A SYSTEM DYNAMICS MODEL FOR SUPPORTING DECISION-MAKERS IN IRRIGATION WATER MANAGEMENT

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Abstract

Water management is a controversial environmental policy issue, due to the heterogeneity of interests associated with a shared resource and the increasing level of conflicts among water uses and users. Nowadays, there is a cumulative interest in enhancing multi-stakeholder decision-making processes to overtake binding mercantile business, in water management domain. This requires the development of dynamic decision-aiding tools able to integrate the different problem frames held by the decision makers, to clarify the differences, to support the creation of collaborative decision-making processes and to provide shared platforms of interactions. In literature, these issues are faced by the concepts such as Ostrom's action arena and Ostanello-Tsoukiàs' interaction space (IS). The analysis of the interactions structure and of the different problem framing involved are fundamental premises for a successful debate for h management of a common pool resource. Specifically, the present paper suggests a dynamic evolution of the IS, highlighting its criticalities. It develops an alternative perspective on the problem by using a system dynamics model (SDM) to explore, how different actions can influence the decision-making processes of various stakeholders involved in the IS. The SDM has been implemented in a multi-stakeholders decision-making situation, in order to support water management and groundwater protection in the agricultural systems in the Capitanata (Apulia region, Southern Italy).

Keywords

Decision Analysis, Water management, System dynamics, Interactions space, Participatory modelling

Highlights

- The management of a limited and shared resource is a complex challenge.
- Increasing interest in supporting decision-making process with multiple stakeholders.
- The Interaction Space can form the basis for further collective decision-making.
- System Dynamics Model supports environmental collective decision-making processes.

1 Water management complexity: the need of stakeholders' participation

Water management is an important environmental policy issue. It faces numerous problems such as the disparity of interests, multiple decision-makers, complex networks of governance and distribution, intensive socio-economic development and climate change concerns (Daniell et al. 2010; FAO 2012; Daniell 2012). The management of a limited and shared resource is a complex challenge (Hess & Ostrom 2003), and as such it often introduces conflicts (e.g. Giordano et al. 2016) especially within the agricultural sector in semi-arid regions (Chen 2017; Sishodia et al. 2016, Knox et al. 2016; Rey et al. 2017). The resulting impacts on the environment may vary depending on the contribution of expanded and intensified agriculture, but are e.g. groundwater depletion, reduced surface flows, salt water intrusion, land subsidence, loss of springs and wetlands and water quality problems (Sishodia et al. 2016).

Water, particularly in the sense of its availability for irrigation, is one of the most extensively studied types of common-pool resource (Sarkera et al. 2009). As a common-pool resource linked to basic human needs and geographically highly distributed, water is used by several competing actors and owned by no one. When decision-makers are completely independent from each other, interacting solely by the fact that they use the same resource, the standard problems of overexploitation, and free-riding arise. Therefore, water management policies requires methods and tools to support the detection, analysis and reduction of conflicts among different users and uses (Giordano et al. 2016; Hassenforder et al. 2016) through a not binding mercantile business.

Two decades of research into the management of common-pool resources suggests that, under particular conditions, local communities can manage shared resources sustainably and successfully (Ostrom 1990; Ostrom 2010). These findings are often considered somehow revolutionary, in that they were able to challenge the long-held belief in the well-known Hardin's tragedy of the commons (Hardin 1968). According to Ostrom (Ostrom 2011), the tragedy is not inevitable when a shared resource is at stake, provided that communities interact and operate in a collective way avoiding the simple market rules constraints.

The above-mentioned issues generate the need to enhance decision-aiding methodologies within an inclusive participatory framework and group modelling activities (Voinov et al. 2016). There is an ever-increasing interest in enhancing public participation in the water resource management, allowing stakeholders, both individuals and organisations, to participate in the decision process and to provide their own knowledge (Giordano et al. 2007), leading to an effective management (Hare et al. 2003; Kotir et al. 2017). The role of participatory processes in water management has also been established by the European Community Water Framework, which strongly encourages the active involvement of all the affected parties (Pahl-Wostl 2015). It enriches decision-making processes mapping out diversity of problem frames (Van Asselt Marjolein & Rijkens-Klomp 2002; Brugnach & Ingram 2012; Hassenforder et al. 2016; Giordano et al. 2016) in order to: i) explicitly challenge existing stakeholders' values; ii) facilitate dialogue across multiple tiers of governance; iii) contribute to the long-term improvement of decisions; iv) establish a shared management process for common-pool resources (Smajgl 2010). Surely, a decision-making process with public actors and common-pool resources generates unpredictable scenarios because of the competing interacting decision-makers (Tsoukiàs 2007; De Marchi et al. 2016; Daniell et al. 2016). While these interactions among a diversity of participants may contribute to the development of beneficial adaptive behaviours, they can also provoke unexpected reactions, since the choices of an individual actors may not necessarily be aligned with the viewpoints, expectations or possibilities held by the others (Giordano et al. 2016; Brugnach & Ingram 2012). This later situation can lead to dysfunctional dynamics and provoke unforeseen reactions, such as policy resistance mechanisms (i.e. the tendency for interventions to be defeated by the response of the system to the intervention itself) (Sterman 2000). Under this perspective, decision-aiding tools involving multiple stakeholders should be capable to: i) clarify and integrate the differences among stakeholders' problem framing, ii) provide shared platforms and interaction spaces in order to set up the process of debate and iv) reconstruct the connections between these platforms and engaged interactions.

Starting from these premises, the present work aims at developing an alternative perspective on the problem by using a system dynamics model (SDM) to operationalize the existing debating formal structures such as the interaction space (Ostanello & Tsoukiàs 1993), leading to reflections on how the establishment of local regulations and rationalities, may support managing commons goods and facilitate stakeholders' consultations. This work aims at answering two important research questions: i) to what extent does the analysis of the interaction frames affecting decision-actors behaviors may improve common goods management? ii) Is the SDM a suitable tool to operationalize the interaction space and to analyses its dynamic nature?

More specifically, the developed SDM intends to: i) model the water management complexity characterized by the presence of several interacting decision-makers and conflictual uses of water resources; ii) explore the different viewpoints, and potentially conflicting objectives of multiple decision-makers involved in water resources management; iii) describe the complexity of their interactions, and the multi-dimensional impacts of specific decisions, particularly focusing on those that might have unintended impacts also on the others. Lastly, the paper underpins the SDM suitability as decision-aiding tool in case of multi-actors decision-making processes, through its implementation in a real case study related to the agricultural water management system in the Apulia region (Southern Italy).

The paper is structured as follows. After the present introduction, section 2 discusses multi-stakeholders decision-making processes and system dynamics modelling approaches. Section 3 illustrates the methodology and the case study. Section 4 describes the obtained results. Concluding remarks are described in section 6.

2 Supporting multi-stakeholders decision-making processes

2.1 The Interaction Space

The management of a common-pool resource is defined by an interconnected network that exhibit high levels of interaction, conflict and uncertainty due to limited information, bounded rationality, disparities in meaning for particular issues and to discrepancies in the way in which the situation is interpreted. According to the assumptions made in the previous paragraph, there is a deficiency of adequate methodologies for problem formulation and objective setting in supporting decision-making processes with multiple stakeholders. Decision aiding in the multi-stakeholder domain focuses on providing an analyst with methodological support that allow it to facilitate stakeholder groups to structure and exchange views (Tsoukiàs 2007; Daniell et al.

2010). This issue is faced also by the concepts of action-arena (Ostrom 1986), interaction space (Ostanello & Tsoukiàs 1993). These formal structures support interactions and enable the establishment of local rules and rationalities.

Action arena (AA) has been defined as a social space where individuals interact, exchange goods and services, solve problems, dominate one another, or fight (Ostrom 1986). It lead to analyse, predict and explain system evolution and it contains mainly elements such as action situation, actors and rules (Ostrom 1990). This structure has mainly been applied to analyse static representations of social systems and the evolution of rules over time may be analysed by comparing different representations (Pahl-Wostl et al. 2008) (Ostrom & Gardner 1993). The key idea of Ostrom is to understand a society as a structure of interconnected and/or nested action situations and involved participants (Ostrom et al. 2012). Participants in AA interact as they are affected by exogenous variables and produce outcomes that in turn affect the participants and the action situation (Pahl-Wostl 2002; Pahl-Wostl et al. 2008). Briefly, in the AA it is possible to identify seven variable sets that define the action situation used to identify patters and regularities of human actions and results (Polski & Ostrom 1999). An AA combines the action situation, which focuses on the rules and norms, with the participants who bring with them their individual preferences, skills and mental models (Andersson & Ostrom 2008; Anderies & Janssen 2013).

