.

Under these conditions, the starting point of the irrigation source selection is the definition of suitable cost functions considering hydrological, technical and economic constraints and their variability in space and time. Specifically, the GW pumping cost function has to take into account both water table depth and groundwater yield as the main parameters, which may be quite variable in space and time, as in the following Eq. 1.

$$GW_{cost}(x,y,t) = c(t)\,\frac{H_1(x,y,t) + H_2(x,y)}{367.2\,\eta} + C_{GW,fix}(x,y) \qquad \left[{}^{€}\!/\!_{m^3}\right] \qquad (1)$$

Equation (1) is meant to express the unit average cost of GW for irrigation (€/m^3) as the sum between the variable and the fixed costs divided by seasonal average groundwater withdrawal. The variable cost is the product of the mechanical work of submerged pumps (in kWh/m^3) by the unit energy cost $c(t)$ (in €/kWh), in which the total head is given by the sum of water table depth including pumping drawdown in the borehole below the soil surface (H_1), i.e. the dynamic GW depth, and the required head pressure (H_2) of the adopted irrigation system, and η is the overall pumping efficiency. Assuming the variability in GW depth, drawdown and pumping wells' features from the case study (details in Table 1), an average variable cost of 0.09 €/m^3 is estimated for an energy cost of 0.25 €/kWh. The fixed costs $C_{GW,fix}$ due to license fee, maintenance and depreciation of the pumping plant is assumed to be equal on average to 0.01 €/m^3. Scale effects are neglected.

Table 1. Main parameters of Eq. 1 for the study area, based on the 3,171 wells in the study area with pumping rights

Parameter	**mean ± st.dev.**
Static GW depth [m]	24±13
Dynamic GW depth [m]	39±16
H_2 [m]	26.5
Discharge [l/s]	5.7±3.7
Overall pumping efficiency [%]	50±10*
Pumping cost [€/m^3]	0.09±0.02

(*) Values from a similar case study are reported in Handa et al. (2019).

The SW collective cost function, mainly depending on the CBC volumetric pricing scheme, is intended to represent the different cost components of the farm scale irrigation service supplied by surface water (Eq. 2):

$$SW_{cost}(x,y,t) = T(x,y,I(x,y,t-1)) + C_{SW,fix}(x,y) \quad \left[{€}/_{m^3}\right] \quad (2)$$

Starting from the above determinants, Eq. (2) reports the unit average cost function at time *t* given by the unit tariff *T* [€/m^3], which depends on the cumulated irrigation volume in the previous time steps of the irrigation season (*t-1*), added to the fixed costs charged by the irrigation board for the access to the SW supply facilities ($C_{SW,fix}$). The variability of *I*, *T* and $C_{SW,fix}$ with space is introduced to identify a specific farm in the study region with its irrigated cropping area (which are associated to the fixed cost). The tariff *T* is based on blocks which are variable from year to year depending on the hydrological state of the reservoirs feeding the collective water scheme and is designed to discourage farmers' uptake from the CBC network when the first block threshold is exceeded. This is due to the fact that CBC allocation is planned for an equal share of 2,050 m^3 to each irrigated hectare (in the served area). The rates per block increase as the time evolution of the reservoir storage during ordinary irrigation seasons often turns to water scarcity conditions, except when extraordinary precipitation in the late spring changes this tendency. During drought years, the scarcity pricing approach is much more restrictive in terms of unit water costs and block thresholds.

The GW and SW cost functions described above were used during a second round of semi-structured interviews with both farmers and CBC managers, to support a systematic analysis based on climatic data and cropping pattern variability, aiming to define robust relationships between water demand patterns and water accessibility perception over a 20-year period. The evidences are reported in the form of a quantitative model scheme putting together farmers' decision modes, water managers' rules, and their combined effects on groundwater storage variability in the long term (Fig. 2). In practice, the proposed model scheme has been developed taking into account different sub-models ranging from hydrological drivers to decision rules and their ultimate impacts of the GW stock which is considered as an overall sustainability indicator of the GW-SW conjunctive use. The following paragraphs provide a more detailed analysis of the single sub-models of the global model plotted in Fig. 2.

