European Water 57: 459-465, 2017.

Assessing groundwater use in irrigation districts with multiple resources (MIGRAD)

D. Zingaro, I. Portoghese*, A. Pagano, R. Giordano and M. Vurro
National Research Council Water Research Institute, UOS Bari, Italy
* *e-mail: ivan.portoghese@cnr.it*

Abstract: A water allocation model at farm-scale was developed to interpret water allocation patterns in an intensive agricultural district of Southern Italy, supplied by groundwater and surface waters (from reservoir) with variable costs and distinct management regimes. The model aims at evaluating the impact of farm-scale water costs on water resources management and groundwater conservation at district scale. Semi-structured interviews were carried out involving local stakeholders to define (i) the relationship between irrigation source selection and water tariff applied by the irrigation district, and (ii) the conjunctive use of groundwater based on water cost convenience. It was demonstrated that farmers' choice depends on the ratio between volumetric 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 an increase in the groundwater use instead of reducing the water consumption. The model allowed to analyze the drivers influencing farmers' behaviour, thus assessing the effectiveness of water protection policies, specifically those related to water tariff.

Key words: water allocation criteria, integrated water management for irrigation, groundwater use, multi-resources water supply system

1. INTRODUCTION

Water resources management needs to taking into account for interests related to sharing an increasingly limited resource (Portoghese et al., 2013). Therefore, an increasing level of conflict between different water users and uses is observed, particularly in the Mediterranean area (Jury and Vaux, 2007), due to water scarcity problems and climatic conditions (Portoghese et al., 2015). Therefore, integrated water resource management (IWRM) requires methods and tools to define how different water managers and users perceive the water resources and behave consequently (Giordano et al., 2013), based on the assessment of the impacts on water resources (Bouwer, 2000). Sustainable management of water resources for irrigation requires the use of integrated approaches (Bouwer, 2000), since agriculture represents the most impacting activity on water resources (Giordano et al., 2013).

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 define an adequate design of economical instruments, such as energy and irrigation water pricing, to help limiting water overexploitation.

The purpose of this study is to evaluate the impact of farm-scale water costs on water resources management and groundwater exploitation at district scale. The selection of specific water sources by farmers is analyzed as a function of both energy- and water-related drivers, considering a water supply system serving multiple users through multiple resources.

The case of Capitanata plain (Southern Italy), characterized by intensive groundwater use for agriculture (Guyennon et al., 2016), is investigated.

2. MATERIALS AND METHODS

2.1 Study area

The case study is characterized by favorable climate conditions for intensive agriculture. The cultivated area 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 with on-demand pressurized networks (Lamaddalena, 2004): (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. 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 ruled by farmers' representatives. Significant alluvial aquifers underling the Capitanata plain are heavily exploited for irrigation through private wells used to increase available volumes under water scarcity conditions.

The Fortore system is an example of conjunctive use of surface water (SW) and groundwater (GW) for irrigation, with significant complexity for water resources management.

Cropping patterns are among the major drivers of irrigation needs and, consequently, of water resources exploitation. To perform a simple but significant assessment of cropping pattern changes (within the irrigated area), a specific subset of crops was selected. Only crops having higher water-requirement and/or covering a wider surface were taken into account with their temporal 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 map (dated 2011) was used to characterize the spatial location of crops. For the sake of simplicity, the "average hectare" approach was adopted to describe the variability of cropping patterns.

2.2 Description of the main dynamics

An interview-based approach was adopted to define how different water managers and users perceive the water resources and behave consequently, 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 CBC were used (Giordano et al., 2013; Giordano et al., 2015).

Farmers' behaviour was investigated mainly to define the relationship between irrigation source selection and water tariff. The irrigation source selection depends on multiple externalities (Irrigation demand, Climate, SW Tariff, Pumping cost, etc.) which jointly influence the farmers' behaviour. The impact of these conditions on groundwater resources exploitation, considering the withdrawals needed to fulfil the irrigation demand, was analysed. Moreover, the impact on GW is indirectly related to the "market conditions" of crop products; in fact, in case of high market price for irrigated products, farmers prefer to increase the irrigated land regardless of SW availability. In such conditions, farmers perceive GW as an easily accessible resource without control by regional authority.

