MIGRAD: A WATER ALLOCATION MODEL FOR MULTI-RESOURCES IRRIGATION SUPPLY SYSTEMS IN THE CAPITANATA DISTRICT, ITALY

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ABSTRACT

The present work describes a model developed to interpret water allocation patterns in an intensive agricultural district of Southern Italy, supplied both by groundwater (at farm-scale) and surface water (managed by a local authority) with variable costs and specific operation. The model aims at evaluating the impact of some drivers (mainly the water cost) on water resources management and groundwater conservation at the district scale. The model is part of a Decision Support System (DSS) developed to investigate the main dynamics in an agricultural district, integrating in a model based on System Dynamics specific sub-modules (e.g. Crop Water Demand, Surface Reservoir Balance, Groundwater Balance and Farmers' Behavioural Model). Semi-structured interviews were carried out with local stakeholders in order to define (i) the relationship between the irrigation source selection and the water tariff applied in the irrigation district, and (ii) the selection of groundwater, based on cost, to fulfil the irrigation needs. The volumes from surface water were evaluated during the model calibration phase according to the expected irrigation needs, and found to be significantly correlated to the water stock in the reservoir well before the start of the irrigation season. The validation phase showed a good agreement between measured and simulated reservoir irrigation uptakes in the period 2000–2012. It was mainly shown that the preference for a water source depends mainly on the ratio between the surface water tariff and the groundwater pumping cost at farm-scale. The results also demonstrated that a restrictive water tariff policy applied during drought periods produced a marked increase in the groundwater use instead of reducing the water-irrigation consumption. Globally the model allows to better describe the drivers influencing farmers' behaviour and, thus, supports assessing the impacts of water policies, such as those related to water tariff.

Keywords: water allocation criteria, integrated water management for irrigation, impact scenarios, multi-resources water supply system.

1 INTRODUCTION

The sustainable management of water resources requires the use of integrated systems [1], especially for irrigation purposes, since agriculture represents the most impacting activity on water resources [2]. Water resources management is, in general, the result of various interests related to shared water resources [3]. Therefore, an increasing level of conflict between different water users and uses is observed, particularly in the Mediterranean area [4]. The Mediterranean area is indeed characterized by water scarcity problems as a result of its climatic conditions [5] and the whole area is expected to become vulnerable to the scarcity and irregular availability of water resources [6]. The issues related to water scarcity are becoming increasingly interconnected with development, and particularly with social, economic, environmental, legal, and political factors at different level from local to international) [7].Therefore, integrated water resource management (IWRM) requires methods and tools to support the detection, analysis and reduction of conflicts among different users and uses [2], based on the assessment of the impacts on water resources [1].

Assuming a competitive and unregulated water extraction regime, the temporal and spatial variability of external drivers results in inefficient pricing and misallocation of the resources

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[8]. Therefore, it is necessary to define an adequate planning of some economical instruments such as energy and irrigation water pricing, to help improving water overexploitation.

The purpose of this study is to evaluate the impact of farm-scale water costs on water resources management and groundwater conservation at district scale. Particularly, the use of specific water sources by farmers was analysed as a function of both energy and water policies, in case of water supply system serving multiple users through multiple resources. In this work, the case of Capitanata plain (southern Italy), an area characterized by intensive groundwater use for agriculture [9], has been investigated.

2 MATERIALS AND METHODS

2.1 Study area

The case study concerns the Capitanata area, a plain within the province of Foggia with favourable climate conditions for intensive agriculture (the area is classified as Cfa according to the updated Köppen-Geiger, i.e. warm temperate, fully humid, hot summer [10]). Agricultural production is mainly characterised by rainfed winter cereals (mainly durum wheat – 54.78%), irrigated summer horticultural crops (mostly tomato – 13.25%), forage and pasture systems (17.11%), olive trees and vineyards (5.48%). The cultivated area at district-level is approximately 500,000 ha. The irrigation network is available approximately on 150,000 ha, but only 126,000 ha are supplied, by means of two irrigation schemes: (a) the Fortore system, on the Northern part, serving an area of 110,000 ha, and the Sinistra Ofanto system, on the South, serving approximately 40,000 ha. Both are on-demand pressurized systems equipped with water-meters and prepaid card devices to monitor water demand [11]. Surface water use for irrigation in both districts is managed by the Consorzio di Bonifica della Capitanata (CBC) which is a governing and technical body directly involving the farmers. It is also worth to consider that the Capitanata plain is located over significant alluvial aquifers, which are heavily exploited for irrigation through private wells used to increase available volumes under water scarcity conditions.