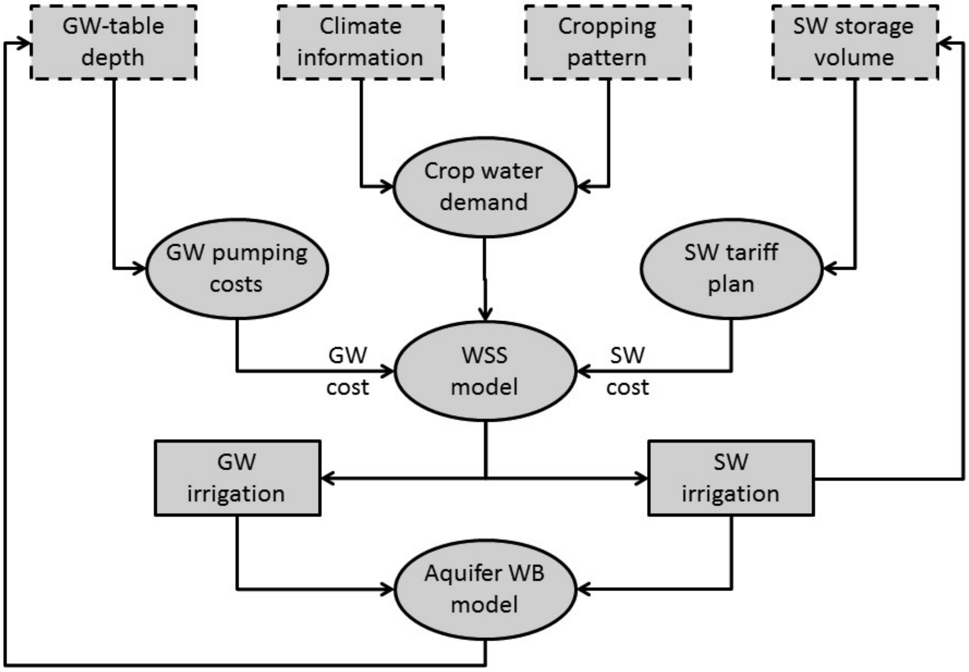


Figure 2. Conceptual scheme of the overall model for the simulation of combined SW and GW uptake at farm scale and consequent feedbacks on SW and GW stocks. Dashed rectangles are for model inputs, while continuous line rectangles are for model outputs and ellipses identify specific sub-models. The model components are thought with a monthly time step for the input and output variables while the spatial model elements may vary from the farm scale to the district or aquifer basin scale.

In case of conjunctive use of SW and GW resources, particular attention was given to the analysis of farmers' behavior with respect to water supply for irrigation, which was found to be sensitive to some technical and economic factors such as GW depth and water pricing scheme as well as the standards of the irrigation service. The conjunctive use of GW wells is first complementary and then becomes substitutive. For the sake of simplicity, the WSS model adopts a territorial approach to integrate the choice model with the water balance model of the SW reservoir and the underground resource (which are territorial by nature). The determinant variable of the WSS model is defined as the unit cost ratio $CR(x,y,t)$ between $SW_{cost}(x,y,t)$ and $GW_{cost\cdot}(x,y,t)$. The following Eq. 3 defines the fraction of the irrigation demand satisfied from surface water supply, and is characterized by a decreasing quadratic trend to simulate farmers' decision to progressively switch from SW to GW during the irrigation season as the increasing block tariff drives to less convenient unit water price. The WSS model equation has the following structure (Eq. 3):

$$\%SW = \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2}\ CR^2 - 2\ CR_M \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2}\ CR + SW_M + CR_M{}^2\ \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2} \quad (3)$$

where SW_m is the %SW value when CR is minimal (i.e. when SW_{cost} is minimal); conversely, SW_M, is the %SW value when CR is maximum (i.e. when SW_{cost} is the highest compared to a steady low GW_{cost}). Similarly, CR_m is the value of CR when SW_{cost} is minimal and CR_M is the value of CR when SW_{cost} is maximum. The quadratic function is therefore used firstly to represent some degree of variability in the behavior of different farmers with their peculiarities. Secondly, the function allows simulating the marked reduction in withdrawals from the CBC when the first threshold is exceeded. The WSS function is represented in Fig. 3, considering a continuous increase of CR. This functional form was built starting from the interviews with the famers, but it has been quantitatively validated with a comparison with the reservoir water balance, as explained in the following section.

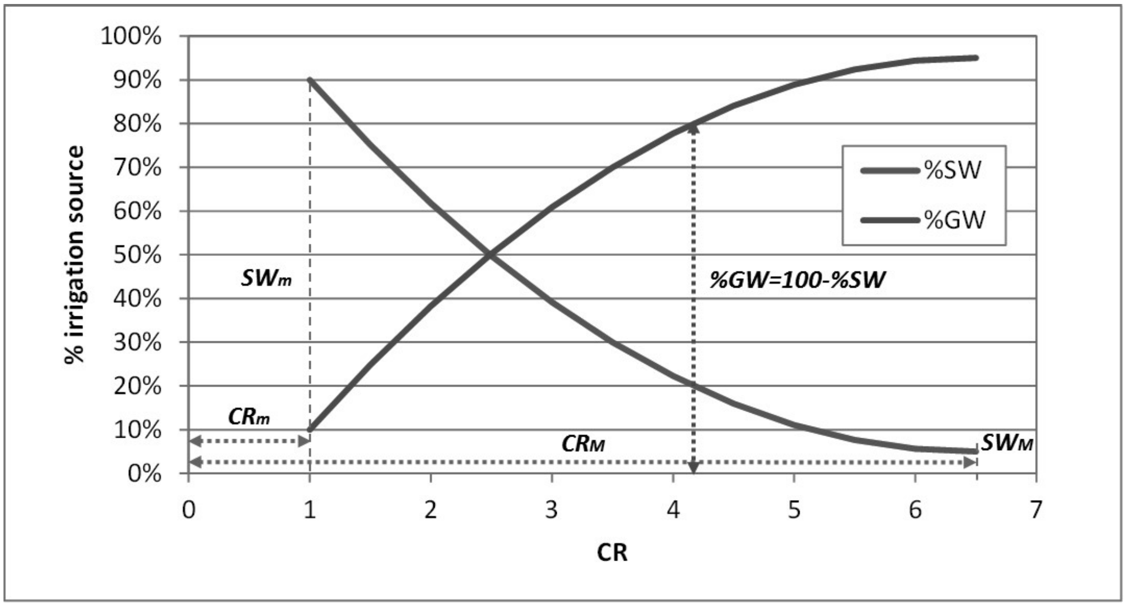


Figure 3. WSS function under hypothesis of a continuous increase of CR.

