Elsevier Editorial System(tm) for Journal of Environmental Management
Manuscript Draft

Manuscript Number: JEMA-D-17-04917R3

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

Article Type: Research Article

Keywords: Water management; Participatory modelling; Decision Analysis; System dynamics; Interactions space; Sustainability.

Corresponding Author: Dr. IRENE PLUCHINOTTA, Ph.D.

Corresponding Author's Institution: LAMSADE-CNRS, Université Paris Dauphine, PSL Research University

First Author: IRENE PLUCHINOTTA, Dr.

Order of Authors: IRENE PLUCHINOTTA, Dr.; Alessandro Pagano, Dr.; Raffaele Giordano, Dr.; Alexis Tsoukiàs, Dr.

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***Title page**

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

Irene Pluchinotta* (*****Corresponding Author)

LAMSADE-CNRS, Université Paris Dauphine, PSL Research University

irene.pluchinotta@lamsade.dauphine.fr

Place du Maréchal de Lattre de Tassigny, 75016 Paris, France

Alessandro Pagano

Water Research Institute - National Research Council

alessandro.pagano@ba.irsa.cnr.it

Viale Francesco de Blasio, 5, 70132 Bari, Italy

Raffaele Giordano

Water Research Institute - National Research Council

raffaele.giordano@ba.irsa.cnr.it

Viale Francesco de Blasio, 5, 70132 Bari, Italy

Alexis Tsoukiàs

LAMSADE-CNRS, Université Paris Dauphine, PSL Research University

alexis.tsoukias@dauphine.fr

Place du Maréchal de Lattre de Tassigny, 75016 Paris, France

Highlights

- The management of limited and shared water resources 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.

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 et al., 2017). The management of a limited and shared resource is a complex challenge (Hess & Ostrom 2003), often introducing conflicts 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 intensified agriculture, such as groundwater depletion, reduced surface flows, salt water intrusion, and loss of wetlands (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 (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 et al., 2014; 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., 2015; Kotir et al., 2017). The role of participatory frameworks in WM has been also established by the European Water Framework Directive (CEE2000/60), 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 & 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 et al., 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 et al., 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): $IS = < A, O, R, S, T >$

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 by the analyst through 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, helping in the simulation building and in the definition of the rules in use, facilitating stakeholders' interactions and the explanation and the prediction of behaviours.

In order to overcome the presented criticalities, System Dynamics Modelling (SDM) is considered a suitable tool for operationalizing the IS. SDM is a computer-aided approach, applying to dynamic problems defined by interdependence, mutual interaction, and circular causality (Vennix, 1996). It has the flexibility and capability to support environmental DMPs, to involve raising public awareness and developing understanding of the connections between potential decision alternatives and system consequences (Bousquet and Le Page, 2004; Gohari et al., 2017).

2.2 System Dynamic Modelling

Historically, SDMs appeared as an outgrowth of the system dynamics approach of Forrester (Forrester, 1961; Forrester, 1968; Forrester, 1987). A SDM describes complex systems through the use of feedback loops, stocks and flows. Stocks characterize the state of the system, and keep memory of it, enabling to describe its status. Flows affect the stocks via inflow or outflow, and interlink the stocks within a system (Sterman, 2000). SDM is both qualitative/conceptual and quantitative/numerical. Qualitative modelling (causal loop diagrams) can improve the conceptual system understanding. Quantitative modelling (stock-and-flow models), allows to investigate and visualize the effects of different actions within the simulation model (Sterman, 2001). SDM is able to integrate a wide range of input parameters in a meaningful way, supporting the recognition that the direction of change is crucial towards managing responses in an adaptive way (Pagano et al., 2017).

Referring to WM issues, Simonovic and Rajasekaram (2004) developed an integrated model using the SD simulation, Goldani et al. (2011) analysed WM and government subsidy policy and Liu et al. (2015) discusses an integrated SDM developed for managing water quality. Specifically for WM in agriculture, 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. modelling a participatory systemic feedback for sustainable WM (Kotir et al. 2017), assessing water scarcity and potential impacts of socio-economic policies in a complex hydrological system (Sušnik et al. 2012), modelling the impact of climate change on agricultural practices (Gohari et al. 2017), supporting policy- and decision-makers designing effective strategies for conservation agriculture practices (Varia et al. 2017), integrating individual stakeholders' mental models (Kopainsky et al. 2017).

The objective of the last part of this section is to make a comparison between SD and other approaches used for modelling WM decision-making issues. In the first place, traditional approaches to support WM aim to identify the *optimal* alternative using decision models represented by analytic functions. Considering the

WM complexity, finding the *optimal* solution is rarely considered the most suitable approach (Daniell, 2012). Such approaches neglect, for example, the decision-makers' abilities to change their DMP due to the interactions with the system and with the other actors (e.g. Brugnach and Ingram 2012; Giordano et al., 2017). 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 neither highlight enough the interaction between users, nor take 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 simulates the system evolution through a detailed analysis of model structure, the latter predicts the future evolution of the system starting from the analysis of the measured data. Nevertheless, these statistical correlations may not truly forecast future system behaviour (Winz et al. 2009). Moreover, a higher level of complexity encompasses a model validation by the stakeholders. This phase becomes a social process where model structure and outcome are negotiated until they are judged valid and useful by all involved parties (Scott et al., 2016).

Lastly, it is necessary to compare SDM with agent-based models (ABM). SDM are used in order to conceptualize variables in terms of stocks and flows (Sterman 2000), focusing on the overall system behaviour deriving from the interactions among the individuals. ABM, by contrast, focuses on detailed elements at a micro scale (Ferber 1999; Wooldridge & Kraus 2012; Weiss 2000). Comparing SDM to ABM, one major SDM weakness is that emergent phenomena from microscale, which often occur within social systems, cannot be properly explored from an aggregated feedback system. However, often the ABM platforms are not user-friendly and are restricted to an expert use (Kelly et al., 2013).

Within such a framework, this work describes a SDM developed for conceptualizing WM in terms of aggregated stocks and flows, for a collective DMP related to a CPR. The SDM has been used to evaluate the impact on WM policies, 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 WM in agricultural systems in the north of the Apulia region (Southern Italy). The area under analysis is characterized by severe phenomena of seawater intrusion caused by intensive agricultural activities in coastal areas, which rely on both surface water (SW) and groundwater (GW) (Giordano et al., 2015; Portoghese et al., 2013). Within the case study, three main stakeholders are identified: Farmers, Water Management Authority, and Regional Authority (RA). The Water Management Authority, i.e. the Irrigation Consortium of Capitanata (IC), is responsible for the management of SW in the area focusing exclusively on irrigation demand. The IC has to deal with the water scarcity in the region, and the SW demand from each Farmer. The objectives of IC are to guarantee an equitable distribution of SW and to maintain a positive economic budget. IC's price policy is based on different volume thresholds with specific water tariffs depending on water availability in the dam: the base water supply volume (0.12 €/m^3 for 2050 m^3/ha) and the additional water supply volume, considerably more expensive (from 0.24 €/m^3 for 2050-4000 m^3/ha). Since irrigated agriculture is highly water-demanding, and the significant climatic uncertainty might limit water availability, each Farmer selects a 'suitable' cropping plan to maximize his/her profits. Besides SW, managed by IC, the availability of individual GW withdrawals, both legal and illegal, need to be considered. In fact, Farmers consider GW easily accessible, thanks to the presence of private wells, and cheaper than SW. Farmers' decisions concern also the selection of the main source of water for irrigation (either GW or SW). Although currently there is not a centralized GW management system, RA needs to protect GW quality and quantity, without impacting dramatically the level of productivity of the agricultural sector. For this aim, the RA implemented in 2009 the Water Protection Plan (according to the CEE 2000/60) to restrict the GW use. 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 modelling processes (performed in Giordano et al., 2017; Giordano et al., 2015; Pluchinotta 2015; Portoghese et al., 2013). The simulated behaviours are based on field observations and on the elicitation of stakeholders' knowledge.

3.2 *The applied methodology*

A methodology capable to operationalize the IS and, in doing so, to support the detection and analysis of 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 actors a with their objects o and resources r. The next stage is to define the hierarchy and relations between these elements. Finally, the dynamic evolution of the IS is simulated using the SDM. A detailed description of the IS, the constructing procedure, and the development of the stakeholder's DMPs through causal loop diagrams are described in Giordano et al. (2017). This paper represents a step forward. It aims at developing a SDM, capable to simulate the dynamic evolution of the IS during the different phases of the DMPs, structuring the interactions between multiple decision-makers and several drivers.

Following Giordano et al. (2017), different problem understandings were integrated in the SDM. The model assumptions are: i) each decision-maker has a personal understanding of the IS and this partial and subjective vision tends to affect behaviours and actions; 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 his/her objects are impacted by the actions implemented by the others.

The SDM development proceeded following the conceptualisation phase via the IS. It was structured in the following main phases (adapted from Vennix, 1996 and Davies and 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 Appendix I (see Supplementary Material).

3.3 Model structure

The overall structure of the SDM, developed with STELLA® (ISEE Systems Inc.), is represented in Figure 1. Based on the conceptual structure of the IS, the model is based on three sub-models, each one focused on the perspective of specific actors involved in WM. The rationale behind the single sub-models and their key dynamics are discussed in the manuscript, while the full list of equations is included in Appendix II (see Supplementary Material), and the results of the Sensitivity Analysis, performed with respect to the main variables are described in Appendix III (see Supplementary Material). The grey variables in the model represent the main connections between different sub-models. The role of these variables is important since they help identifying connections and influences among different sub-models, which are typically neglected by the actors. These variables allowed us to align the stakeholders' problem understandings and to develop an integrated model (Giordano et al., 2017).

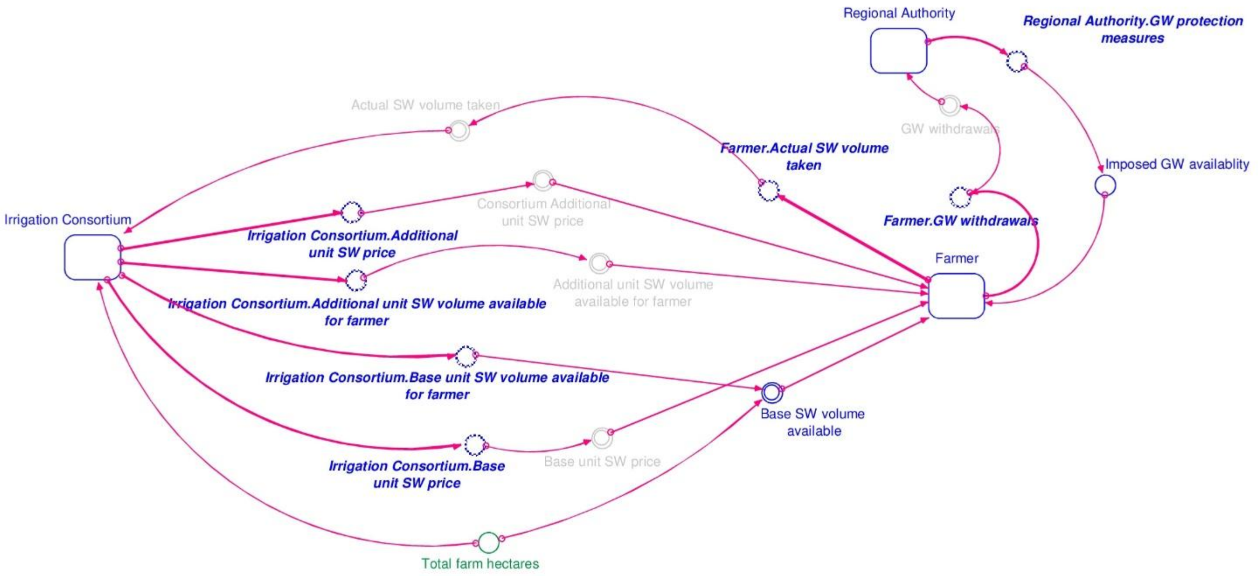


Figure 1 - The complete SDM built with STELLA® (ISEE Systems Inc.)

The SDM supports the representation of the existing situation and a broad conceptualization of system structure in order to explore its behaviour. The model is run for ten years, with a time step of one year. It is assumed that there is only one irrigation season yearly. The analysis is carried at farm scale, referring to the average farm size in the area (10 ha).

The IC's decision model (Figure 2) was developed with reference both to the results of individual interviews (Giordano et al., 2017; Pluchinotta, 2015) and to the analysis of the IC's water pricing strategies implemented in the last ten years. The 'Water volumes sub-module' focuses on the physical aspects. The key variable is the stock 'Water volume in the reservoir'. The input is given by a set of historical data, while the outflows are related to irrigation and drinking use. Since the drinking water must be always guaranteed, the

‘Water volume for irrigation’ is variable and given by the difference between ‘Water volume in the reservoir’ and ‘Outflow potable’. The comparison between the available ‘Water volume for irrigation’ and the ‘Expected water demand’ defines the initial IC ‘Budget’, which is the key element to define the yearly irrigation management strategy, i.e. the amount of water available per Farmer (‘Base unit SW volume available per Farmer’ and ‘Additional unit SW volume available per Farmer’). 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. Considering the dominant crops of the region, the SDM considers the ‘Expected irrigation demand’ of the tomato (approx. 6000 m^3/ha). According to the IC's problem understanding, the pricing policy (described in the ‘Economic sub-module’) is directly related to the identification of the ‘Base’ and the ‘Additional’ volume thresholds, and of the associated ‘Base unit SW price’ and ‘Additional unit SW price’. The price definition should allow matching the availability and the demand, at least in normal conditions (i.e. SW restrictions may be applied in dry years), leading to an equitable access to water for all Farmers. The economic feedback simulates the impact of the Farmer’s consumption of SW (‘Actual SW volume taken’) on the IC’s budget, i.e. the stock ‘Consortium budget’. The main IC’s goal is to keep this variable positive. The IC’s budget is influenced by: i) the fixed fees paid by each Farmers (i.e. ‘Yearly fee’ depending on ‘Total Farm hectares’) for irrigation networks maintenance, and management costs; ii) the ‘Farmer payment for irrigation’, depending on the ‘Actual SW taken’ and SW prices. The data used in the model were collected by the IC budget reports.

An imbalance in the system may be determined by an increase in irrigation water demand, caused by the increasing Farmer’s inclination towards intensive irrigated agriculture. Therefore, 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, mainly based on 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, pushing to 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.