The Fortore system is an example of combined use of both surface water and groundwater for irrigation, with significant complexity for water resources management. The purpose of the present study is mainly to shed light on the selection of the water source for irrigation with particular attention to the issues of cost and environmental impacts.

2.2 Analysis of the main dynamics of the system

As already mentioned, two main water sources are available for irrigation: surface water in an artificial reservoir (Occhito) managed by the CBC, and groundwater from private wells.

Significant information on the case study were collected integrating and structuring different categories of data. An interview-based approach was implemented to identify the main system dynamics, under the assumption that past behaviours can be used to predict the future evolution. Semi-structured interviews involving both local farmers and members of the consortium were performed (e.g. [2], [12]), and then replicated.

Firstly, the behaviour of farmers was investigated, mainly in order to define the relationship between irrigation source selection and water tariff. The irrigation source selection, limited to surface water (SW, deriving from the reservoir) and groundwater (GW, deriving from individual pumping), depends on various externalities (Irrigation demand, Climate condition, SW Tariff, Pumping cost, etc.) which jointly influence the behaviour of farmers. The impact of these conditions on groundwater resources exploitation, considering the withdrawals needed due to fulfil the irrigation demand, is analysed.

Secondly, the behaviour of CBC is analysed as well. The consortium mainly determines the SW tariff, depending on water availability in the reservoir at the beginning of the irrigation season and on other variables (e.g. economic conditions, expected irrigation water demand, climate conditions).

Starting from surveys and interviews, the present study allowed to define the criteria regulating the use of both SW and GW for irrigation. The ratio between Surface Water price and Groundwater price seems to be the key driver to describe water use for irrigation.

2.3 Available data

2.3.1 Irrigation tariffs for surface water

The CBC has mandate to implement a water policy aiming to equitably fulfil as much as possible farmers' irrigation needs at reasonable costs, simply guaranteeing the recovery of operational costs for the consortium.

The SW price is defined by the CBC on yearly basis. More in details, the consortium sets the tariff plan as a function of available water stock at the beginning of irrigation season. The tariff plan has increasing unit prices (SW_{price}) according to specific volume thresholds. The minimal tariff corresponds to a first slot, which guarantees a basic water allocation. The other thresholds are meant to decrease accessibility to excessive SW volume, thus imposing a constrain to over-consumption of water for irrigation. The following Table 1 contains the tariff plans in the period between 1993 to 2012.

Table 1: Tariff plans and accessibility degree.

Tariff plan [€/m³]								
Year	*Volumetric thresholds [m3/ha]*							*Accessibility degree*
	600	*1600*	*2050*	*2500*	*3000*	*4000*	*6000*	
1993	0.09	0.09	0.52	0.52	0.52	0.52	0.52	3
1994	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
1995	0.09	0.09	0.52	0.52	0.52	0.52	0.52	3
1996	0.09	0.09	0.52	0.52	0.52	0.52	0.52	3
1997	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
1998	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
1999	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
2000	0.09	0.52	0.52	0.52	0.52	0.52	0.52	2
2001	-	-	-	-	-	-	-	1
2002	-	-	-	-	-	-	-	1
2003	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
2004	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
2005	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
2006	0.09	0.09	0.09	0.18	0.18	0.24	0.24	4
2007	0.09	0.09	0.52	0.52	0.52	0.52	0.52	3
2008	0.09	0.52	0.52	0.52	0.52	0.52	0.52	2
2009	0.12	0.12	0.12	0.18	0.24	0.36	0.36	4
2010	0.12	0.12	0.12	0.18	0.24	0.36	0.36	4
2011	0.12	0.12	0.12	0.18	0.18	0.18	0.24	4
2012	0.12	0.12	0.12	0.18	0.18	0.18	0.24	4

Particularly, the 'Accessibility degree' is defined as a generalization of the scheme used for the tariff, mainly depending on the first threshold, ranging from (1) in drought years, to (4) in normal conditions. The data for the applied irrigation tariffs were provided by CBC except for the years between 1993 and 1999. In this period, the tariff plans were defined generalizing the scheme adopted by the CBC (see Section 2.4.3 for further details) based on the available data. In 2001 and 2002, the reservoir was almost empty due to drought conditions: this resulted in unavailability of SW, with a subsequent GW over-exploitation for irrigation. Based on the surface-water tariff and estimated pumping cost, a mathematical function (WSS function) has been developed to simulate farmers' selection of water source.