As such, the WSS function reflects the attitude of farmers to prefer groundwater source (%GW) with respect to surface water (%SW) as the SW_{cost} gets higher (i.e. with an increasing CR), representing the effects of GW depth as well as of SW pricing scheme, in combination with the irrigation need of a given farm during the irrigation season. As such SW supply is preferred over GW pumping until their cost ratio (CR) is below 2.5.

Another key driver for irrigation cost assessment at farm scale is obviously the crop water demand which is variable on a seasonal and inter-annual basis mainly according to climate variability, cropping extension and patterns, and irrigation techniques. Similarly, at the district scale the size of irrigated land and cropping patterns are among the major determinants of irrigation water needs and, consequently, of water resources exploitation at basin scale. To account for cropping pattern changes over time, a specific subset of representative crops was selected. Crops having higher water-requirement and/or covering a wider area were only taken into account, with their temporal variabilities (according to data by the Italian Statistical Service), namely: processing tomatoes (19,000-30,000 ha), grapes (28,500-44,200 ha), olives (52,500-55,000 ha), peaches (2,800-4,400 ha) and vegetables (2,200-3,100 ha). The annual irrigation requirements (I_{rrd}) were estimated accordingly for the main crops in the study area using CROPWAT by FAO (Allen et al. 1998) for the investigated period, and compared to those provided by CBC irrigation advise and a few interviews with farmers dated 2017 (Table 2).

Table 2. Comparison between irrigation requirements estimated from CROPWAT for the study period, CBC irrigation advice communication and farmers interviews.

Irrig. req. [m³/ha]	**Olive**	**P. Tomato**	**Orchards**	**T. Grape**	**Vegetables**
CROPWAT	1,450±530*	4,880±560*	4,020±740*	2,990±600*	4,330±390*
CBC irrig. advice	2,000÷3,000	4,000÷5,000	3,000	2,500÷3,000	-
Interviews	1,500÷1,800	5,500÷6,500	3,000÷4,000	2,500÷3,000	-

(*) variability expressed as mean value and standard deviation.

Spatially averaged soil hydraulic properties were considered for the irrigation requirement estimation, while the efficiency of the irrigation systems was estimated considering drip irrigation (efficiency set to 0.9) with an additional reduction coefficient applied to take into account both deficit irrigation techniques (e.g. for olives) and the practice of reducing irrigated areas to have higher unit water volumes available from the SW system. All these parameterizations were based on farmers' interviews and allowed predicting the consumptive water use starting from the agronomic irrigation requirement estimated through CROPWAT throughout the period of interest (Fig. 4). Overall annual irrigation requirement is compared in the same Figure to SW irrigation supply resulting from the reservoir monthly water balance calculations.

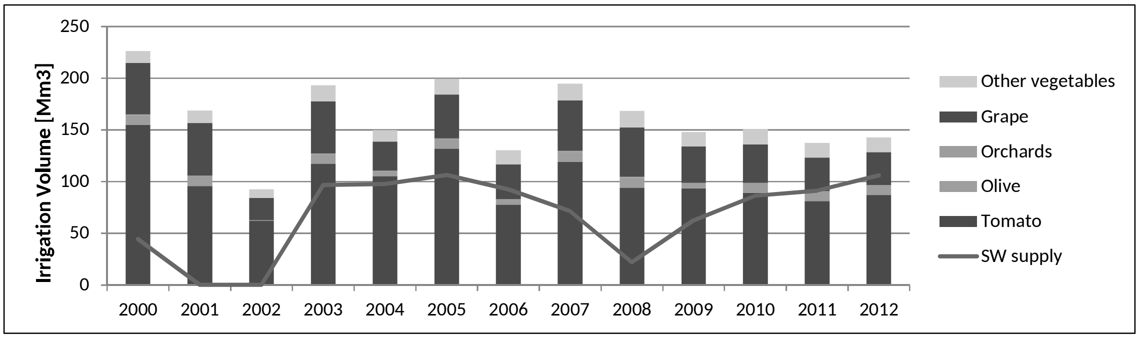


Figure 4. Irrigation water requirement as predicted from the unit crop irrigation demand modelled by CROPWAT and the agricultural census data, and SW supply.