On the other side, the CBC has mandate to implement a water policy aiming at equitably fulfilling farmers' irrigation needs at reasonable costs, and guaranteeing the recovery of operational costs for the consortium. Consequently, the behaviour of CBC managers was analysed concerning their year-by-year decision on the SW tariff, which depends 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).

The tariff plan has increasing unit prices (SW_{price}) according to specific volume thresholds with a minimum tariff corresponding to the first slot, which guarantees a basic water allocation (BWA). The other thresholds are meant to gradually decrease accessibility to SW use, thus imposing a constrain to over-consumption of water for irrigation. An 'Accessibility degree' is defined to generalize the scheme used for the tariff plans, mainly depending on the first threshold, ranging from (1) in drought years, to (4) in normal conditions. The records of 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 decision rules adopted by the CBC (see Section 2.3.3 for further details).

2.3 Water Source Selection model

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

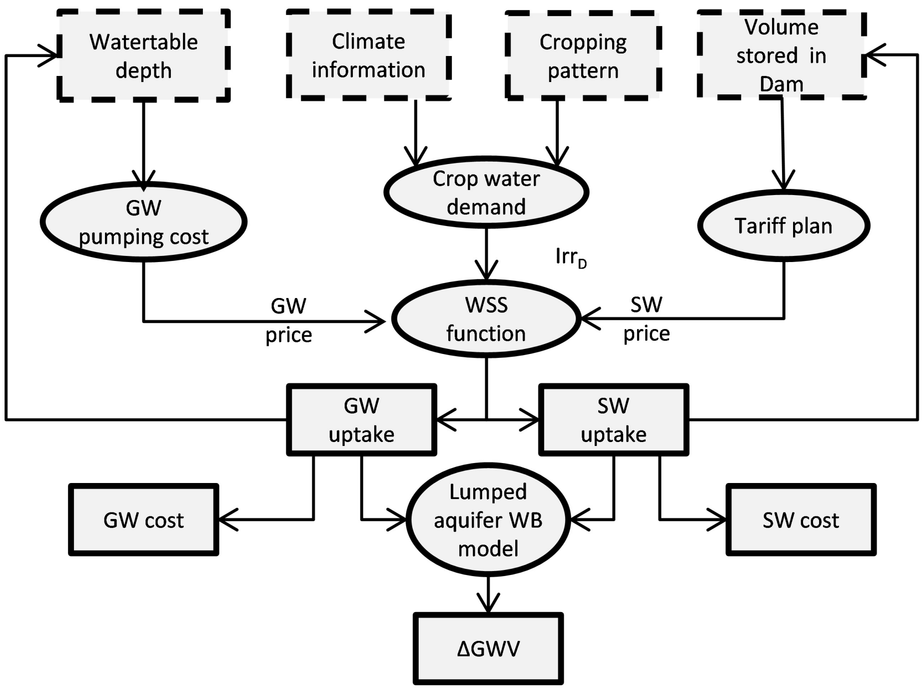

Figure 1. Conceptual model. The rectangles with dashed line are model inputs. The rectangles with continuous line are model outputs. Ellipses identify specific submodels.

2.3.1 WSS (Water Source Selection) function

The behaviour of farmers with respect to water use for irrigation depends on energy and water pricing. The selection of water source for irrigation, particularly, aims at reducing production 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 details in the following) for unit volume. The model equation (1) has the following structure:

$$\%SW= (Y)\, CR^2-2CR_M(Y)\, CR+SW_M+(CR_M^2)\, (Y) \tag{1}$$

where: $Y=((SW_m-SW_M))/((CR_m-CR_M)^2)$; SW_m, is *%SW* value when *CR* is minimal (i.e. SW_{price} is minimal assuming a constant GW_{price}); SW_M, is *%SW* value when *CR* is maximum (i.e. SW_{price} is the highest assuming a constant GW_{price}); CR_m is the value of *CR* when SW_{cost} is minimal; CR_M is the value of *CR* when SW_{price} is maximum.