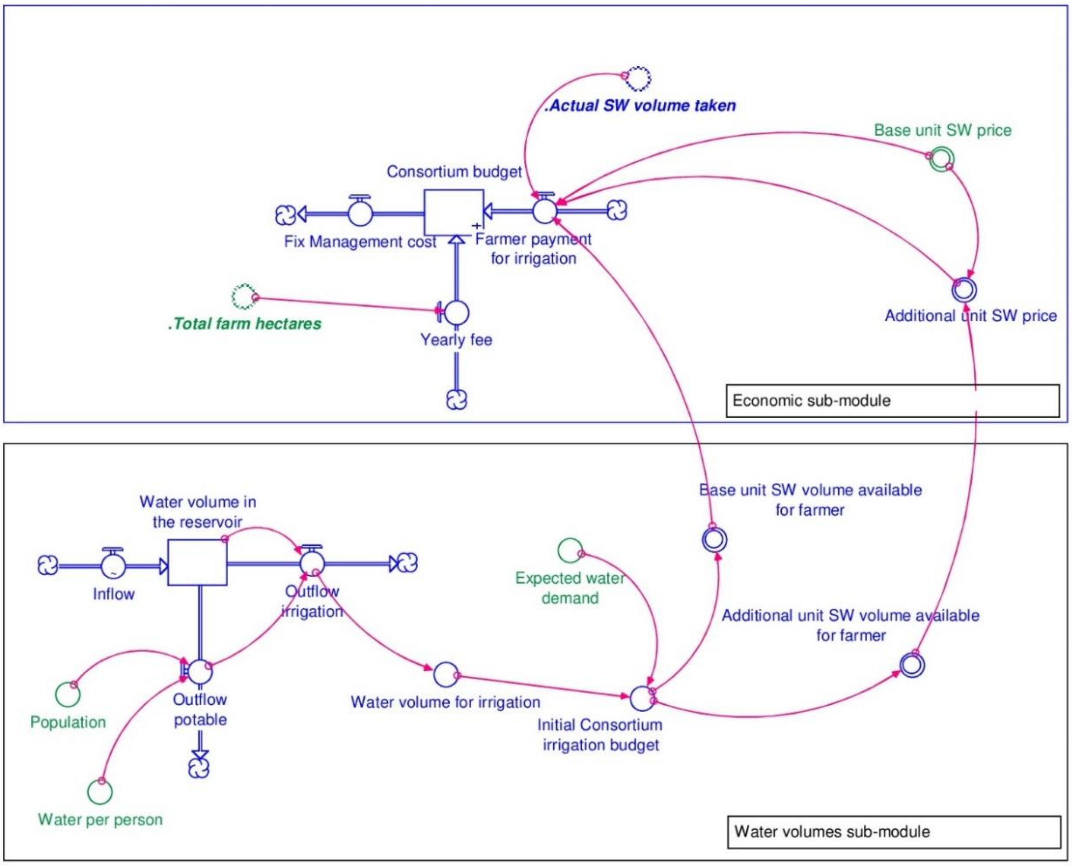


Figure 2 – Irrigation Consortium's sub-models

The Farmer's sub-model (Figure 3) was developed by involving a sample of Farmers working in the Capitanata area through individual interviews. A few associations of Farmers were also involved in the modelling 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 and Özesmi, 2004). The sample was created by considering the different characteristics of farms, i.e. size, crop patterns, irrigation techniques and access to the IC's network. The main Farmer's goal is to maximize his/her economic yield choosing a mix of irrigated and not-irrigated crops, considering the available water (and its cost). According to the characteristics of the study area, the model assumes that only half of the average farm area (5 ha) is irrigated at the beginning of the simulation and that the presence of multi-annual crops is negligible. The key element of this sub-model is the simulation of the yearly crop plan based on two stocks and their mutual changes: the 'Cultivated areas', representing agricultural areas with non-irrigated crops (e.g. durum wheat), and the 'Irrigated areas', i.e. areas with crops having a significant irrigation demand (e.g. tomato). The transition from 'Cultivated' to 'Irrigated' areas depends on several issues. It significantly depends on the 'Farmers' perception of price' (i.e. the tomato average 'Prices in the market' over 3 years, with a delay). It depends also on the current situation, mainly in terms of: i) water availability through the variable 'Irrigation deficit', which defines the ratio between 'Final Farm irrigation budget' and 'Actual water requirement' (in case it is higher than 10%, non-irrigated crops are preferred, and thus the associated areas increase with time); ii) 'Economic budget', which proposes a simplified economic assessment based on the comparison between costs (‘Irrigation cost’ and ‘Other costs’) and revenues (‘Subsidies’ and the profit associated, with a delay, to both irrigated and non-irrigated crops). The model considers a significantly different profitability of such crops (500 €/ha vs. 10000 €/ha), which drives the Farmers towards the selection of irrigated crops.

Another key element is the dynamic of water source selection. Each Farmer knows the SW availability for the irrigation season (i.e. ‘Base unit SW volume available per Farmer’ and ‘Additional unit SW volume available per Farmer’), and related prices. Individual GW sources are also generally available (Portoghese et al., 2013 estimated a ‘Unit GW cost’ of 0.18 €/m^3 for the area), but their legal use is regulated by the RA. Surveys (Giordano et al. 2015; Pluchinotta, 2015) showed that Farmers are independent in their actions and they are self-interested driven by an economic rationality. According to the interviews carried out, Farmers perceive GW as an almost unlimited and easily accessible resource and they do not acknowledge any potential environmental complication. Therefore, after IC establishes the SW unit prices, each Farmer decides the best water source (‘GW source preference’ in the top-right part of Figure 3), mainly considering the water cost. The variable ‘GW source preference’ depends on SW unit costs and availability, ‘Unit GW cost’ and ‘Imposed GW availability’ (which depends on GW protection policies that are activated by the RA). The presence of ‘GW withdrawal monitoring’ may also be a limiting factor for the ‘GW source preference’.

The core issue according to Famers’ problem understanding is the ‘Final Farmer Irrigation budget’. Farmers were required to specify the main causes that could result in a negative value for the problem core. The most mentioned cause was the volume of SW distributed by IC. IC aims to reduce 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 illegal use.

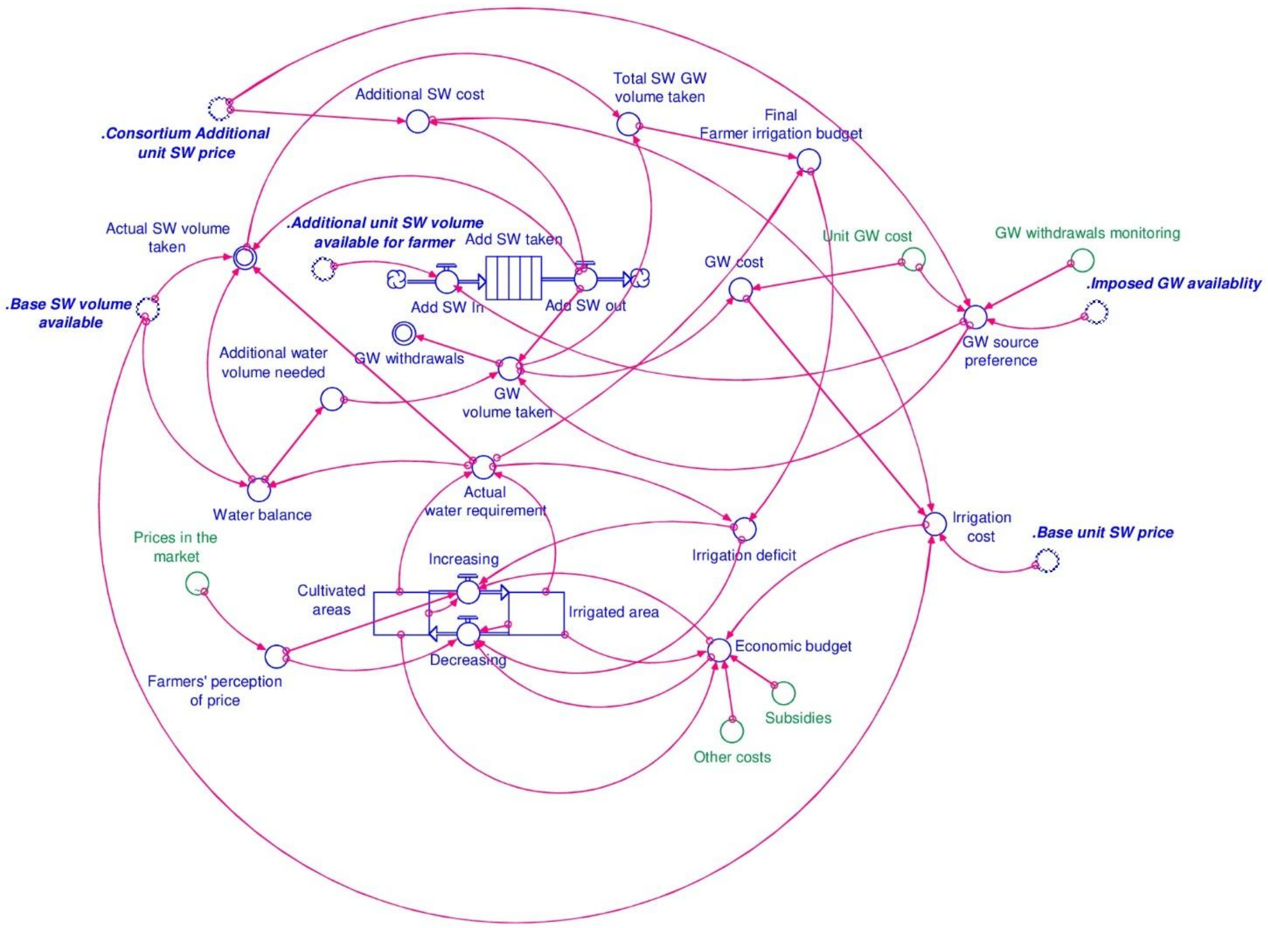


Figure 3 – Farmers' sub-model

The RA's sub-model is proposed in Figure 4. The RA uses legislations to impose constraints on GW exploitation (according to the Water Protection Plan), which is responsible for the decrease of 'GW volume'. The 'GW volume' stock is a qualitative variable, useful to perform a global assessment of GW state, ranging from 0 (extremely low) to 100 (extremely high). The current state is identified with an average value (50). Typically, the volume of the aquifer ranges from 500 Mm^3 and 1500 Mm^3, with an average of 1100 Mm^3 (Guyennon et al., 2016). The 'increasing' rate takes into account the natural annual recharge rate of the system (about 10% of the GW volume) and the role of 'GW protection measures level' and 'Pressure for GW protection measures' (which increases significantly as the 'GW volume' becomes lower). The annual natural recharge rate can be considered approximately the 10% of GW volume, and is included in the 'Increasing' flow. The 'GW volume' decreases due to the 'GW withdrawals' for irrigation purposes.

Irrigated agriculture is crucial for the area and 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 (Giordano et al. 2017). According to the RA's problem understanding, any improvement in the sustainability of GW use, should have implications on water demand. Therefore, the RA needs to impose limits to GW use for irrigation ('Imposed GW Availability').

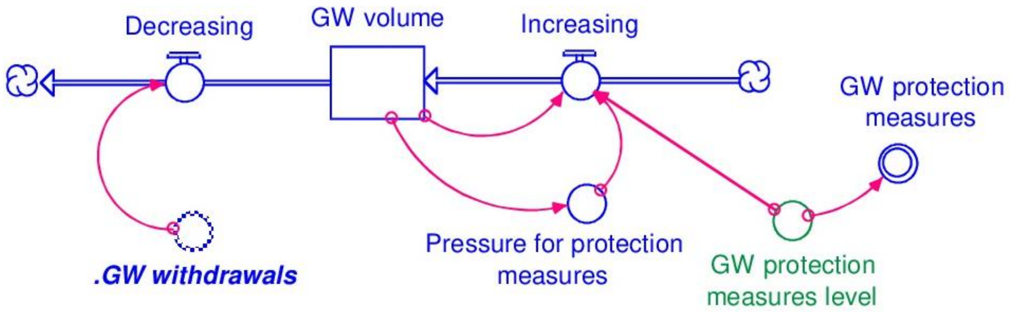


Figure 4 – Regional Authority's sub-model

In summary, there is a set of 'transition' variables shared between the different decision makers' sub-models (Table 1). These variables are significant, since they identify specific elements that are explicitly part of a sub-model (e.g. they can be controlled by the actor), 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).

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 measures	a_3	Regional Authority	a_2	Farmers
GW withdrawals	a_2	Farmers	a_3	Regional Authority

Table 1 – 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 perceptions that might be responsible for a misalignment of the different ISs. This could be originated by e.g.: a) one or more actors 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- and policy-makers. This could significantly support the success of participatory modelling processes and reduce ambiguity in the analysis, besides being a crucial step to assess the effectiveness of measures and policies, identifying benefits, co-benefits and potential drawbacks.

A second round of semi-structured interviews was held with all the actors involved in model building, and a group of experts (academics and researchers) to validate the individual sub-models and their relationship (see Giordano et al., 2013; Pluchinotta, 2015; Giordano et al., 2017).

4 Results

The present section focuses on the neglected interactions among different decision-makers, and on the analysis of the potential effects of these interactions on the dynamic evolution of the IS. The SDM demonstrated how the decisions taken by each decision-maker referring exclusively to his/her own individual understanding of the IS may provoke unexpected reactions by the others, leading to policy resistance mechanisms and, thus, towards unsustainable system evolution trajectories. The potentials 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. (2017) 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 to show how changes in one or more variables may have a significant impact on several output variables (Table 2):

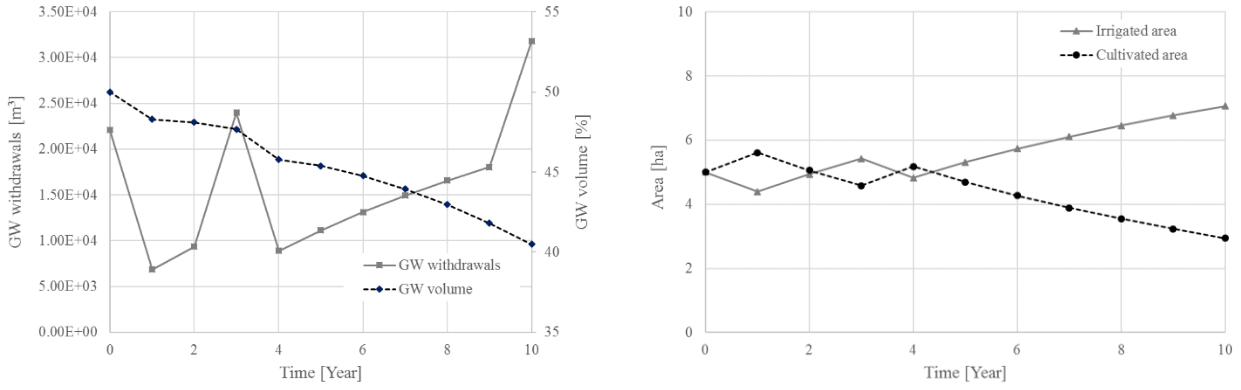
- Scenario 1. Change in GW cost
- Scenario 2. Change in SW cost
- Scenario 3. Combined change in GW cost, implementation of a system for GW withdrawals monitoring and adoption of GW protection measures

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

Table 2 – 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: i) the change in GW quality, due to its overexploitation; ii) the change in the ratio of cultivated lands (i.e. areas with non-irrigated crops) 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 CPRs management principles.