2.4 Aquifer water balance conceptual model

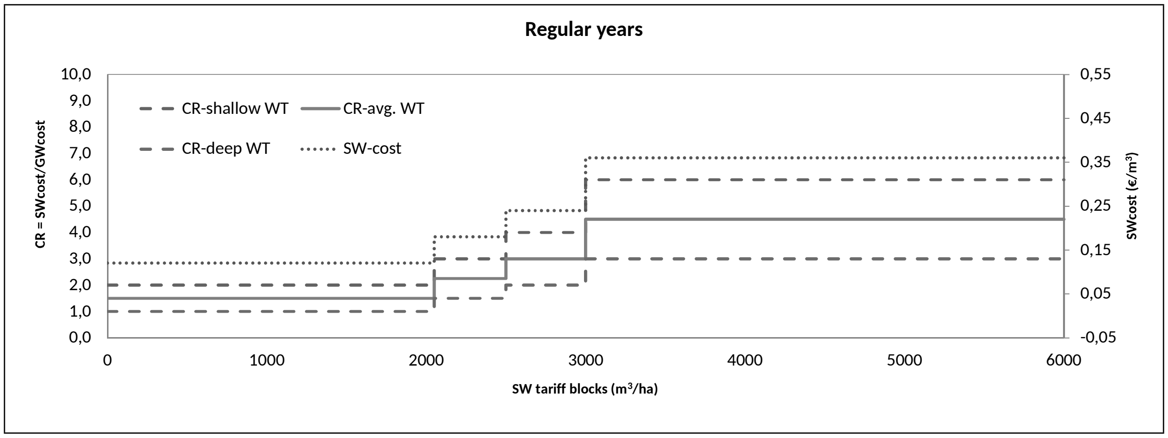
To jointly analyze the dynamics of groundwater volume and irrigation-water uses, a conceptual water balance model of the study area has been implemented (Guyennon et al. 2016) for the period of interest. The water balance of the aquifer system (Fig. 2) was evaluated applying a lumped conceptual scheme to the groundwater reservoir as a whole, under the effect of variable irrigation practices and reservoir management rules. The input terms are the following: a) the irrigation demand related to the variability of climate and cropping pattern; b) the available surface water stock and consequent supply management rules; c) the groundwater recharge computed by the GMAT monthly soil water balance model (Portoghese et al. 2005); d) the monthly groundwater abstractions from individual on-farm wells estimated using the WSS model; e) the groundwater outflow as discharge-to-sea and baseflow to the river network, whose monthly rate is assumed to be proportional (under the linear reservoir hypothesis) to the volume stored in the aquifer (Guyennon et al. 2016). The historical records of climate and cropping patterns were included in the implemented model, allowing to estimate the variability of groundwater balance as a lumped stock and flow system. This simplified approach, compared to other physically-based distributed GW models, allowed us to investigate the sensitivity of GW storage to climate and SW tariff variations, including other variations in crops and water management models.

3 RESULTS

3.1 Parameterization and validation of the WSS function

The present study was performed over a 20-years period (1993-2012) for which most of the needed datasets were available, namely: i) climate information, reporting two drought events with severe deficit of the SW collective supply, followed by above-average rainfall years; ii) a concurrent hydrological dataset including the reservoir water balance and GW table measurements; iii) time series of the cropping patterns for the whole basin, referring both to the district area equipped with the CBC network and to the outside area. During this period, large areal variations, mostly due to the CAP reform implementation between 2000 and 2009, were observed for both durum wheat (between 282,000 ha in 2002 and 165,000 ha in 2011) and for processing tomato (between 30,000 ha in 2000 and 19,000 ha in 2012) as well as for the other crop types for which an adjustment toward more profitable productions was observed (Zingaro et al. 2017).

Following the CBC decision rule detailed in Section 2.2, the SW pricing scheme from year to year was defined according to the volume stored in the reservoir in March when the wet season is almost over. Considering the marked climate variability of the investigated region, 4 different pricing schemes were adopted during period 1993-2012, which correspond to distinct *CR* patterns. The block tariff thresholds commonly observed during the study period are reported in Fig. 5 together with the *CR* steps for different GW depths (‘shallow’, ‘average’ and ‘deep’ i.e. respectively 20 m, 40 m and 70 m).



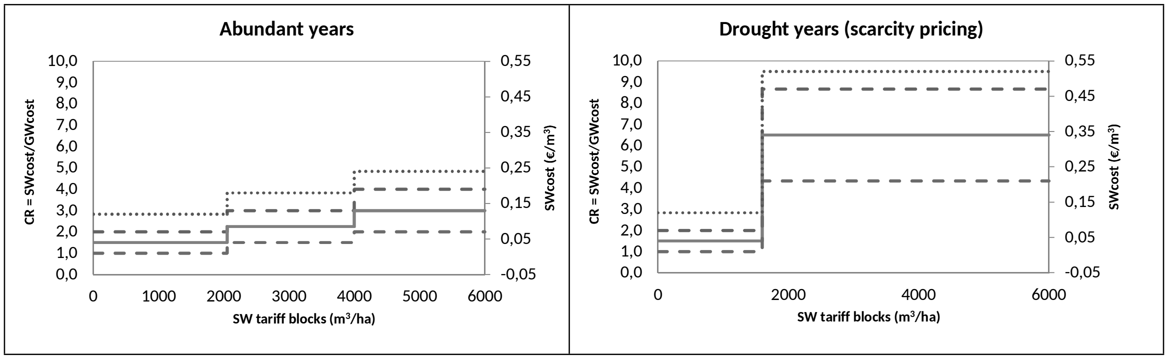


Figure 5. SW pricing scheme for regular, abundant and drought conditions of SW availability and consequent *CR* steps for different water table depths.