This function simulates the attitude of farmers to prefer groundwater source (*%GW*) as the SW_{price} gets higher.

2.3.2 GW pumping cost

The pumping cost per unit volume of water (GW_{price}) is defined by means of the following equation (2):

$$P = H_{tot}/(367{,}2\ \eta)\ [\mathrm{kWh/m^3}] \qquad (2)$$

where: $H_{tot} = H_1 + H_2$ [m] is the total head given by the sum of water table depth (H_1) below the soil surface and the 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. 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 neglected for the purposes of the present work.

2.3.3 Tariff plan

The CBC defines a tariff plan for SW on yearly basis, based on the volume stored in the reservoir in March. Then, considering the available tariff plans in the period 2000-2012, and the strategies selected under similar hydrological conditions, four different types of tariff were identified, and associated to a water 'accessibility degree'. A linear correlation between the accessibility degree and the water volume in March (R^2=0,97) allows assigning the expected tariff plan as a function of the volume stored in the dam in other years. This linear function has been adopted to predict the SW tariffs in the years with no official data.

2.3.4 Crop water demand

The irrigation demand is variable according to the seasonal climate variability and to the cropping patterns. CROPWAT 8.0 was used to estimate the monthly irrigation demand (Irr_d) throughout the period of interest with the "average hectare". Hydraulic soil properties (mean spatial values) and crop properties (crop coefficients K_c, crop yield, etc.) were considered as well. Particularly, the most suitable K_c coefficients for evapotranspiration calculation were attributed according to the FAO database. 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.

3. RESULTS AND DISCUSSION

3.1 Parameterization and validation of the WSS function

The parameters of WSS function were defined as follows. 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 up to the BWA. While, 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, depending on the irrigation demand and tariff thresholds, and quantifies the preference for groundwater source (*%GW*), when the SW_{price} increases. The validation of the WSS model has been performed comparing the simulated and measured irrigation volumes withdrawn from the reservoir. Measured values were modified considering the conveyance efficiency (0,87 as in Guyennon et al., 2016) to take into account the water losses in the pressurized network. The results of this comparison show a good agreement (R^2=0,91), proving a reliable reconstruction of farmers' behaviour under different tariff and/or climate conditions.