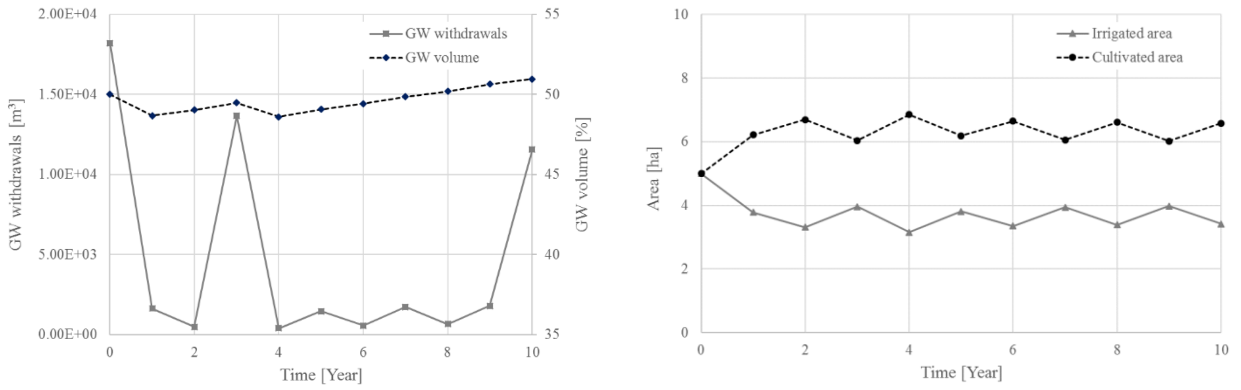
The BAU scenario clearly denotes a significant decrease of 'GW volume' (Figure 5a), which is also acknowledged by other studies performed in the same area (Giordano et al., 2015; Portoghese et al., 2013; Giordano et al., 2017). The same studies also underline that this is due to the high GW withdrawals at a low cost and without any significant control, as an additional/complementary resource to the SW, which may also 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 impact on 'GW volume'.



a) b)

Figure 5 – Business-as-usual scenario

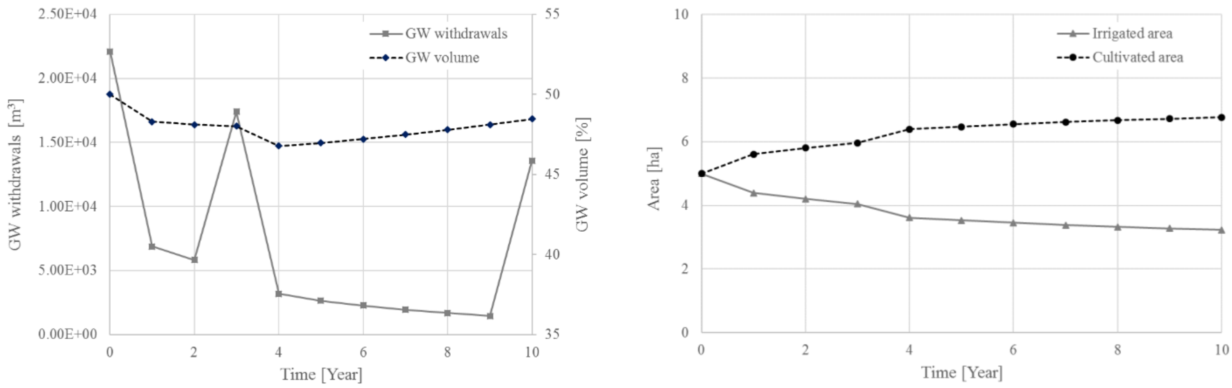
The Scenario (1) analyses the impacts, the other conditions being the same (i.e. 'GW protection measures level' and 'GW withdrawals monitoring' in the BAU state), of a significant change in the 'Unit GW cost' (from 0.18 €/m^3 to 0.5 €/m^3). The value 0.18 €/m^3 represents pumping and management costs and it is derived from Portoghese et al. (2013). Instead, 0.5 €/m^3 denotes a cost comparable to 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 use and there is not a centralized price policy. Figures 6a and 6b show that increasing the cost of GW (i.e. reducing its accessibility) may drive the system towards more sustainable conditions, i.e. respectively a gradual improvement of GW volume and a stabilization of irrigated areas.



a) b)

Figure 6 – Scenario (1)

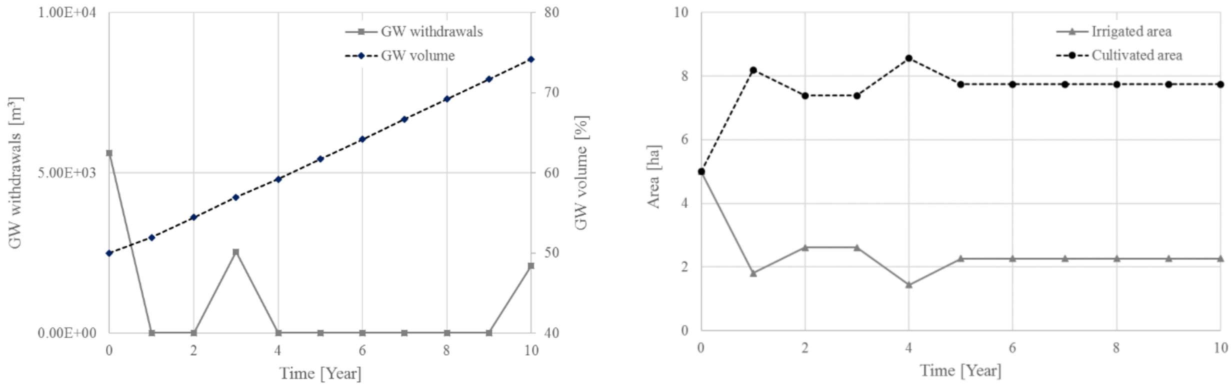
The Scenario (2) is based on the analysis of the impact of a change in SW cost, only referring to the first volumetric threshold distributed by the IC ('Base unit SW price' from 0.12 €/m^3 to 0.24 €/m^3). Alike to Scenario (1), the level of 'GW protection measures level' and 'GW withdrawals monitoring' are in the BAU state. It is highly interesting to notice that, despite this is not directly related to GW management, it might have a relevant indirect impact on GW state. 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 (increase of ‘GW volume’), at least in comparison with the BAU scenario (Figure 7a). This scenario shows that although some issues might be outside of the understanding/interest of a specific actor, his/her choices have cascading impacts on the others.



a) b)

Figure 7 – Scenario (2)

The Scenario (3) shows, instead, how the combination of different measures (GW pricing policies, GW protection measures level, GW withdrawals monitoring) supports the achievement of sustainable conditions, i.e. an increase in ‘GW volume’ (Figure 8a) and a stable reduction of irrigated areas (Figure 8b).



a) b)

Figure 8 – Scenario (3)

It is worth mentioning that the present approach does not aim at directly providing solutions or strategies to improve the WM 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 to display the importance of exploiting the potentialities of participatory approaches to build comprehensive models able to unravel the complexity of WM 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 perceived by single agents.

Specifically, the scenario analysis aimed to show how the joint variation of different variables (e.g. the ‘GW protection measures level’ and the ‘GW withdrawals monitoring’ controlled by the RA) and ‘unit GW cost’ may condition Farmers’ behaviours and consequently affect the state of GW. The model conceptualization derived from the IS allows to offer hints for a different GW protection strategy, while the dynamic analysis of the current system through the SDM leads to recalibrate the objectives of an integrated management of a shared resource, e.g. the current policy does not consider any (direct or indirect) strategy for increasing the GW cost. The analysis of this scenarios allowed us to demonstrate that the RA policy target (coherently with the Water Framework Directive), that is to significantly reduce the GW withdrawals by farmers (the target value is about the 20-40% of the actual value as discussed in Giordano et al. 2017), is unrealistic unless multiple protection measures are implemented ranging from GW withdrawals monitoring, to SW and GW pricing policies.

5 Discussion

SDM is currently considered as one of the most promising methodologies for understanding multi-DMPs within complex socio-environmental system. For the purposes of the present work, it has been used to provide direct insights in the processes related to WM in an agricultural context, coherently with the theoretical framework of the IS, aiming to support collective DMPs involving a CPR. The SDM proved to be capable of representing the complexity of WM issues, formalizing the behaviours of water users and managers, based both on field data and on the evidences of participatory modelling activities. It dynamically investigates the impacts of decisions on the whole system, identifying even the hidden feedbacks and loops that may affect system evolution. In such sense, SDM also revealed significant potentialities in the integrated analysis of different variables and dynamics. It is a transparent modelling approach aiming to describe the complex, multi-dimensional nature of WM and stakeholders can help develop the simulation model representing the system structure (e.g. Costanza and Ruth, 1998; Chen et al., 2014; Scott et al., 2016). Surely the whole methodology, i.e. from model conceptualization via IS to SDM development, represents an effective and comprehensive approach for supporting CPRs management. Particularly, the application of the IS framework integrated with the SDM approach, allows the analysts to deal with different stakeholders, formalizing a system structure and, consequently, helping them to be actively involved in a more inclusive decision-making, improving transparency of the process and increasing participation. Nevertheless, the developed stock and flow model is context-specific, and its replicability is strictly related to the specificities of the case study under consideration.

6 Conclusions

Challenges in WM have led to the need for developing methods for enhancing the understanding of interactions and interdependencies in multi-stakeholders DMP for an improved participatory management of CPRs. The SDM proposed in the present work aimed to represent 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' decision-making 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 his/her 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 WM policies, identifying critical feedbacks, aiming to enhance the understanding of the dynamic evolution of the system. Certainly, the research effort is not aimed to provide 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 WM and policy design.

Acknowledgements

The research activities described in this work was partially supported by Professors D. Borri and D. Camarda (Technical University of Bari, Italy) providing insights that assisted the research during the corresponding author's Ph.D. We would like to thank the institutional and non-institutional stakeholders that provided their knowledge and expertise at the base of this work.

Supplementary Material

The Supplementary Material section includes additional details related to the SDM developed. The key variables relating the IS with the SDM (Appendix I) and the full list of the equations used for the model (Appendix II) are included. The source files (.STM format, STELLA® ISEE Systems Inc.) are available upon request (please contact the corresponding author). Furthermore, the results of the sensitivity analysis are provided as well (Appendix III).

Appendix I – Model key variables

The following is the supplementary data related to the key variables connecting the IS and the SDM.

IS			SDM
Objects	**Actors**	**Resources**	**Variables**
$\boldsymbol{o}_1$ Environmental protection	a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level
			GW quantity
			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
			Unit GW cost
			GW withdraws monitoring
			SW cost additional and base volumes
		r_6 Illegal actions	GW volume taken
			Irrigation deficit
			Actual water requirement
			Unit GW cost
			SW cost additional and base volumes
			GW source preference
			GW withdraws monitoring
		r_8 Yield	Irrigated area/Cultivated (non-irrigated) 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
		r_3 Information flow	Water volume in the reservoir
			Water volume for irrigation
			Initial IC budget
	a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level
			GW quantity
			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
			Unit GW cost
			SW cost additional and base volumes
			GW source preference
			GW withdraws monitoring
		r_8 Yield	Irrigated area/Cultivated (non-irrigated) area
			Economic F’s budget
			Irrigation cost
	a_3 RA	r_2 Legislative constraints and regulations	GW quantity
			GW protection measures level
			GW withdrawals
$\boldsymbol{o}_5$ Decrease of GW	a_3 RA	r_2 Legislative constraints	GW protection measures level

overexploitation		and regulations	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
o 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
o 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
o Env. econ. and social sustainability of the agricultural activities	a_3 RA	r_2 Legislative constraints	GW quantity
		r_9 Control of the territory	GW protection measures level

Table A.1 – Key variables for the transition from model conceptualization via IS to the SDM model

Appendix II – Model equations

The full list of the equations characterizing the SDM is displayed in the following.

Global SDM (Figure 1 of the Manuscript)

Actual_SW_volume_taken = Farmer.Actual_SW_volume_taken
Additional_unit_SW_volume_available_for_farmer =
Irrigation_Consortium.Additional_unit_SW_volume_available_for_farmer
Base_SW_volume__available =
Total_farm_hectares*Irrigation_Consortium.Base_unit_SW_volume_available_for_farmer
Base_unit_SW_price = Irrigation_Consortium.Base_unit_SW_price
Consortium_Additional_unit_SW_price = Irrigation_Consortium.Additional_unit_SW_price
GW_withdrawals = Farmer.GW_withdrawals
Imposed_GW_availablity = 1-Regional_Authority.GW_protection_measures
Total_farm_hectares = 10

Irrigation Consortium Sub-model (Figure 2 of the Manuscript)

Consortium_budget(t) = Consortium_budget(t - dt) + (Farmer_payment__for_irrigation + Yearly_fee - Fix_Management_cost) * dt
INIT Consortium_budget = 0
INFLOWS:
Farmer_payment__for_irrigation =
Base_unit_SW_volume_available_for_farmer*Base_unit_SW_price+(.Actual_SW_volume_taken-Base_unit_SW_volume_available_for_farmer)*Additional_unit_SW_price
Yearly_fee = .Total_farm_hectares*15.5
OUTFLOWS:
Fix_Management_cost = 8000

Water_volume_in__the_reservoir(t) = Water_volume_in__the_reservoir(t - dt) + (Inflow - Outflow__irrigation - Outflow_potable) * dt
INIT Water_volume_in__the_reservoir = 50000000
INFLOWS:

Inflow = GRAPH(TIME)
(0.00, 1.7e+008), (1.11, 6.9e+007), (2.22, 4.5e+007), (3.33, 1e+008), (4.44, 3e+008), (5.56, 2.4e+008), (6.67, 3.6e+008), (7.78, 2.7e+008), (8.89, 5.8e+007), (10.00, 1.2e+008)
OUTFLOWS:
Outflow__irrigation = Water_volume_in__the_reservoir-Outflow_potable
Outflow_potable = Population*Water_per_person
Additional_unit_SW_price = IF Additional_unit_SW_volume_available_for_farmer>0 THEN 2*Base_unit_SW_price ELSE 4*Base_unit_SW_price

Additional_unit_SW_volume_available_for_farmer = IF Initial_Consortium__irrigation_budget>0 THEN 1000 ELSE 0
Base_unit_SW_price = 0.12
Base_unit_SW_volume_available_for_farmer = IF Initial_Consortium__irrigation_budget>0 THEN 2050 ELSE 600
Expected_water_demand = 15000000
Initial_Consortium__irrigation_budget = Water_volume_for_irrigation-Expected_water_demand
Population = 240000
Water_per_person = 250
Water_volume_for_irrigation = Outflow__irrigation

Farmer Sub-model (Figure 3 of the Manuscript)

Add_SW_taken(t) = Add_SW_taken(t - dt) + (Add_SW_In - Add_SW_out) * dt
INIT Add_SW_taken = 0
TRANSIT TIME = 1
INFLOW LIMIT = INF
CAPACITY = 1000
INFLOWS:
Add_SW_In = .Additional_unit_SW_volume_available_for_farmer*(1-GW_source__preference)
OUTFLOWS:
Add_SW_out = CONVEYOR OUTFLOW

Cultivated__areas(t) = Cultivated__areas(t - dt) + (Decreasing - Increasing) * dt
INIT Cultivated__areas = 5
INFLOWS:
Decreasing = IF Economic_budget<=0 OR Irrigation_deficit>0.1 THEN (Irrigated_area/Farmers'_perception__of_price*Irrigation_deficit) ELSE 0
OUTFLOWS:
Increasing = IF Economic_budget>1000 AND Irrigation_deficit<0.1 THEN (Cultivated__areas*Farmers'_perception__of_price/10) ELSE 0

Irrigated_area(t) = Irrigated_area(t - dt) + (Increasing - Decreasing) * dt
INIT Irrigated_area = 5
INFLOWS:
Increasing = IF Economic_budget>1000 AND Irrigation_deficit<0.1 THEN (Cultivated__areas*Farmers'_perception__of_price/10) ELSE 0
OUTFLOWS:
Decreasing = IF Economic_budget<=0 OR Irrigation_deficit>0.1 THEN (Irrigated_area/Farmers'_perception__of_price*Irrigation_deficit) ELSE 0