For the case study application in the Capitanata plain, the parameters of the WSS function were defined according to the discrete tariff thresholds of the SW tariff plans and GW unit average costs corresponding to an average dynamic depth of the water table around 40 m.

In case of 'regular' climatic and hydrologic conditions, when the reservoir is full and the irrigation season can be operated normally, starting from $\%SW_m=0.9$, the WSS function predicts step-wise decreases in SW reliance according to the increasing SW unit cost as the seasonally cumulated irrigation exceed the BWA. However, in case of years with limited water availability (i.e. 2000, 2007 and 2008) SW is accessed up to the BWA, and then SW supply is thus drastically reduced (Fig. 5) with $\%SW_M=0.05$ as the unit SW cost becomes unaffordable. As such, the parameterized WSS function allows to simulate the source selection criteria, depending on the irrigation demand and tariff thresholds, and to quantify the growing preference for groundwater source (%GW) during the irrigation season, when the SW_{cost} becomes less convenient (Fig. 6a). The validation of the WSS model was performed by comparing the simulated irrigation supply from SW facilities with the overall uptake volume operated by the CBC for irrigation purposes (Figure 6c). Measured monthly uptake values were modified considering a conveyance efficiency of 87% (Guyennon et al. 2016) to take into account water losses in the pressurized network. The results of this comparison show a good agreement ($R^2=0.91$, see Fig. 6c), proving a reliable reconstruction of farmers' allocation from both SW and GW under different tariff and/or climate conditions.

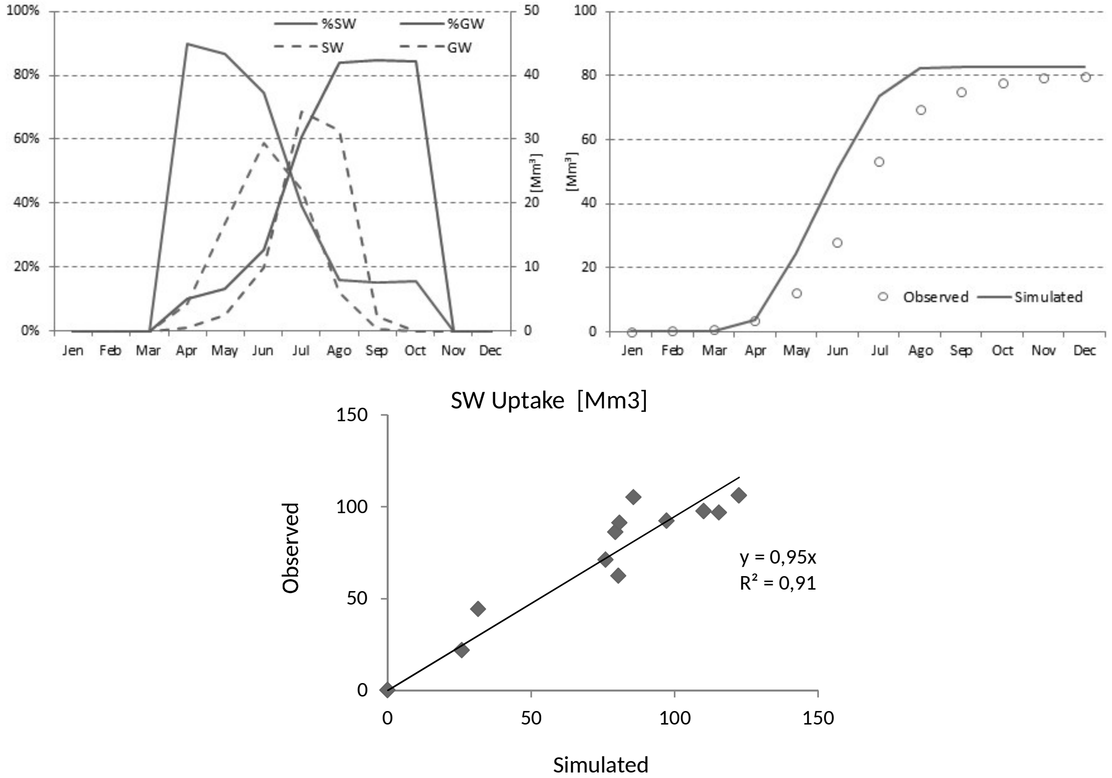


Figure 6. a) Average monthly SW and GW allocation expressed both as percentage (continuous lines) and absolute values (dashed lines); b) cumulative monthly mean of SW uptake; c) annual modelled and observed withdrawals from SW reservoirs.