On the other side, the Ostanello and Tsoukiàs' interaction space (IS) (Ostanello & Tsoukiàs 1993) is a collaborative space where a meta-object is identified as the merge/articulation of the participants' problem representation. Similar to the AA, the IS can form the basis for further collective discussion and decision-making. IS is a virtual informal spaces where decision-makers can operate on the understating and resolution of a problem. In fact, (Mazri 2007; Daniell et al. 2010) define an IS as: "a formal or informal structure that is governed by a number of rules and is aimed at providing a field of interaction to a finite set of actors". The concept of IS has been introduced in order to represent a meeting structure of subjects from different organizations, an informal and abstract structure that allows exchange and communication condition by a public confrontation. A set of elements (participants A, objects O and resources R) and an architecture of relations S on this set constitute an interaction space model. The definition of primary elements sets carries out the identification of the IS state and the multi-step procedure that enables the building of the IS is explained in Ostanello and Tsoukiàs (1993). The identification of the IS state allows the analyst to indicate some organizational/political features that the acting system has assigned to the IS. What is more, the identification can generate hypotheses on the coherence of future actions that a participant could be willing to undertake. Such a formal model, even if simplified to just a few theoretically important variables, can provide a useful basis for understanding decision dynamics with multiple-stakeholders. It is expected that using IS allows the analysts to deal with different participants, formalizing a formal structure and consequently, the participants in a decision process can discuss. This process can improve transparency of the process and increases participation. The construction of this artefact should allow, on the one hand, the clients to recognise their position within the decision process for which they asked the decision support. On the other hand, it would allow the analyst to better understand the problem statement within the decision process and the interconnected networks in which decision-makers operate. In conclusion, the IS is a descriptive and explicative model that could support participative decision-process.

It is important to understand the dynamics of a system in order to extract critical functioning parts and attempt to build a model that captures its essence by making assumptions to account for external variables. A dynamic IS model should provide a careful description of the field of interaction between a finite set of actors and be able to analyse their evolutions. Such a structure enables the establishment of local regulations and rationalities, escaping for instance from market regulations in the case of commons goods and facilitates stakeholders interactions and the explanation and the prediction of behaviours.

Hence, the use of the actual structure of IS has several drawbacks:

- The IS is an evolving structural idea, it nevertheless remains a static picture of the problem that allows to explain the meaning of the behaviour of actors. However, the interactions among decision-makers are not static. They can be influenced by the boundary conditions, implementation of policies, both as internal and as external drivers, involvement of other actors with different objects and resources~~,~~ Thus, the analysis of the IS requires tools and methodologies capable to account for such a dynamic nature.
- As Ostrom suggested for the AA, the IS also lacks detailed analyses of rules, strategies and actions that can allow the analyst to better understand how an IS model for a stakeholder is constructed and its interdependencies with other ones. In a multi-stakeholder decision-process, each decision-maker has its own frame of the IS, which leads him to have a personal rational model and to, consequently, decide his own plan of actions in order to achieve his objectives neglecting the existence of the other agents.
- The IS is a descriptive approach and in its current structure does not have collective features for understanding interactions. Thus, it is not able to explain the complexity of debates in its entirety and to fulfil the need of a prescriptive model. The introduction of dynamism and the simulations of future scenarios could improve the model.

The IS model should allow the analysts to identify a joint set of objectives and to create a shared problem definition used to generate new knowledge and management strategies. Within this context, a more dynamic IS model should be defined not only by sets of agents A, objects O, resources R and a structure of relations S that develop between these sets, but also contains selected rational models allowing its evolution.

$$IS = < A, O, R, S, T >$$

Under the hypothesis of decision-makers driven by a subjective rationality, T represent the set of agents' rational behaviour models in a specific IS configuration. Several agents operating with their own locally rational decision rules (intended rationality and not casual rationality) characterize these decision environments. T regulates the nature and dynamics of action situations. Thus, the formalization of T, made by the analyst through the different possible approaches (e.g. linear or non-linear programming, system dynamic, multi-agent system etc.), can be adapted to each case study, depending on the modelling needs. T supplies the dynamism to the system concerning a timeline, helps in the simulation building and in the definition of the rules in use.

In order to overcome the presented criticalities, SDM is considered s suitable tool for operationalizing the IS.

SDM is a computer-aided approach, applying to dynamic problems defined by interdependence, mutual interaction, information feedback, and circular causality (Vennix, 1996). It has the flexibility and capability to support environmental decision processes to involve raising public awareness of the issue and developing understanding of the connections between potential decision alternatives and system consequences (Bousquet & Le Page 2004; Gohari et al. 2017).

2.2 System Dynamic Modelling

Historically, System Dynamics (SD) appeared as an outgrowth of the system dynamics approach of Forrester (Forrester 1961; Forrester 1968; Forrester 1987). SD has become popular when its general principles of feedback were presented under the label of system thinking (Barlas, 1996). A SDM describes complex systems through the use of feedback loops, stocks and flows. Stocks characterize the state of the system. They are the memory of a system, enabling to describe its status. Flows affect the stocks via inflow or outflow and interlink the stocks within a system (Sterman, 2000). SDM methods are both qualitative/conceptual as well as quantitative/numerical (Dolado, 1992). On one hand, qualitative modelling (causal loop diagrams) can improve the conceptual system understanding. On the other hand, quantitative modelling (stock-and-flow models), allows to investigate and visualize the effects of different action within the simulation model (Sterman 2001). SDM is able to integrate a wide range of input parameters in a meaningful way, the recognition that the direction of change is a key parameter toward managing responses in an adaptive way (Pagano et al. 2017).

The objective of this last part of this section is to make a comparison between SD and other approaches used for modelling water management decision-making issues. In the first place, traditional approaches to support water management aimed to identify the *optimal* alternative using decision models represented by analytic functions. Considering the complexity of water management, finding the *optimal* decisions is rarely considered the most suitable approach (Winz, et al., 2009). Linear programming assumes that the decision-makers act according to a well-defined and unchangeable rational decision model. These approaches neglect, for example, the decision makers' abilities to change their decision model, due to the interactions with the system and with the other actors (e.g. Brugnach & Ingram 2012; Giordano et al. 2016). Focusing on farming systems, more representative models have been built for short-term strategies related to a farm or mixed models have appeared from coupling a farm model with a physical water model (Winter et al. 2017). However, those approaches may not highlight enough the interaction between users, nor takes into account multi-annual changes (Dent et al. 1995; Filippi et al. 2017). Secondly, considering both SDM and statistical approaches, a significant difference is related to the focus of the analysis. The former simulate the system evolution through a detailed analysis of the model structure, the latter predicts the future evolution of the system starting from the analysis of the measured data. Statistical forecasting involves a methodology that fit historical data as closely as possible. However, there is no guarantee that these statistical correlations truly forecast future system behaviour (Winz et al. 2009). Moreover, higher levels of complexity involve a validation of the model by the involved stakeholders. This phase becomes a social process where model structure and outcome are negotiated until judged valid and useful by all involved parties (Scott et al. 2016). Lastly, it is necessary to compare SDM with the agent-based models (ABM). Surely, both approaches are designed to support analysts in exploring the systems behaviours. SD are used to conceptualizing variables in terms of aggregated quantities through stocks and flows (Sterman 2000). ABM, by contrast, focuses more on detailed elements at a micro scale (Ferber 1999; Wooldridge & Kraus 2012; Weiss 2000). Such overall behaviour of the system arises out of the interactions among the individuals. Researches in the ABM discipline rely heavily upon the discrete and stochastic modelling methodology. Comparing SD to ABM, one major SD weakness is that emergent phenomena from micro scale, which often occur within social systems, cannot be properly explored from an aggregated feedback system. In contrast to SDM, often the ABM platforms are not user-friendly and are restricted to an expert use.

Since SD has been developed mainly for providing direct insight on the structural mechanism of complex systems, we consider that SDM is one of the most promising methodologies for understanding multi- decision-makers dynamics within a socio environmental system. SDM appears to be a fairly suitable methodology for many multi-disciplinary and multi-stakeholder problems, such as the ones dealt with in this paper (Stave, 2003; Vennix, 1996) (Winz, et al., 2009; Bousquet & Le Page, 2004; Sterman, 2000; Barlas & Carpenter, 1990; Richardson & Pugh III, 1981). It is transparent modelling approach aiming at recognizing the complex, multi-dimensional nature of water resource management and at the most participatory level, stakeholders can help develop the simulation model that represents system structure (Costanza & Ruth 1998; Scott et al. 2016). For instance, Simonovic & Rajasekaram (2004) developed an integrated water resources management model using the SD simulation, Goldani et al. in 2011 analyse water resource management and government subsidy policy, and an interactive decision support tool for urban planners enabling citizen's participation is studied by Loibl et al. (2014). Referring specifically to agricultural activities, the use of SD based approaches is wide and successful in the scientific literature (e.g. Li et al. 2012; Walters et al. 2016). Several studies are available, e.g. to model a participatory systemic feedback for sustainable water management (Kotir et al. 2017), to assess water scarcity and potential impacts of socio-economic policies in a complex hydrological system (Sušnik et al. 2012), to model the impact of climate change on agricultural practices (Gohari et al. 2017), to support policy- and decision-makers designing effective strategies to support conservation agriculture practices (Varia et al. 2017), to integrate individual stakeholders' mental models (Kopainsky et al. 2017).

Within such framework, this work describes a SDM developed to conceptualize the water management process in terms of aggregated stocks and flows, in order support a more collective decision-making of a common pool resource. The model has been used to evaluate the impact on the water management policies, identifying critical feedbacks, aiming to enhance the understanding of the dynamic evolution of the IS.