2.3.2 Irrigated cropping patterns

Together with climate and hydrological conditions, cropping patterns are among the major drivers of irrigation needs and, consequently, of water resources exploitation. In order to perform a simple but significant assessment of cropping pattern changes (within the irrigated area), a specific subset of crops was selected. More in details, only the crops having higher water-requirement and/or covering a wider surface were taken into account with their variabilities (according to data by the Italian Statistical Service), namely: Industrial Tomato (190–300 km^2), Grape (285–442 km^2), Olive (525–550 km^2), Peach (28–44 km^2) and Vegetables (22–31 km^2). A regional land use (2011) was used to characterize the area under investigation and to map the spatial location of crops. For the sake of simplicity, a "average hectare" approach was adopted to describe the variability of cropping patterns.

2.4 Developed models

The proposed model has been defined taking into account different sub-models. The global structure is roughly represented in the following diagram (Fig. 1), while the following subsections provide a more detailed analysis of the sub-models.

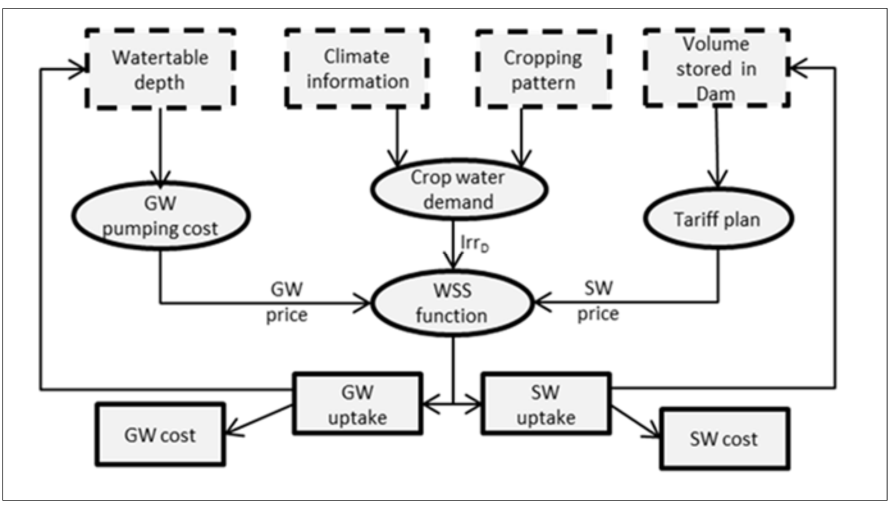

Figure 1: Conceptual model. The rectangles with dashed line are model inputs. The rectangles with continuous line are model outputs. Ellipses identify specific sub-models.

2.4.1 WSS (Water Source Selection) function

The behaviour of farmer with respect to water use for irrigation is sensitive to some policy instruments such as energy and water pricing. Several interviews underlined that farmers respond to policies changing their behaviour in order to maximize medium- and short-term profits. The selection of water source for irrigation, particularly, aims at reducing costs.

The developed model is able to define the fraction of irrigation demand that is satisfied from consortium irrigation network (*%SW*), which is estimated as a function of unit cost ratio (*CR*) between unit SW_{price} and GW_{price} (explained in detail in the following) for a cubic meter of water. Groundwater exploitation is estimated as the difference between Irrigation demand and *%SW*.

The model eqn (1) has the following structure:

$$\%SW = \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2}\ CR^2 - 2\ CR_M \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2}\ CR + SW_M + CR_M{}^2\ \frac{(SW_m - SW_M)}{(CR_m - CR_M)^2}, \quad (1)$$

where: SW_m is *%SW* value when *CR* is minimal that is, assuming a constant GW_{price}, when SW_{price} is minimal; SW_M is *%SW* value when *CR* is maximum that is, assuming a constant GW_{price}, when SW_{price} is the highest; CR_m is the value of *CR* when SW_{cost} is minimal; CR_M is the value of *CR* when SW_{price} is maximum.