3.2 Modelled irrigation water balance in conjunctive SW-GW allocation schemes

The WSS model was validated for the period 1993-2012 through the dataset collected in Zingaro et al. (2017) related to the cropping pattern variability, along with the climate records and the reservoir water budgets. Starting from the monthly time series of CROPWAT irrigation requirements, I_{rrd}, the WSS model allowed estimating monthly GW abstraction cumulated over the entire district as well as SW uptake volumes from the reservoir. During each month of the irrigation season, spatially averaged CR values were set as input to WSS function yielding %GW and %SW over the whole district area.

Simulated monthly time series of SW and GW uptakes are plotted in Fig. 7 along with SW uptakes derived from the reservoir operation record for the same period. Clearly, SW exploitation resulted variable according to reservoir storage and consequent volumetric tariff adjustments in both simulated and observed SW uptakes. Under the extreme conditions of failure in the WS storage (i.e. 2001 and 2002), the model correctly satisfied the irrigation needs solely through GW uptake. Similarly, higher GW exploitation (mean %GW= 76%)

were estimated in years with reduced reservoir storage (i.e. 2000, 2007 and 2008). While under regular climatic and hydrological conditions, lower pressure on GW resources is estimated (mean %GW= 40%) with SW supply system assuring 60% of the district irrigation demand.

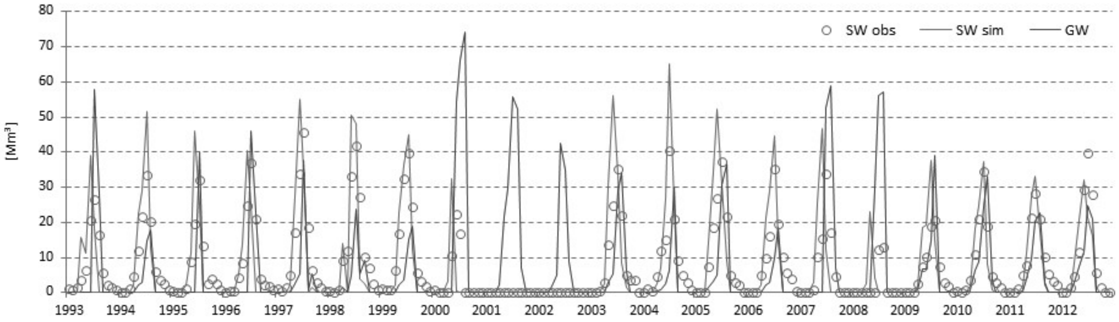


Figure 7. Modelled irrigation uptakes from GW and SW resources, compared with SW uptakes resulting from the observed reservoir volumes (SW_{obs}) for the study period.

3.3 Impacts of water pricing and irrigation demand on GW storage dynamics

Although GW protection is out of the scope of CBC water management strategy, the level of tapping into the GW is 56% on average in conjunctive use areas, while in extreme drought years and outside the CBC collective service area farmers rely on GW extraction to cover 100% of their irrigation needs. The validation of GW component in the overall model scheme in Fig. 2 was provided in terms of monthly GW storage volume (Guyennon et al. 2016). Using GW records from the regional monitoring network (Passarella et al. 2017), water table depth measurements from the 55 monitoring wells were adopted as representative of the entire aquifer domain and then converted into estimates of GW storage (Fig. 8). For each GW campaign covering the period 2001-2009, point measurements were scaled by the effective porosity and then summarized using box-whisker plots.

The comparison between simulated and observation-based GW storage variability substantially proves the good performance of the overall modeling chain (Fig. 8). Despite the temporal stationarity of rainfall during the study period, which included severe drought episodes in 2001-2002 and 2008 followed by wet years with full recovery of rainfall deficits, a permanent loss in GW volume of about 20% was observed at the end of the period. In other terms, the negative impacts of drought years on GW storage are emphasized by the concurrent reduced GW recharge and increased withdrawal. This mechanism is clearly driven by climatic variability and irrigation demand patterns but on the other side accessibility to SW and GW resources may indeed have an important role.