3 Water management and groundwater protection policy within the agricultural sector of the Apulia region

3.1 Overview of the case study

The case study is focused on water management in agricultural systems in the Apulia region (Southern Italy). Within the case study, three main stakeholders are identified, namely: Farmers, the Water Management

Authority, and the Regional Authority (RA) (Table 1). The Water Management Authority, i.e. the Irrigation Consortium of Capitanata (IC), is responsible for the management of surface water resources in the area (Occhito dam) focusing exclusively on irrigation demand (although the dam has some operational constraints due to drinking water demand and environmental flows). The IC has on the one hand to deal with the scarcity of water of the region, and on the other with the demand for surface water (SW) from each Farmer. According to a set of semi-structured interviews already performed (Giordano et al. 2016; Pluchinotta 2015), the main objective of IC is to guarantee an equitable distribution of water resources. IC's price policy is based on two different volume thresholds with a specific water tariff: the base water supply volume (0.12 e/m^3 for the first 2050 m^3/ha) and the additional water supply volume, which is considerably more expensive (0.36 e/m^3 for 2050-4000 m^3/ha). From the perspective of farmers, irrigated agriculture is highly water-demanding, and it is crucial to adequately share the same resource, which could be limited particularly in drought conditions. Under a significant uncertainty related to climate, each Farmer is expected to choose and schedule a suitable cropping plan in order to maximize his/her profits. Besides SW, which is managed by IC, the availability of individual GW withdrawals should be also considered. Farmers consider GW cheaper than the additional water supply volume and easily accessible thanks to the presence of wells in their private propriety. Farmers' decisions thus concern also the selection of the main source of water for irrigation (either GW or SW, but potentially also non-conventional sources). There is currently not a centralized GW management system, and the overexploitation of the source is responsible for social and environmental problems. RA thus needs to protect GW quality and quantity, without impacting dramatically the level of productivity of the agricultural sector. For this aim, in 2009 RA implemented the Water Protection Plan, in order to significantly restrict the GW use (according to the European Water Framework Directive, CEE 2000/60) The main dynamics associated to these three stakeholders were defined by integrating the scientific knowledge available in literature with expert knowledge elicited through semi-structured interviews and participatory processes (Giordano et al. 2016; Giordano et al. 2015; Portoghese et al. 2013). The simulated behaviours are based on field observations and on the elicitation stakeholders' knowledge.

		Actor	**Type**
a_1	IC	Irrigation Consortium	Organization
a_2	F	Farmer	Individual
a_3	RA	Regional Authority	Organization

Table 1 – The involved stakeholders

3.2 The applied methodology

A methodology capable to operationalize the IS and, in doing so, to support the detection and analysis of the policy resistance mechanisms has been developed using a SDM. The IS building process goes through a multi-step procedure, adapted from Ostanello and Tsoukiàs (1993). The construction of the IS starts with the identification of the involved agents with their attributes, objects and resources. The next stage is to define the hierarchy and relations between these elements. Finally, the dynamic evolution of the interaction space is simulated using the SDM. A detailed description of the IS (actors a, objectives o and resources r), the constructing procedure, and the development of the stakeholder's decisional processes through causal loop diagrams are described in Giordano et al. (2016). This paper represents a step forward. It aims at developing and implementing a SDM, capable to simulate the dynamic evolution of the IS during the different phases of the decision-making process. To this aim, the interactions between multiple decision-makers concerned by the both SW and GW management, use and protection policy, as well as between them and physical and economic external drivers were structured in the SDM.

Following Giordano et al. (2016), different problem understandings were integrated in the SDM. The model assumptions are: i) each decision makers has a personal understanding of the IS and this partial and subjective vision tends to affect behaviours and action choices; ii) not all the decision-makers are interested/forced to enter in the IS in the early stages of the action implementation; iii) a decision-maker enters in the IS when her/his objects are impacted by the actions implemented by the others.

We then proceeded with model development following the conceptualisation phase via the IS. The SDM development process was structured in the following main phases (adapted from Vennix, 1996 and Davies & Simonovic 2011): i) understanding the system and its boundaries through the IS model conceptualization; ii) identifying the key variables typifying the IS elements; iii) describing the relationships between variables through mathematical relationships; iv) creating the graphical structure of the model.

The key variables relating the IS with the SDM are displayed in the following table 2.

IS						SDM
	Objects	**Actors**		**Resources**		**Variables**
$\boldsymbol{o_1}$	Environmental protection	a_3	RA	r_2	Legislative constraints and regulations	GW protection measures level
						Estimated GW quality
						Pressure for protection measures
$\boldsymbol{o_2}$	Agricultural productivity	a_1	IC	r_1	Economic resources	Additional unit SW price
						Base unit SW price
						Consortium budget
				r_3	Information flow	Additional unit SW volume available for F
						Base unit SW volume available for F
		a_2	F	r_5	Water accessibility	Water balance
						Actual SW taken
						GW cost
						GW withdraws monitoring
						SW cost additional and base volumes
				r_6	Illegal actions	F GW volume taken
						Irrigation deficit
						Actual water requirement
						GW cost
						SW cost additional and base volumes
						GW source preference
						GW withdraws monitoring
				r_8	Yield	Irrigated area/Cultivated area
						Economic F’s budget
						Irrigation cost
$\boldsymbol{o_3}$	Effectiveness of the irrigation water management	a_1	IC	r_1	Economic resources	Farmer payment for irrigation
						Fix Management cost
						Consortium budget
						Yearly fee
						Actual SW volume taken
					Information flow	Water volume in the reservoir

			r_3	Water volume for irrigation
				Initial IC budget
		a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level
				Estimated GW quality
				Pressure for protection measures
$\boldsymbol{o_4}$	Water availability	a_1 IC	r_3 Information flow	Expected water demand
				Additional unit SW volume available for F
				Base unit SW volume available for F
				Actual SW volume taken
		a_2 F	r_3 Information flow	Additional unit SW volume available for F
				Base unit SW volume available for F
				GW cost
				SW cost additional and base volumes
			r_6 Illegal actions	Irrigation deficit
				Actual water requirement
				F GW volume taken
				GW cost
				SW cost additional and base volumes
				GW source preference
				GW withdraws monitoring
			r_8 Yield	Irrigated area/Cultivated area
				Economic F's budget
				Irrigation cost
		a_3 RA	r_2 Legislative constraints and regulations	Estimated GW quality
				GW protection measures level
				GW volume
$\boldsymbol{o_5}$	Decrease of GW overexploitation	a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level
				Estimated GW quality
				Pressure for protection measures
		a_1 IC	r_1 Economic resources	Additional unit SW price
				Base unit SW price
			r_7 Technical resources	Water volume for irrigation
$\boldsymbol{o_6}$	Water distribution and control of the irrigation network	a_1 IC	r_1 Economic resources	Additional unit SW price
				Base unit SW price
			r_2 Legislative constraints and regulations	Additional unit SW volume available for F
				Base unit SW volume available for F
			r_4 Decisional power	Additional unit SW price
				Base unit SW price
			r_7 Technical resources	Water volume for irrigation
$\boldsymbol{o_7}$	Reduction of water consumption during drought	a_1 IC	r_4 Decisional power	Additional unit SW price
				Base unit SW price
			r_2 Legislative constraints and regulations	Additional unit SW volume available for F
				Base unit SW volume available for F
			r_7 Technical resources	Water volume for irrigation
$\boldsymbol{o_8}$	Env. econ. and social sustainability of the agricultural activities	a_3 RA	r_2 Legislative constraints	Estimated GW quality
			r_9 Control of the territory	GW protection measures level

Table 2 – Key variables for the transition from model conceptualization via IS to the SDM model development

3.3 Model structure

The overall structure of the SDM is represented in the following figure 1. Following the conceptual structure of the IS, the model is based on several sub-models, each one focused on the perspective of specific actors involved in water resources management (i.e. the boxes identified as 'Irrigation Consortium', 'Farmer' and

‘Regional Authority’). The integration among the IS and the decision-makers’ conceptual models allowed to develop the sub-models, described in full details in the following.

The grey variables in the model represent the connections between different sub-models. The role of these variables is particularly important since they help identifying connections and influences among different sub-models, which are typically neglected by the individual agents. These variables allowed us to align the stakeholders problem understandings and to develop an integrated model (Giordano et al., 2016). The general SDM supports the representation of the existing situation within the case study and a broad conceptualization of system structure in order to explore its behaviour.

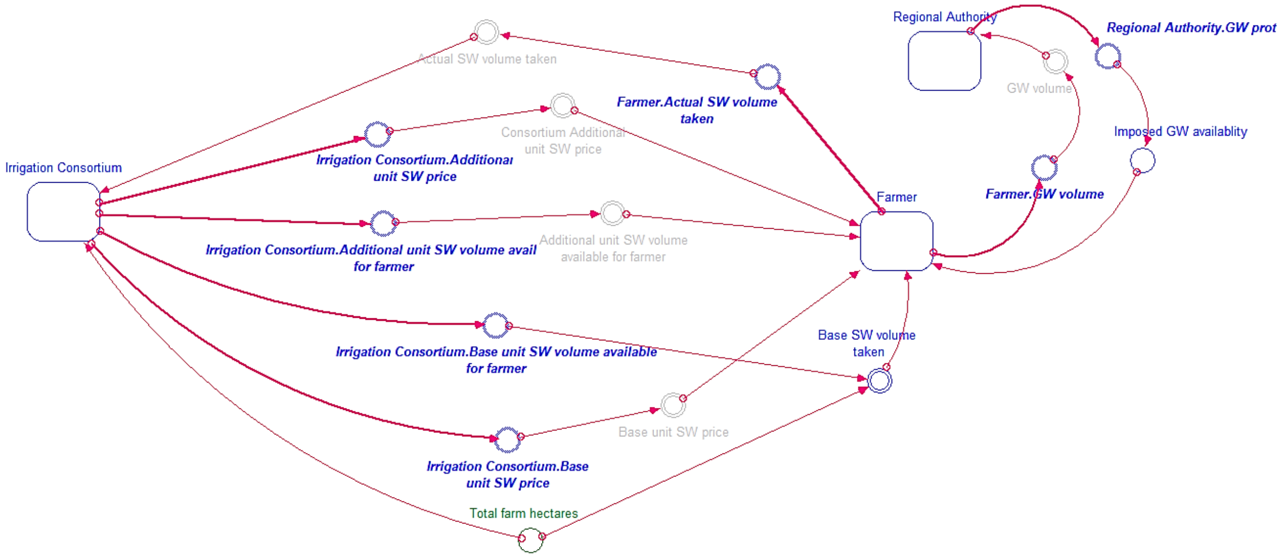


Figure 1 - Representation of the complete SDM

The model is run for ten years, with a time step of one year. It is assumed that there is only one crop season yearly. The analysis is also carried out assuming a standard farm, representative of the average farm size in the area, having an area of 10 ha.