Actual_SW_volume_taken = IF Water_balance >0 THEN .Base_SW_volume__available+Add_SW_out ELSE Actual_water_requirement

Actual_water_requirement = Irrigated_area*6000+Cultivated__areas*400
Additional_SW_cost = Add_SW_out*.Consortium_Additional_unit_SW_price
Additional_water_volume_needed = Water_balance
Economic_budget = Subsidies+(DELAY1(Cultivated__areas,1)*500+DELAY1(Irrigated_area,1)*10000)-(Irrigation_cost*10+Other_costs)
Farmers'_perception__of_price = MEAN(DELAY(Prices_in_the__market, 1), DELAY(Prices_in_the__market,2), DELAY(Prices_in_the__market, 3))/MEAN(Prices_in_the__market)
Final_Farmer_irrigation_budget = Total_SW_GW_volume_taken-Actual_water_requirement
GW_cost = Unit_GW_cost*GW__volume_taken
GW_source__preference = IF(Unit_GW_cost<.Consortium_Additional_unit_SW_price) THEN 0.9-GW_withdrawals_monitoring/2 ELSE (.Consortium_Additional_unit_SW_price/Unit_GW_cost)*.Imposed_GW_availablity*(1-GW_withdrawals_monitoring)*0.9
GW_withdrawals = GW__volume_taken
GW_withdrawals_monitoring = 0.1
GW__volume_taken = IF (Additional_water_volume_needed-Add_SW_out)>0 THEN (Additional_water_volume_needed-Add_SW_out)*GW_source__preference ELSE 0
Irrigation_cost = (.Base_SW_volume__available*.Base_unit_SW_price)+GW_cost+Additional_SW_cost
Irrigation_deficit = ABS(Final_Farmer_irrigation_budget/Actual_water_requirement)
Other_costs = 0
Subsidies = 0
Total_SW_GW_volume_taken = Actual_SW_volume_taken+GW__volume_taken
Unit_GW_cost = 0.18
Water_balance = IF (Actual_water_requirement-.Base_SW_volume__available)>0 THEN (Actual_water_requirement-.Base_SW_volume__available) ELSE 0
Prices_in_the__market = GRAPH(TIME)
(0.00, 179), (1.11, 185), (2.22, 188), (3.33, 158), (4.44, 207), (5.56, 201), (6.67, 223), (7.78, 237), (8.89, 254), (10.00, 200)

<u>Regional Authority Sub-model (Figure 4 of the Manuscript):</u>

GW_quantity(t) = GW_quantity(t - dt) + (Increasing - Decreasing) * dt
INIT GW_quantity = 50
INFLOWS:
Increasing = 0.1*GW_protection_measures_level*Pressure_for_protection_measures*GW_quantity
OUTFLOWS:
Decreasing = (.GW_withdrawals/10000)

GW_protection_measures = GW_protection_measures_level
GW_protection_measures_level = 0.1
Pressure_for_protection_measures = 50/GW_quantity

Appendix III – Sensitivity Analysis

The sensitivity analysis was performed with respect to a relevant subset of parameters, through the Sensitivity Specs dialog box available in *Stella*® (ISEE Systems Inc.). The sensitivity analysis aims to verify to what extent the model is capable to describe the impact of the variation of specific variables on some key dynamics (Mateus and Franz 2015, Pagano et al. 2017). It is worth considering that the sensitivity analysis is a highly useful process to evaluate the contribution of specific input parameters on model behavior, identifying the most influential ones. Nevertheless, this kind of analysis might be significantly complex in case several different parameters have to be jointly taken into consideration. Furthermore, it should be also considered that isolating individual parameters might partially hide the complexity of the system under investigation, which is instead well described by the developed SDM.

The sensitivity analysis proposed in the present section refers to some key variables of the model, whose relevance is widely discussed in the manuscript, under the assumption that all the other variables are kept in their BAU state. Specifically: a) focusing on the 'Regional Authority' sub-model, the analysis of the changes in the 'GW quantity' according to the 'GW protection measures level' and the 'GW withdrawals' (from 0 to 60000 m^3) was performed. Results are provided in the following Figures S1 and S2; b) focusing on the 'Farmers' sub-model, the variation of 'Irrigated areas' according to changes in 'Base unit SW price', 'Consortium additional unit SW price' and 'Unit GW cost' is proposed in the following Figures S3, S4 and S5 respectively.

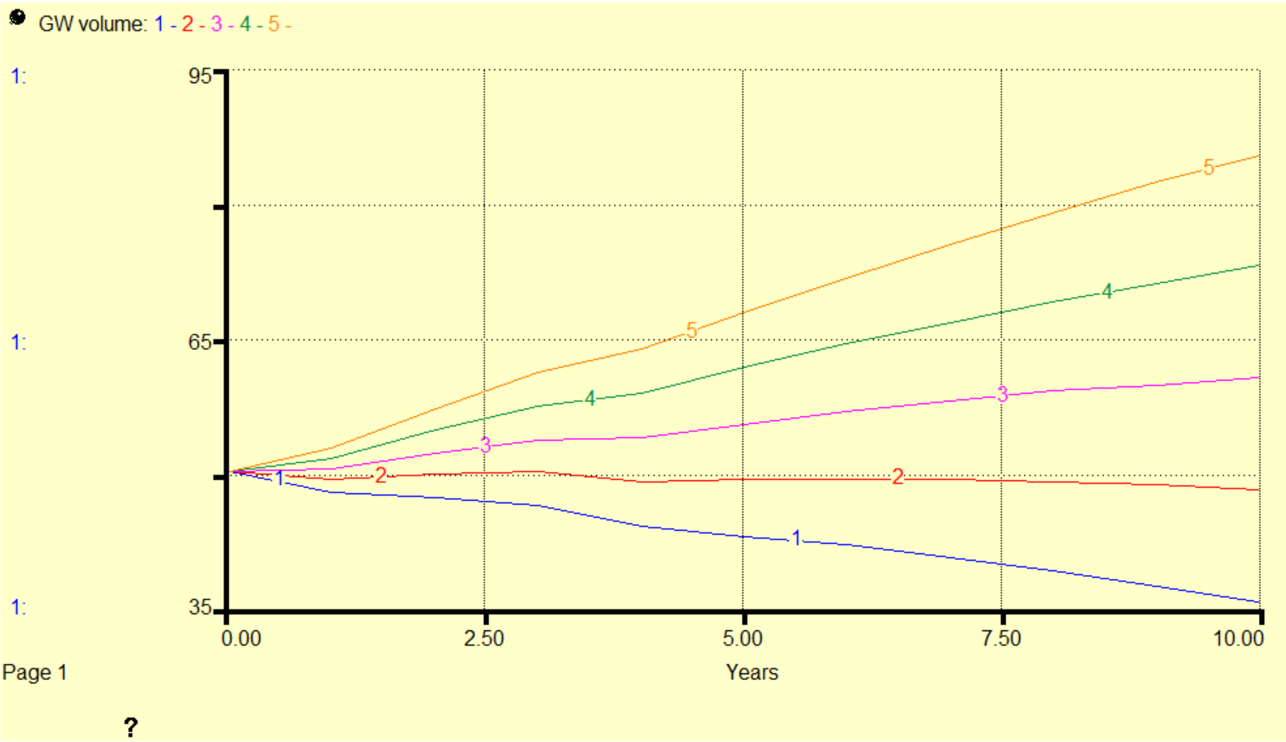


Figure S1 – Sensitivity analysis focused on the 'GW volume' in the RA sub-model. The variation of the 'GW protection measures level' from 0 (run 1) to 1 (run 5) is analyzed.

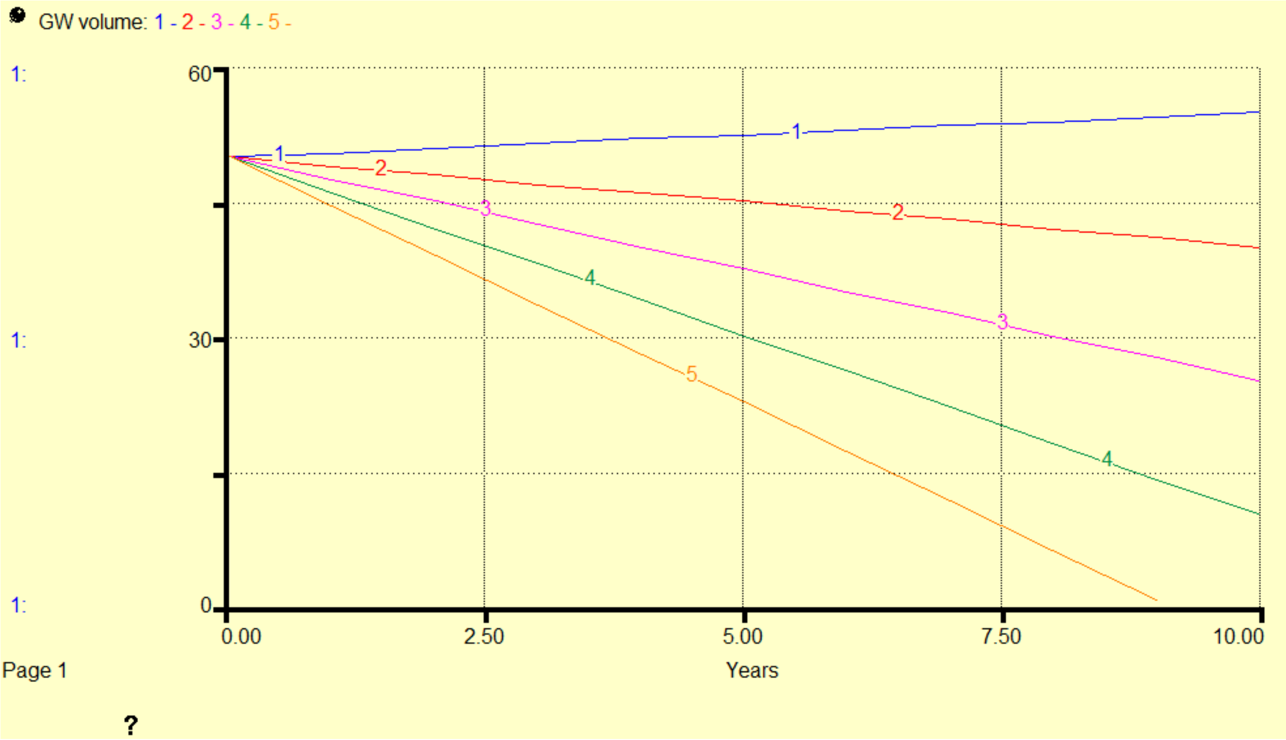


Figure S2 – Sensitivity analysis focused on the 'GW volume' in the RA sub-model. The variation of the 'GW withdrawals' from 0 (run 1) to 60000 m^3 (run 5) is analyzed.

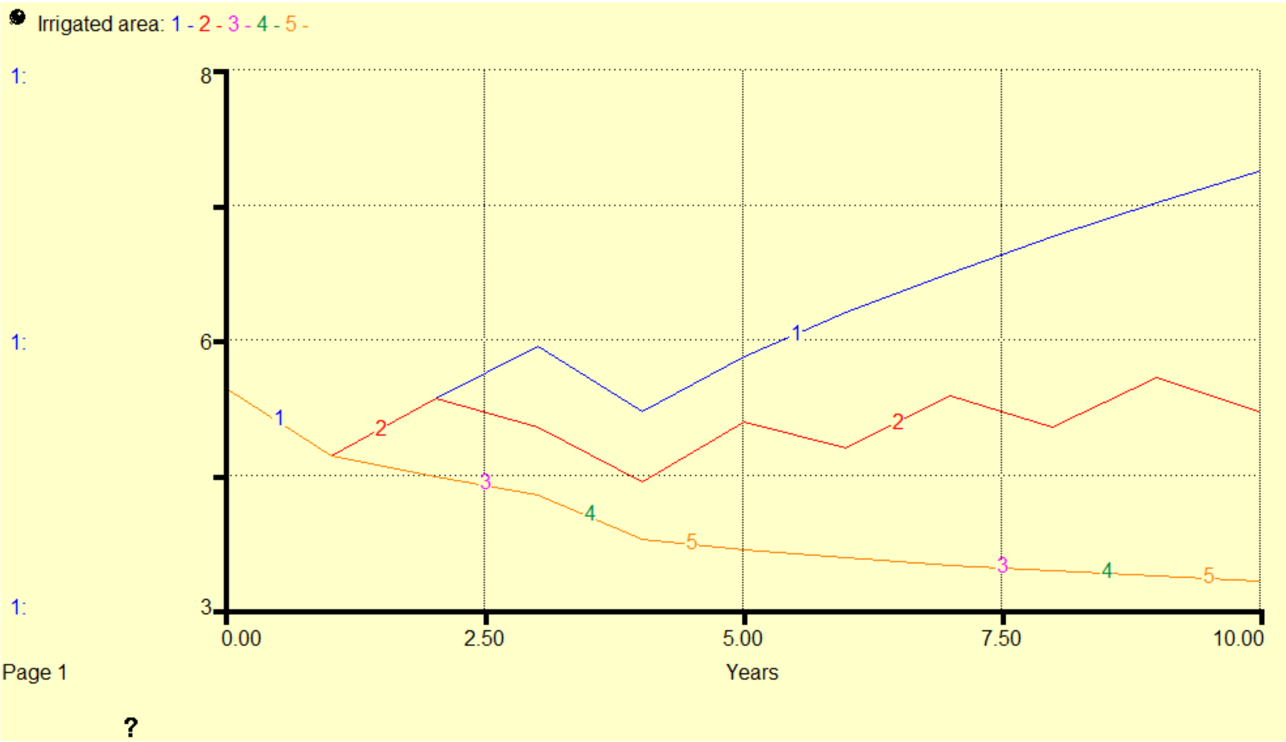


Figure S3 – Sensitivity analysis focused on the 'Irrigated area' in the 'Farmers' sub-model. Variation of the 'Base unit SW price' from 0.05 (run 1) to 0.5 (run 5).

