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Research article

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 conflict among water uses and users. Nowadays, there is a cumulative interest in enhancing multi-stakeholder decision-making processes, overtaking 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 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 the 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, using a System Dynamics Model (SDM), exploring 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 area (Apulia region, Southern Italy).

1. Water management complexity: the need of stakeholders' participation

Water management (WM) 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; Lewis and Randall, 2017). The management of a limited and shared resource is a complex challenge (Hess and Ostrom, 2003), often introducing conflicts especially within the agricultural sector in semi-arid regions (Chen, 2017; Sishodia et al., 2017; Knox et al., 2016; Rey et al., 2017). The resulting impacts on the environment may vary depending on the contribution of intensified agriculture, such as groundwater depletion, reduced surface flows, salt water intrusion, and loss of wetlands (Sishodia et al., 2017).

Water, particularly in the sense of its availability for irrigation, is one of the most extensively studied types of common-pool resource (CPR) (Sarkera et al., 2009). As a CPR 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 problems of overexploitation and free-riding arise.

Therefore, WM policies require methods to support the detection, analysis and reduction of conflicts among different users and uses (Giordano et al., 2017; Hassenforder et al., 2016) through a not binding mercantile business. Two decades of research about the management of CPRs suggests that, under particular conditions, local communities can manage shared resources sustainably and successfully (Ostrom, 1990). Hardin's "tragedy of the commons" (1968) is not inevitable when a shared resource is at stake, if communities interact and operate collectively avoiding the simple market rules (Ostrom, 2012).

The above-mentioned issues generate the need to enhance decision-aiding methodologies within inclusive participatory modelling activities (e.g. Chen, 2017; Voinov et al., 2016), allowing stakeholders to participate in the decision-making process (DMP) and to provide their own knowledge (Giordano et al., 2007), leading to an effective management (Hare et al., 2003; Carmona et al., 2013; Kotir and Brow, 2017). The role of participatory frameworks in WM has been also established by the European Water Framework Directive (CEE2000/60),

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which strongly encourages the active involvement of all the affected parties (Pahl-Wostl, 2015). It enriches DMPs mapping out diversity of problem frames (Brugnach and Ingram, 2012; Hassenforder et al., 2016; Giordano et al., 2017) in order to: i) explicitly challenge stakeholders' values; ii) facilitate dialogue across multiple tiers of governance; and iii) establish a shared management process for CPRs (Smajgl, 2010). Surely, a DMP with public actors and CPRs generates unpredictable scenarios because of the competing interacting decision-makers (Tsoukiàs, 2007; Daniell et al., 2016; De Marchi 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 actor may not necessarily be aligned with the viewpoints, expectations or possibilities held by the others (Brugnach and Ingram, 2012; Giordano et al., 2017). This can lead to dysfunctional dynamics, 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 such a perspective, decision-aiding tools involving multiple stakeholders should be capable to: i) integrate the differences among stakeholders' problem framing, ii) provide shared platforms to set up the process of debate, iii) reconstruct the connections between such platforms and engaged interactions.

Starting from these premises, the present work aims to develop 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 and 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 to answer 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 IS and to analyse its dynamic nature?

The developed SDM intends to: i) explore the different viewpoints, and potentially conflicting objectives of multiple decision-makers; ii) 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 DMP, 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 DMP and SDM approaches. Section 3 illustrates the methodology and the case study. Section 4 and 5 discuss the obtained results. Concluding remarks are described in section 6.

2. Supporting multi-stakeholders decision-making processes

2.1. The interaction space

There is a deficiency of adequate methodologies for problem formulation and objective setting in supporting DMPs with multiple stakeholders in case of CPR management. Decision-aiding in multi-stakeholder context focuses on providing the analyst's methodological support to facilitate stakeholders to structure and exchange views (Tsoukiàs, 2007; Daniell et al., 2010). This issue is introduced by concepts such as the action-arenas (AA) (Ostrom, 1986) or the interaction space (IS) (Ostanello and Tsoukiàs, 1993), formal structures supporting interactions and the implementation of local rules and rationalities.

AA have been defined as a social space where individuals interact, exchange goods and services, solve problems, dominate one another, or fight (Ostrom, 1990). AA has mainly been applied to analyse static depictions of social systems and the evolution of rules over time, comparing different representations (Pahl-Wostl, 2002). The key idea of Ostrom is to understand a society as a structure of interconnected action situations and involved participants (Ostrom, 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). AA combines the action situation, which focuses on the rules and norms, with the participants' individual preferences, skills and DMPs (Andersson and Ostrom, 2008; Anderies and Janssen, 2013).

On the other side, Ostanello and Tsoukiàs' IS is a collaborative space where a *meta-object* is identified as the merge/articulation of the participants' problem representation. Similarly to the AA, the IS can form the basis for further collective discussion and DMP. The concept of IS has been introduced in order to represent a meeting structure of subjects from different organizations, allowing exchange condition by a public confrontation. Mazri (2007) and 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". A set of elements (participants A, objects O and resources R) and an architecture of relations $S = \{S_o, S_{ao}, S_{aor}\}$ on these sets constitute an IS.

The multi-step procedure that enables the IS building is explained in Ostanello and Tsoukiàs (1993). The identification of the IS state allows the analyst to generate hypotheses on the coherence of future actions that a participant could be willing to undertake (e.g. the different IS states are controlled and non-controlled expansion, stalemate, controlled contraction, dissolution, institutionalization). Such model, even if simplified to just a few variables, can provide a useful basis for understanding decision dynamics with multi-stakeholders. IS allows the analysts to deal with different participants, formalizing a formal structure and consequently, improving transparency of participation processes. IS is a descriptive and explicative model that could support participative DMPs. The construction of this artefact allows, on the one hand, the clients to recognise their position within the DMP for which they asked the support. On the other hand, it allows the analyst to better understand the problem under analysis and the interconnected networks in which decision-makers operate.

Hence, the use of the current structure of IS has drawbacks. Firstly, the IS is an evolving structural idea, although it remains a static picture of the problem. 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 IS requires methodologies capable to account for such a dynamic nature. Secondly, as Ostrom suggested for the AA, 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 which interdependencies it has with the others. In a multi-stakeholder DMP, each decision-maker has its own frame of the IS, which leads him/her to have a personal rational model to achieve his/her objectives neglecting the existence of the other agents. Lastly, IS is a descriptive approach, without collective features for understanding interactions. It is not able to fully explain the complexity of debates and to fulfil the need for 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. A dynamic IS model should be defined including besides the sets of agents A, objects O, resources R and a structure of relations S that develop between these sets, selected rational models allowing its evolution (denoted as T): $IS = \langle A, O, R, S, T \rangle$.

Under the hypothesis of decision-makers driven by a subjective rationality, T represents 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. The formalization of T, made

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