The IC’s decision model (see figure 2) was developed with reference to both to the results of the interviews developed in (Giordano et al. 2016; Pluchinotta 2015) and to the analysis of the IC’s water price strategies implemented in the last ten years. It is additionally divided into two parts. The lowest part of IC’s sub-model is focused on the physical aspects, i.e. water availability in the reservoir, and the comparison with water demand mainly for irrigation purposes (the volumes needed for drinking purpose are also included). The main aim of this model section is to define the yearly irrigation management strategy, which is mainly based on the identification the amount of water available per Farmer (i.e.’ Base unit SW volume available per Farmer’ and ‘Additional unit SW volume available per Farmer’). These two volumes are associated to the specific IC’s pricing strategy. The IC’s water price strategy, analysed in the ‘economic’ part of the sub-model, is based on the comparison between the available ‘Water volume for irrigation’ in the reservoir and the ‘Expected water demand’. During the interviews, the IC stressed that the water demand is not monitored directly by collecting data about the actual crops in the area. Instead, the expected water demand is assumed as the mean of the water distributed for irrigation in the previous years. As already mentioned, the model simulates the behaviour of a reference farm in the Capitanata area (10 ha), assuming that at the beginning of the simulation only half of the area is devoted to irrigated crops. Considering the dominant crops of the region the SDM considers the expected irrigation demand of the tomato (approx. 6000 mc/ha). According to the IC's understanding of the problem under analysis, the pricing policy which is based on the identification of different volume thresholds (mainly a 'Base' volume and an 'Additional' volume) allows matching the availability and the demand, at least in normal conditions (i.e. restrictions to water withdrawals may be applied in dry years), allowing an equitable access to water for all Farmers. An imbalance may be determined by the increase of irrigation water demand, which could be caused by the increasing Farmer's inclination towards intensive irrigated agriculture. Thus, the need for additional water volumes would push the SW demand toward an unsustainable level. In this condition, the IC would implement a water conservation policy aiming to drive Farmers to reduce the water consumption, thus guaranteeing enough water to all users. This strategy is mainly based a market scheme either increasing the 'Additional unit SW price' or reducing the volume made available at the base SW price. This, in general should support reducing the irrigated areas, with the cultivation of less water-demanding crops. Nevertheless, this strategy totally neglects specific dynamics that emerged in other sub-models, e.g. the use of GW instead of SW. The top section the IC's sub-model shows the resulting economical budget. The economic feedback simulates the impact of the Farmer's decision on the IC's budget, i.e. 'Consortium budget'. The main IC's goal is to keep this variable positive. The IC's budget is influenced by: i) the fees paid by each Farmers (i.e. 'Yearly fee' depending on the 'Total Farmer's hectares') for the irrigation maintenance networks, and management costs; ii) the access to the SW volumes (i.e. 'Farmer payment for irrigation' depending on 'Actual SW taken' and SW prices). The data were collected by the Consortium budget reports. The input variables of the IC sub-models are: 'Total Farmer hectares' and 'Expected water demand' per Farmer, and 'Water per person' and 'Population' associated to the urban 'potable outflow'. The IC's sub-model does not consider the actions taken by the authority managing the urban drinking water distribution network (Acquedotto pugliese, AQP), because drinking water supply has to be guaranteed in any case, and thus is could not be limited. The output variables are: 'Base unit SW volume available per Farmer', 'Additional unit SW volume available per Farmer', 'Base unit SW price', ' Additional unit SW price'.

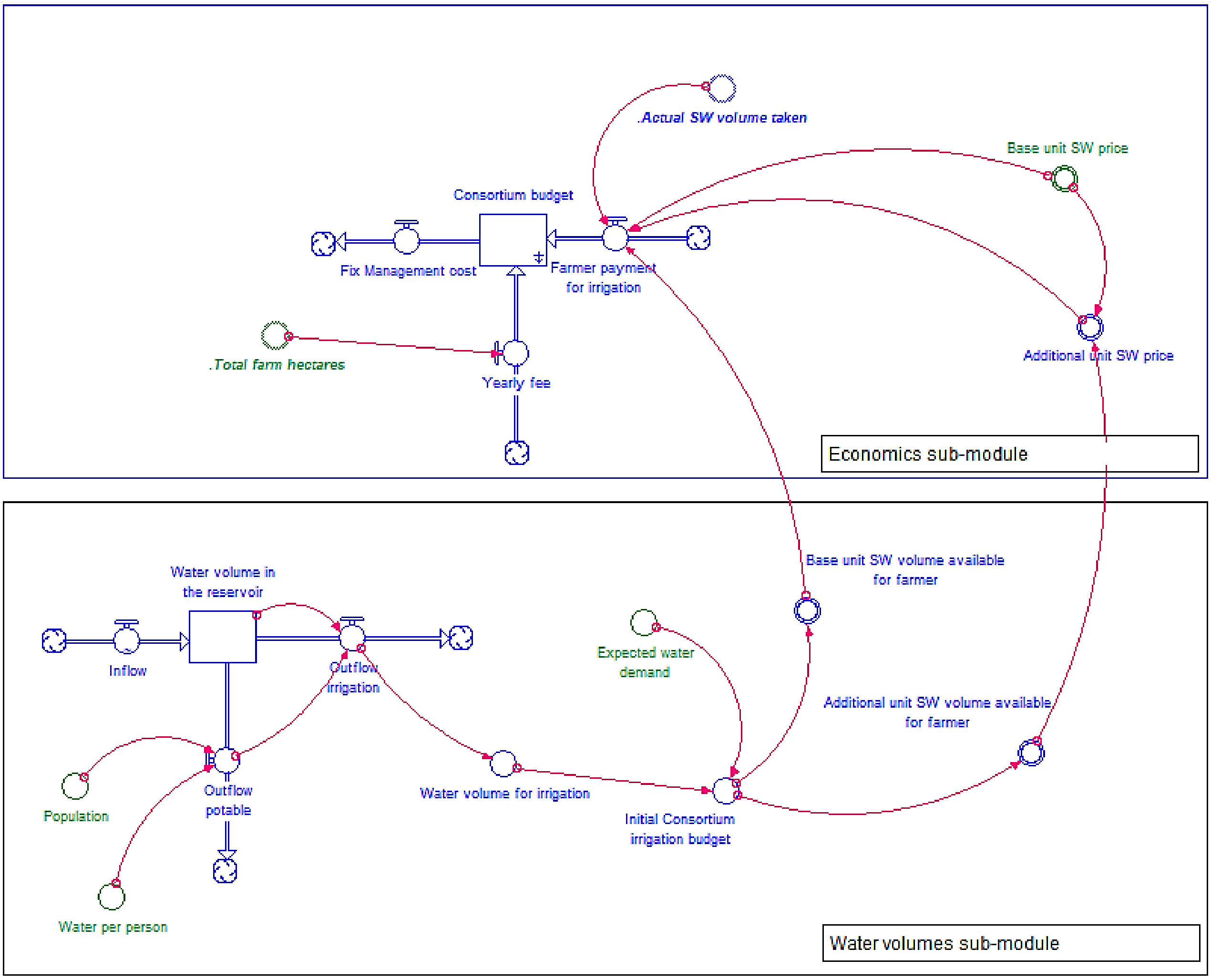


Figure 2 – Irrigation Consortium's sub-models

The Farmer's sub-model was developed by involving a sample of Farmers working in the Capitanata area in a set of individual interviews. A few associations of Farmers were also involved in the process. The process of individual sub-model aggregation ended when no new concepts and/or relationships emerged after a number of interviews (e.g. Özesmi & Özesmi 2004). The sample was created by considering the different characteristics of Farmers, i.e. farm size, crop patterns, irrigation techniques and access to the IC's network (Giordano et al. 2016). Moreover, we assumed that only a fraction – i.e. 5 hectares – of the farm area was irrigated at the beginning of the scenario simulation and we did not consider multi-annual crops because they are not common in the study area. Specifically, each Farmer defines yearly different crop areas (i.e. 'Cultivated area', 'Irrigated area') and knows the SW availability for the irrigation season approximately in March thanks to the IC's management activity (i.e. 'Base unit SW volume available per Farmer' and 'Additional unit SW volume available per Farmer'). The individual GW availability is regulated by the Regional Authority ('Imposed GW availability'), but only for legal withdrawals. Each year she/he decides the yearly crop plan, which respond to crop preferences, previous experiences, agronomic and market rules ('Prices in the market' considering the price change in the last ten years, and 'Farmers' perception of price', assuming a delay in the average market price in the last 3 years), and water availability and price ('Irrigation cost', 'Irrigation deficit').