3.2 Modelled water allocation

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

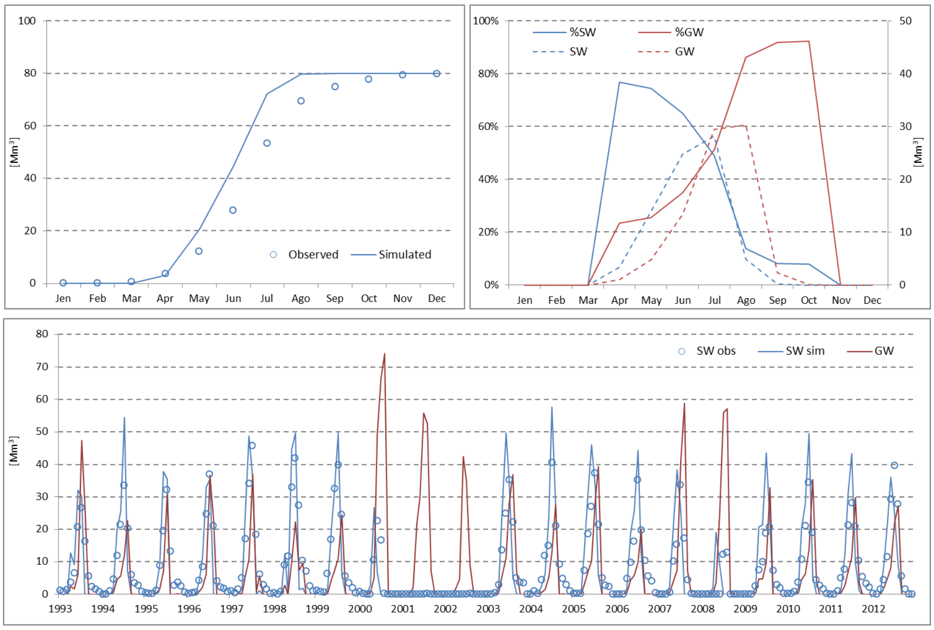

Figure 2. Upper panel on the left: Cumulative monthly mean of SW uptake. Upper panel on the right: Average monthly of the percentage and absolute values (dashed and continuous line respectively) of the SW and GW. Bottom panel: monthly GW and SW uptakes.

The model results are shown in Fig. 2 in terms of variability of SW and GW uptakes, according to the variations of climate and cropping patterns, and compared with observed SW uptakes. As expected, SW uptakes change according to both SW availability and tariff accessibility. The years with the highest percentage of the GW uptake were 2001 and 2002 *(%GW* = 100%), due to the failure of the SW system caused by severe drought conditions. GW exploitation was also high in 2000, 2007 and 2008 ($\%GW_{mean}$= 76%) due to the limited SW availability. During the years with regular irrigation season, the average fraction of GW uptake was lower ($\%GW_{mean}$=40%). Conversely, in such conditions, the SW supply is able to cover approximately 60% of the whole irrigation demand. Considering the effects of water tariff plans on water accessibility, the restrictive tariff plans applied under drought conditions produce a marked increase in the groundwater use, rather than reducing the overall water consumption.

Concerning the irrigation costs from one year to the other, variations are explained in terms of Irr_d and tariff plan (SW_{price}). However, even when irrigation costs increase, the negative effect on farmer's economy is limited and masked by other policies affecting farmers' behaviour on water use (Giannoccaro and Berbel, 2011).

3.4 Impacts of water price and Irr_d on GW volume

Understanding the impacts of changes in both Irr_d and tariff plans on agricultural production and groundwater exploitation is essential for ensuring the sustainability of groundwater resources. To jointly analyse the dynamics of groundwater volume and irrigation-water consumptions, a simplified water balance of the study area has been implemented (Guyennon et al., 2016) throughout the period of interest using a System Dynamics (SD) approach in order to account for the complex network of interaction (i.e. feedbacks and delay mechanisms) influencing the system dynamic evolution. Conceptual GW stock and flow equations were implemented using STELLA®. 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, the groundwater balance was simulated in terms of GW volume variability. The simulation allowed to investigate the sensitivity of GW storage to climate and SW tariff variations, including other variabilities occurred in crops and water management. Groundwater table depth measurements by the regional monitoring network (Passarella et al., 2016) were converted into GW volume changes and plotted in Fig. 3 as spatially averaged values, to validate model results.

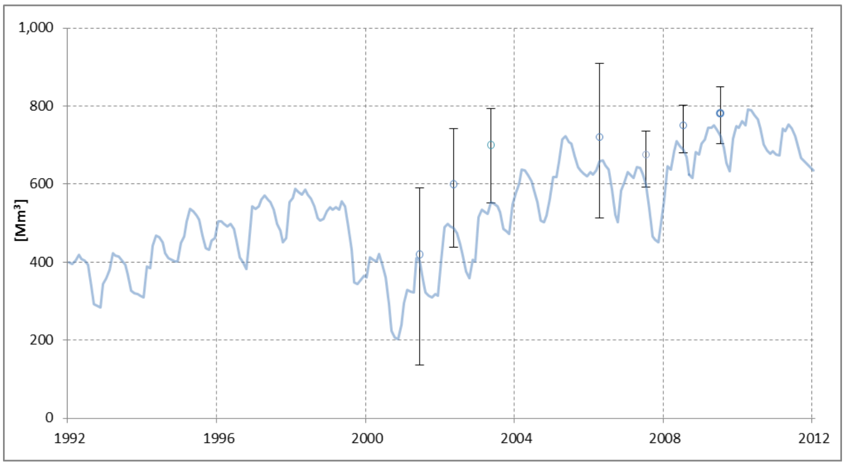

Figure 3. Simulated GW volume at monthly time-scale. Observations are reported like spatial median (Blue circles) with associated error bars.