The selection criterion is based on a second order polynomial function, so that when *CR* increases, *%SW* significantly decreases. This correspond to the attitude of farmers to prefer groundwater source (*%GW*) as the SW_{price} gets higher. The WSS function is represented in Fig. 3 under the hypothesis of a continuous increase of *CR*.

2.4.2 GW pumping cost

The unit cost of groundwater exploitation for irrigation was estimated according to the classical formula for submerged pumps, allowing to estimate the unit pumping cost per cubic meter of water (GW_{price}) as a function of mechanical work, which depends on the total head required.

This mechanical work transmitted to the fluid is given by the following eqn (2):

$$P = \frac{Htot}{(102 * \eta * 3{,}6)}\ [\text{kWh/m}^3], \quad (2)$$

where: $H_{tot} = H_1 + H_2$ [m] is total head given by the sum of water table depth (H_1) below the soil surface and required hydrant pressure (H_2) and η is the pump efficiency.

Finally, the Groundwater pumping cost (GW_{price}) is estimated as a product between *P* and *c*, where c is unit energy cost [kWh]. In our case study we considered the following values: H_1 = 40 [m], H_2 = 26,5 [m], η = 0,5 and c = 0,22 [€/kWh]. The resulting average GW_{price} is 0.08 [€/m^3]. Additional costs such as maintenance and depreciation are currently neglected.

2.4.3 Tariff plan

The CBC defines a tariff plan for SW on yearly basis, at the beginning of each irrigation season. Based on semi-structured interviews held with consortium members, from a merely technical point of view the volume stored in the reservoir in March resulted the most influential driver. Then, after the analysis of the available tariff plans in the period 2000–2012, and the analysis of the strategies selected under similar external conditions, four different types of tariff were identified, and associated to a water 'accessibility degree'. The following Fig. 2 proposes a linear correlation between the accessibility degree and the water volume in March, which allows assigning the expected tariff plan as a function of the volume stored in the dam in other years. The correlation in Fig. 2 has been adopted to predict the SW tariffs in the years with no official data.

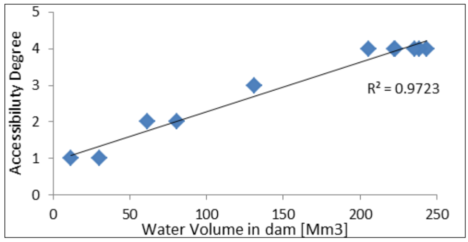

Figure 2: Correlation between the accessibility degree and water volume in the reservoir.

2.4.4 Crop water demand

The irrigation demand is variable according to the seasonal climate variability and to the specific cropping patterns. CROPWAT 8.0 was used to calculate the monthly variability of irrigation demand throughout the period of interest. It represents a decision support tool developed by the Land and Water Development Division of FAO for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. Using the "schedule module", the monthly Irr_d for the "average hectare" was estimated. Precipitation and temperature (mean monthly values were provided by the regional hydro-climatic service), which attributed to a single virtual station representing the whole area. Hydraulic soil properties (mean spatial values) and crops properties (crop coefficients Kc, crop yield, etc.) were included as well. Particularly, the most suitable Kc coefficients for evapotranspiration calculation were attributed according to the FAO Paper n. 56 [13]. The efficiency of irrigation systems was estimated considering drip irrigation (efficiency set to 0.9). An additional reduction coefficient was 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. The results are reported in Fig. 5.

3 RESULTS AND DISCUSSION

3.1 Parameterization and validation of the WSS function

The function describing the selection of the irrigation water source (SW from the Consortium network) and GW has been defined referring to the eqn (1). In particular, in case of years with limited water availability (2000, 2007 and 2008) $SW_M = 0$ e $SW_m = 1$, which means that SW is accessed only for what concerns the volume corresponding to the minimum tariff. Additional volumes are extracted from GW, to fulfil irrigation requirements.

In case of 'average' climatic conditions, when the reservoir is full and the irrigation season can be performed regularly, $SW_m = 0.9$ and $SW_M = 0.1$. The resulting function defines the source selection criteria by farmers, depending on the irrigation demand and on tariff thresholds, and quantifies the preference for groundwater source (*%GW*), when the SW_{price} increases. The result considering the ordinary tariff plan adopted by the CBC is represented in the Fig. 3.

The validation of the WSS function and its parameterization has been performed comparing the simulated and measured irrigation volumes withdrawn from the reservoir. Measurements were provided by the Regional Water Authority (AdB Puglia) and modified considering the conveyance efficiency (0.87 as in [14]) to take into account the losses within the consortium pressurized network. The results of this comparison are represented in the Fig. 4.