The main Farmer's goal is to maximize her/his economic yield choosing, according to the specific conditions, a sustainable mix of irrigated and not-irrigated crops in order to optimize available water with the respect to the numbers of hectares. For the sake of simplicity, but also considering the characteristics of the study area, the SDM simulates that the irrigated crop is mainly tomato. This fragment of the complete model shows the first Farmer's decision concerning the crop plan (lowest part of the figure 3). After IC establishes the SW unit prices, each Farmer reacts and decides the best water source, taking into account the final available water volume, and total water cost. Surveys show that Farmers are independent in their actions and they are self-interested driven by an economic rationality. Furthermore, according to the interview carried out, the Farmer actor perceives the GW as an almost unlimited and easily accessible resource and they do not acknowledge any environmental complications that their combined effort will bring about. The top-right part of the sub-model models this second Farmer's decision. The main constrains are SW unit costs and availability, i.e. 'Unit GW cost' (input variable referred to an average GW withdrawal cost, as defined by (Portoghese et al. 2013) and 'Imposed GW availability' (which depends on GW protection policies that are activated by the RA). The presence of 'GW withdrawal monitoring' could also be a relevant driver to model the 'GW source preference' for the Farmer.

As shown, the core issue according to Famers' problem understanding is the 'Final Farmer Irrigation budget'. Farmers perceived the balance between 'Actual water requirement' and SW availability as a key element. During the knowledge elicitation phase, Farmers were required to specify the main causes that could results in a negative value for the problem core. The most mentioned cause was the volume of SW distributed by IC. IC aims at reducing the SW volume by reducing the 'Additional unit SW volume available per Farmer'. Farmers perceive this policy as a fundamental barrier, stopping the full satisfaction of the water demand and encouraging a more intensive GW use. The output variables of this sub-model are the 'Actual SW volume taken' and 'GW taken' linked to the 'Final Farmer irrigation budget'.

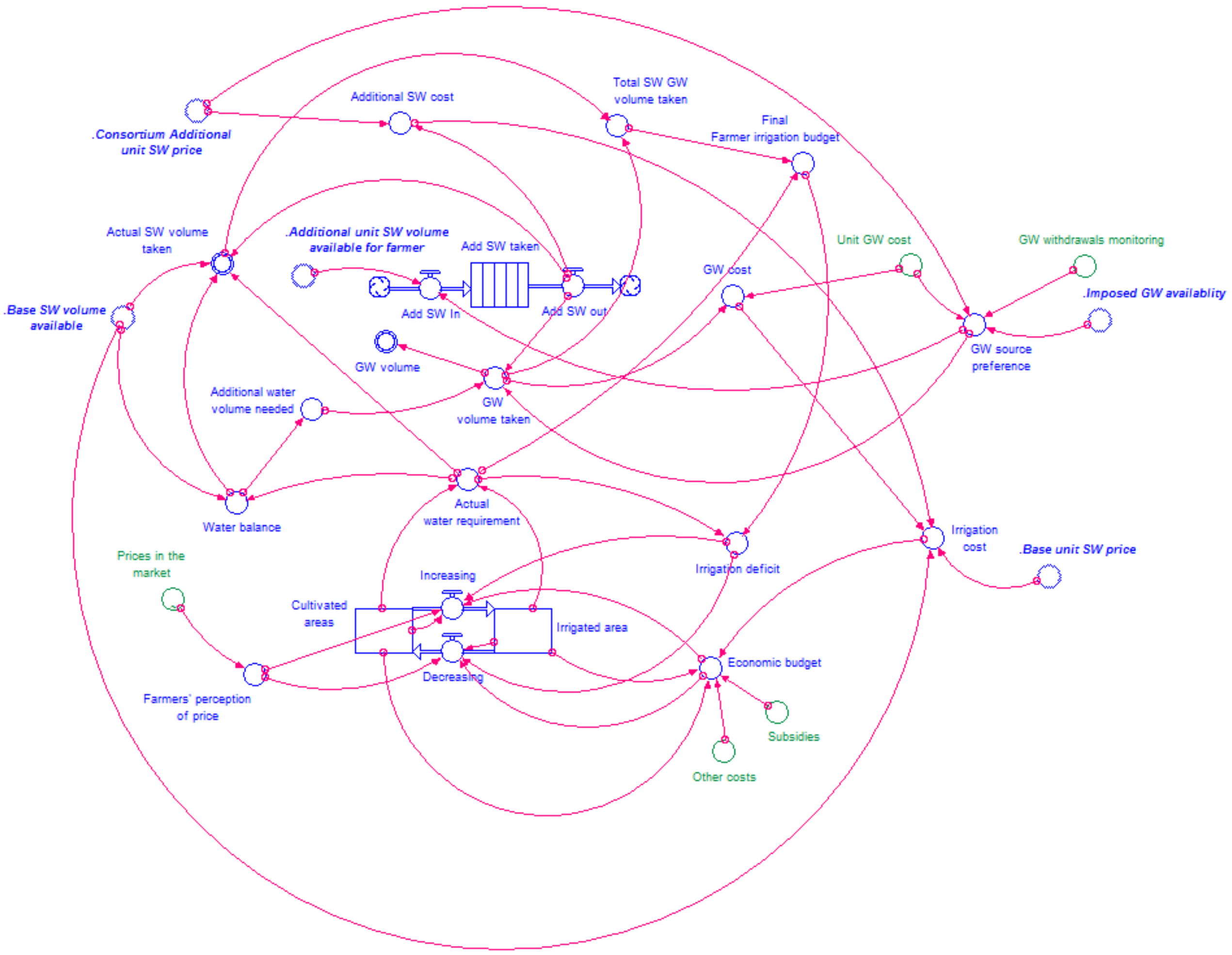


Figure 3 – Farmer’s sub-model

Lastly, RA uses norms to send unilateral instructions to other decision-makers (i.e. the Farmers) in order to impose constraints on GW exploitation (following the Water Protection Plan). However, RA does not have enough resources to take control over the territory (‘Groundwater withdrawals monitoring’), and this results in a significant illegal GW abstraction level. RA considers the GW exploitation for irrigation purposes as the main cause of the continuous decrease of ‘GW volume’ and ‘Estimated GW quality’ (figure 4). Irrigated agriculture represents one of the most important economic sectors at a regional level, and it is the main user/consumer of GW. RA believes that an increase of GW exploitation is likely to occur, provoked by an uncontrolled increase of water demand, due to the tendency of Farmers to prefer irrigated crops (which are also associated to higher economic revenues). According to the RA's problem understanding, any improvement in the sustainability of GW use, given the continuing trend towards GW exploitation, should have implications on water demand. Therefore, the increasing pressure on GW resources implies the need for the regional authority to impose limits to GW use for irrigation purposes.

For the reasons showed previously, in the implemented model we considered only the RA controller role, through a strict constraint for the GW use. The output variable is ‘GW protection measures level’.

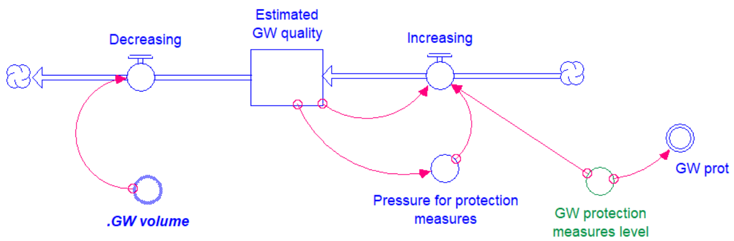


Figure 4 – Regional Authority's sub-model

In summary, there is a set of 'transition' variables shared between the different decision makers' sub-models. The importance of such variables is crucial, since they identify specific elements that are explicitly part of a sub-model (e.g. they can be controlled by the agent), but at the same time are directly or indirectly influential also on other sub-models (e.g. have an impact on the dynamics described by other sub-models). The 'transition' variables are summarized in the following table 3:

Key variables		**Actors - Output**		**Actors - Input**
Base unit SW price	a_1	Irrigation Consortium	a_2	Farmers
Base unit SW volume available	a_1	Irrigation Consortium	a_2	Farmers
Additional unit SW price	a_1	Irrigation Consortium	a_2	Farmers
Additional unit SW volume available	a_1	Irrigation Consortium	a_2	Farmers
Actual SW volume taken	a_2	Farmers	a_1	Irrigation Consortium
GW protection	a_3	Regional Authority	a_2	Farmers
GW volume	a_2	Farmers	a_3	Regional Authority

Table 3 – key transition variables between the different decision-makers' sub-models

The importance of these variables emerges moving from the analysis of individual sub-models to the definition of an aggregated version. Such integration process allows identifying the potential discrepancies among different problem framing and perception that might be responsible for a misalignment of the different IS. This could be originated by e.g.: a) one or more agents ignoring the presence of a subset of variables, or neglecting one or more causal connections; b) the 'transition' variables having different values (or being perceived differently) in specific sub-models; c) some 'real' processes are not well-defined or neglected in the models.