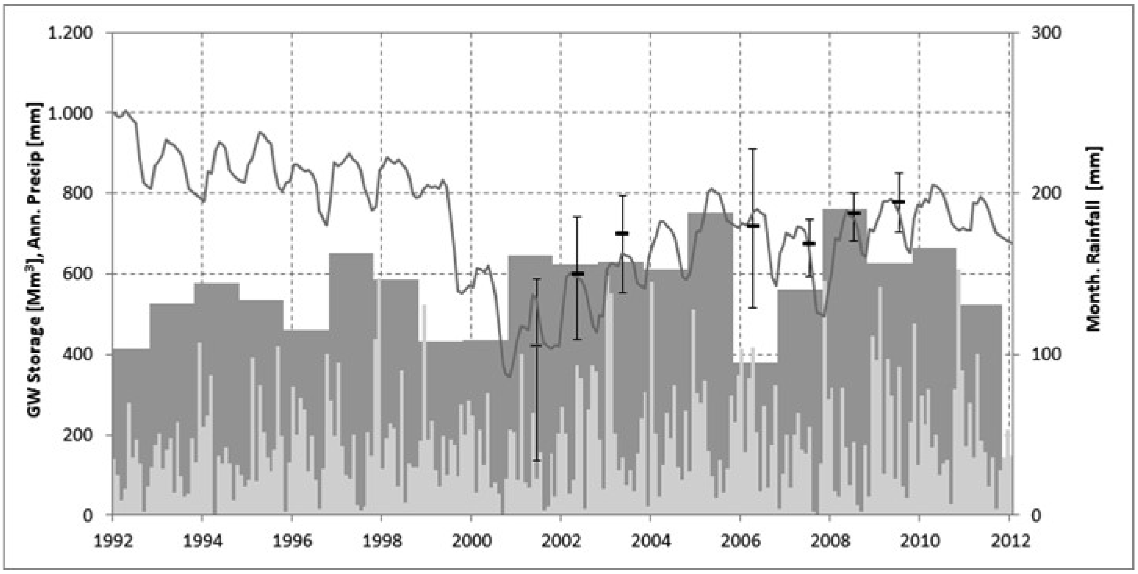


Figure 8. Simulated monthly GW storage (blue line) with observations reported as spatial median (black segments) with associated 25th and 75th percentiles as error bars. Moving average (8-yrs window) of monthly rainfall is also reported (grey circles, right axis).

To test the sensitivity of GW balance simulations to climate and water tariff variations a few scenarios were defined by altering the adopted time series (Tab. 3). In particular, the effects on GW storage due to CBC pricing policy was evaluated by adopting a 50% increase in SW tariffs (S1), while the effect of climate on GW storage was investigated by a 10% reduction on precipitation (S2). Furthermore, the S1 water pricing scenario was combined with the climate scenario S2 in the combined S3 scenario.

Table 3. Water pricing and hydrological scenarios adopted for the sensitivity analysis.

Scenarios	**SW pricing**	**Precipitation**
S0	Historical	Historical
S1	+50 %	Historical
S2	Historical	-10 %
S3	+50 %	-10 %

For each of the three scenarios, the trends of GW volumes are presented in the following Figure 9, with the aim of highlighting the differences between scenarios in terms of impacts on GW storage with respect to the S0 condition, which corresponds to the historical baseline.

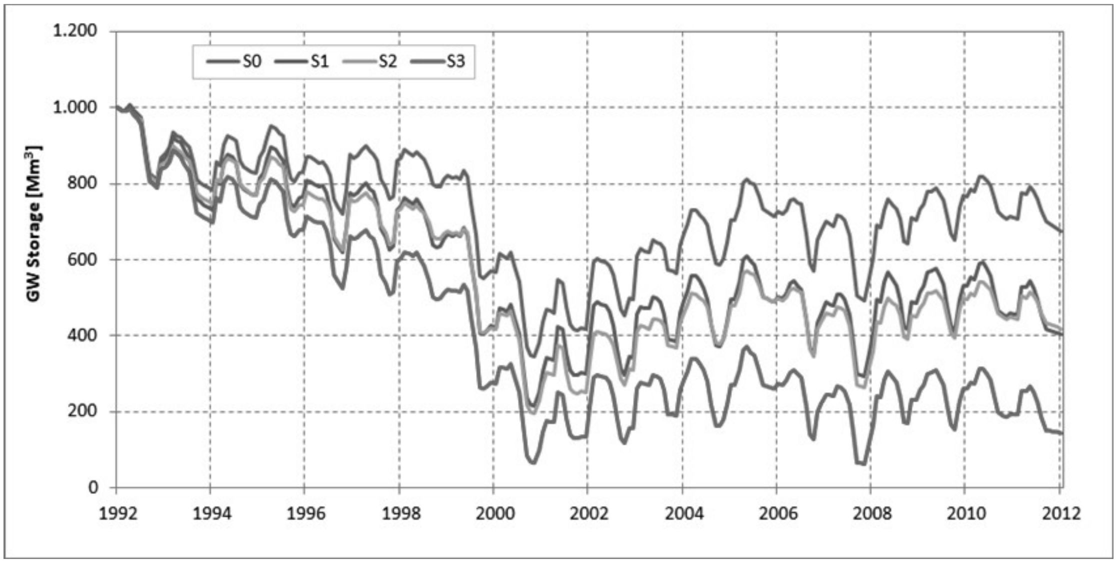


Figure 9. Scenarios of simulated groundwater volume under different conditions of climate and SW pricing according to Tab. 2.

More specifically, the first two scenarios, respectively the 50% increase of water pricing levels (S1) and the climate induced decrease in GW recharge (S2) , were found to yield quite similar results on the dynamic of GW storage so that they could be associated to an almost equivalent impact, i.e. an overall 25% reduction of the GW stock compared to the baseline S0, in 20 years. In other words, according to this modelling study, farmers are expected to react to the increase of SW prices by increasing GW exploitation thus causing similar impacts on GW quantitative state as those caused by a 10% reduction in precipitation. Consequently, the worst but not totally unlikely scenario resulting from the combination of S1 and S2, namely the scenario S3, is expected to cause a 67% reduction on GW storage in about 20 years.