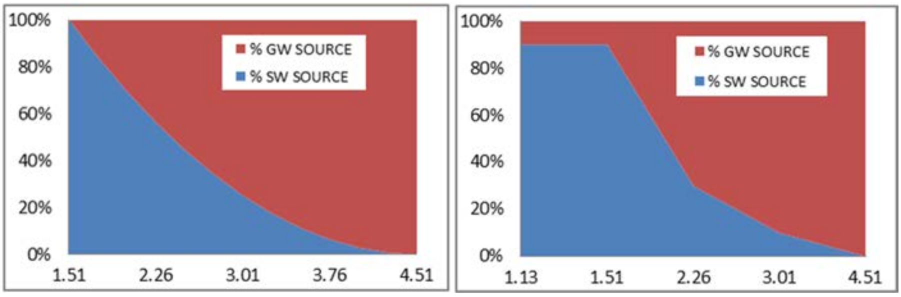

Figure 3: WSS function under hypothesis of a continuous increase of *CR* (left panel). WSS function for regular irrigation season (right panel).

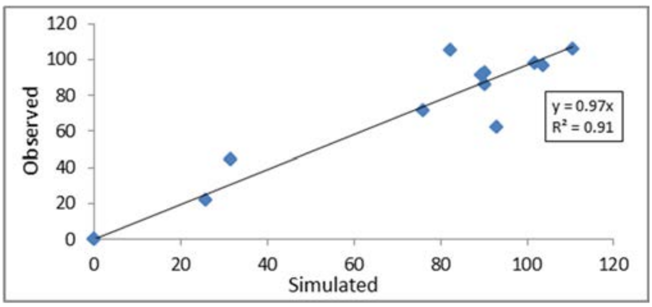

Figure 4: Annual SW uptake (Mm^3). Comparison between observed and simulated values for 2000–2012.

The correlation showed a good agreement between measured and observed surface water volumes used for irrigation over the whole period. This result may thus provide a reliable generalization of farmers' behaviour under different tariff and/or climate scenarios, as will be further investigated in the following.

3.2 Results for 1993–2012

The model was applied in the case study for the period 1993–2012, evaluating the monthly uptake volumes, provided both by the SW irrigation system and by farm-scale GW pumping. For each irrigation season, starting from the cumulated Irr_d, the *CR* was calculated and then both GW and SW uptakes estimated by means of the WSS function. Therefore, the yearly uptakes provided by both available irrigation sources were estimated. The results are showed in the Fig. 5.

The Fig. 5 shows a certain increase of the Irr_d over the whole period, which change yearly according to the variations both of climate conditions and cropping pattern. The trends both in the SW uptakes and GW uptakes are also plotted. The uptakes change according both to the variations in SW availability (stored volume in Occhito reservoir) and SW accessibility (tariff plan). The years with the highest GW uptake were 2001 and 2002 ($\%GW$ = 100%), due to the failure of the SW system caused by severe droughts conditions. GW exploitation was also significantly high in 2000, 2007 and 2008 ($\%GW_{mean}$ = 64%) due to the limited SW availability at the beginning of the irrigation season.