The definition of a global SDM helps modeling the potential impacts of such discrepancies, which might be often neglected by decision-makers and policy-makers. This could significantly support the success of participatory processes and reduce ambiguity in the analysis, besides being a crucial step to assess the effectiveness of measures, actions and policies, identifying benefits, co-benefits and potential drawbacks.

A second round of semi-structured interviews was held with both the agents involved in model building, and a group of experts (academics and researchers) in order to validate the individual sub-models (see Giordano et al. 2013; Pluchinotta 2015; Giordano et al. 2016).

4 Results and discussion

The developed SDM aims at analysing the neglected interactions among different decision-makers, and the analysis of the potential effects of these interactions on the dynamic evolution of the IS. As described further in the text, the SDM demonstrated how the decisions taken by each decision-maker referring exclusively to her/his own individual understanding of the IS may provoked unexpected reactions by the others, leading to policy resistance mechanisms and, thus, towards unsustainable system evolution trajectories. The potentialities of the tool were analysed through scenario analysis, which is particularly useful to support the research hypothesis. Considering the IS described in Giordano et al. (2016) different scenarios have been built. In addition to the Business-As-Usual (BAU) scenario (i.e. the current situation, in which no specific policies are implemented to control GW withdrawals), the following scenarios were built in order to show how changes in one or more variables may have a significant impact on several output variables (table 4):

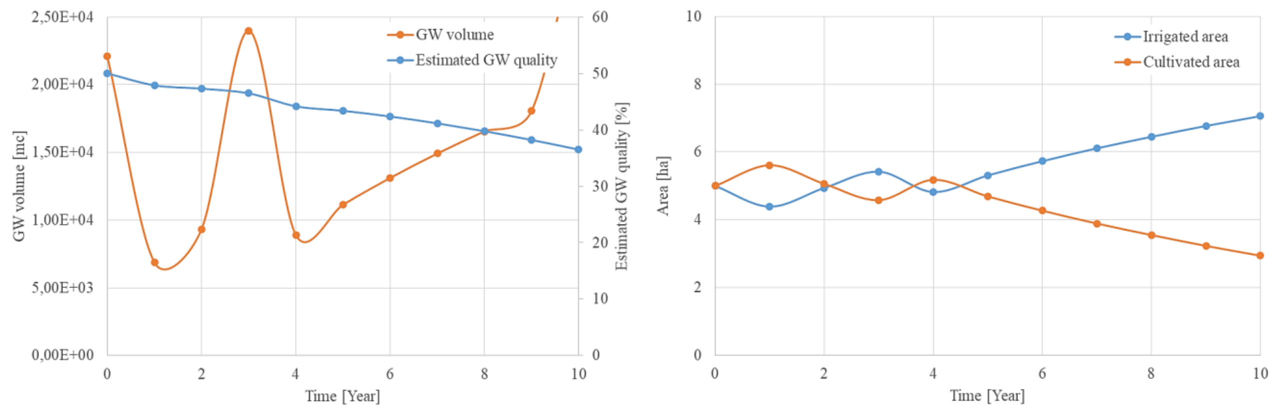
- Scenario 1. Change in GW cost.
- Scenario 2. Change in SW cost.
- Scenario 3. Combined change in GW cost, implementation of a system for GW withdrawals monitoring and adoption of GW protection measures.

Scenario	Variables	Value(s)
Business-as-usual scenario	GW protection level [-]	0.1
	GW withdrawals monitoring [-]	0.1
	GW cost – SW cost (I) [€]	0.18 – 0.12
Scenario 1	GW protection level [-]	0.1
	GW withdrawals monitoring [-]	0.1
	GW cost – SW cost (I) [€]	0.5 – 0.12
Scenario 2	GW protection level [-]	0.1
	GW withdrawals monitoring [-]	0.1
	GW cost – SW cost (I) [€]	0.18 – 0.24
Scenario 3	GW protection level [-]	0.5
	GW withdrawals monitoring [-]	0.5
	GW cost – SW cost (I) [€]	0.5 – 0.12

Table 4 – Scenarios and key variables. The variables denoted with [-] are dimensionless and their value ranges between 0 and 1

The scenarios are analysed mainly focusing on two issues, which are among the most relevant within the study area: i) the change in GW quality, due to its overexploitation; ii) the change in the ratio of cultivated and irrigated areas. They are directly related to the changes in the variable "GW source preference", which represents the pivotal element for a GW protection policy considering the common good management principles.

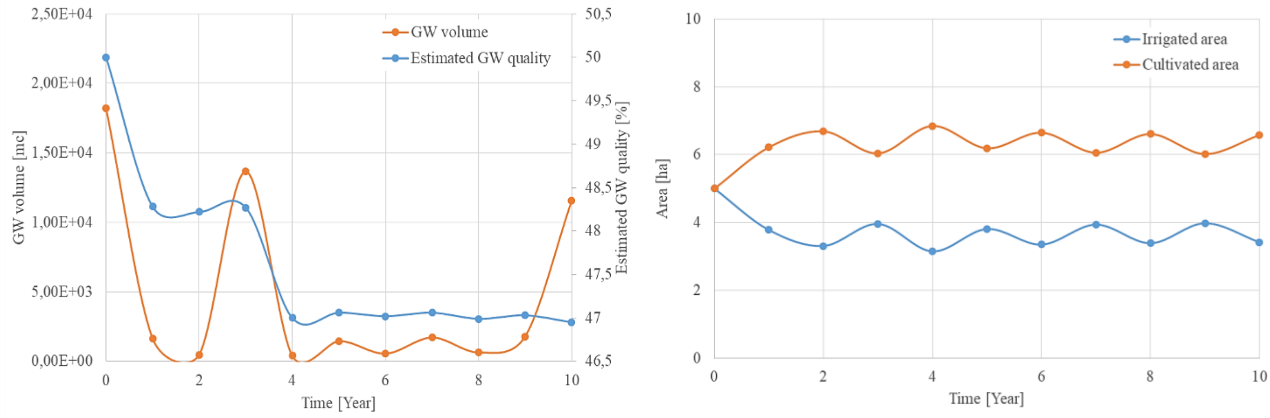
The BAU scenario clearly denotes a significant decrease of GW quality (figure 5a), which is also acknowledged by other studies performed in the same area (Giordano et al. 2015; Portoghese et al. 2013; Giordano et al. 2016; Pluchinotta 2015). The same studies also underline that the accessibility of high GW volumes at a low cost and without any significant control or monitoring, as an additional/complementary resource to the SW, may increase the attractiveness of irrigated crops. Despite some oscillations due to unfavourable conditions (e.g. drought, market conditions, etc.) a trend of increase of the irrigated areas is shown in figure 5b. This directly contributes to increase the irrigation water demand which, considering the limited availability of SW, is largely satisfied by GW, with an increasingly negative impact on the GW quality highlighted in the figures 5a and 5b. This is related both to the variable GW withdrawal and to a progressively higher 'Pressure for GW protection measures'.



a) b)

Figure 5 – Business-as-usual scenario

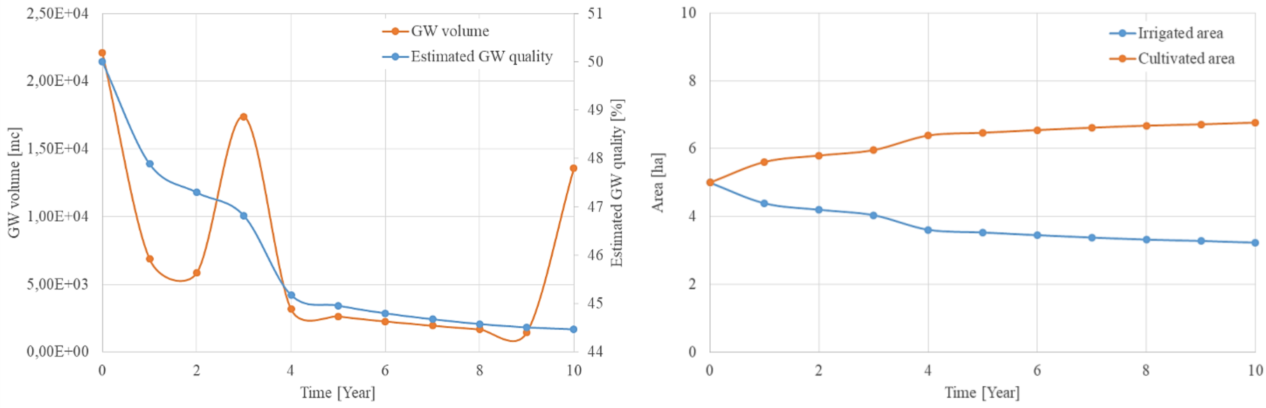
The Scenario (1) analyses the impacts, the other conditions being the same, of a significant change in the GW cost (from 0.18 €/mc to 0.5 €/mc). The value 0.18 €/mc represents pumping and systems management costs and it is derived from Portoghese et al. (2013). Instead, 0.5 €/mc denotes a cost comparable the one defined by IC for the ‘additional SW volume’ in case of drought. It is worth reminding that currently there is not a specific control on GW, and thus there is not a centralized price policy. Figures 6a and 6b show respectively, that increasing the cost of GW (i.e. reducing its accessibility) may drive the system towards more sustainable conditions, i.e. a negligible reduction of GW quality and a slight reduction of irrigated areas.



a) b)

Figure 6 – Scenario (1)