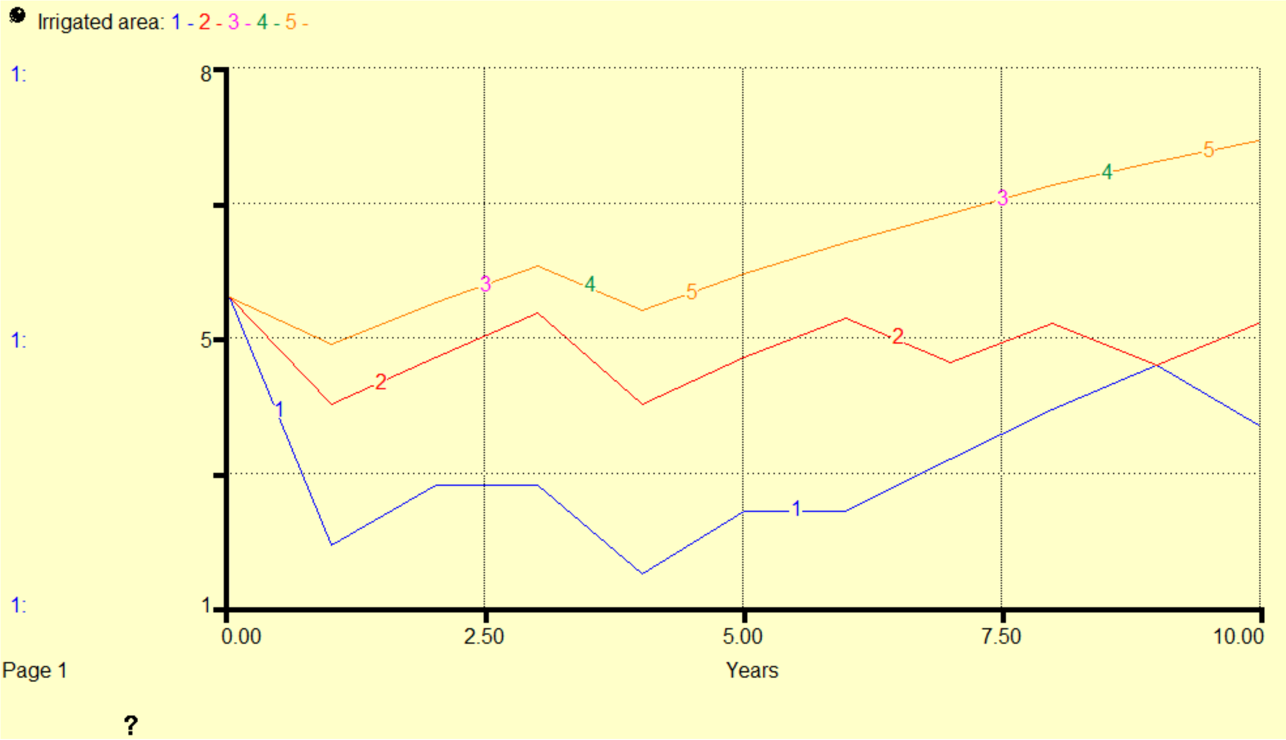


Figure S4 – Sensitivity analysis focused on the 'Irrigated areas' in the 'Farmers' sub-model. Variation of the 'Additional unit SW price' from 0.1 (run 1) to 0.5 (run 5).

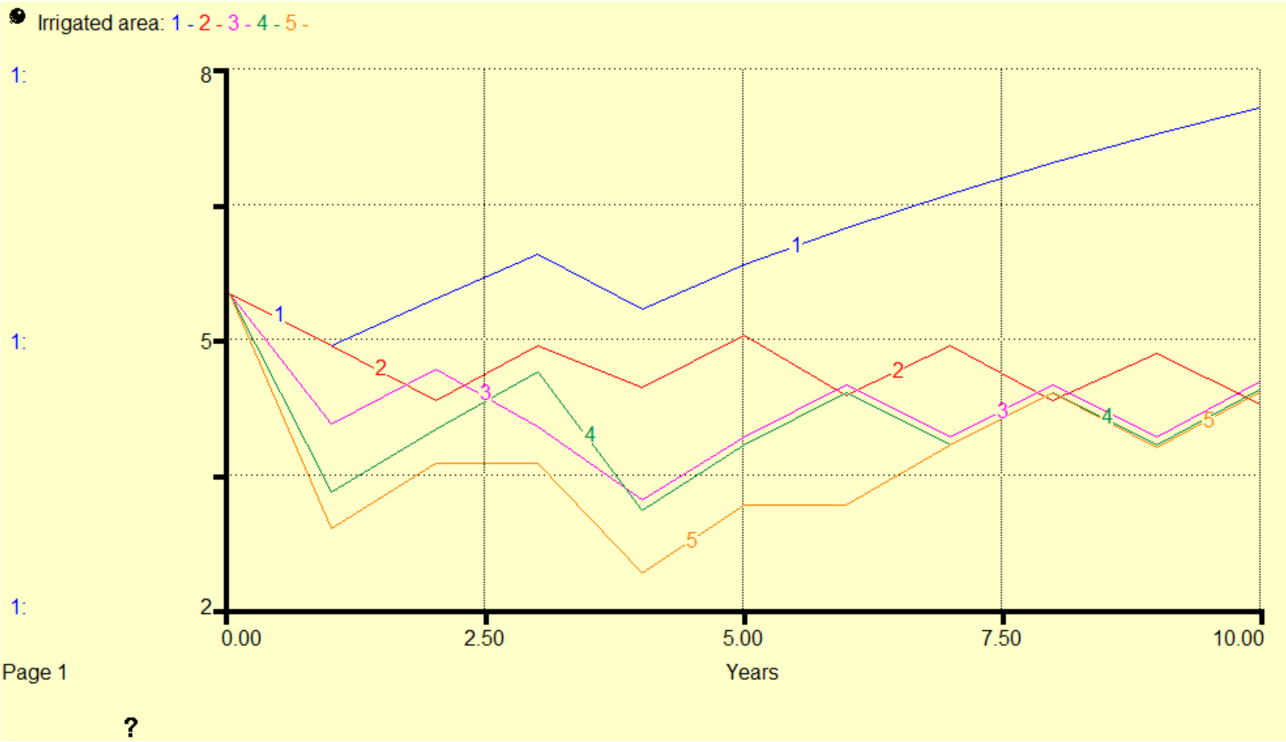


Figure S5 – Sensitivity analysis focused on the 'Irrigated area' in the 'Farmers' sub-model. Variation of the 'Unit GW cost' from 0.1 (run 1) to 1 (run 5)

The sensitivity analysis was highly helpful for the process of model validation and calibration, and supported underlining the role of crucial variables, also on dynamics that are generally ignored or partially neglected by the other agents. More specific scenarios are discussed in the manuscript.

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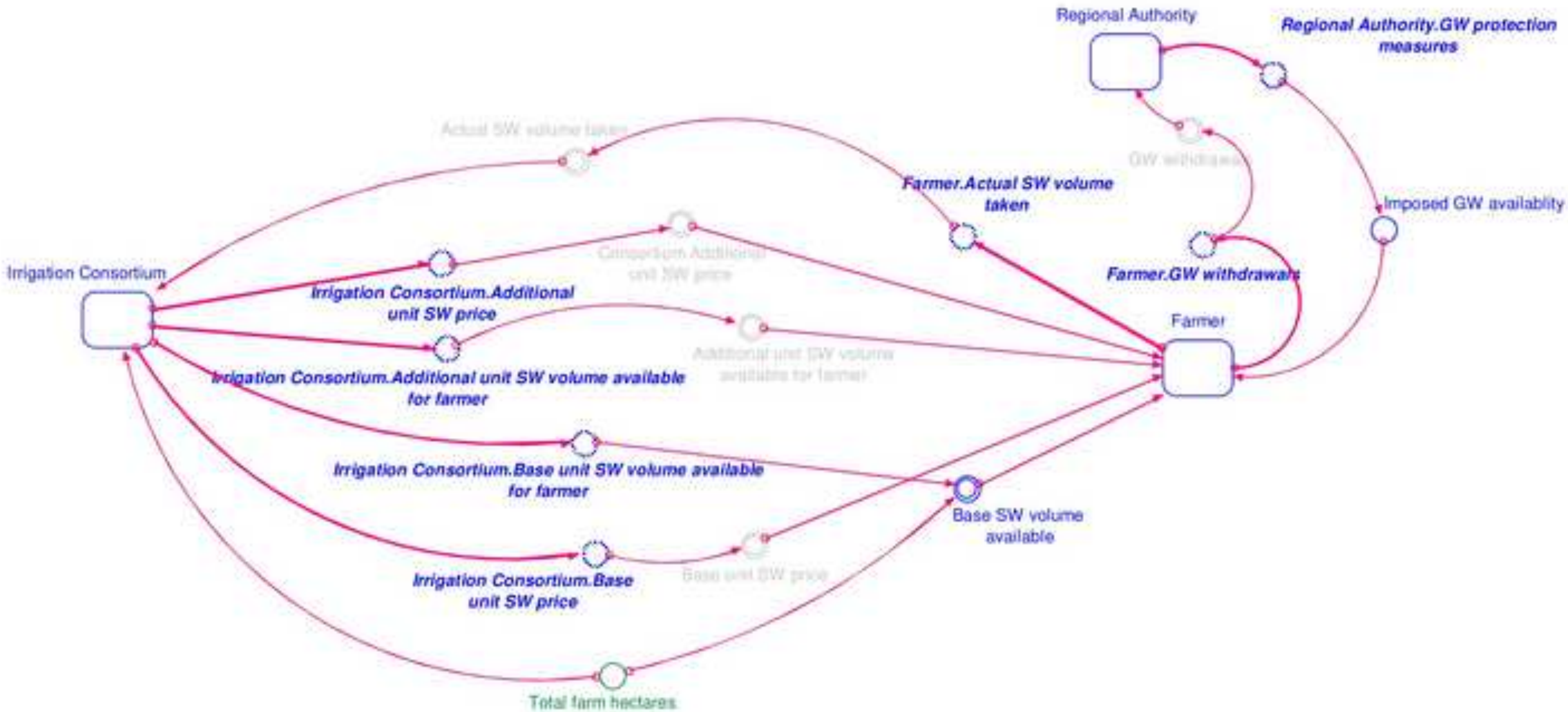

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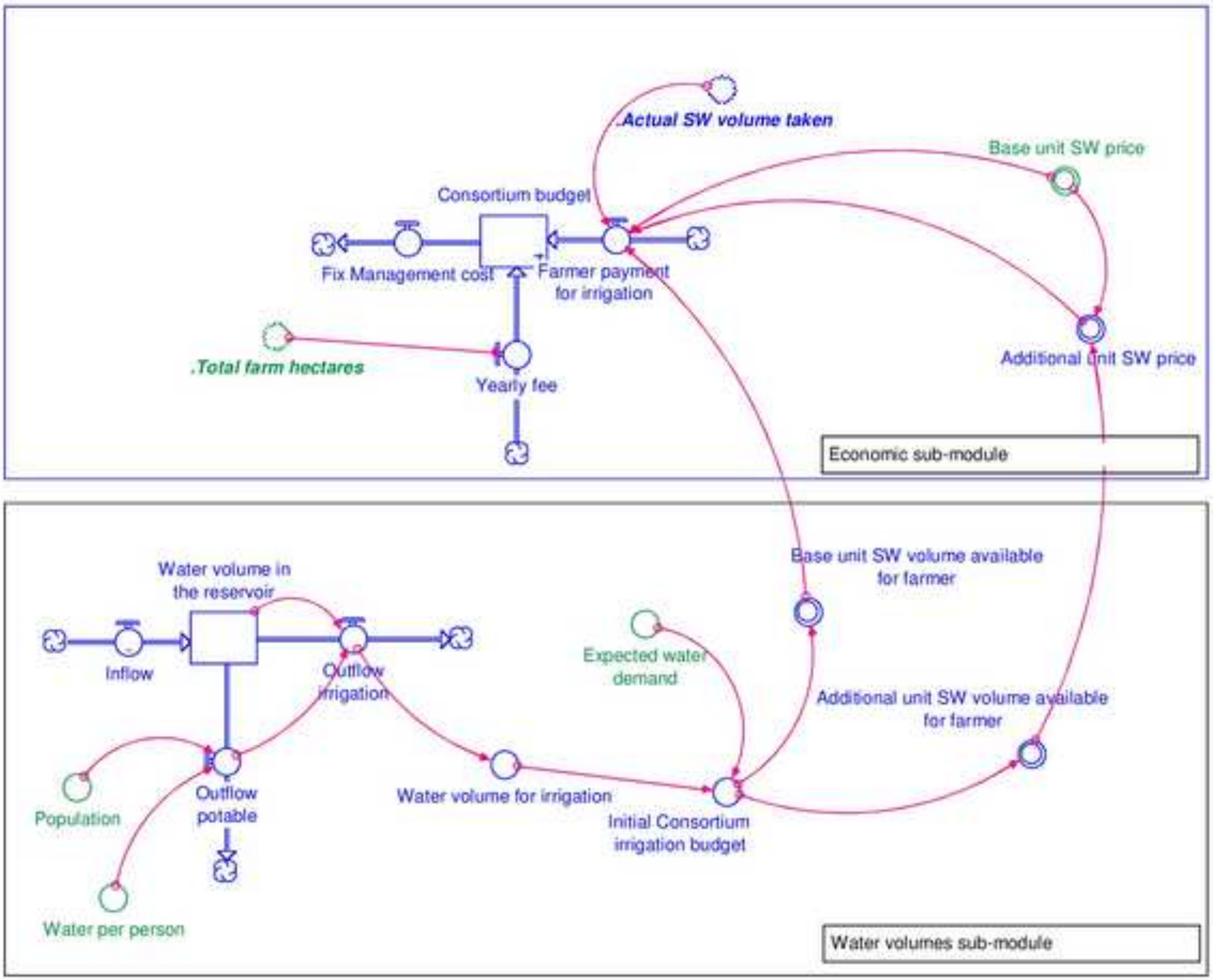

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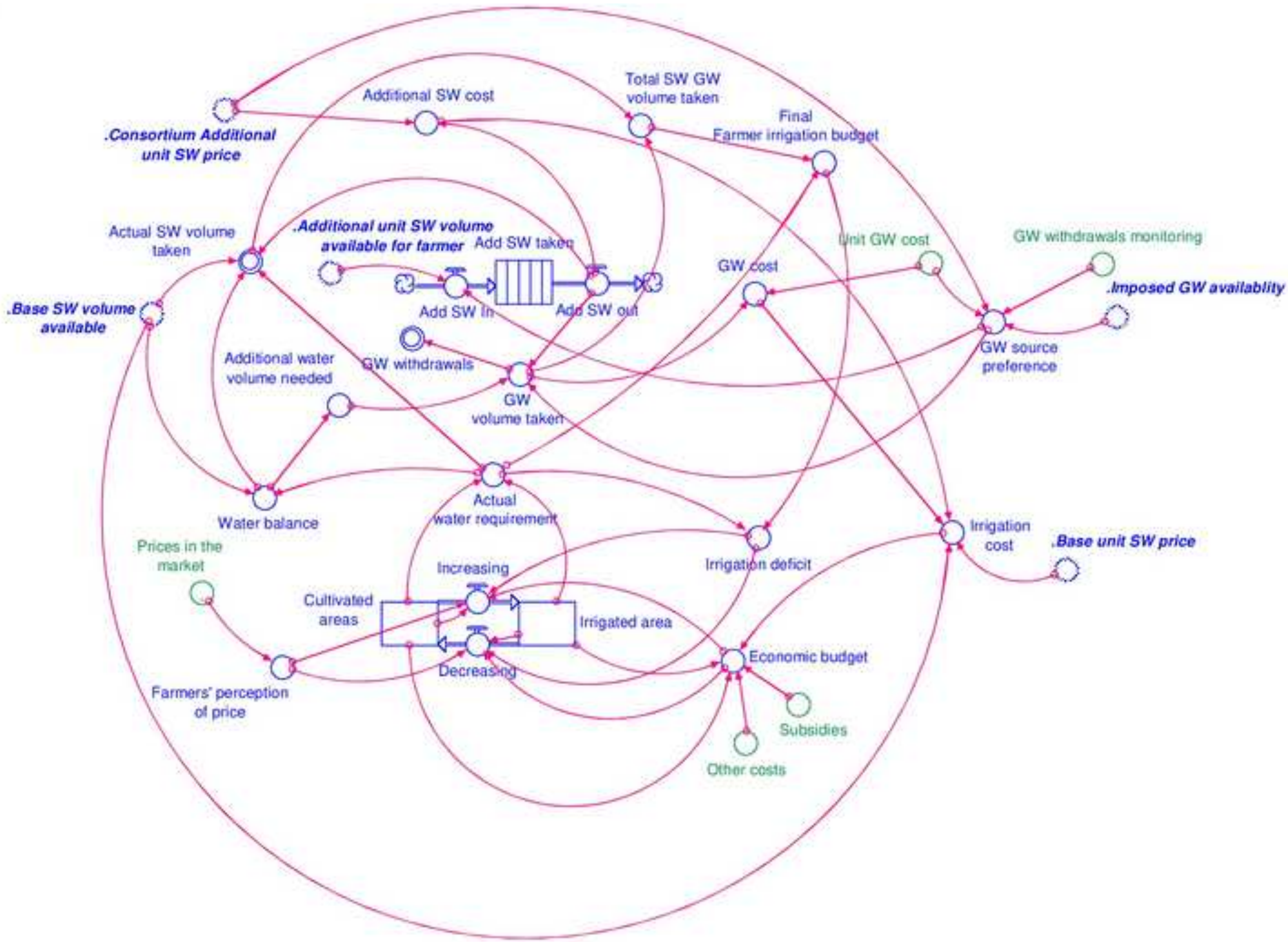