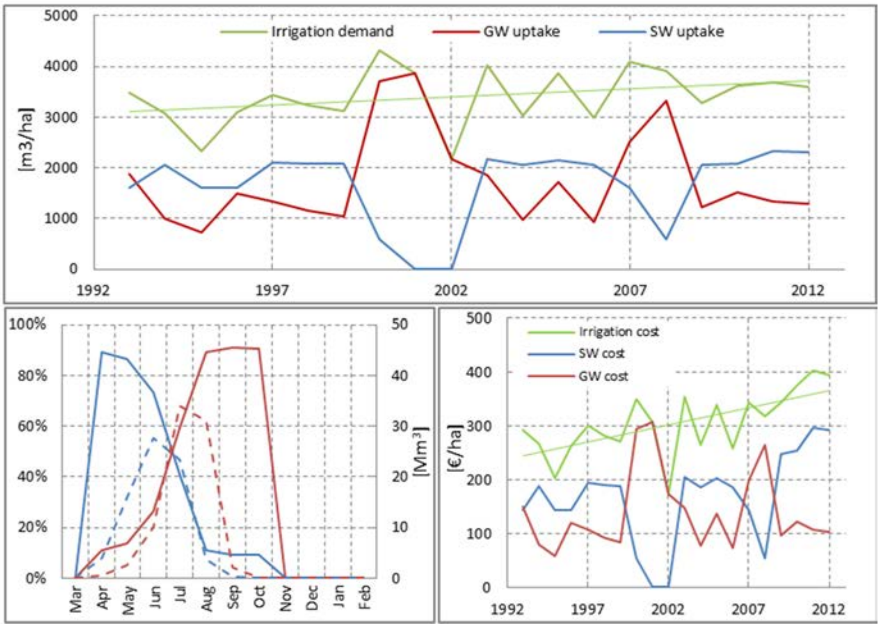

Figure 5: Irrigation demand, SW uptake and GW uptake (upper panel). Average monthly values (bottom panel on the left): percentage and absolute values (dashed and continuous line respectively) of the SW and GW uptake (blue and red line respectively). Irrigation cost, SW cost and GW cost (bottom panel on the right).

During the years when an ordinary irrigation season was performed, the average fraction of GW uptakes was lower ($\%GW_{mean}$ = 38%). Conversely, during ordinary irrigation seasons, the SW supply system is able to cover approximately 60% of the whole irrigation demand. Therefore, GW contribution to the irrigation demand is always significant, and becomes higher in case of limited availability of SW resources. Considering the effects of a specific water tariff plan on the accessibility of water resources, the restrictive tariff applied in case of drought produces a marked increase in the groundwater use ratio, without driving to an effective reduction in the overall water consumption. Nevertheless, as discussed in the next section, the use of restrictive water tariffs does have effects on the seasonal irrigation costs.

3.3 SW availability and irrigation costs

Depending on both GW and SW uptake volumes, the costs associated to irrigation were evaluated (respectively GW_{cost} and SW_{cost}). Only the “variable” fraction of costs for irrigation was taken into account, whereas the “fixed” costs (i.e. maintenance and depreciation costs of farm infrastructures and on-farm irrigation systems) and the fixed yearly contribution per hectare due to the consortium are neglected. The variable components of irrigation costs are shown in the Fig. 6 for the period of interest, which shows an increasing trend of Irrigation costs over the whole period (+29%). The costs vary, from one year to another, as a function of both Irr_d (which depends on one hand on the changes in cropping patterns and, on the other hand, on climate) and the tariff plan (SW_{price}). However, even if the Irrigation costs increase, the negative effect on farmer’s economy is limited [15]. Starting from 2001, economic conditions are highly threatened by both the reduction in market-prices and the reduction in agricultural subsidies (as a result of the CAP reform). In fact, CAP policies can affect farmers' behaviour on water use by reinforcing or conflicting with the water protection policies [16].

3.4 Impacts of water price and climate change scenarios on GW

Understanding the impact of both climate changes and tariff plans on agricultural production and groundwater exploitation is essential for ensuring the sustainability of future groundwater resources. To analyse and predict possible vulnerability conditions related to groundwater volume and irrigation-water consumptions, the water balance of the study area has been simulated under different climatic conditions and water tariff conditions using a System Dynamics (SD) approach. Groundwater dynamics have been evaluated by developing stock and flow diagrams using STELLA®. Going further into details, the variability of groundwater volumes is represented as a stock variable depending on inflow and outflow components defined by means of a GW balance model developed within the same area [14]. Among GW outflows, irrigation uptakes from private wells are introduced using the WSS function. Adopting the historical records of climate, cropping patterns and SW tariffs (i.e. S0 in Table 2), the groundwater balance was simulated in terms of GW volume variability. The dynamic of GW volume was also simulated under the hypothesis of no GW exploitation (i.e. WW in Table 2).

With the purpose of estimating the sensitivity of the GW dynamics to climate and water tariff variations, both the climate and the SW pricing records were varied by altering the historical series. More specifically, the sensitivity of GW volume to direct (e.g. natural recharge) and indirect (e.g. SW availability) effects was tested according to four scenarios, based on different combinations of the perturbation factors applied to SW pricing and precipitation (Table 2). Groundwater table depth measured by the regional GW monitoring network [17] are plotted in Fig. 6 as spatially averaged values, along with the model results. Some trends of GW volumes are also presented, highlighting the differences between scenarios with their magnitudes.