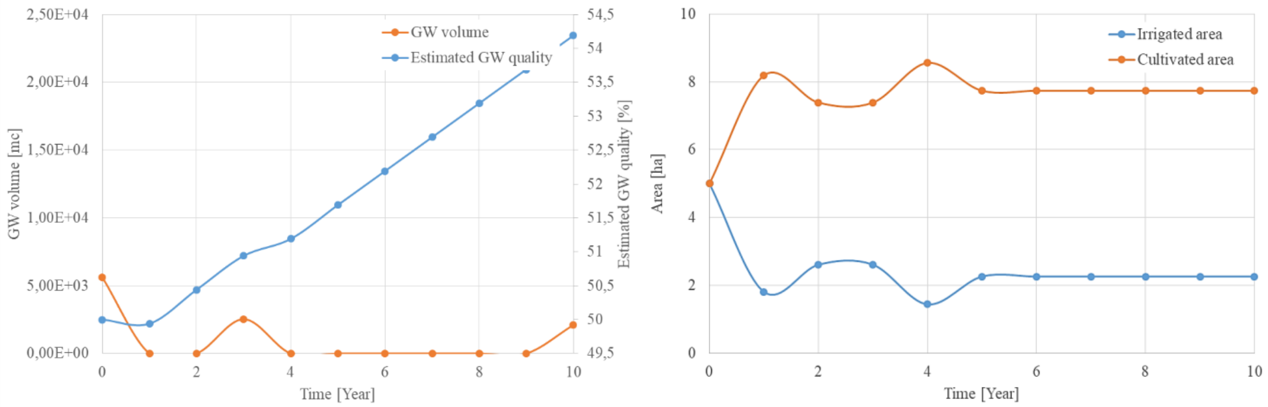
The Scenario (2) is mainly based on the analysis of the impact of a change in SW cost, only referring to the first volumetric threshold distributed by the IC (from 0.12 €/mc to 0.24 €/mc). Alike to Scenario (1), the level of ‘GW protection level’ is 0.1. It is highly interesting to notice that, despite this is not directly related to GW management, it might have a relevant indirect impact. In fact, the change of SW pricing policy may drive towards the reduction of intensively irrigated areas (figure 7b), thus contributing also to a reduction of GW overexploitation, at least in comparison with the BAU scenario (figure 7a). This scenario allows to show that although some issues might be outside of the understanding / interest of a specific actor, his/her choices have cascading impacts or consequences that might also involve or condition other actors.



a) b)

Figure 7 – Scenario (2)

The last Scenario (3) shows instead how the combination of different measures (GW pricing, GW protection level, GW monitoring) supports in achieving sustainable conditions (e.g. an improvement in GW quality) (figure 8a and figure 8b). It is worth mentioning that the present approach does not aim at directly providing solutions or strategies to improve the management of water resources in the area. In fact, there are several issues that are crucial to drive Farmers' behaviours, but are currently neglected in the model for the sake of simplicity. Just to provide an intuitive example, the role of subsidies, which is highly relevant in agriculture and might significantly contribute to support the Farmers in the transition towards crops having lower irrigation requirements. Further developments of the study will be more directly oriented to the assessment of these aspects. The model, currently, mainly aims at showing the importance of exploiting the potentialities of participatory approaches to build comprehensive models able to unravel the complexity of water management issues in systems characterized by several decision-makers and conflicting water uses/interests. This helps underlining the limitedness of single viewpoints and supports analysing the multidimensional impacts that specific decisions and strategies might have, supporting the idea that the real dynamic evolution of complex systems is much more complex than it is actually perceived by single agents.



a) b)

Figure 8 – Scenario (3)

Particularly, the scenario analysis aims at showing how the joint variation of the impacts of the RA implementation of GW protection policy ('protection level') and 'GW cost' may condition Farmers' behaviours and consequentially the qualitative state of GW. The model conceptualization derived from the IS allows to offer hints for a different GW protection strategy, while the evolutionary analysis of the current system through the SDM leads to recalibrate the objectives of an integrated management of a shared resource. It is worth mentioning that the current policy does not consider any (direct or indirect) strategy for increasing the GW cost.

Therefore, the SDM was capable of representing the complexity of water management systems, where simulated behaviours are based on field observations and on participatory modelling activities, formalizing the behaviours of water users and managers. This work describes a SDM developed to conceptualize the water management process in terms of aggregated stocks and flows coherently to the IS, in order support a more collective decision-making of a common pool resource. From model conceptualization via IS to SDM development we proposed a different perspective for a common pool resource management.

5 Conclusions

Challenges in water management have led to the need for developing methods for enhancing the understanding of interactions and interdependencies in multi-stakeholders decision-making processes for an improved participatory management of a common-pool resource. The SDM proposed in the present work aimed at representing the existing situation in our case study (Capitanata area in Apulia region, Southern Italy), operationalizing the IS and understanding the structure of the macro behaviour of a system through its internal decision sub-models. The SDM helped describing the interactions among multiple stakeholders' decisional models, providing a flexible simulation tool involving physical and social components. It enabled analysts to account for interactions among disparate interacting sub-systems that drive the long-term system behaviour, and define the system structure and its network of causal relations and feedback loops which contribute to develop the IS evolutionary (dynamic) attributes. The SDM had the objective to model the architecture of interactions between involved actors in the IS, formalizing the behaviours of water users and management authorities and the consequences of their actions on the system. The SDM demonstrated how the decisions taken by each agent referring exclusively to her/his own individual understanding of the IS provoked unexpected reactions by the others, leading the system towards unsustainable evolution trajectories. The model has been used to evaluate the impact on the water management policies, identifying critical feedbacks, aiming to enhance the understanding of the dynamic evolution of the system. Certainly, the research effort is not aimed at providing the optimal solution for water allocation, price decision and cropping plan. Instead, the goal is to show to the decision-makers the possible consequences of their decision and actions. The results of this work could be used as a starting point for future research activities dealing with the complexity of water resources management and policy design.

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References

Anderies, J.M. & Janssen, M.A., 2013. Sustaining the Commons. Center for the Study of Institutional Diversity, Arizona State University. *International Journal of the Commons*, 8(1).

Andersson, K.P. & Ostrom, E., 2008. Analyzing decentralized resource regimes from a polycentric perspective. *Policy Sciences*, 41, pp.71–93.

Van Asselt Marjolein, B.A. & Rijkens-Klomp, N., 2002. A look in the mirror: reflections on participation in integrated assessment from a methodological perspective. *Global Environmental Change*, 12(3), pp.167–184.

Bousquet, F. & Le Page, C., 2004. Multi-agent simulations and ecosystem management: A review. *Ecological Modelling*, 176(3–4), pp.313–332.

Brugnach, M. & Ingram, H., 2012. Ambiguity: The challenge of knowing and deciding together. *Environmental Science and Policy*, 15(1), pp.60–71.

Chen, A., 2017. Spatially explicit modelling of agricultural dynamics in semi-arid environments. *Ecological Modelling*, 363, pp.31–47. Available at: https://doi.org/10.1016/j.ecolmodel.2017.08.025.

Costanza, R. & Ruth, M., 1998. Using dynamic modeling to scope environmental problems and built consensus. *Environmental Managment*, 22(2), pp.185–195.

Daniell, K.A., 2012. *Co-engineering and Participatory Water Management: Organisational Challenges for Water Governance*, Cambridge, UK: Cambridge University Press.

Daniell, K.A., Mazri, C. & Tsoukiàs, A., 2010. Real world decision-aiding: a case of participatory water management. *e-Democracy: A Group Decision and Negotiation Perspective*, pp.125–150.

Daniell, K.A., Morton, A. & Ríos Insua, D., 2016. Policy analysis and policy analytics. *Annals of Operations*

Research, 236(1), pp.1–13.

Davies, E.G.R. & Simonovic, S.P., 2011. Global water resources modeling with an integrated model of the social-economic-environmental system. *Advances in Water Resources*, 34(6), pp.684–700. Available at: http://dx.doi.org/10.1016/j.advwatres.2011.02.010.

Dent, J.B., Edwards-Jones, G. & McGregor, M.J., 1995. Simulation of ecological, social and economic factors in agricultural systems. *Agr. Syst.*, 49, pp.337–351.

FAO, 2012. *An action framework for agriculture and food security. Water report, coping with water scarcity.*, Rome.

Ferber, J., 1999. *Multi-agent system. An introduction to distribuited artificial intelligence*, Addison-Wesley.

Filippi, C., Mansini, R. & Stevanato, E., 2017. Mixed Integer Linear Programming models for optimal crop selection. *Computers & Operations Research*, 81, pp.26–39.

Forrester, J.W., 1961. *Industrial dynamics*, Cambridge, MA, USA: The MIT Press.

Forrester, J.W., 1987. Lessons from system dynamics modelling. *System Dynamics Review Dyn Rev*, 3(2), pp.136–149.

Forrester, J.W., 1968. *Principles of systems*, Portland: Productivity.

Gintis, H., 2000. *Game Theory Evolving*, Princeton, NJ: Princeton University Press.

Giordano, R. et al., 2013. Bayesian Belief Network to support conflict analysis for groundwater protection: The case of the Apulia region. *Journal of Environmental Management*, 115, pp.136–146.

Giordano, R. et al., 2015. Evaluating acceptability of groundwater protection measures under different agricultural policies. *Agricultural Water Management*, 147, pp.54–66.