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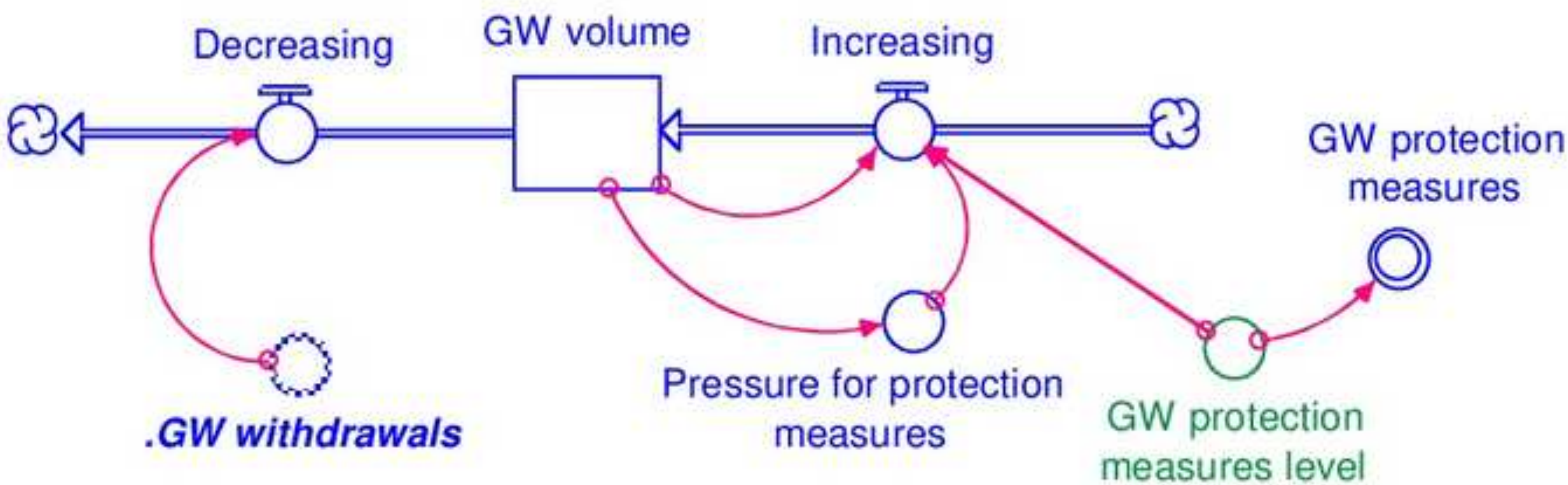

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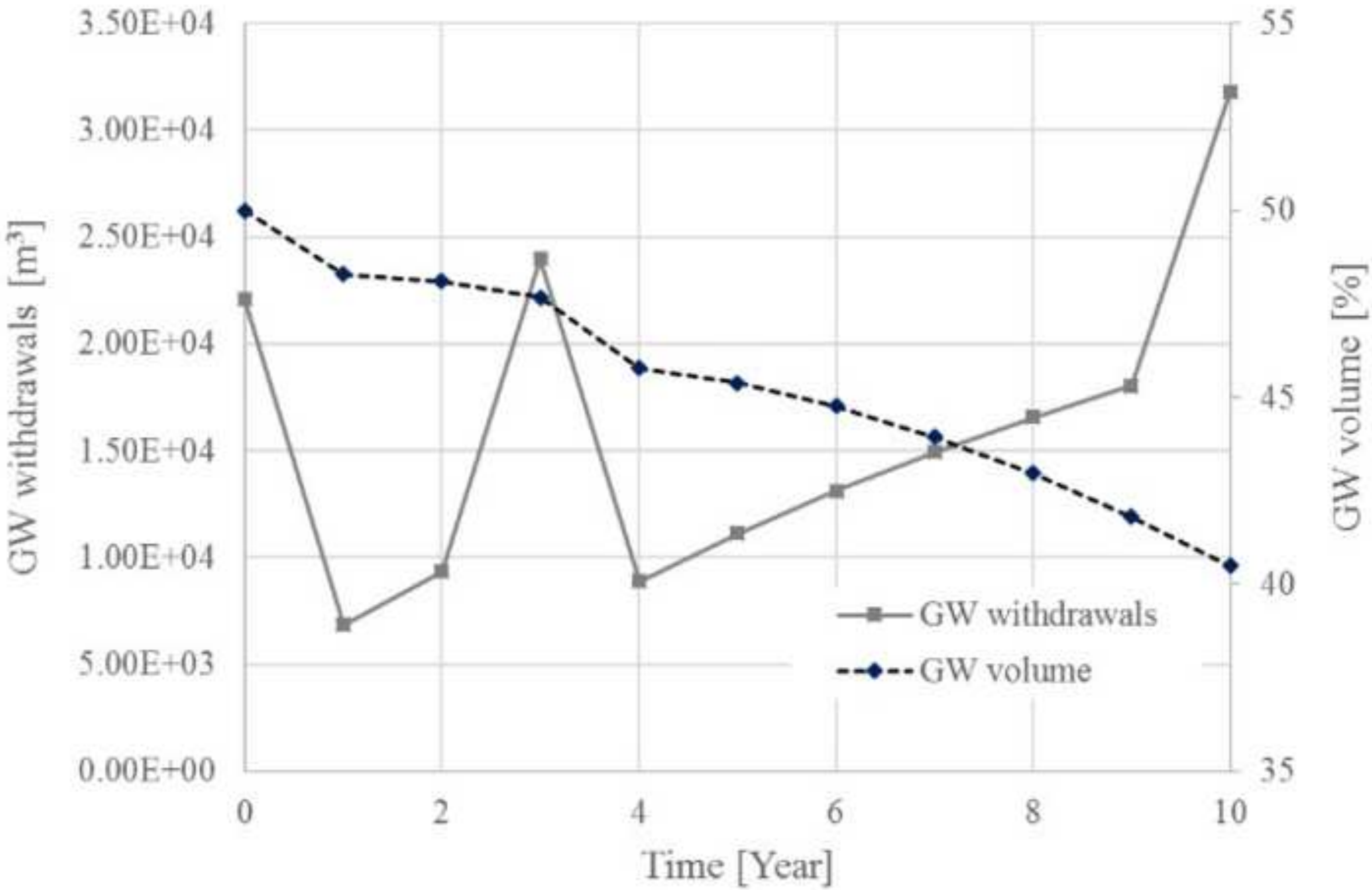

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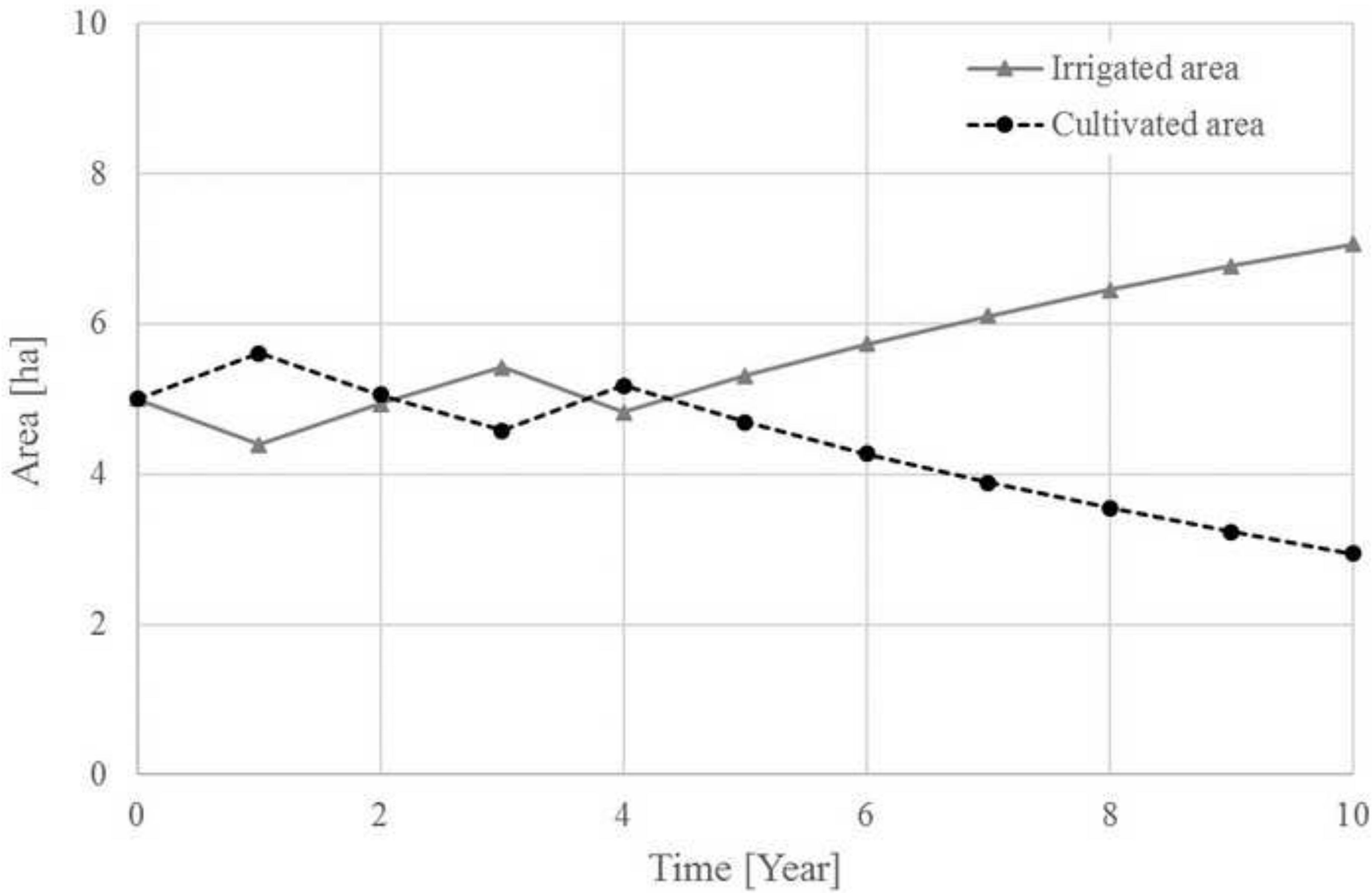

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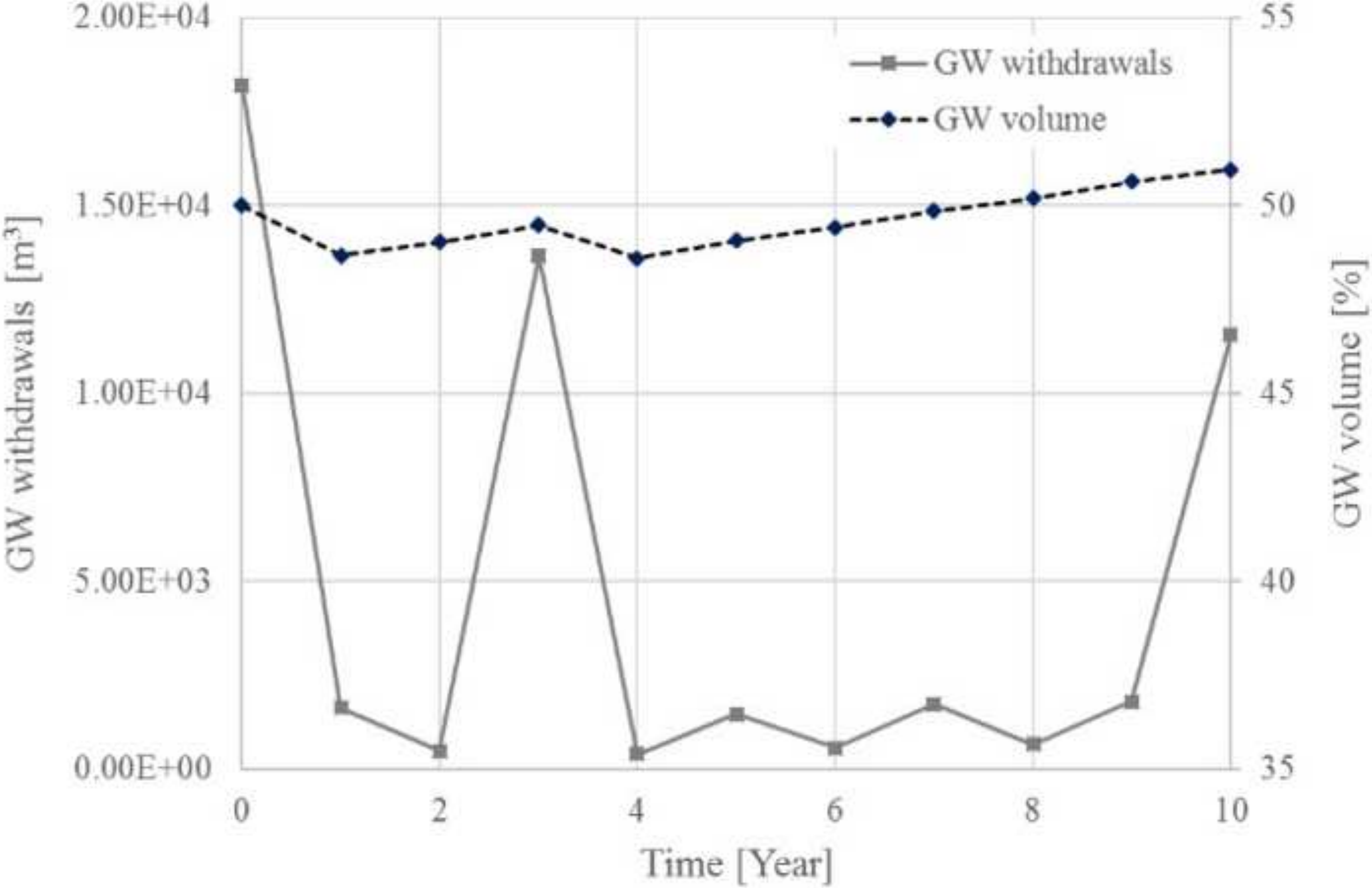

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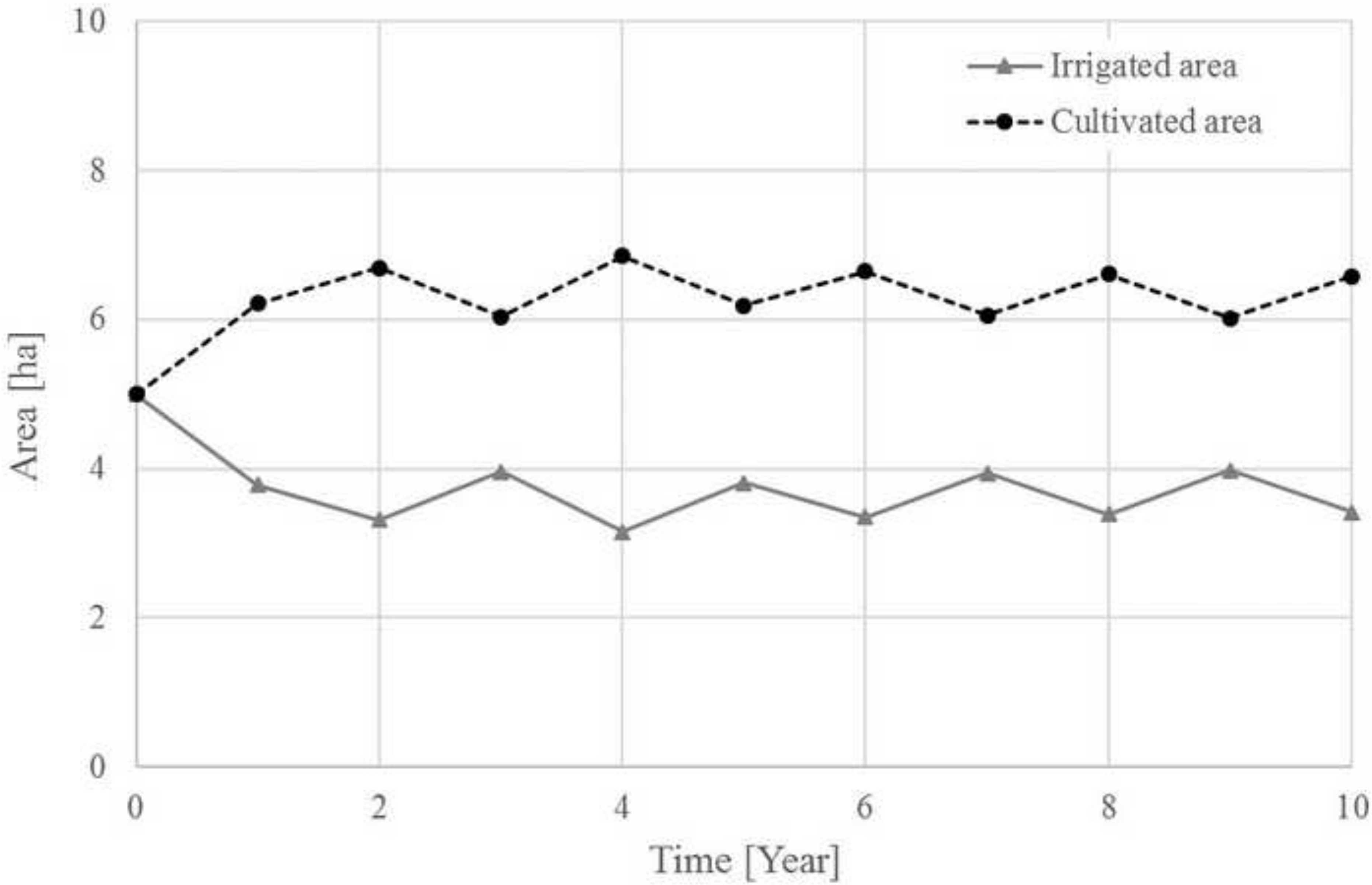

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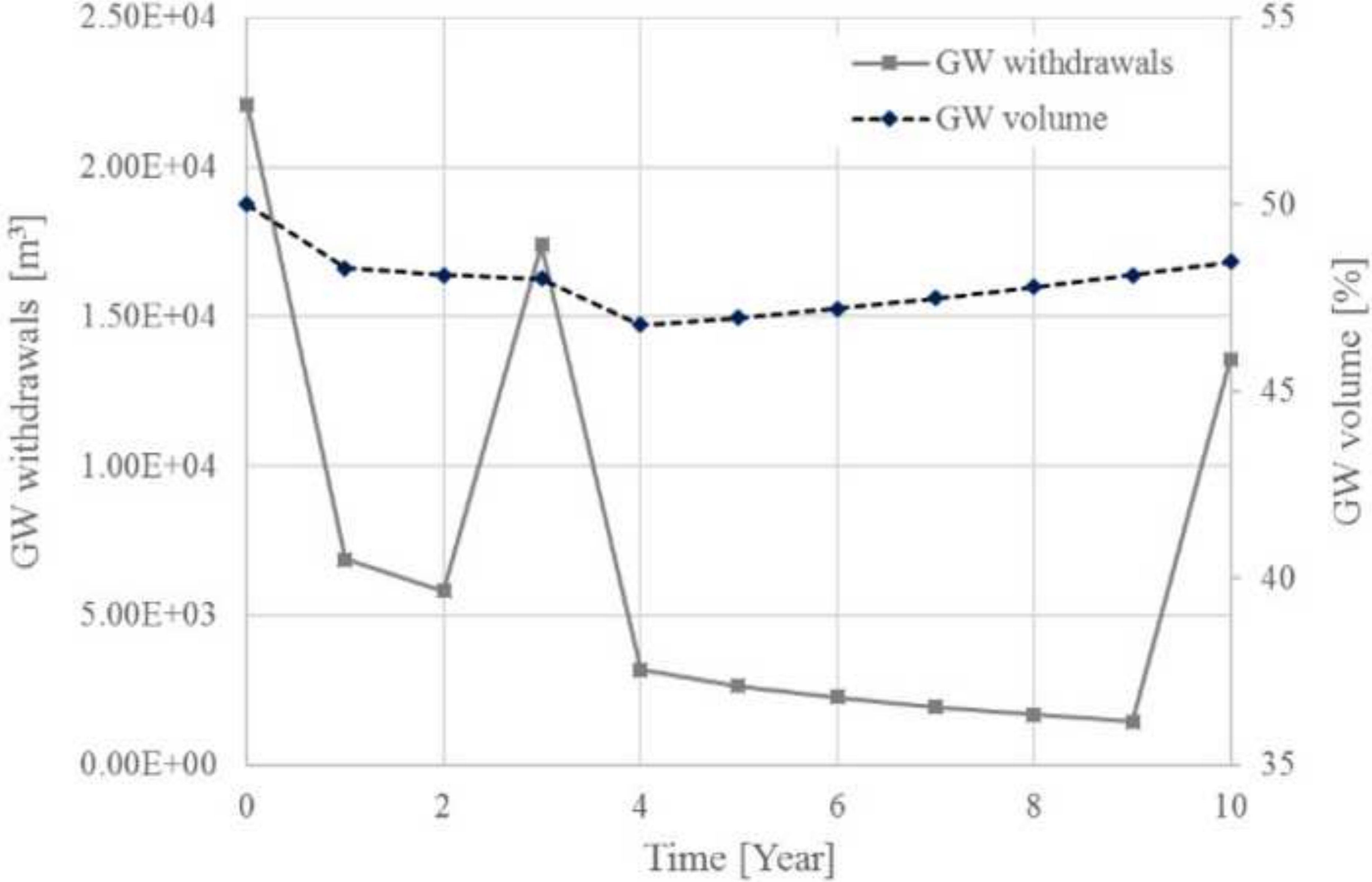

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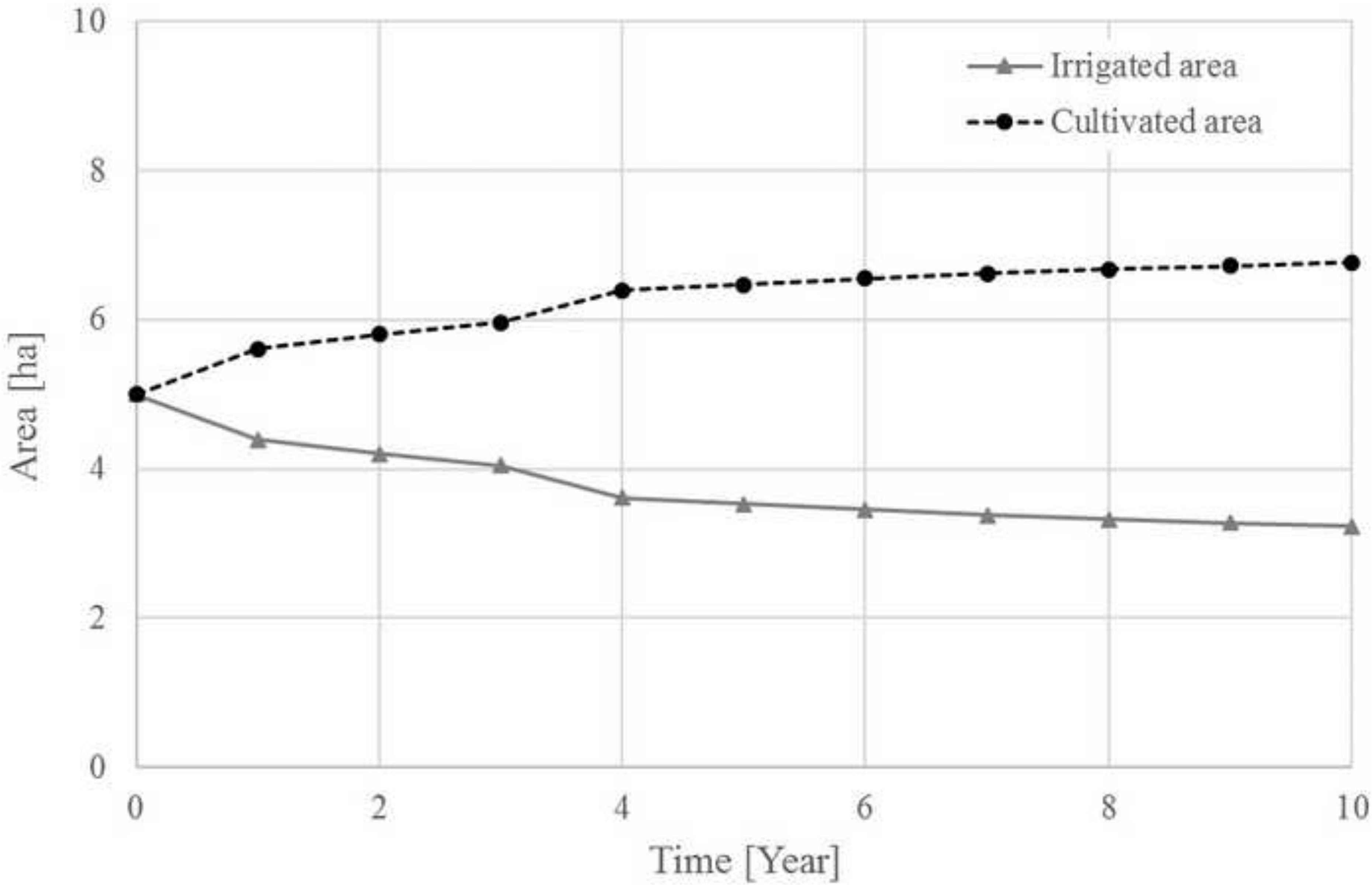

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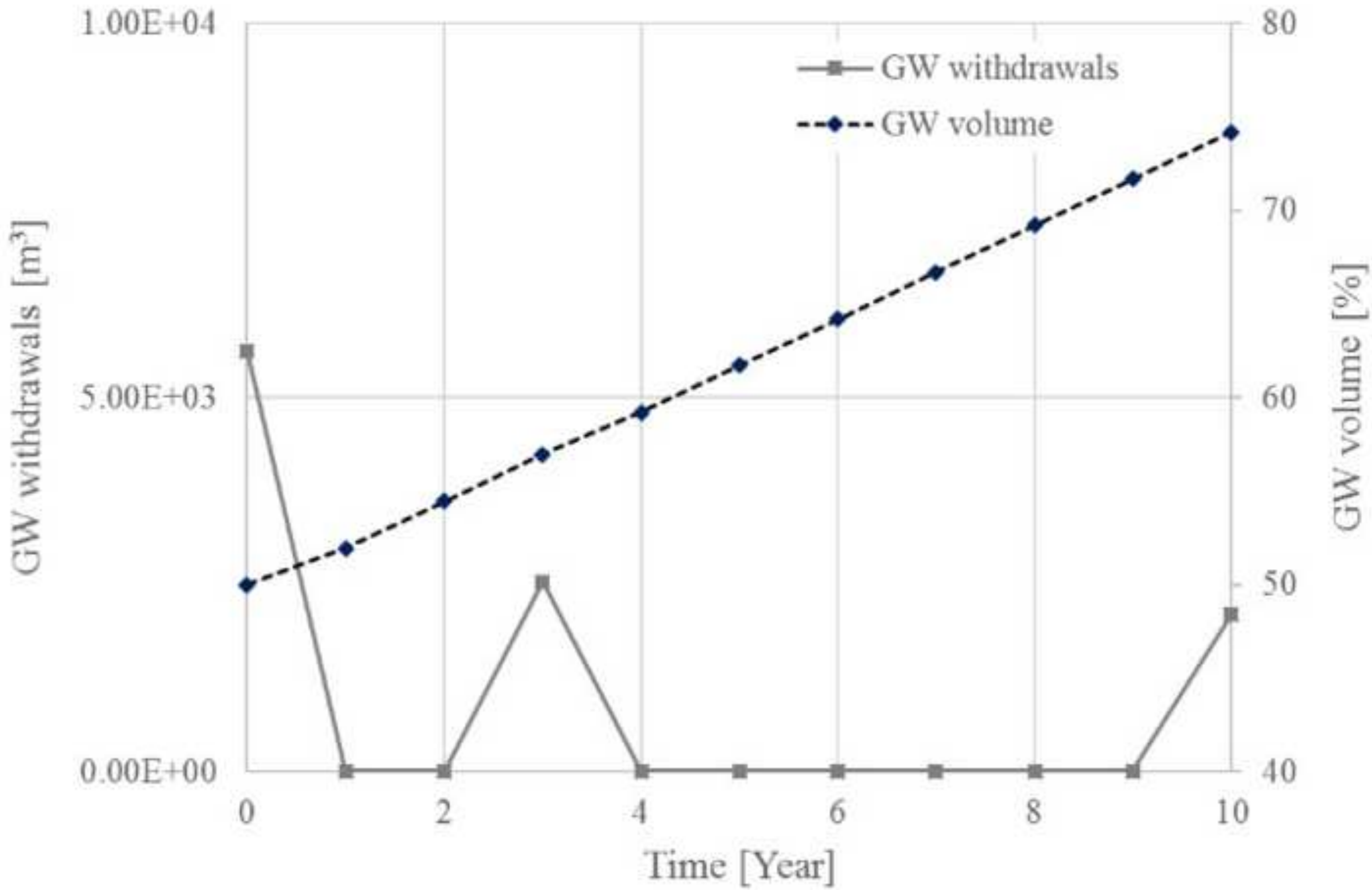

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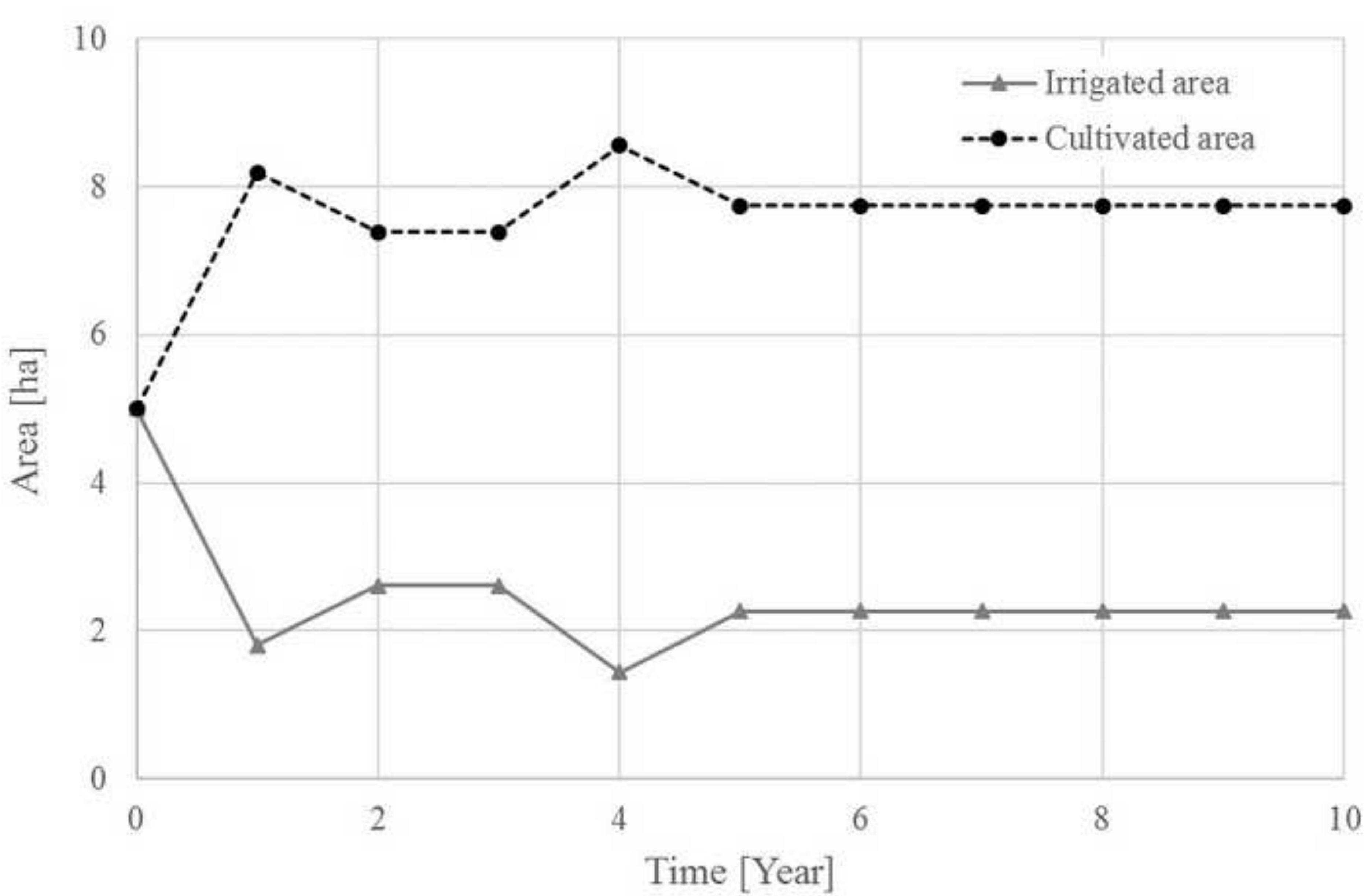

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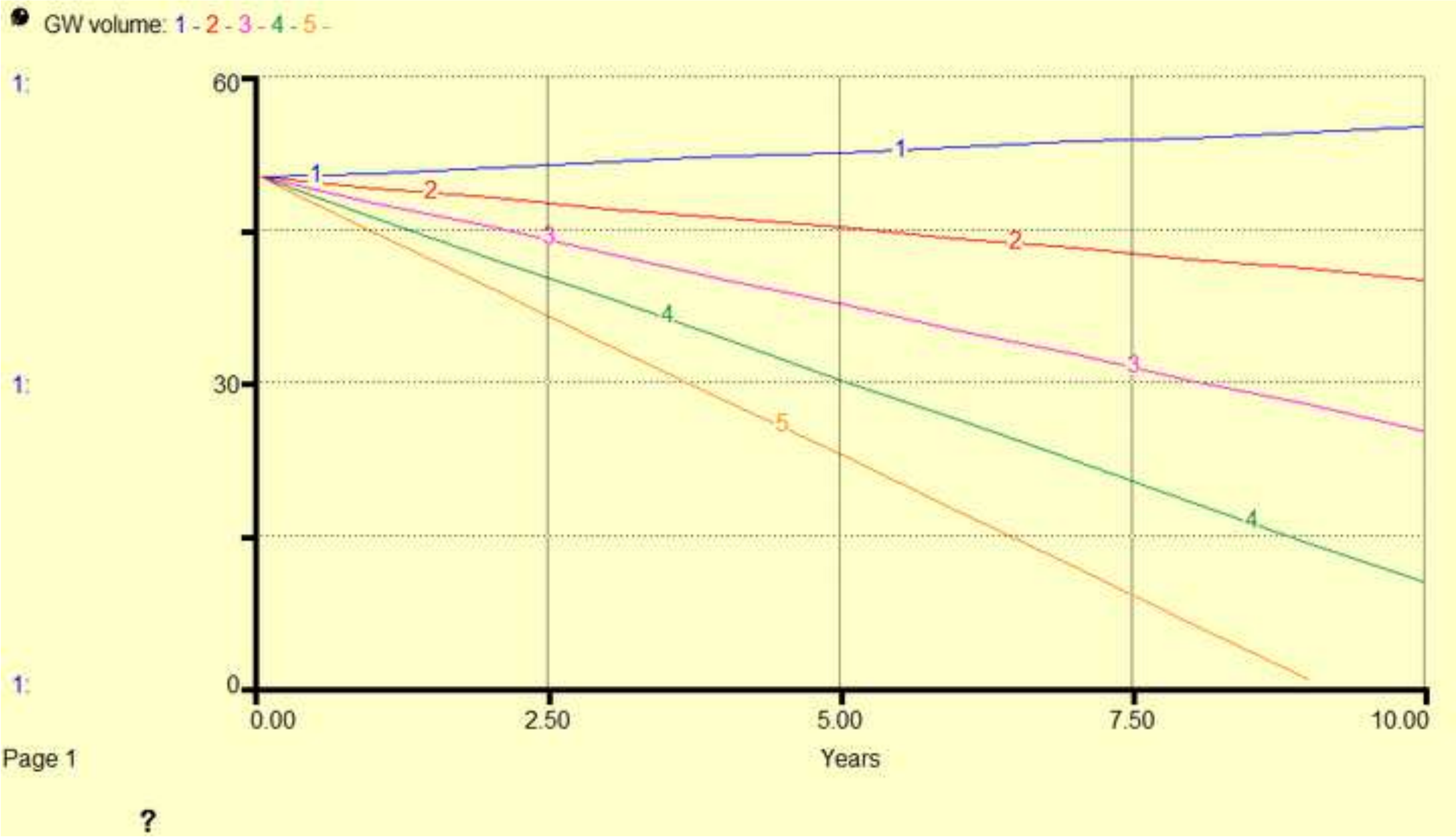

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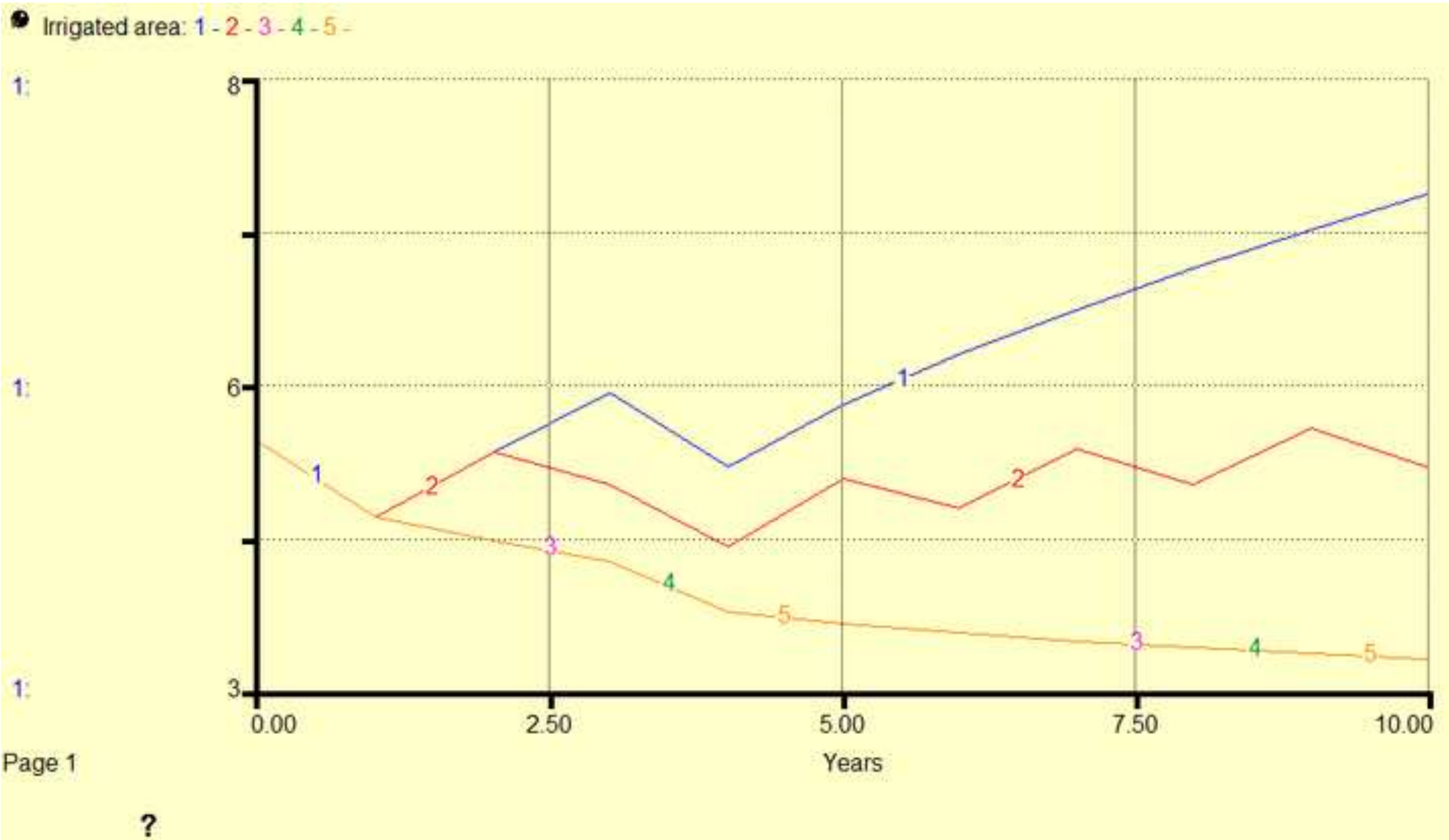

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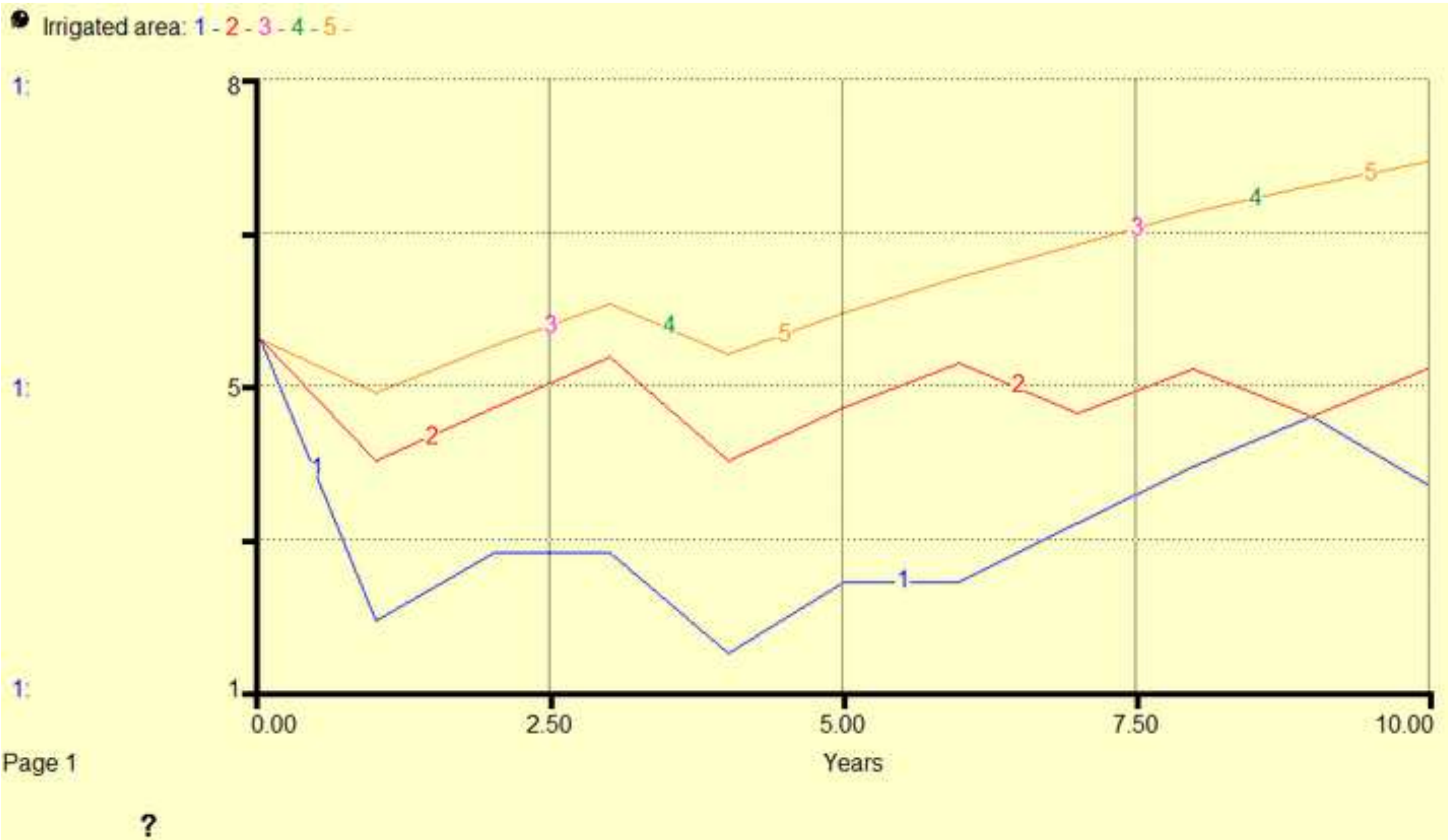

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