The analysis of model results regarding the baseline scenario (i.e. S0) shows that: (i) the whole period under investigation corresponds to a GW recharge period, since GW volume increased significantly (+55%) in the last decades, due to higher effective rainfall; (ii) during drought years, when the SW accessibility is low (e.g. 2001, 2002, 2008), GW volume depletion is more evident than in regular irrigation seasons; (iii) between 2005 and 2012 the aquifer seems to reach a new dynamic equilibrium condition.

Table 2: Scenarios with associated nomenclature and perturbed variables.

Scenarios	SW pricing	P natural recharge
S0	Historical	Historical
S1	+20%	Historical
S2	–20%	Historical
S3	+20%	–10%
S4	–20%	+10%
WW	Historical balance Without Withdrawals	

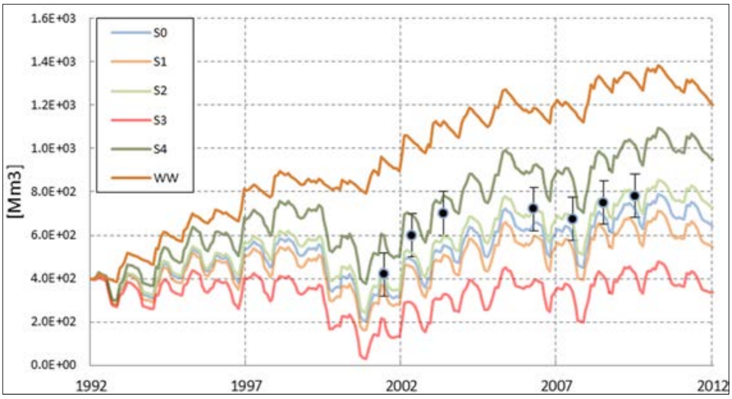

Figure 6: Scenarios simulated groundwater volume (GWV). Observations are reported as spatial median and associated error bars (black circles).

In the WW scenario, the GW uptakes were not considered in order to emphasize the potential state without GW exploitation. The final GW volume in this case is 87% greater than the S0, thus providing a quantitative measure of irrigation withdrawals on GW resources.

Additional scenarios allowed to underline the impact of economic policies (tariff plans) and of natural changes (in terms of natural recharge). Scenarios (S1) and (S2) represent only the effect produced by water tariff change, in terms of variation on GW volume (respectively –15% and +13%). Scenarios (S3) and (S4) instead represent the combined effect of tariff interventions and climate changes; the results show a significant change in the final GW volumes (respectively –48% and +47%).

These results highlight that climate variations may have a stronger impact than the variations in water tariffs; therefore, for a more sustainable management of GW resources, especially during drought periods, the reduction of Irr_d seems more effective than a tariff-driven reduction of SW accessibility.

4 CONCLUSIONS

A DSS has been developed to investigate the quantitative vulnerability of irrigation withdrawals under various SW pricing policies and climate change scenarios. SW tariff policies and climatic conditions were identified as the main drivers of GW state. The developed WSS function helped explaining how GW uptakes may depend on the evaluation of economic convenience performed by farmers: particularly in the case study, SW supply is preferred to GW source until their cost ratio (*CR*) is below 1.5. Modelling both climate changes and increases in irrigated areas over the considered period resulted in unsustainable GW exploitation. More specifically, farmers respond to water pricing policies by changing their behaviour to maximize short- and medium-term profits. An interview-based modelling approach was also useful to understand the interconnections between the consortium (i.e. water management criteria) and farmers. During persistent recharge periods (2002–2012), an increase in SW accessibility highlighted potentially positive impacts in avoiding inefficient surplus of SW at the end of irrigation season and suggested to exploit the residual reservoir capacity for reducing GW uptakes also increasing the annual consortium's revenue. Conversely, during drought periods, an effective decrease of GW uptakes may be achieved only through reduction of the irrigation demand (e.g. supporting a reduction of the irrigated land by means of subsidies).

The present study underlined that a feasible integrated management of GW resources requires to take into account various interactions among decision-makers, policies and climatic conditions [12]. More in detail, the key aspects to be considered are: (i) the main variables related to Irr_d, both direct (environmental) and indirect (e.g. cropping pattern mainly related to agriculture subsidies and SW accessibility), (ii) the behaviours of various stakeholders at different levels and (iii) GW response under different conditions impacting on GW recharge and exploitation.

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