Giordano, R. et al., 2007. Integrating conflict analysis and consensus reaching in a decision support system for water resource management. *Journal of Environmental Management*, 84(2), pp.213–228.

Giordano, R., Brugnach, M. & Pluchinotta, I., 2016. Ambiguity in Problem Framing as a Barrier to Collective Actions: Some Hints from Groundwater Protection Policy in the Apulia Region. *Group Decision and Negotiation*, December, pp.1–22.

Gohari, A., Mirchi, A. & Madani, K., 2017. System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management*, 31(5), pp.1413–1434.

Goldani, M., Amadeh, H. & Zamanipour, M., 2011. A System Dynamics Approach in Water Resource Management and Government Subsidy Policy: A Case Study of Tajan Basin in Tran,. In *The 29 th International Conference of the System Dynamics Society*.

Haasnoot, M., Kwakkel, J.H. & Walker, W.E., 2013. Dynamic adaptive policy pathways : A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), pp.485–498.

Hardin, 1968. The Tragedy of the Commons. *Advancement Of Science*, 162(3859), pp.1243–1248. Available at: http://www.jstor.org/stable/1724745.

Hare, M., Letcher, R.A. & Jakeman, A.J., 2003. Participatory Modelling in Natural Resource Management:

A Comparison of Four Case Studies. *Integrated Assessment*, 4(2), pp.62–72.

Hassenforder, E. et al., 2016. Managing frame diversity in environmental participatory processes - Example from the Fogera woreda in Ethiopia. *Journal of Environmental Management*, 177, pp.288–297. Available at: http://dx.doi.org/10.1016/j.jenvman.2016.03.052.

Hess, C. & Ostrom, E., 2003. Ideas, Artifacts, and Facilities: Information as a Common-Pool Resource. *Law and Contemporary Problems*, 111(1998), pp.111–146.

Keeney, R.L., 1996. *Value -Focused Thinking: A Path to Creative Decision- making*, Harvard University Press.

Knox, J. et al., 2016. Meta-analysis of climate impacts and uncertainty on crop yields in Europe. *Environmental Research Letters*, 11(11), p.113004. Available at: http://stacks.iop.org/1748-9326/11/i=11/a=113004?key=crossref.5de49cf73fe34c5c8725bec8b356a3ed.

Kopainsky, B. et al., 2017. Transforming food systems at local levels: Using participatory system dynamics in an interactive manner to refine small-scale farmers' mental models. *Ecological Modelling*, 362, pp.101–110. Available at: http://dx.doi.org/10.1016/j.ecolmodel.2017.08.010.

Kotir, J.H. et al., 2017. Systemic feedback modelling for sustainable water resources management and agricultural development: An application of participatory modelling approach in the Volta River Basin. *Environmental Modelling and Software*, 88, pp.106–118. Available at: http://dx.doi.org/10.1016/j.envsoft.2016.11.015.

Li, F.J., Dong, S.C. & Li, F., 2012. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecological Modelling*, 227, pp.34–45. Available at: http://dx.doi.org/10.1016/j.ecolmodel.2011.12.005.

De Marchi, G., Lucertini, G. & Tsoukiàs, A., 2016. From evidence-based policy making to policy analytics. *Annals of Operations Research*, 236(1), pp.15–38.

Mazri, C., 2007. *Apport méthodologique pour la structuration de processus de décision publique en contexte participatif. Le cas des risques industriels majeurs en France.*, Paris: Université Paris-Dauphine.

Ostanello, A. & Tsoukiàs, A., 1993. An explicative model of "public" interorganizational interactions. *European Journal of Operational Research*, 70, pp.67–82.

Ostrom, E., 1986. An Agenda for the study of institutions. *Public Choic*, 48(1), pp.3–25.

Ostrom, E., 2010. Beyond markets and states: Polycentric governance of complex economic systems. *American Economic Review*, 100, pp.641–672.

Ostrom, E., 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*, Cambridge, U. K.: Cambridge Univ. Press.

Ostrom, E., 2011. The Future of the Commons. *Radical History Review*, 2011, pp.101–107.

Ostrom, E. et al., 2012. *The Future of the Commons: Beyond Market Failure and Government*, London: The Institute of Economic Affairs.

Ostrom, E. & Gardner, R., 1993. Coping with asymmetries in the commons: Self-governing irrigation systems can work. *Journal of Economic Perspectives*, 7(4), pp.93–112.

Özesmi, U. & Özesmi, S.L., 2004. Ecological models based on people's knowledge: A multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, 176(1–2), pp.43–64.

Pagano, A. et al., 2017. Drinking water supply in resilient cities: Notes from L'Aquila earthquake case study. *Sustainable Cities and Society*, 28, pp.435–449. Available at: http://dx.doi.org/10.1016/j.scs.2016.09.005.

Pahl-Wostl, C., 2002. Participative and stakeholder-based policy design, evaluation and modeling processes. *Integrated Assessment*, 3, pp.3–14.

Pahl-Wostl, C. et al., 2008. The NeWater Management and Transition Framework: state and development process. *Adaptive and Integrated Water Management: Coping with Complexity and Uncertainty*, 511179, pp.74–96.

Pahl-Wostl, C., 2015. *Water Governance in the Face of Global Change: From Understanding to Transformation* C. Pahl-Wostl & G. Joyeeta, eds., Springer International Publishing Switzerland.

Pluchinotta, I., 2015. *Multi-Agent Modelling For Distributed Intelligent Decision In Water Management. Doctoral thesis in Computer Science (LAMSADE-CNRS, Université Paris Dauphine, PSL Univ, France) and in Civil and Enviromental Engegneering (Techinical University of Bari, Ital*,

Polski, M. & Ostrom, E., 1999. An Institutional Framework for Policy Analysis and Design. *Development*, pp.1–41.

Portoghese, I. et al., 2013. An integrated modelling tool to evaluate the acceptability of irrigation constraint measures for groundwater protection. *Environmental Modelling & Software*, 46, pp.90–103.

Rey, D., Holman, I.P. & Knox, J.W., 2017. Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change*, 17(5), pp.1527–1540.

Sarkera, A., Baldwinb, C. & Rossa, H., 2009. Managing groundwater as a common-pool resource: An Australian case study. *Water Policy*, 11(5), pp.598–614.

Scott, R.J., Cavana, R.Y. & Cameron, D., 2016. Recent evidence on the effectiveness of group model building. *European Journal of Operational Research*, 249(3), pp.908–918. Available at: http://dx.doi.org/10.1016/j.ejor.2015.06.078.

Simonovic, S.P. & Rajasekaram, V., 2004. Integrated Analyses of Canada's Water Resources: A System Dynamics Approach. *Canadian Water Resources Journal*, 29(4), pp.223–250. Available at: http://www.tandfonline.com/doi/abs/10.4296/cwrj223.

Sishodia, R.P. et al., 2016. Current and future groundwater withdrawals: Effects, management and energy policy options for a semi-arid Indian watershed. *Advances in Water Resources*. Available at: http://dx.doi.org/10.1016/j.advwatres.2017.05.014.

Smajgl, A., 2010. Challenging beliefs through multi-level participatory modelling in Indonesia. *Environmental Modelling and Software*, 25(11), pp.1470–1476.

Sterman, J.D., 2000. *Business dynamics: Systems thinking and modeling for a complex world* Irwin/McGraw-Hill, ed., Boston.

Sterman, J.D., 2001. System dynamics modeling: Tools for learning in a complex world. *California* *management review*, 43(4), pp.8–25.

Sušnik, J. et al., 2012. Integrated System Dynamics Modelling for water scarcity assessment: Case study of the Kairouan region. *Science of the Total Environment*, 440, pp.290–306.

Tsoukiàs, A., 2007. On the concept of decision aiding process: An operational perspective. *Annals of Operations Research*, 154(1), pp.3–27.

Varia, F. et al., 2017. System dynamics model to design effective policy strategies aiming at fostering the adoption of conservation agriculture practices in sicily. *Chemical Engineering Transactions*, 58, pp.763–768. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026399859&doi=10.3303%2FCET1758128&partnerID=40&md5=c80b85ae8a3db7d8bad42a122556ca22.

Vennix, J.A.M., 1996. Group model-building: tackling messy Problems. *System Dynamics Review*, 15(4), pp.379–401.

Voinov, A. et al., 2016. Modelling with stakeholders - Next generation. *Environmental Modelling and Software*, 77, pp.196–220.

Walters, J.P. et al., 2016. Exploring agricultural production systems and their fundamental components with system dynamics modelling. *Ecological Modelling*, 333, pp.51–65. Available at: http://dx.doi.org/10.1016/j.ecolmodel.2016.04.015.

Weiss, G., 2000. *Multiagent Systems - A Modern Approach To Distributed Artificial Intelligence*,

White, L. & Bourne, H., 2007. Voices and values : Linking values with participation in OR / MS in public policy making. *Omega*, 35(5), pp.588–603.

Winter, J.M. et al., 2017. Integrating water supply constraints into irrigated agricultural simulations of California. *Environmental Modelling and Software*, 96, pp.335–346. Available at: http://dx.doi.org/10.1016/j.envsoft.2017.06.048.

Winz, I., Brierley, G. & Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. *Water Resources Management*, 23(7), pp.1301–1323.

Wooldridge, M. & Kraus, 2012. Delegating Decisions in Strategic Settings.