The comparison in Fig. 3 shows that: (i) the whole period under investigation corresponds to a GW recharge period, since GW volume increased significantly (+55% from 2002 to 2012), due to higher rainfall; (ii) during drought years, SW accessibility is low (e.g. 2001, 2002, 2008) and GW volume depletion is more evident than in regular irrigation seasons; (iii) between 2005-2012 aquifers seem to reach a new dynamic equilibrium. These results highlight how climate variations combined with SW pricing have stronger negative impacts on GW storage during droughts that should properly addressed.

4. CONCLUSIONS

A farm-scale water allocation model has been developed to investigate the dynamics of water resources exploitation at district scale. An interview-based modelling approach was useful to understand interconnections between the water management authority, farmers and physical system. SW tariff policies and climatic conditions were identified as the main drivers of GW sustainability. 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. More specifically, farmers respond to restrictive SW pricing policies by increasing GW uptake to reduce their production costs related to irrigation practice. During persistent recharge periods (2002-2012), an increase in SW accessibility was highlighted by higher %SW volume. Conversely, during drought periods, SW supply was reduced but %GW increased. Therefore, in such conditions, 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 (Giordano et al., 2015). 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.

AKNOWLEDGEMENT

This research is co-funded by the FCRP foundation under the grant n. 3329/2015 for the MIGRAD Project.

REFERENCES

Bouwer, H., 2000. Integrated water management: emerging issues and challenges. Agric. Water Manag.; 45: 217–228.

Giannoccaro, G., Berbel, J., 2011. Influence of the Common Agricultural Policy on the farmer's intended decision on water use. Spanish J. Agric. Res.; 9: 1021–1034.

Giordano, R., D'Agostino, D., Apollonio, C., et al., 2013. Bayesian Belief Network to support conflict analysis for groundwater protection: The case of the Apulia region. J. Environ. Manage.; 115: 136–146.

Giordano, R., D'Agostino, D., Apollonio, C., et al., 2015. Evaluating acceptability of groundwater protection measures under different agricultural policies. Agric Water Manag.; 147: 54–66.

Guyennon, N., Romano, E., Portoghese, I., 2016. Long-term climate sensitivity of an integrated water supply system: The role of irrigation. Sci Total Environ.; 565: 68–81.

Jury, W.A., Vaux, H.J., 2007. The Emerging Global Water Crisis: Managing Scarcity and Conflict Between Water Users. Adv. Agron.; 95: 1–76.

Katic, P.G., Grafton, R.Q., 2012. Economic and spatial modelling of groundwater extraction. Hydrogeol J.; 20: 831–834.

Lamaddalena, N., 2004 Modern Irrigation Schemes and Impact on Drought Mitigation. OPTIONS méditerranéennes, Series B, n°48; 265: 245–265.

Passarella, G., Barca, E., Sollitto, D., et al., 2017. Cross-Calibration of Two Independent Groundwater Balance Models and Evaluation of Unknown Terms: The Case of the Shallow Aquifer of "Tavoliere di Puglia" (South Italy). Water. Resour. Manage.; 31(1): 327-340.

Portoghese, I., D'Agostino, D., Giordano, R., et al., 2013. An integrated modelling tool to evaluate the acceptability of irrigation constraint measures for groundwater protection. Environ. Model Softw.; 46: 90–103.

Portoghese, I., Vurro, M., Lopez, A., 2015. Assessing the Impacts of Climate Change on Water Resources: Experiences From the Mediterranean Region. Managing Water Resources under Climate Uncertainty: Examples from Asia, Europe, Latin America, and Australia. Springer International Publishing, Cham, 177–195.