Overall, these scenario simulations have further demonstrated the capability of the adopted modelling scheme to investigate the combined effects of climate variations, farmers' choices and management rules on the sustainability of GW resources.

4 DISCUSSION

The present work argues that a sustainable management of water resources in complex socio-hydrological contexts needs a thorough analysis of water exploitation mechanisms, including the potential side effects that irrigation water pricing strategies might have on water source selection and use. A WSS function is built for the purpose, in a system with a conjunctive use of SW and GW, considering both the GW pumping cost and the SW collective tariff. With specific reference to the proposed case study (the Capitanata area), both qualitative and quantitative evidences suggest that the SW is preferred over GW until the cost ratio (*CR*) of 2.5 is exceeded, and that a relevant exploitation of GW occurs (ranging from 56% on average in conjunctive use areas to 100% in drought years and outside the CBC collective service area). Results feed a water balance model which highlights, through a scenario analysis performed in different climate and SW pricing conditions, the occurrence of potentially unsustainable conditions for the system. Evidence is specifically provided of the potential onset of side effects in terms of GW overexploitation, as a consequence of the implementation of specific SW water pricing strategies.

The activities contribute to provide an answer to the specific research questions raised in the Introduction. First of all, concerning the role of irrigation water pricing on the farmers' decisions related to water source selection and use, although it is well known that water policies could be a valuable option to affect the users' behavior and to improve efficiency, it should be carefully considered that they may have unintended consequences and side effects. For example, with specific reference to the case study, the SW pricing policies implemented in drought years by the irrigation board, which are meant to allocate scarce water volume, may rather drive farmers towards a potential overexploitation of GW resources through individual on-farm wells. There are both qualitative (i.e. from semi-structured individual interviews) and quantitative evidences (i.e. data related to SW supply) confirming this during a production season. The proposed work provides a solid description of these results, although it should be highlighted that the system is characterized by a high complexity, which cannot be fully unraveled by the model. Just to make an example, the market conditions (which are indirectly taken into account through the crop pattern and therefore the irrigation requirements) as well as the farm size/type, are also relevant issues of farmers' decisions, and could have a significant impact on the selection of a specific water source.

Secondly, the information collected regarding water use and the process of source selection have been structured in a quantitative WSS function, which models the economic convenience driving farmers either towards SW or GW, under specific conditions, during a given irrigation season. This function has been then included in an aquifer balance model, in order to quantitatively assess the potential effect of SW collective pricing strategies and GW variable cost on the state of GW resources. Despite the mentioned model assumptions, the impact of SW collective pricing strategies on the overexploitation of GW resources, particularly during dry years, clearly emerges. This may drive the system, along with other issues such as the effects of climate change, towards unsustainable conditions. Additional efforts are needed, however, in exploring the effects of other policies (e.g. supporting crop change) that can be implemented along with or instead of pricing strategies, producing better systemic effects.

Lastly, one of the key general evidences from the modelling process and from the scenario analysis, is that in such complex socio-hydrological systems the implementation of specific ‘sectoral’ actions and strategies may have unintended consequences on the system as a whole. Understanding the side effects e.g. of a restrictive SW pricing policy on GW uptake is not straightforward, but definitely relevant at a strategic level. The model, despite the needed assumptions and simplifications, could help decision-makers dealing with a complex issues such as irrigation water management in a more systemic way. Results can be used to support raising the awareness regarding the potential multiple effects that policies and strategies may have on the system as a whole, and drive towards the selection of effective solutions. Although the evidences from the specific case study may allow drawing some general considerations and conclusions on the different effects of water pricing strategies on irrigation systems, additional efforts are needed to replicate a similar approach in other contexts and in even more complex conditions.

5. CONCLUSIONS

The present work proposes an insight into the issue of sustainable water resources use for irrigation, considering a district with both SW and GW availability (collective and individual on-farm services, respectively). The focus is specifically on the influence that variable costs for irrigation water can have on source selection during the irrigation season. An intuitive WSS function to describe water source selection is built to formally reflect the evidences of the interviews as well as the data series of all relevant variables, and takes jointly into account the crop water demand, along with the average GW pumping cost and the SW collective tariff, with its variation in different hydrological conditions. Based on the WSS function, GW balance simulations are performed in different scenarios, showing potential unsustainable conditions. Although the model in its current form provides a simplification of some dynamics, results highlight the relevance of systemic approaches for an effective GW sustainable management of resources, and the need to take into account the multiple interactions among decision-makers, physical systems, policies and local conditions. In this direction, the role of the proposed model could be highly relevant to understand system evolution and to explicitly consider potential side effects or unintended consequences of actions, mainly in a threefold direction: i) providing indications on the impacts of possible changes in the SW tariff system; ii) identifying potential tipping points for the GW system, under specific climatic and resources use conditions; iii) providing a structured support for the identification of suitable policies for an integrated SW and GW management. Future research activities will follow these research lines.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: