

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

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Abstract

1 Water management is a controversial environmental policy issue, due to the heterogeneity of interests
2 associated with a shared resource and the increasing level of conflict among water uses and users.
3 Nowadays, there is a cumulative interest in enhancing multi-stakeholder decision-making processes,
4 overtaking binding mercantile business, in water management domain. This requires the development of
5 dynamic decision-aiding tools able to integrate the different problem frames held by the decision makers, to
6 clarify the differences, to support the creation of collaborative decision-making processes and to provide
7 shared platforms of interactions. In literature, these issues are faced by concepts such as Ostrom’s action
8 arena and Ostanello-Tsoukiàs’ interaction space (IS). The analysis of the interactions structure and of the
9 different problem framing involved are fundamental premises for a successful debate for the management of
10 a common-pool resource. Specifically, the present paper suggests a dynamic evolution of the IS, highlighting
11 its criticalities. It develops an alternative perspective on the problem, using a System Dynamics Model
12 (SDM), exploring how different actions can influence the decision-making processes of various stakeholders
13 involved in the IS. The SDM has been implemented in a multi-stakeholders decision-making situation in
14 order to support water management and groundwater protection in the agricultural systems in the Capitanata
15 area (Apulia region, Southern Italy).
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1 Water management complexity: the need of stakeholders' participation

1 Water management (WM) is an important environmental policy issue. It faces numerous problems such as
2 the disparity of interests, multiple decision-makers, complex networks of governance and distribution,
3 intensive socio-economic development and climate change concerns (Daniell et al., 2010; FAO, 2012; Lewis
4 et al., 2017). The management of a limited and shared resource is a complex challenge (Hess & Ostrom
5 2003), often introducing conflicts especially within the agricultural sector in semi-arid regions (Chen, 2017;
6 Sishodia et al., 2016; Knox et al., 2016; Rey et al., 2017). The resulting impacts on the environment may
7 vary depending on the contribution of intensified agriculture, such as groundwater depletion, reduced surface
8 flows, salt water intrusion, and loss of wetlands (Sishodia et al. 2016).

9 Water, particularly in the sense of its availability for irrigation, is one of the most extensively studied types
10 of common-pool resource (CPR) (Sarkera et al., 2009). As a CPR linked to basic human needs and
11 geographically highly distributed, water is used by several competing actors and owned by no one. When
12 decision-makers are completely independent from each other, interacting solely by the fact that they use the
13 same resource, the problems of overexploitation and free-riding arise.

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

20 The above-mentioned issues generate the need to enhance decision-aiding methodologies within inclusive
21 participatory modelling activities (e.g. Chen et al., 2014; Voinov et al., 2016), allowing stakeholders to
22 participate in the decision-making process (DMP) and to provide their own knowledge (Giordano et al.
23 2007), leading to an effective management (Hare et al., 2003; Carmona et al., 2015; Kotir et al., 2017). The
24 role of participatory frameworks in WM has been also established by the European Water Framework
25 Directive (CEE2000/60), which strongly encourages the active involvement of all the affected parties (Pahl-
26 Wostl 2015). It enriches DMPs mapping out diversity of problem frames (Brugnach and Ingram, 2012;
27 Hassenforder et al., 2016; Giordano et al., 2017) in order to: i) explicitly challenge stakeholders' values; ii)
28 facilitate dialogue across multiple tiers of governance; and iii) establish a shared management process for
29 CPRs (Smajgl 2010). Surely, a DMP with public actors and CPRs generates unpredictable scenarios because
30 of the competing interacting decision-makers (Tsoukiàs, 2007; Daniell, et al., 2016; De Marchi et al., 2016).
31 While these interactions among a diversity of participants may contribute to the development of beneficial
32 adaptive behaviours, they can also provoke unexpected reactions, since the choices of an individual actor
33 may not necessarily be aligned with the viewpoints, expectations or possibilities held by the others
34 (Brugnach and Ingram, 2012; Giordano et al., 2017). This can lead to dysfunctional dynamics, such as policy
35 resistance mechanisms, i.e. the tendency for interventions to be defeated by the response of the system to the
36 intervention itself (Sterman 2000). Under such a perspective, decision-aiding tools involving multiple
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1 stakeholders should be capable to: i) integrate the differences among stakeholders' problem framing, ii)
2 provide shared platforms to set up the process of debate, iii) reconstruct the connections between such
3 platforms and engaged interactions.

4 Starting from these premises, the present work aims to develop an alternative perspective on the problem by
5 using a System Dynamics Model (SDM) to operationalize the existing debating formal structures such as the
6 interaction space (Ostanello and Tsoukiàs, 1993), leading to reflections on how the establishment of local
7 regulations and rationalities may support managing commons-goods and facilitate stakeholders'
8 consultations. This work aims to answer two important research questions: i) to what extent does the analysis
9 of the interaction frames affecting decision-actors behaviors may improve common-goods management? ii)
10 Is the SDM a suitable tool to operationalize the IS and to analyse its dynamic nature?

11 The developed SDM intends to: i) explore the different viewpoints, and potentially conflicting objectives of
12 multiple decision-makers; ii) describe the complexity of their interactions, and the multi-dimensional impacts
13 of specific decisions, particularly focusing on those that might have unintended impacts also on the others.
14 Lastly, the paper underpins the SDM suitability as decision-aiding tool in case of multi-actors DMP, through
15 its implementation in a real case study related to the agricultural water management system in the Apulia
16 region (Southern Italy).

17 The paper is structured as follows. After the present introduction, section 2 discusses multi-stakeholders
18 DMP and SDM approaches. Section 3 illustrates the methodology and the case study. Section 4 and 5 discuss
19 the obtained results. Concluding remarks are described in section 6.

20 **2 Supporting multi-stakeholders decision-making processes**

21 **2.1 The Interaction Space**

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

28 AA have been defined as a social space where individuals interact, exchange goods and services, solve
29 problems, dominate one another, or fight (Ostrom, 1990). AA has mainly been applied to analyse static
30 depictions of social systems and the evolution of rules over time, comparing different representations (Pahl-
31 Wostl et al., 2002). The key idea of Ostrom is to understand a society as a structure of interconnected action
32 situations and involved participants (Ostrom, 2012). Participants in AA interact as they are affected by
33 exogenous variables and produce outcomes that in turn affect the participants and the action situation (Pahl-
34 Wostl et al., 2002). AA combines the action situation, which focuses on the rules and norms, with the
35 participants' individual preferences, skills and DMPs (Andersson and Ostrom, 2008; Anderies and Janssen,
36 2013).

1 On the other side, Ostanello and Tsoukiàs' IS is a collaborative space where a *meta-object* is identified as the
2 merge/articulation of the participants' problem representation. Similarly to the AA, the IS can form the basis
3 for further collective discussion and DMP. The concept of IS has been introduced in order to represent a
4 meeting structure of subjects from different organizations, allowing exchange condition by a public
5 confrontation. Mazri (2007) and Daniell et al. (2010) define an IS as: "a formal or informal structure that is
6 governed by a number of rules and is aimed at providing a field of interaction to a finite set of actors". A set
7 of elements (participants A , objects O and resources R) and an architecture of relations $S = \{S_o, S_{ao}, S_{aor}\}$ on
8 these sets constitute an IS.
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10 The multi-step procedure that enables the IS building is explained in Ostanello and Tsoukiàs (1993). The
11 identification of the IS state allows the analyst to generate hypotheses on the coherence of future actions that
12 a participant could be willing to undertake (e.g. the different IS states are controlled and non-controlled
13 expansion, stalemate, controlled contraction, dissolution, institutionalization). Such model, even if simplified
14 to just a few variables, can provide a useful basis for understanding decision dynamics with multi-
15 stakeholders. IS allows the analysts to deal with different participants, formalizing a formal structure and
16 consequently, improving transparency of participation processes. IS is a descriptive and explicative model
17 that could support participative DMPs. The construction of this artefact allows, on the one hand, the clients
18 to recognise their position within the DMP for which they asked the support. On the other hand, it allows the
19 analyst to better understand the problem under analysis and the interconnected networks in which decision-
20 makers operate.
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22 Hence, the use of the current structure of IS has drawbacks. Firstly, the IS is an evolving structural idea,
23 although it remains a static picture of the problem. However, the interactions among decision-makers are not
24 static. They can be influenced by the boundary conditions, implementation of policies, both as internal and as
25 external drivers, involvement of other actors with different objects and resources. Thus, the IS requires
26 methodologies capable to account for such a dynamic nature. Secondly, as Ostrom suggested for the AA, IS
27 also lacks detailed analyses of rules, strategies and actions that can allow the analyst to better understand
28 how an IS model for a stakeholder is constructed and which interdependencies it has with the others. In a
29 multi-stakeholder DMP, each decision-maker has its own frame of the IS, which leads him/her to have a
30 personal rational model to achieve his/her objectives neglecting the existence of the other agents. Lastly, IS
31 is a descriptive approach, without collective features for understanding interactions. It is not able to fully
32 explain the complexity of debates and to fulfil the need for a prescriptive model.
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34 The introduction of dynamism and the simulations of future scenarios could improve the model. The IS
35 model should allow the analysts to identify a joint set of objectives and to create a shared problem definition
36 used to generate new knowledge and management strategies. A dynamic IS model should be defined
37 including besides the sets of agents A , objects O , resources R and a structure of relations S that develop
38 between these sets, selected rational models allowing its evolution (denoted as T): $IS = \langle A, O, R, S, T \rangle$
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40 Under the hypothesis of decision-makers driven by a subjective rationality, T represents the set of agents'
41 rational behaviour models in a specific IS configuration. Several agents operating with their own locally
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1 rational decision rules (intended rationality and not casual rationality) characterize these decision
2 environments. T regulates the nature and dynamics of action situations. The formalization of T , made by the
3 analyst through different possible approaches (e.g. linear or non-linear programming, system dynamic, multi-
4 agent system etc.), can be adapted to each case study, depending on the modelling needs. T supplies the
5 dynamism to the system concerning a timeline, helping in the simulation building and in the definition of the
6 rules in use, facilitating stakeholders' interactions and the explanation and the prediction of behaviours.
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9 In order to overcome the presented criticalities, System Dynamics Modelling (SDM) is considered a suitable
10 tool for operationalizing the IS. SDM is a computer-aided approach, applying to dynamic problems defined
11 by interdependence, mutual interaction, and circular causality (Vennix, 1996). It has the flexibility and
12 capability to support environmental DMPs, to involve raising public awareness and developing
13 understanding of the connections between potential decision alternatives and system consequences
14 (Bousquet and Le Page, 2004; Gohari et al., 2017).
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22 **2.2 System Dynamic Modelling**

23 Historically, SDMs appeared as an outgrowth of the system dynamics approach of Forrester (Forrester, 1961;
24 Forrester, 1968; Forrester, 1987). A SDM describes complex systems through the use of feedback loops,
25 stocks and flows. Stocks characterize the state of the system, and keep memory of it, enabling to describe its
26 status. Flows affect the stocks via inflow or outflow, and interlink the stocks within a system (Sterman,
27 2000). SDM is both qualitative/conceptual and quantitative/numerical. Qualitative modelling (causal loop
28 diagrams) can improve the conceptual system understanding. Quantitative modelling (stock-and-flow
29 models), allows to investigate and visualize the effects of different actions within the simulation model
30 (Sterman, 2001). SDM is able to integrate a wide range of input parameters in a meaningful way, supporting
31 the recognition that the direction of change is crucial towards managing responses in an adaptive way
32 (Pagano et al., 2017).
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40 Referring to WM issues, Simonovic and Rajasekaram (2004) developed an integrated model using the SD
41 simulation, Goldani et al. (2011) analysed WM and government subsidy policy and Liu et al. (2015)
42 discusses an integrated SDM developed for managing water quality. Specifically for WM in agriculture, the
43 use of SD based approaches is wide and successful in the scientific literature (e.g. Li et al., 2012; Walters et
44 al., 2016). Several studies are available, e.g. modelling a participatory systemic feedback for sustainable WM
45 (Kotir et al. 2017), assessing water scarcity and potential impacts of socio-economic policies in a complex
46 hydrological system (Sušnik et al. 2012), modelling the impact of climate change on agricultural practices
47 (Gohari et al. 2017), supporting policy- and decision-makers designing effective strategies for conservation
48 agriculture practices (Varia et al. 2017), integrating individual stakeholders' mental models (Kopainsky et al.
49 2017).
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57 The objective of the last part of this section is to make a comparison between SD and other approaches used
58 for modelling WM decision-making issues. In the first place, traditional approaches to support WM aim to
59 identify the *optimal* alternative using decision models represented by analytic functions. Considering the
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1 WM complexity, finding the *optimal* solution is rarely considered the most suitable approach (Daniell,
2 2012). Such approaches neglect, for example, the decision-makers' abilities to change their DMP due to the
3 interactions with the system and with the other actors (e.g. Brugnach and Ingram 2012; Giordano et al.,
4 2017). Focusing on farming systems, more representative models have been built for short-term strategies
5 related to a farm or mixed models have appeared from coupling a farm model with a physical water model
6 (Winter et al. 2017). However, those approaches neither highlight enough the interaction between users, nor
7 take into account multi-annual changes (Dent et al., 1995; Filippi et al., 2017).

8 Secondly, considering both SDM and statistical approaches, a significant difference is related to the focus of
9 the analysis. The former simulates the system evolution through a detailed analysis of model structure, the
10 latter predicts the future evolution of the system starting from the analysis of the measured data.
11 Nevertheless, these statistical correlations may not truly forecast future system behaviour (Winz et al. 2009).
12 Moreover, a higher level of complexity encompasses a model validation by the stakeholders. This phase
13 becomes a social process where model structure and outcome are negotiated until they are judged valid and
14 useful by all involved parties (Scott et al., 2016).

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

22 Within such a framework, this work describes a SDM developed for conceptualizing WM in terms of
23 aggregated stocks and flows, for a collective DMP related to a CPR. The SDM has been used to evaluate the
24 impact on WM policies, aiming to enhance the understanding of the dynamic evolution of the IS.
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42 **3 Water management and groundwater protection policy within the agricultural sector of the** 43 **Apulia region**

44 **3.1 Overview of the case study**

45 The case study is focused on WM in agricultural systems in the north of the Apulia region (Southern Italy).
46 The area under analysis is characterized by severe phenomena of seawater intrusion caused by intensive
47 agricultural activities in coastal areas, which rely on both surface water (SW) and groundwater (GW)
48 (Giordano et al., 2015; Portoghese et al., 2013). Within the case study, three main stakeholders are identified:
49 Farmers, Water Management Authority, and Regional Authority (RA). The Water Management Authority,
50 i.e. the Irrigation Consortium of Capitanata (IC), is responsible for the management of SW in the area
51 focusing exclusively on irrigation demand. The IC has to deal with the water scarcity in the region, and the
52 SW demand from each Farmer. The objectives of IC are to guarantee an equitable distribution of SW and to
53 maintain a positive economic budget. IC's price policy is based on different volume thresholds with specific
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1 water tariffs depending on water availability in the dam: the base water supply volume (0.12 €/m³ for 2050
2 m³/ha) and the additional water supply volume, considerably more expensive (from 0.24 €/m³ for 2050-4000
3 m³/ha). Since irrigated agriculture is highly water-demanding, and the significant climatic uncertainty might
4 limit water availability, each Farmer selects a 'suitable' cropping plan to maximize his/her profits. Besides
5 SW, managed by IC, the availability of individual GW withdrawals, both legal and illegal, need to be
6 considered. In fact, Farmers consider GW easily accessible, thanks to the presence of private wells, and
7 cheaper than SW. Farmers' decisions concern also the selection of the main source of water for irrigation
8 (either GW or SW). Although currently there is not a centralized GW management system, RA needs to
9 protect GW quality and quantity, without impacting dramatically the level of productivity of the agricultural
10 sector. For this aim, the RA implemented in 2009 the Water Protection Plan (according to the CEE 2000/60)
11 to restrict the GW use. The main dynamics associated to these three stakeholders were defined by integrating
12 the scientific knowledge available in literature with expert knowledge elicited through semi-structured
13 interviews and participatory modelling processes (performed in Giordano et al., 2017; Giordano et al., 2015;
14 Pluchinotta 2015; Portoghese et al., 2013). The simulated behaviours are based on field observations and on
15 the elicitation of stakeholders' knowledge.
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27 **3.2 The applied methodology**

28 A methodology capable to operationalize the IS and, in doing so, to support the detection and analysis of
29 policy resistance mechanisms has been developed using a SDM. The IS building process goes through a
30 multi-step procedure adapted from Ostanello and Tsoukiàs (1993). The construction of the IS starts with the
31 identification of the involved actors *a* with their objects *o* and resources *r*. The next stage is to define the
32 hierarchy and relations between these elements. Finally, the dynamic evolution of the IS is simulated using
33 the SDM. A detailed description of the IS, the constructing procedure, and the development of the
34 stakeholder's DMPs through causal loop diagrams are described in Giordano et al. (2017). This paper
35 represents a step forward. It aims at developing a SDM, capable to simulate the dynamic evolution of the IS
36 during the different phases of the DMPs, structuring the interactions between multiple decision-makers and
37 several drivers.
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45 Following Giordano et al. (2017), different problem understandings were integrated in the SDM. The model
46 assumptions are: i) each decision-maker has a personal understanding of the IS and this partial and subjective
47 vision tends to affect behaviours and actions; ii) not all the decision-makers are interested/forced to enter in
48 the IS in the early stages of the action implementation; iii) a decision-maker enters in the IS when his/her
49 objects are impacted by the actions implemented by the others.
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54 The SDM development proceeded following the conceptualisation phase via the IS. It was structured in the
55 following main phases (adapted from Vennix, 1996 and Davies and Simonovic 2011): i) understanding the
56 system and its boundaries through the IS model conceptualization; ii) identifying the key variables typifying
57 the IS elements; iii) describing the relationships between variables through mathematical relationships; iv)
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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).

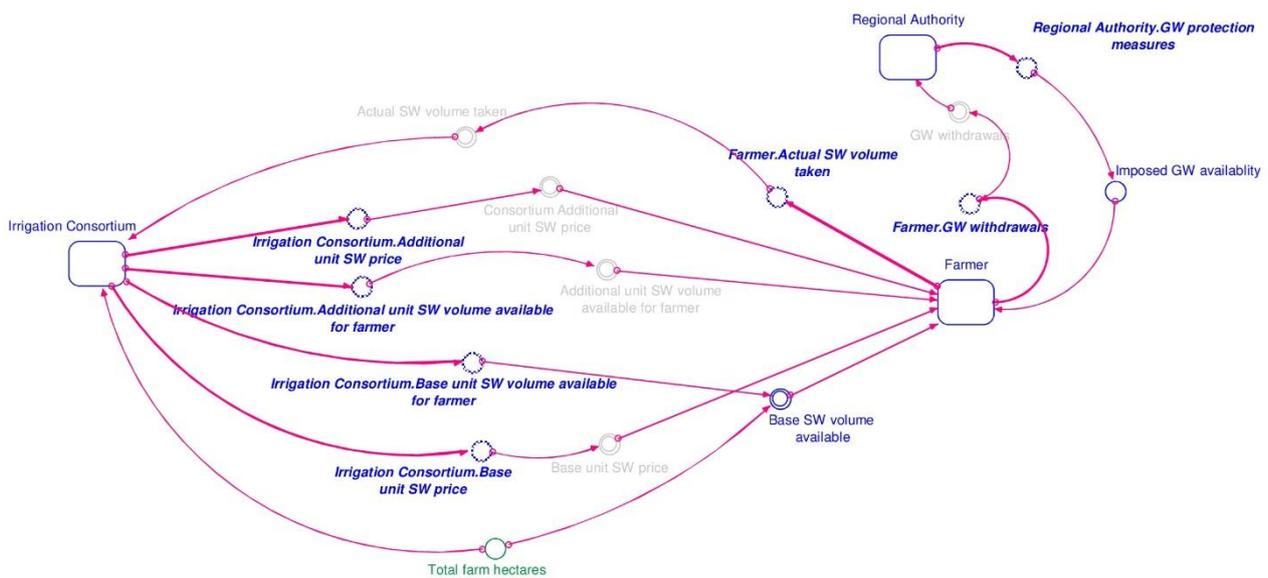


Figure 1 - The complete SDM built with STELLA® (ISEE Systems Inc.)

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

1 'Water volume for irrigation' is variable and given by the difference between 'Water volume in the
2 reservoir' and 'Outflow potable'. The comparison between the available 'Water volume for irrigation' and
3 the 'Expected water demand' defines the initial IC 'Budget', which is the key element to define the yearly
4 irrigation management strategy, i.e. the amount of water available per Farmer ('Base unit SW volume
5 available per Farmer' and 'Additional unit SW volume available per Farmer'). During the interviews, the IC
6 stressed that the water demand is not monitored directly by collecting data about the actual crops in the area.
7 Instead, the expected water demand is assumed as the mean of the water distributed for irrigation in the
8 previous years. Considering the dominant crops of the region, the SDM considers the 'Expected irrigation
9 demand' of the tomato (approx. 6000 m³/ha). According to the IC's problem understanding, the pricing
10 policy (described in the 'Economic sub-module') is directly related to the identification of the 'Base' and the
11 'Additional' volume thresholds, and of the associated 'Base unit SW price' and 'Additional unit SW price'.
12 The price definition should allow matching the availability and the demand, at least in normal conditions (i.e.
13 SW restrictions may be applied in dry years), leading to an equitable access to water for all Farmers. The
14 economic feedback simulates the impact of the Farmer's consumption of SW ('Actual SW volume taken') on
15 the IC's budget, i.e. the stock 'Consortium budget'. The main IC's goal is to keep this variable positive. The
16 IC's budget is influenced by: i) the fixed fees paid by each Farmers (i.e. 'Yearly fee' depending on 'Total
17 Farm hectares') for irrigation networks maintenance, and management costs; ii) the 'Farmer payment for
18 irrigation', depending on the 'Actual SW taken' and SW prices. The data used in the model were collected
19 by the IC budget reports.

20 An imbalance in the system may be determined by an increase in irrigation water demand, caused by the
21 increasing Farmer's inclination towards intensive irrigated agriculture. Therefore, the need for additional
22 water volumes would push the SW demand toward an unsustainable level. In this condition, the IC would
23 implement a water conservation policy, mainly based on a market scheme either increasing the 'Additional
24 unit SW price' or reducing the volume made available at the base SW price. This, in general should support
25 reducing the irrigated areas, pushing to the cultivation of less water-demanding crops. Nevertheless, this
26 strategy totally neglects specific dynamics that emerged in other sub-models, e.g. the use of GW instead of
27 SW.

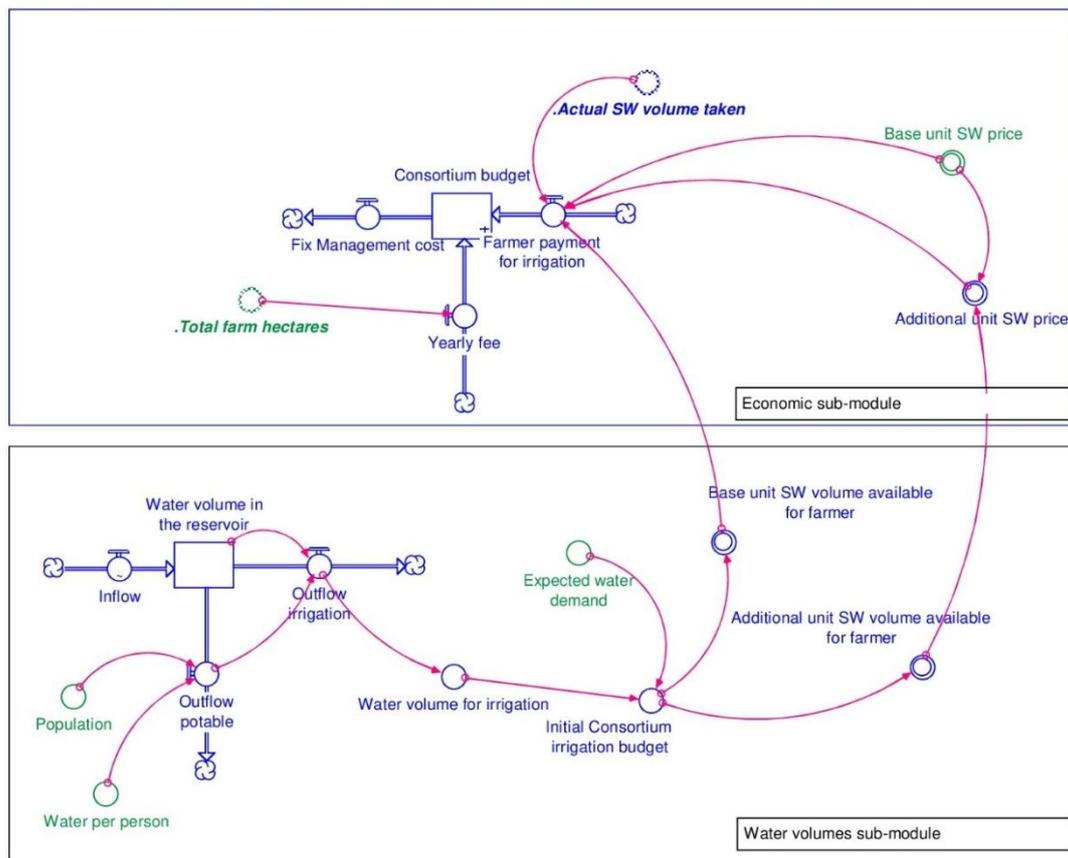


Figure 2 – Irrigation Consortium’s sub-models

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. Özsesmi and Özsesmi, 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

1 costs ('Irrigation cost' and 'Other costs') and revenues ('Subsidies' and the profit associated, with a delay, to
2 both irrigated and non-irrigated crops). The model considers a significantly different profitability of such
3 crops (500 €/ha vs. 10000 €/ha), which drives the Farmers towards the selection of irrigated crops.

4 Another key element is the dynamic of water source selection. Each Farmer knows the SW availability for
5 the irrigation season (i.e. 'Base unit SW volume available per Farmer' and 'Additional unit SW volume
6 available per Farmer'), and related prices. Individual GW sources are also generally available (Portoghese et
7 al., 2013 estimated a 'Unit GW cost' of 0.18 €/m³ for the area), but their legal use is regulated by the RA.
8 Surveys (Giordano et al. 2015; Pluchinotta, 2015) showed that Farmers are independent in their actions and
9 they are self-interested driven by an economic rationality. According to the interviews carried out, Farmers
10 perceive GW as an almost unlimited and easily accessible resource and they do not acknowledge any
11 potential environmental complication. Therefore, after IC establishes the SW unit prices, each Farmer
12 decides the best water source ('GW source preference' in the top-right part of Figure 3), mainly considering
13 the water cost. The variable 'GW source preference' depends on SW unit costs and availability, 'Unit GW
14 cost' and 'Imposed GW availability' (which depends on GW protection policies that are activated by the
15 RA). The presence of 'GW withdrawal monitoring' may also be a limiting factor for the 'GW source
16 preference'.

17 The core issue according to Farmers' problem understanding is the 'Final Farmer Irrigation budget'. Farmers
18 were required to specify the main causes that could result in a negative value for the problem core. The most
19 mentioned cause was the volume of SW distributed by IC. IC aims to reduce the SW volume by reducing the
20 'Additional unit SW volume available per Farmer'. Farmers perceive this policy as a fundamental barrier,
21 stopping the full satisfaction of the water demand and encouraging a more intensive GW illegal use.
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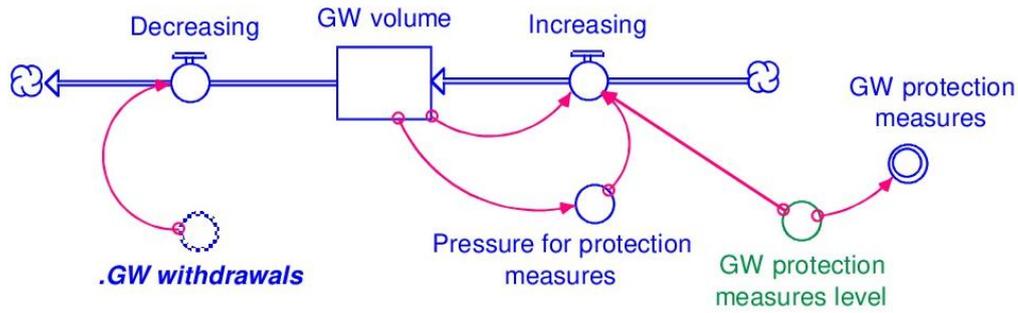


Figure 4 – Regional Authority’s sub-model

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; Portoghesi 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’.

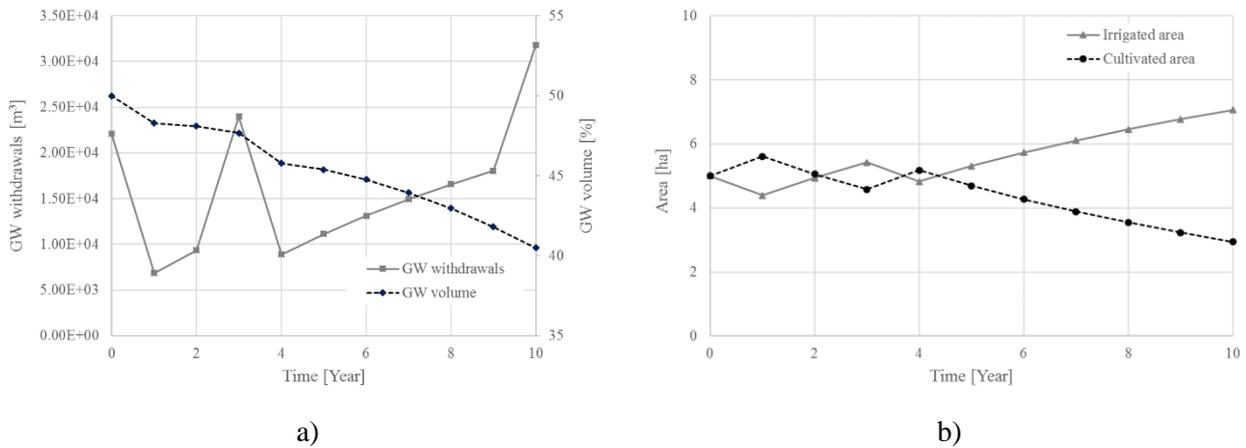


Figure 5 – Business-as-usual scenario

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 €/m³ to 0.5 €/m³). The value 0.18 €/m³ represents pumping and management costs and it is derived from Portoghese et al. (2013). Instead, 0.5 €/m³ 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.

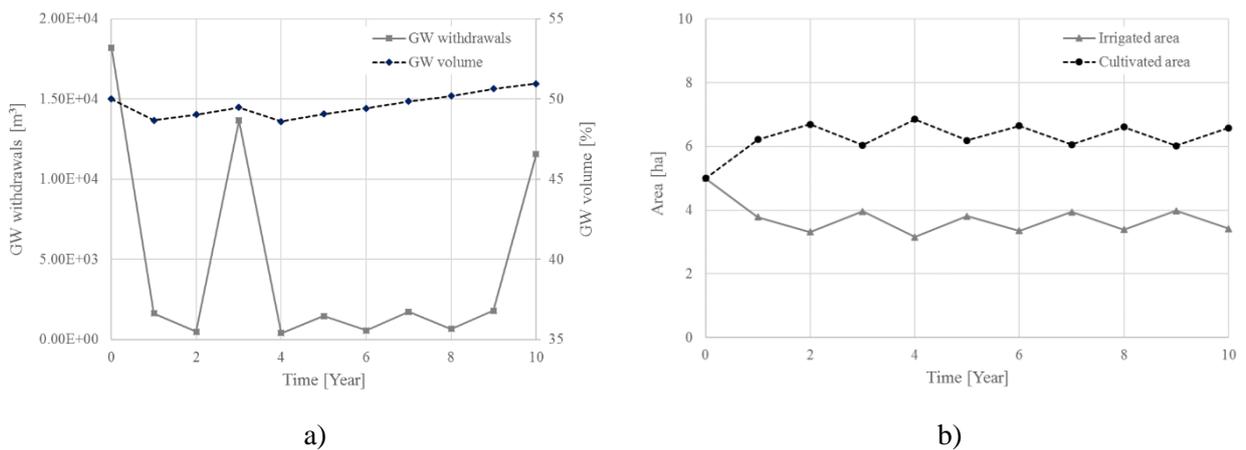


Figure 6 – Scenario (1)

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 €/m³ to 0.24 €/m³). 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

1 have a relevant indirect impact on GW state. In fact, the change of SW pricing policy may drive towards the
 2 reduction of intensively irrigated areas (Figure 7b), thus contributing also to a reduction of GW
 3 overexploitation (increase of ‘GW volume’), at least in comparison with the BAU scenario (Figure 7a). This
 4 scenario shows that although some issues might be outside of the understanding/interest of a specific actor,
 5 his/her choices have cascading impacts on the others.
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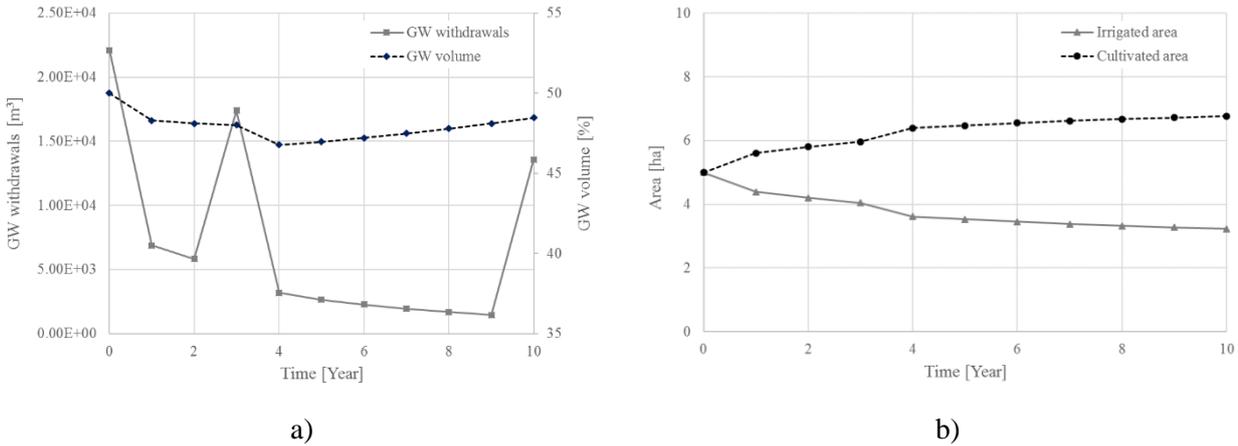


Figure 7 – Scenario (2)

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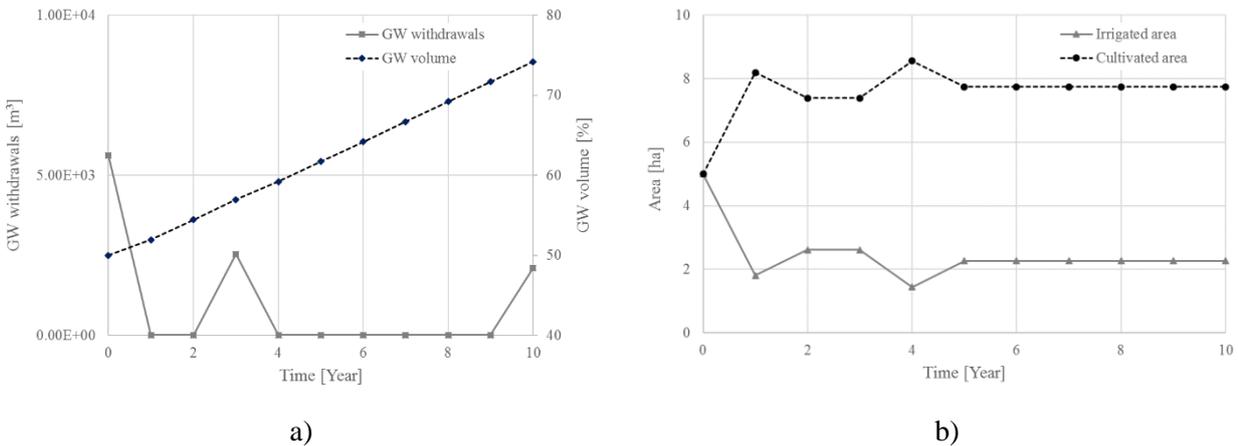


Figure 8 – Scenario (3)

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

1 be more directly oriented to the assessment of these aspects. The model, currently, mainly aims to display the
2 importance of exploiting the potentialities of participatory approaches to build comprehensive models able to
3 unravel the complexity of WM issues in systems characterized by several decision-makers and conflicting
4 water uses/interests. This helps underlining the limitedness of single viewpoints and supports analysing the
5 multidimensional impacts that specific decisions and strategies might have, supporting the idea that the real
6 dynamic evolution of complex systems is much more complex than it is perceived by single agents.
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8 Specifically, the scenario analysis aimed to show how the joint variation of different variables (e.g. the ‘GW
9 protection measures level’ and the ‘GW withdrawals monitoring’ controlled by the RA) and ‘unit GW cost’
10 may condition Farmers’ behaviours and consequently affect the state of GW. The model conceptualization
11 derived from the IS allows to offer hints for a different GW protection strategy, while the dynamic analysis
12 of the current system through the SDM leads to recalibrate the objectives of an integrated management of a
13 shared resource, e.g. the current policy does not consider any (direct or indirect) strategy for increasing the
14 GW cost. The analysis of this scenarios allowed us to demonstrate that the RA policy target (coherently with
15 the Water Framework Directive), that is to significantly reduce the GW withdrawals by farmers (the target
16 value is about the 20-40% of the actual value as discussed in Giordano et al. 2017), is unrealistic unless
17 multiple protection measures are implemented ranging from GW withdrawals monitoring, to SW and GW
18 pricing policies.
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30 **5 Discussion**

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

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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	
1	o_1 : Environmental protection	a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level	
2				GW quantity	
3				Pressure for protection measures	
4	o_2 : Agricultural productivity	a_1 IC	r_1 Economic resources	Additional unit SW price	
5				Base unit SW price	
6				Consortium budget	
7			r_3 Information flow	Additional unit SW volume available for F	
8				Base unit SW volume available for F	
9					
10			a_2 F	r_5 Water accessibility	Water balance
11					Actual SW taken
12					Unit GW cost
13				r_6 Illegal actions	GW withdraws monitoring
14					SW cost additional and base volumes
15					GW volume taken
16			r_8 Yield	Irrigation deficit	
17				Actual water requirement	
18				Unit GW cost	
19				SW cost additional and base volumes	
20				GW source preference	
21				GW withdraws monitoring	
22				Irrigated area/Cultivated (non-irrigated) area	
23				Economic F's budget	
24				Irrigation cost	
25	o_3 : Effectiveness of the irrigation water management	a_1 IC	r_1 Economic resources	Farmer payment for irrigation	
26				Fix Management cost	
27				Consortium budget	
28				r_3 Information flow	Yearly fee
29					Actual SW volume taken
30					Water volume in the reservoir
31					Water volume for irrigation
32					Initial IC budget
33					GW protection measures level
34		a_3 RA	r_2 Legislative constraints and regulations	GW quantity	
35				Pressure for protection measures	
36				Expected water demand	
37	o_4 : Water availability	a_1 IC	r_3 Information flow	Additional unit SW volume available for F	
38				Base unit SW volume available for F	
39				Actual SW volume taken	
40			a_2 F	r_3 Information flow	Additional unit SW volume available for F
41					Base unit SW volume available for F
42					GW cost
43				r_6 Illegal actions	SW cost additional and base volumes
44					Irrigation deficit
45					Actual water requirement
46					F GW volume taken
47					Unit GW cost
48					SW cost additional and base volumes
49				GW source preference	
50				GW withdraws monitoring	
51				Irrigated area/Cultivated (non-irrigated) area	
52				Economic F's budget	
53				Irrigation cost	
54				GW quantity	
55		a_3 RA	r_2 Legislative constraints and regulations	GW protection measures level	
56				GW withdrawals	
57				GW protection measures level	
58	o_5 : Decrease of GW	a_3 RA	r_2 Legislative constraints	GW protection measures level	
59					

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_t 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_t 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_t 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_availability = 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:

```

1 Inflow = GRAPH(TIME)
2 (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),
3 (6.67, 3.6e+008), (7.78, 2.7e+008), (8.89, 5.8e+007), (10.00, 1.2e+008)
4 OUTFLOWS:
5 Outflow__irrigation = Water_volume_in__the_reservoir-Outflow_potable
6 Outflow_potable = Population*Water_per_person
7 Additional_unit_SW_price = IF Additional_unit_SW_volume_available_for_farmer>0 THEN
8 2*Base_unit_SW_price ELSE 4*Base_unit_SW_price
9
10 Additional_unit_SW_volume_available_for_farmer = IF Initial_Consortium__irrigation_budget>0 THEN
11 1000 ELSE 0
12 Base_unit_SW_price = 0.12
13 Base_unit_SW_volume_available_for_farmer = IF Initial_Consortium__irrigation_budget>0 THEN 2050
14 ELSE 600
15 Expected_water_demand = 15000000
16 Initial_Consortium__irrigation_budget = Water_volume_for_irrigation-Expected_water_demand
17 Population = 240000
18 Water_per_person = 250
19 Water_volume_for_irrigation = Outflow__irrigation
20
21
22
23
24 Farmer Sub-model (Figure 3 of the Manuscript)
25
26 Add_SW_taken(t) = Add_SW_taken(t - dt) + (Add_SW_In - Add_SW_out) * dt
27 INIT Add_SW_taken = 0
28     TRANSIT TIME = 1
29     INFLOW LIMIT = INF
30     CAPACITY = 1000
31
32 INFLOWS:
33 Add_SW_In = .Additional_unit_SW_volume_available_for_farmer*(1-GW_source__preference)
34 OUTFLOWS:
35 Add_SW_out = CONVEYOR OUTFLOW
36
37
38 Cultivated__areas(t) = Cultivated__areas(t - dt) + (Decreasing - Increasing) * dt
39 INIT Cultivated__areas = 5
40 INFLOWS:
41 Decreasing = IF Economic_budget<=0 OR Irrigation_deficit>0.1 THEN
42     (Irrigated_area/Farmers'_perception__of_price*Irrigation_deficit) ELSE 0
43 OUTFLOWS:
44 Increasing = IF Economic_budget>1000 AND Irrigation_deficit<0.1 THEN
45     (Cultivated__areas*Farmers'_perception__of_price/10) ELSE 0
46
47
48 Irrigated_area(t) = Irrigated_area(t - dt) + (Increasing - Decreasing) * dt
49 INIT Irrigated_area = 5
50 INFLOWS:
51 Increasing = IF Economic_budget>1000 AND Irrigation_deficit<0.1 THEN
52     (Cultivated__areas*Farmers'_perception__of_price/10) ELSE 0
53 OUTFLOWS:
54 Decreasing = IF Economic_budget<=0 OR Irrigation_deficit>0.1 THEN
55     (Irrigated_area/Farmers'_perception__of_price*Irrigation_deficit) ELSE 0
56
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58
59 Actual_SW_volume_taken = IF Water_balance >0 THEN .Base_SW_volume__available+Add_SW_out
60 ELSE Actual_water_requirement
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1 Actual_water_requirement = Irrigated_area*6000+Cultivated__areas*400
2 Additional_SW_cost = Add_SW_out*.Consortium_Additional_unit_SW_price
3 Additional_water_volume_needed = Water_balance
4 Economic_budget = Subsidies+(DELAY1(Cultivated__areas,1)*500+DELAY1(Irrigated_area,1)*10000)-
5 (Irrigation_cost*10+Other_costs)
6 Farmers'_perception__of_price = MEAN(DELAY(Prices_in_the__market, 1),
7 DELAY(Prices_in_the__market,2), DELAY(Prices_in_the__market, 3))/MEAN(Prices_in_the__market)
8 Final_Farmer_irrigation_budget = Total_SW_GW_volume_taken-Actual_water_requirement
9 GW_cost = Unit_GW_cost*GW__volume_taken
10 GW_source__preference = IF(Unit_GW_cost<.Consortium_Additional_unit_SW_price) THEN 0.9-
11 GW_withdrawals_monitoring/2 ELSE
12 (.Consortium_Additional_unit_SW_price/Unit_GW_cost)*.Imposed_GW_availability*(1-
13 GW_withdrawals_monitoring)*0.9
14 GW_withdrawals = GW__volume_taken
15 GW_withdrawals_monitoring = 0.1
16 GW__volume_taken = IF (Additional_water_volume_needed-Add_SW_out)>0 THEN
17 (Additional_water_volume_needed-Add_SW_out)*GW_source__preference ELSE 0
18 Irrigation_cost = (.Base_SW_volume__available*.Base_unit_SW_price)+GW_cost+Additional_SW_cost
19 Irrigation_deficit = ABS(Final_Farmer_irrigation_budget/Actual_water_requirement)
20 Other_costs = 0
21 Subsidies = 0
22 Total_SW_GW_volume_taken = Actual_SW_volume_taken+GW__volume_taken
23 Unit_GW_cost = 0.18
24 Water_balance = IF (Actual_water_requirement-.Base_SW_volume__available)>0 THEN
25 (Actual_water_requirement-.Base_SW_volume__available) ELSE 0
26 Prices_in_the__market = GRAPH(TIME)
27 (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,
28 254), (10.00, 200)
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Regional Authority Sub-model (Figure 4 of the Manuscript):

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35
36
37 GW_quantity(t) = GW_quantity(t - dt) + (Increasing - Decreasing) * dt
38 INIT GW_quantity = 50
39 INFLOWS:
40 Increasing = 0.1*GW_protection_measures_level*Pressure_for_protection_measures*GW_quantity
41 OUTFLOWS:
42 Decreasing = (.GW_withdrawals/10000)
43
44
45 GW_protection_measures = GW_protection_measures_level
46 GW_protection_measures_level = 0.1
47 Pressure_for_protection_measures = 50/GW_quantity
48
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Appendix III – Sensitivity Analysis

51 The sensitivity analysis was performed with respect to a relevant subset of parameters, through the
52 Sensitivity Specs dialog box available in *Stella*® (ISEE Systems Inc.). The sensitivity analysis aims to verify
53 to what extent the model is capable to describe the impact of the variation of specific variables on some key
54 dynamics (Mateus and Franz 2015, Pagano et al. 2017). It is worth considering that the sensitivity analysis is
55 a highly useful process to evaluate the contribution of specific input parameters on model behavior,
56 identifying the most influential ones. Nevertheless, this kind of analysis might be significantly complex in
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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 m³) 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.

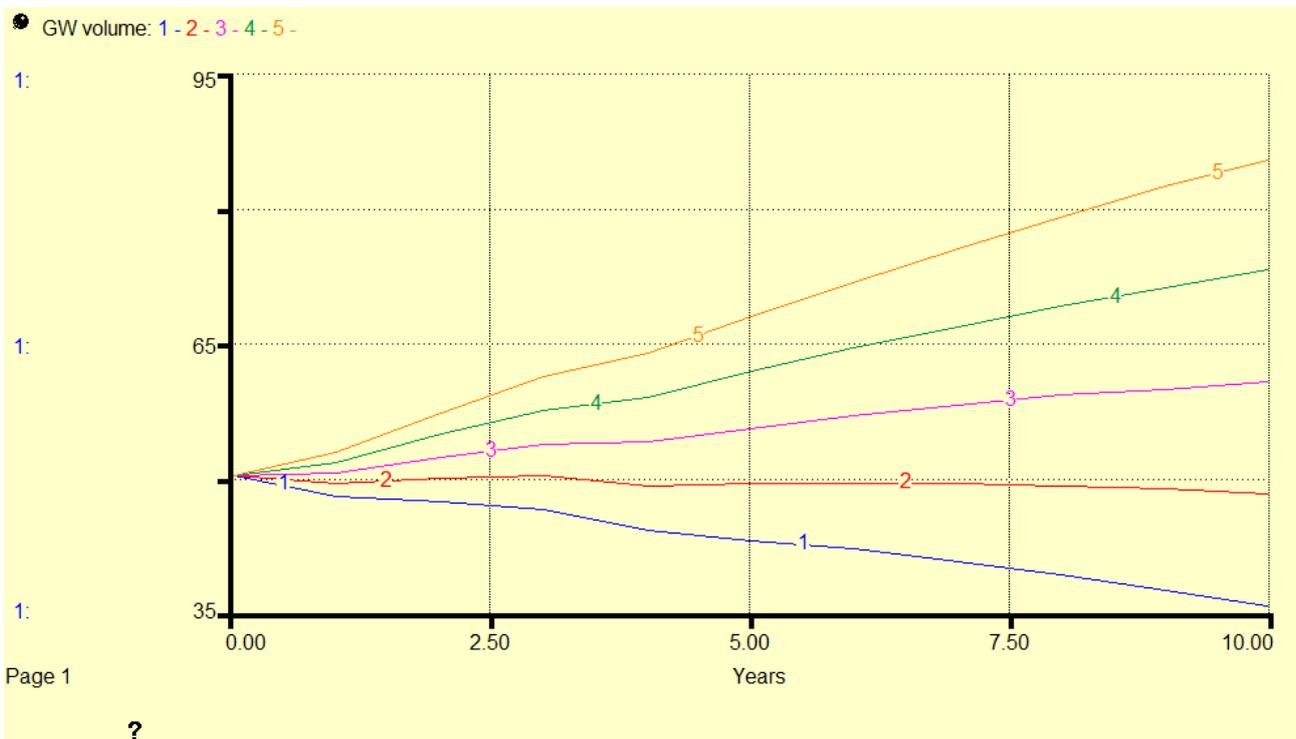


Figure S1 – Sensitivity analysis focused on the ‘GW volume’ in the RA sub-model. The variation of the ‘GW protection measures level’ from 0 (run 1) to 1 (run 5) is analyzed.

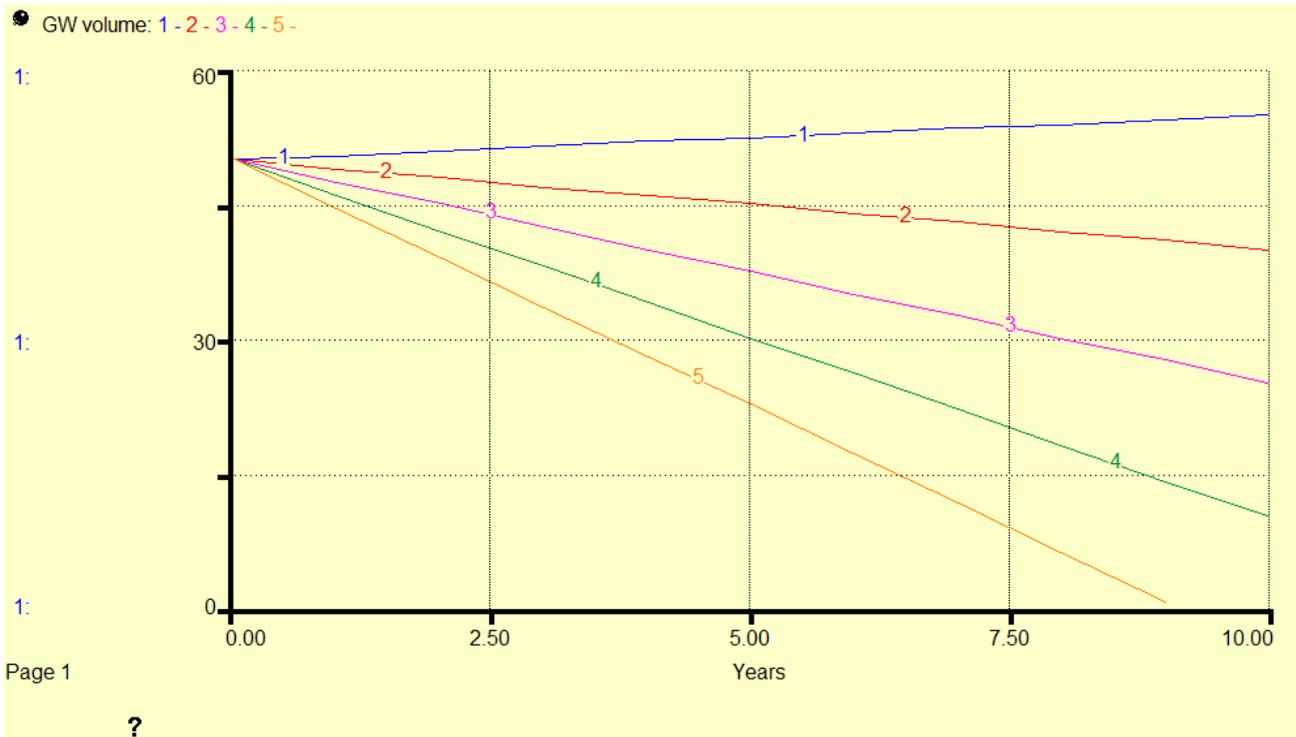


Figure S2 – Sensitivity analysis focused on the ‘GW volume’ in the RA sub-model. The variation of the ‘GW withdrawals’ from 0 (run 1) to 60000 m³ (run 5) is analyzed.

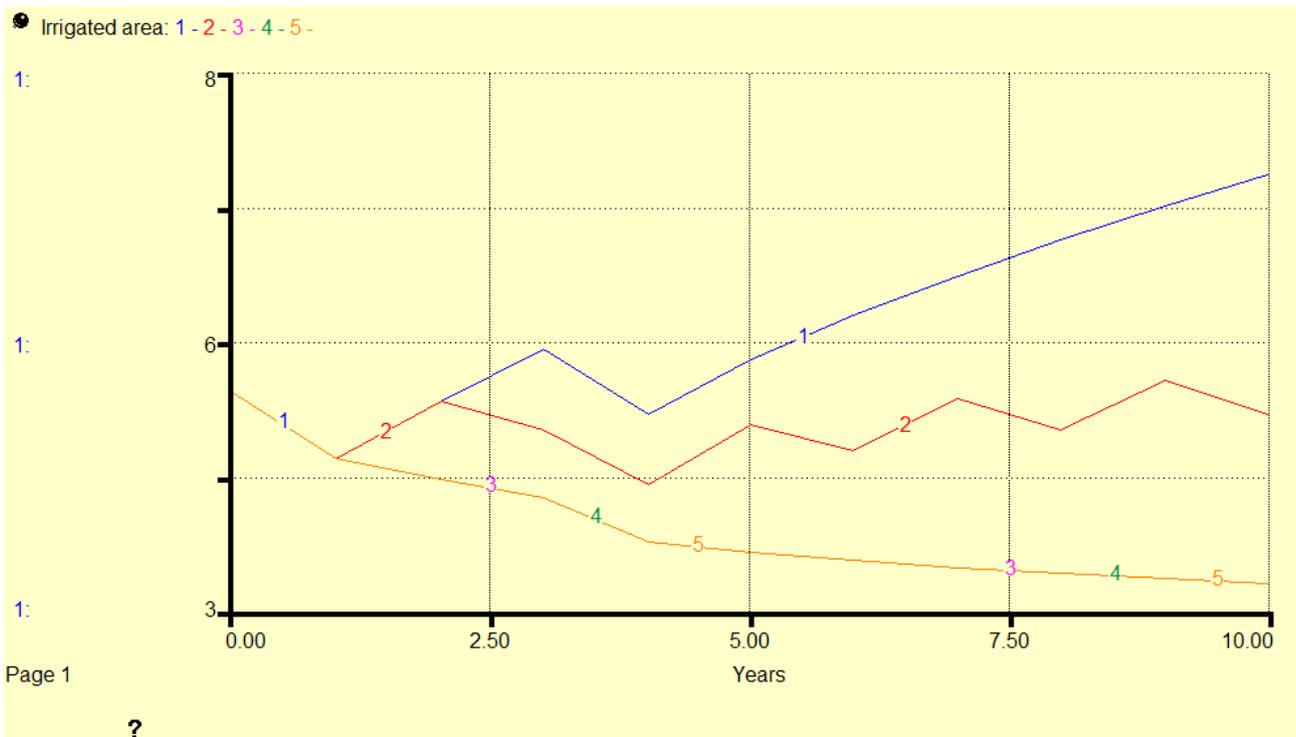


Figure S3 – Sensitivity analysis focused on the ‘Irrigated area’ in the ‘Farmers’ sub-model. Variation of the ‘Base unit SW price’ from 0.05 (run 1) to 0.5 (run 5).

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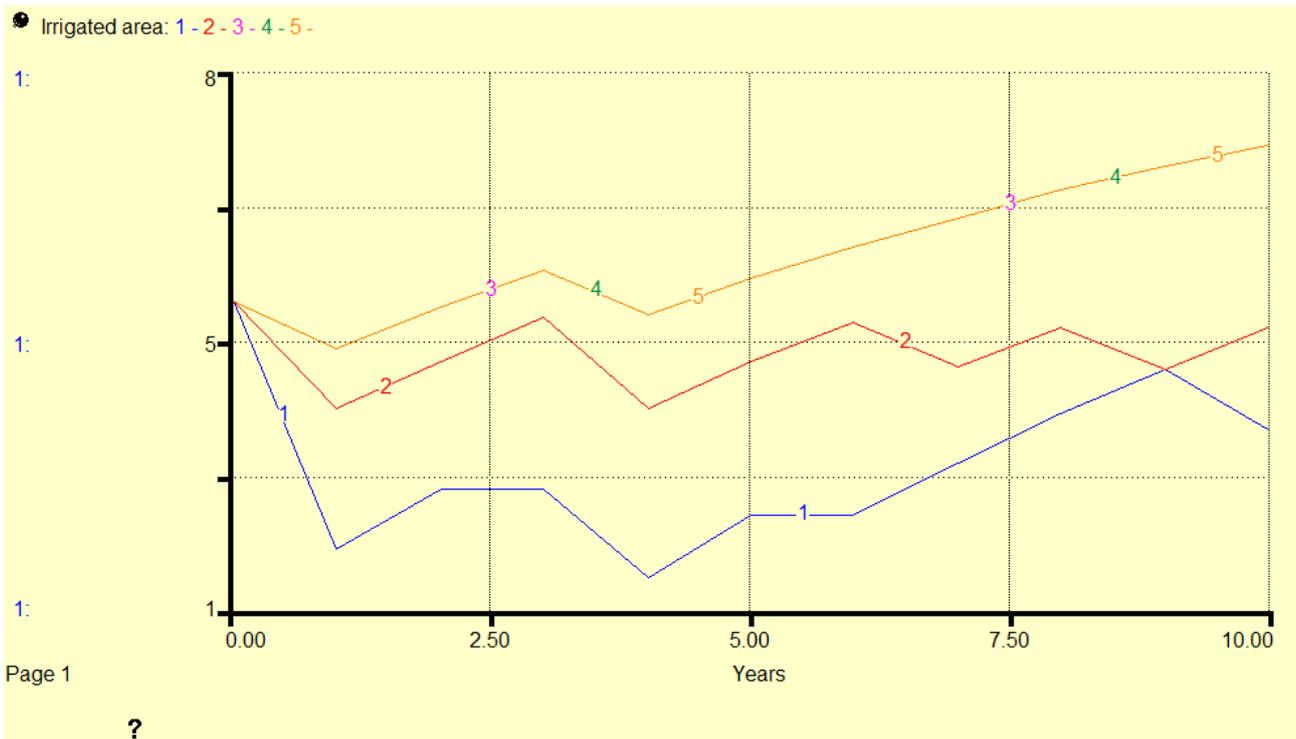


Figure S4 – Sensitivity analysis focused on the ‘Irrigated areas’ in the ‘Farmers’ sub-model. Variation of the ‘Additional unit SW price’ from 0.1 (run 1) to 0.5 (run 5).

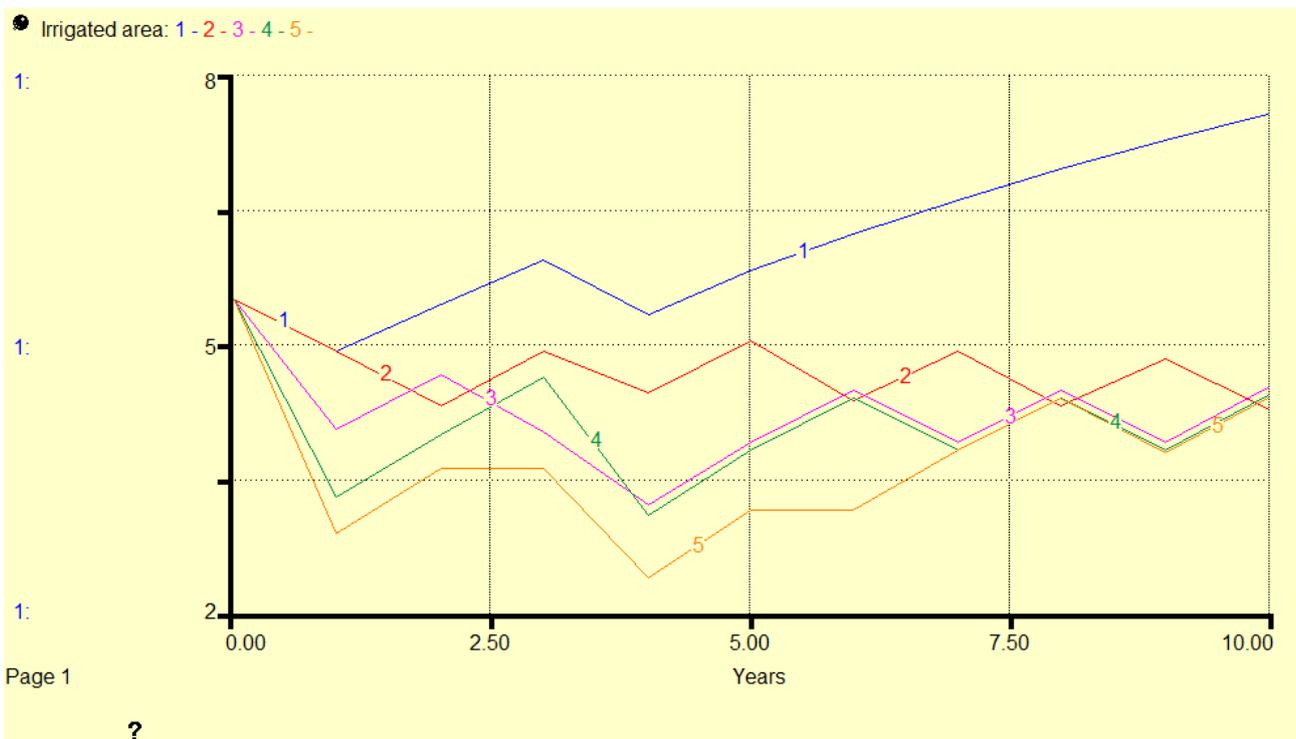


Figure S5 – Sensitivity analysis focused on the ‘Irrigated area’ in the ‘Farmers’ sub-model. Variation of the ‘Unit GW cost’ from 0.1 (run 1) to 1 (run 5)

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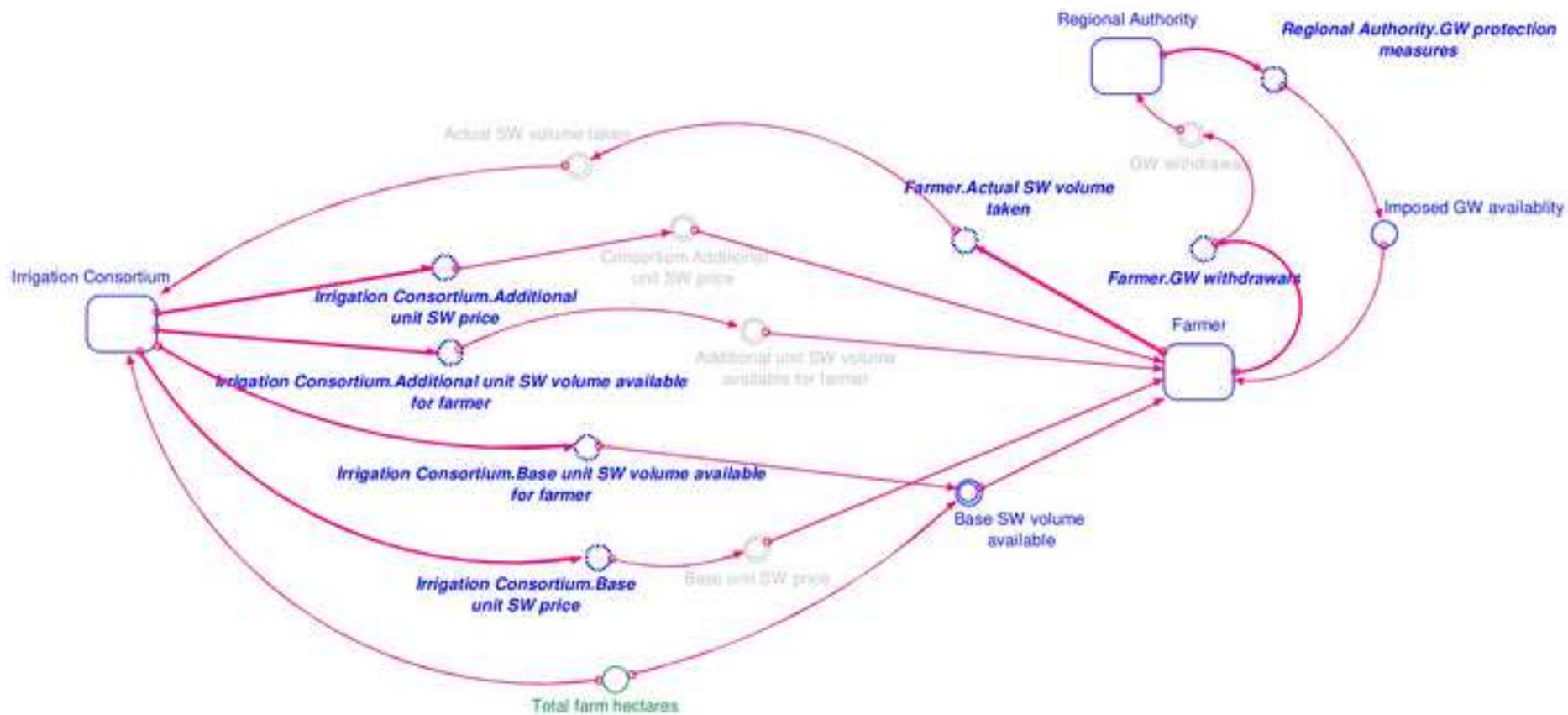
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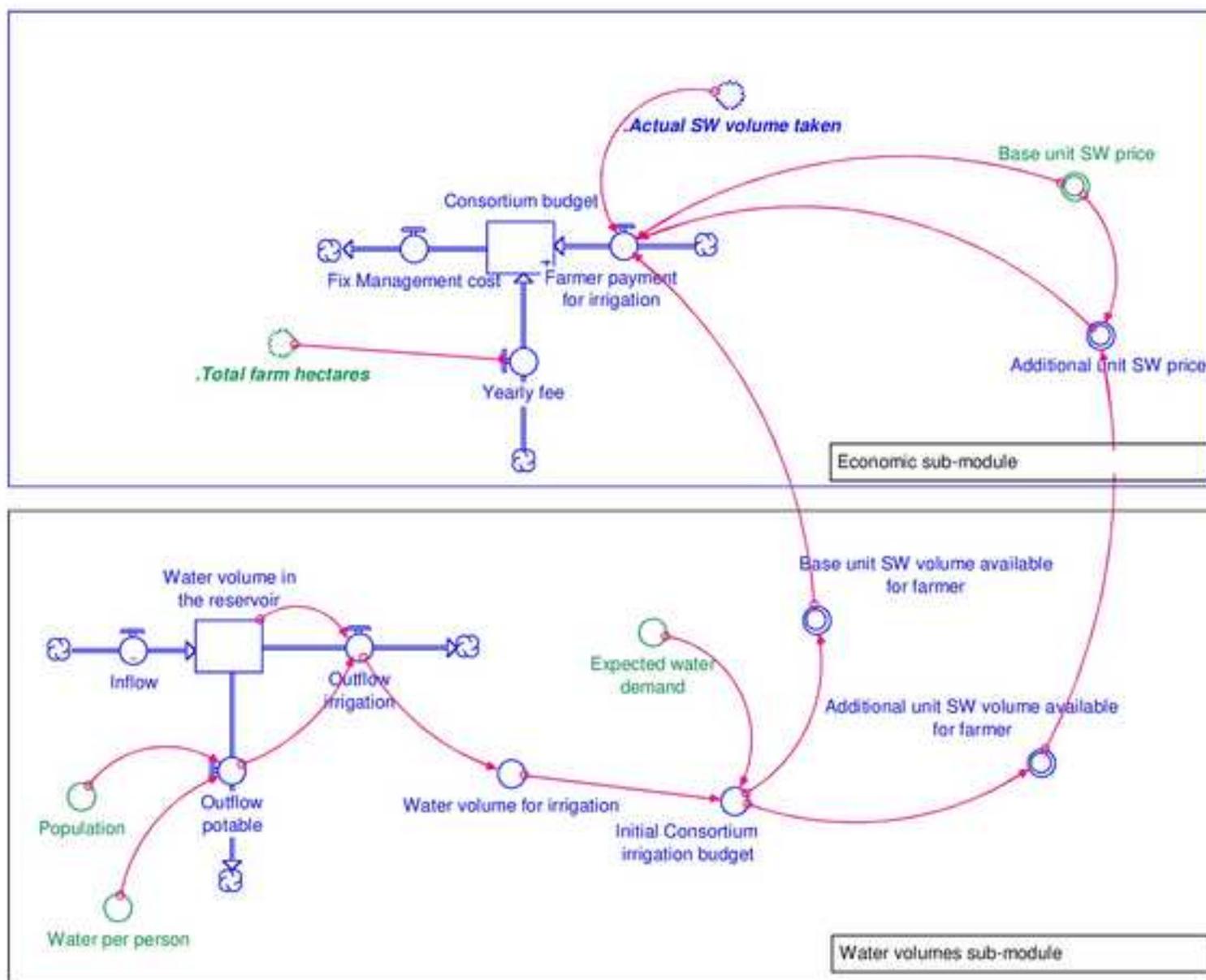


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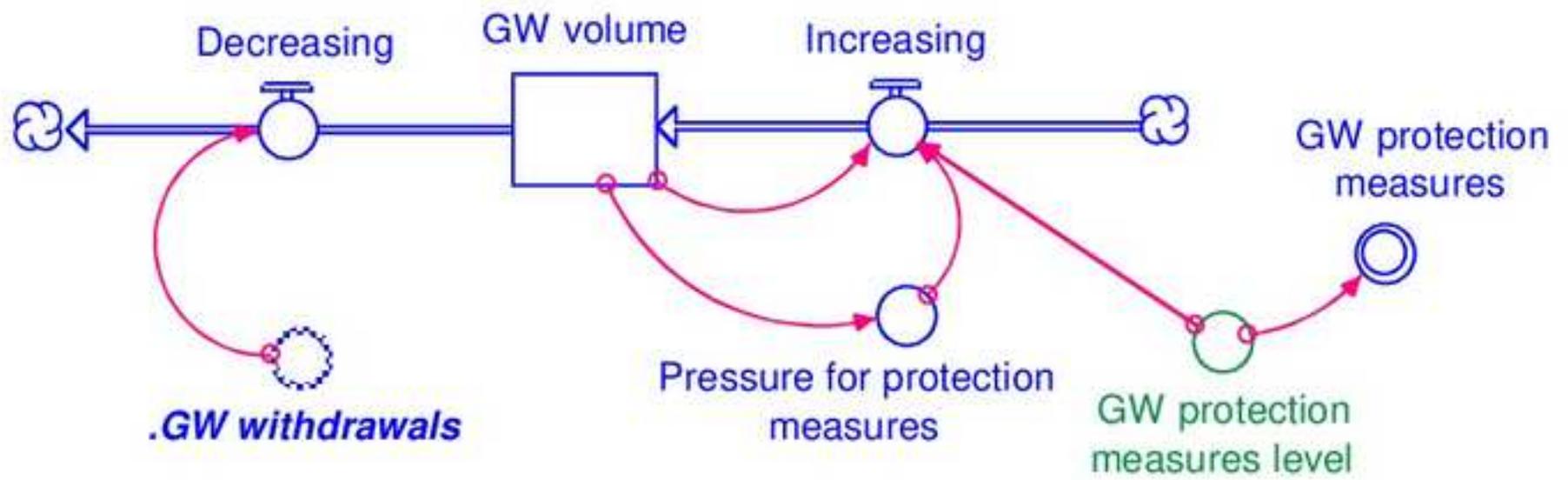


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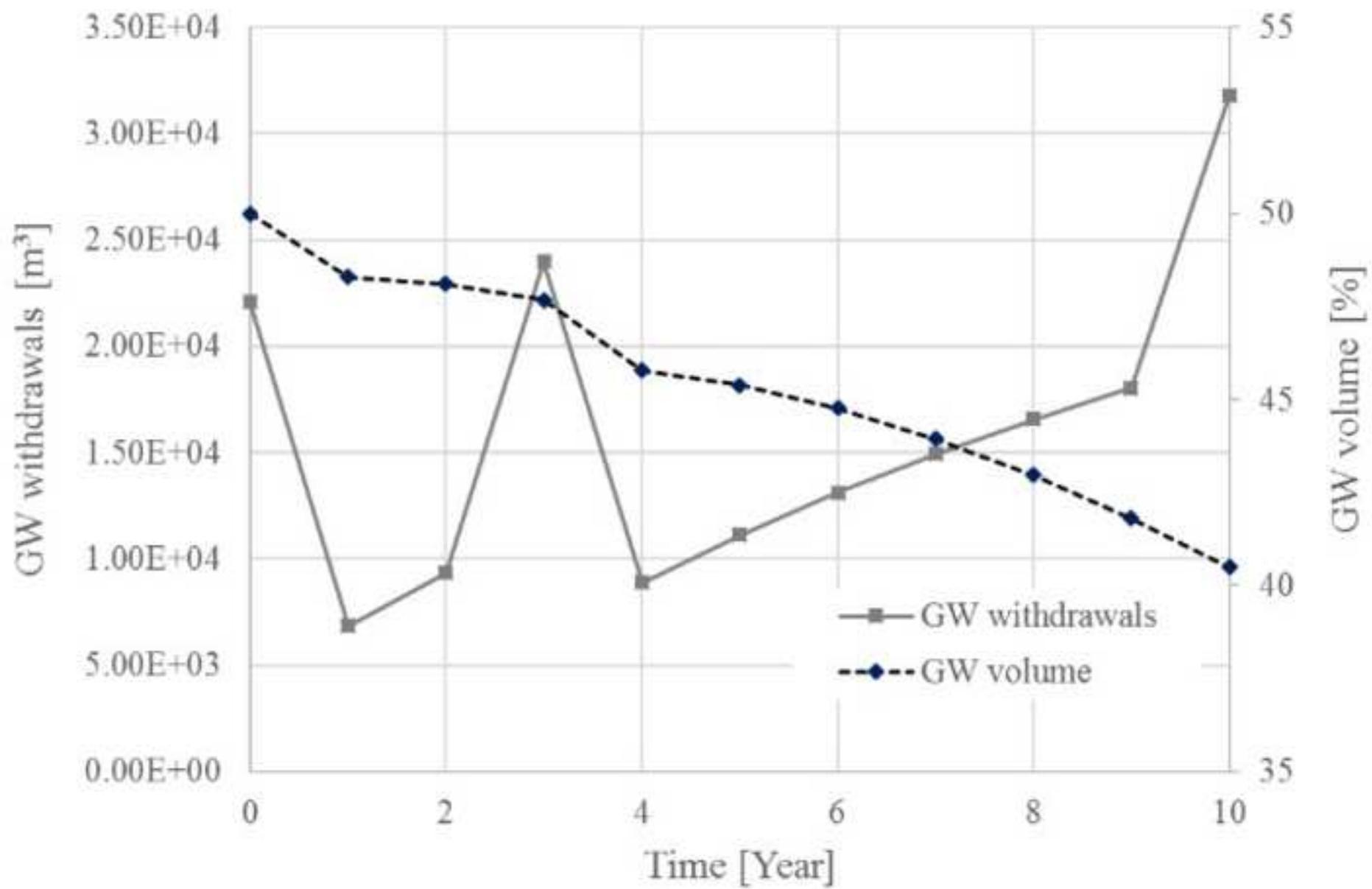


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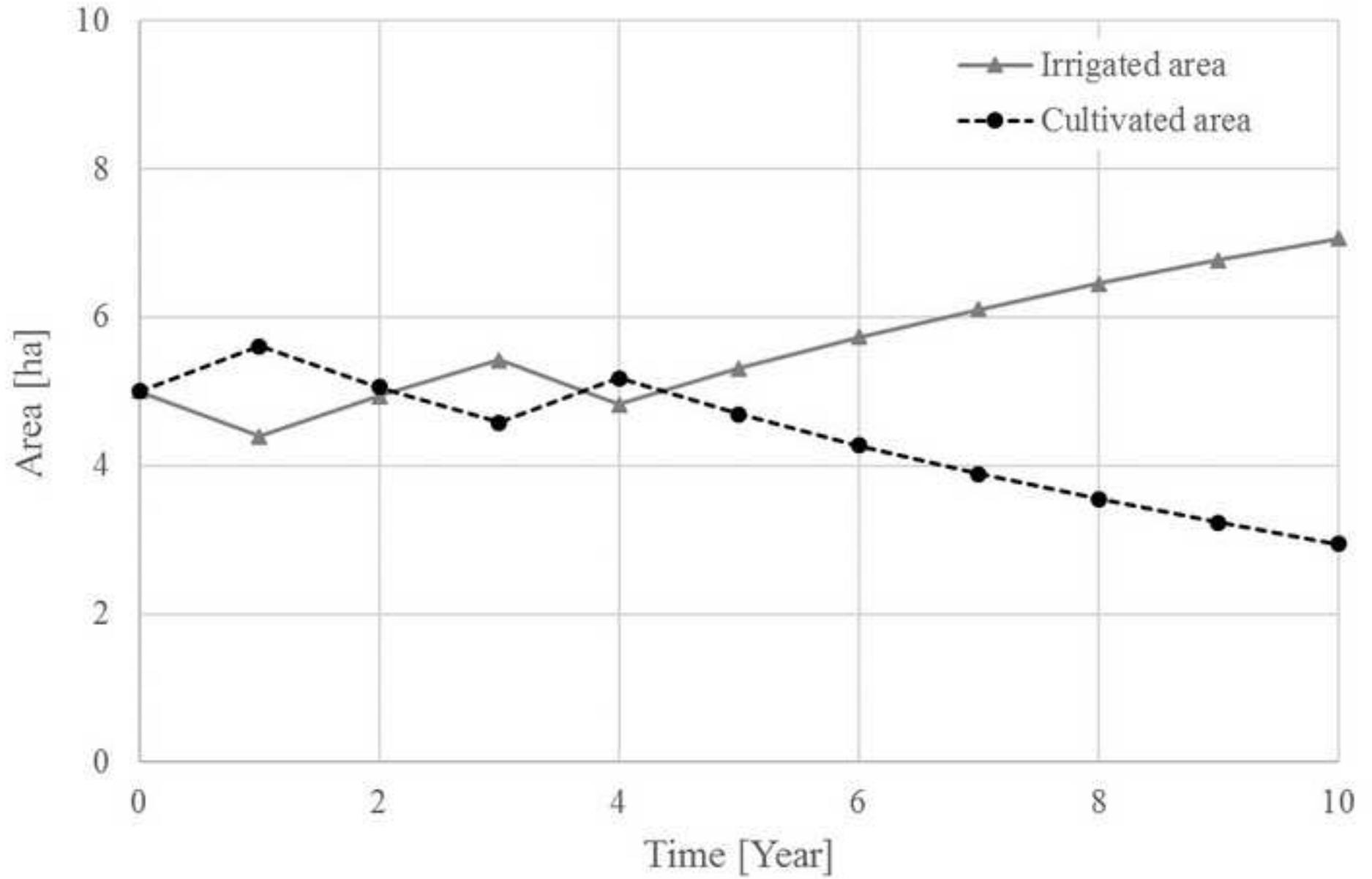


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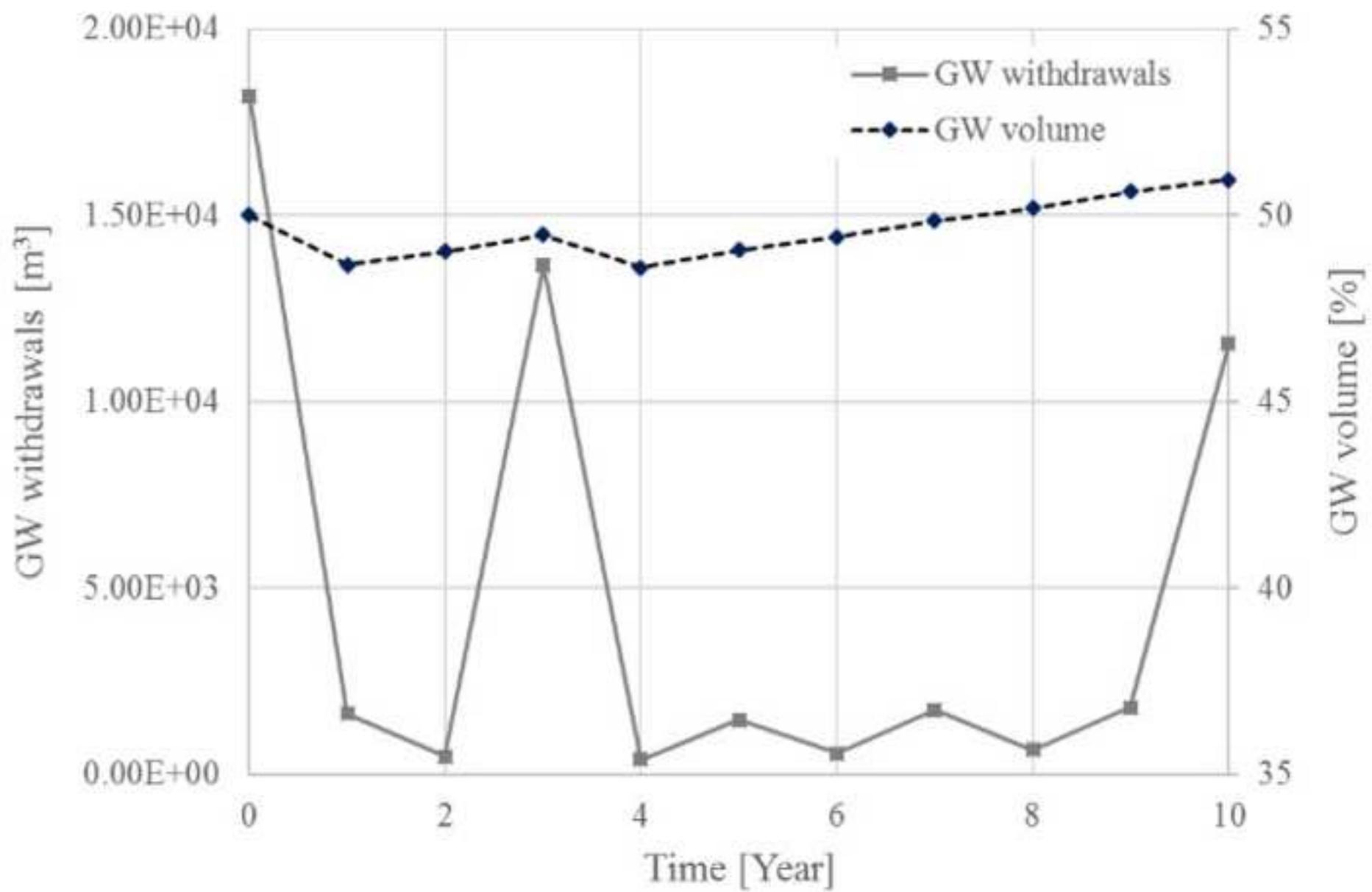


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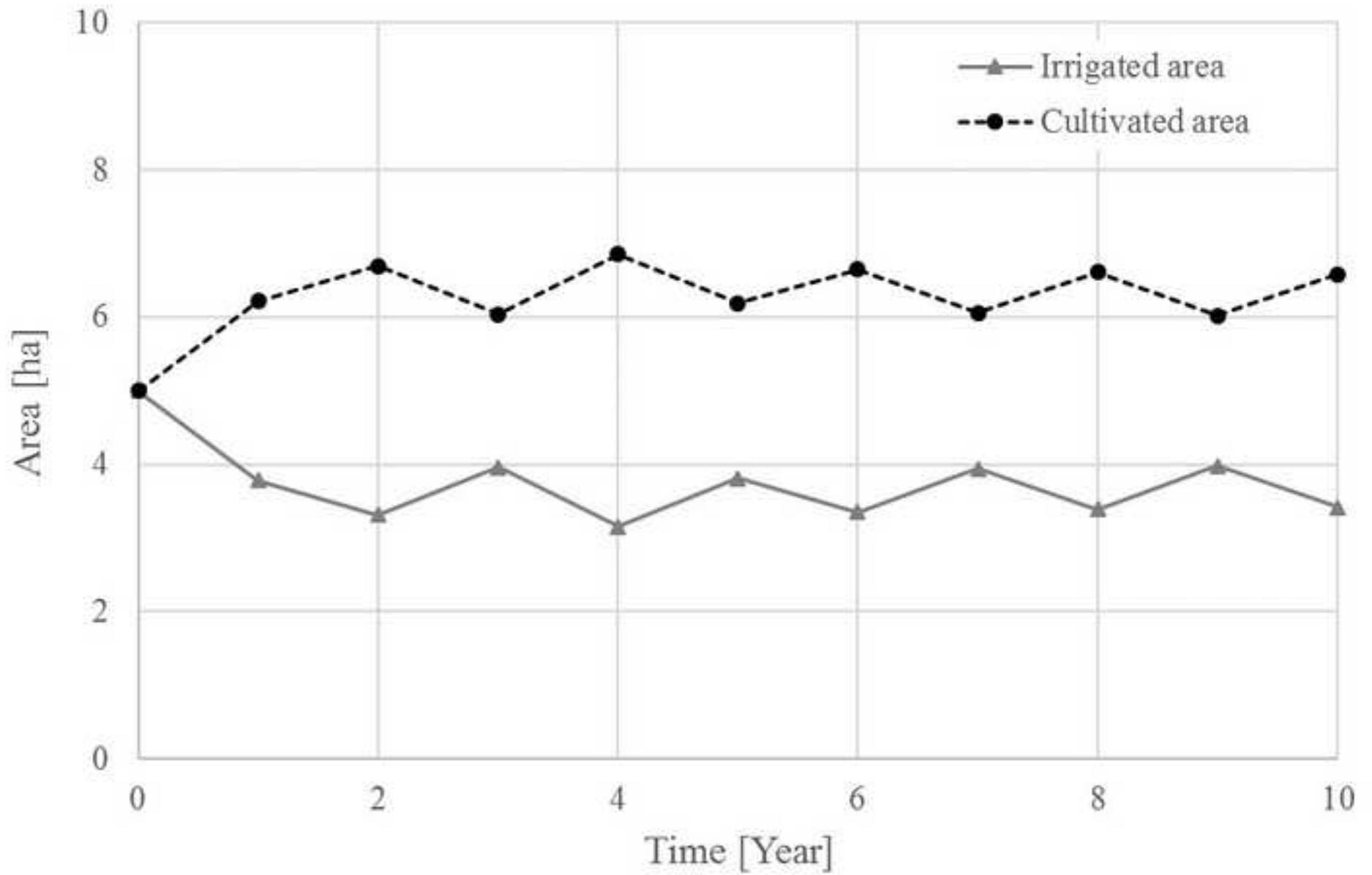


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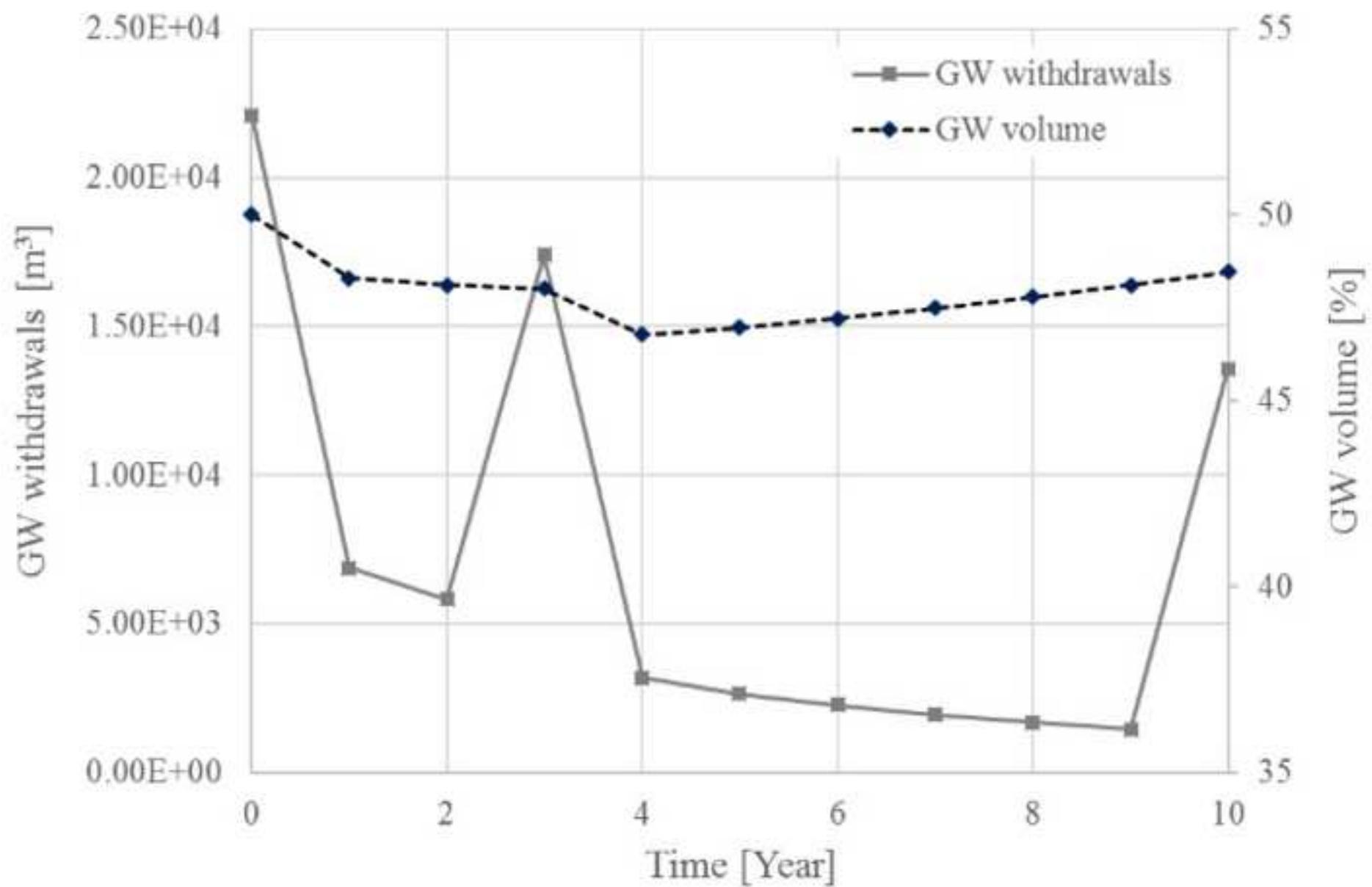


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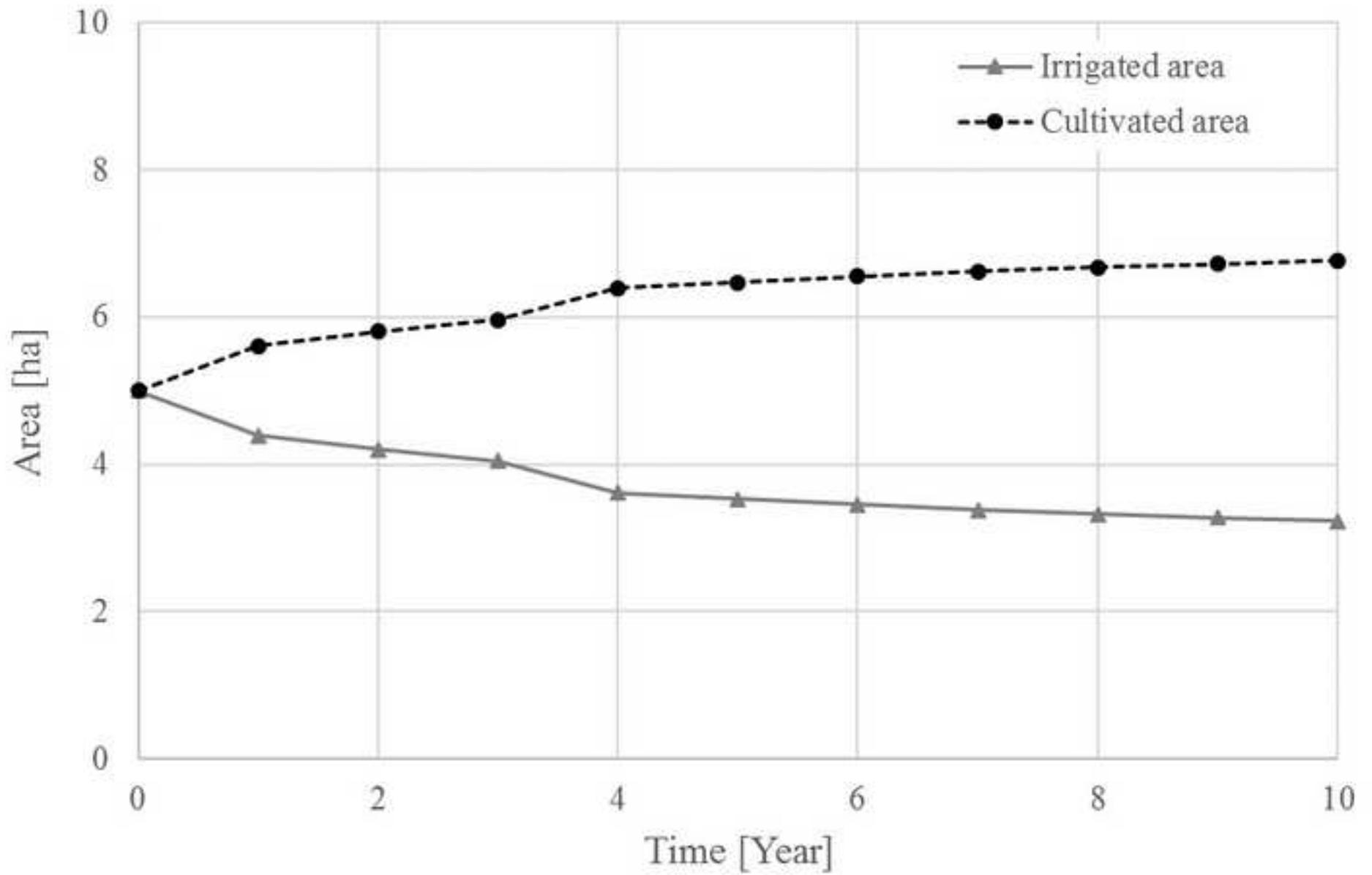


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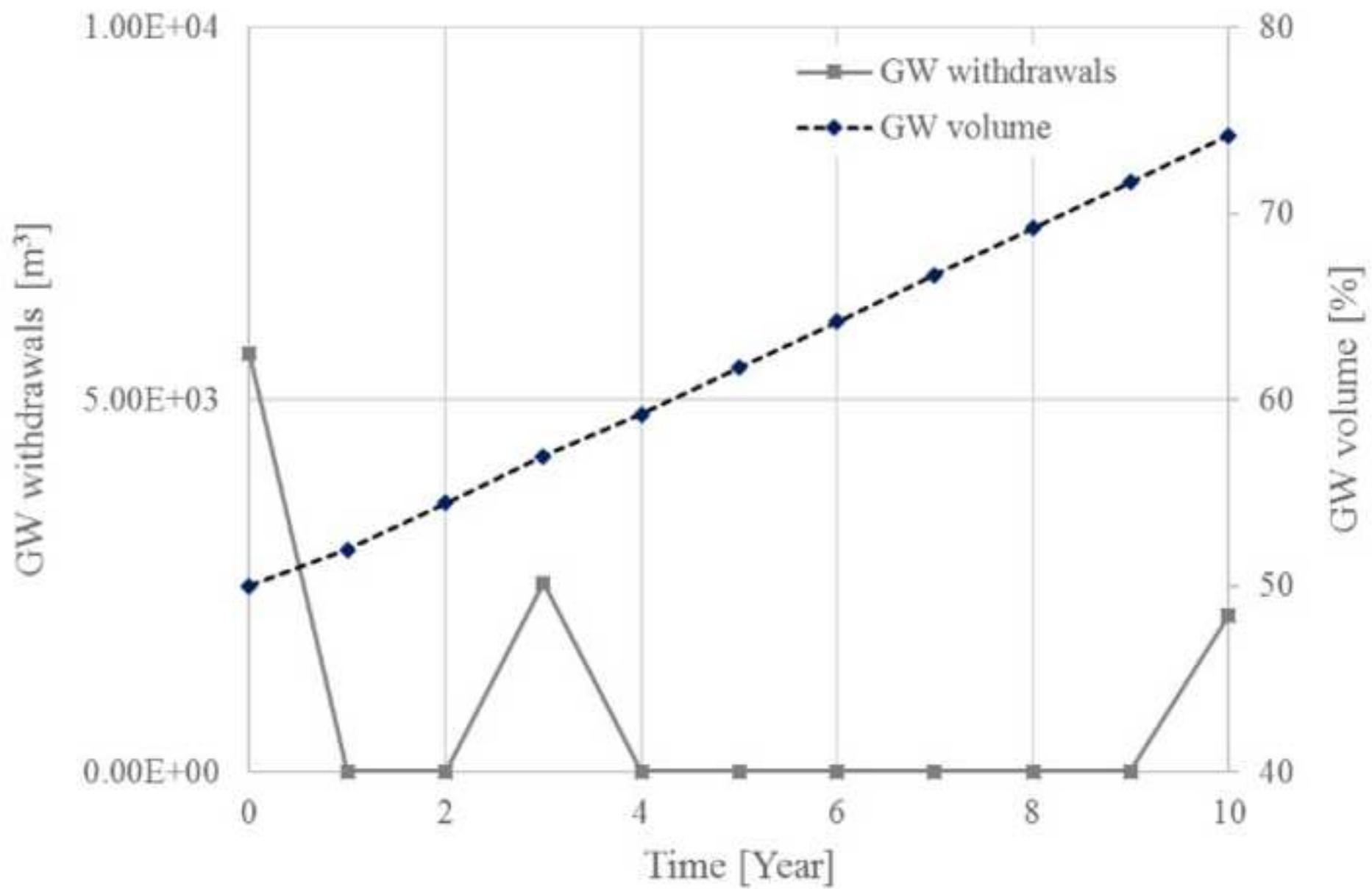


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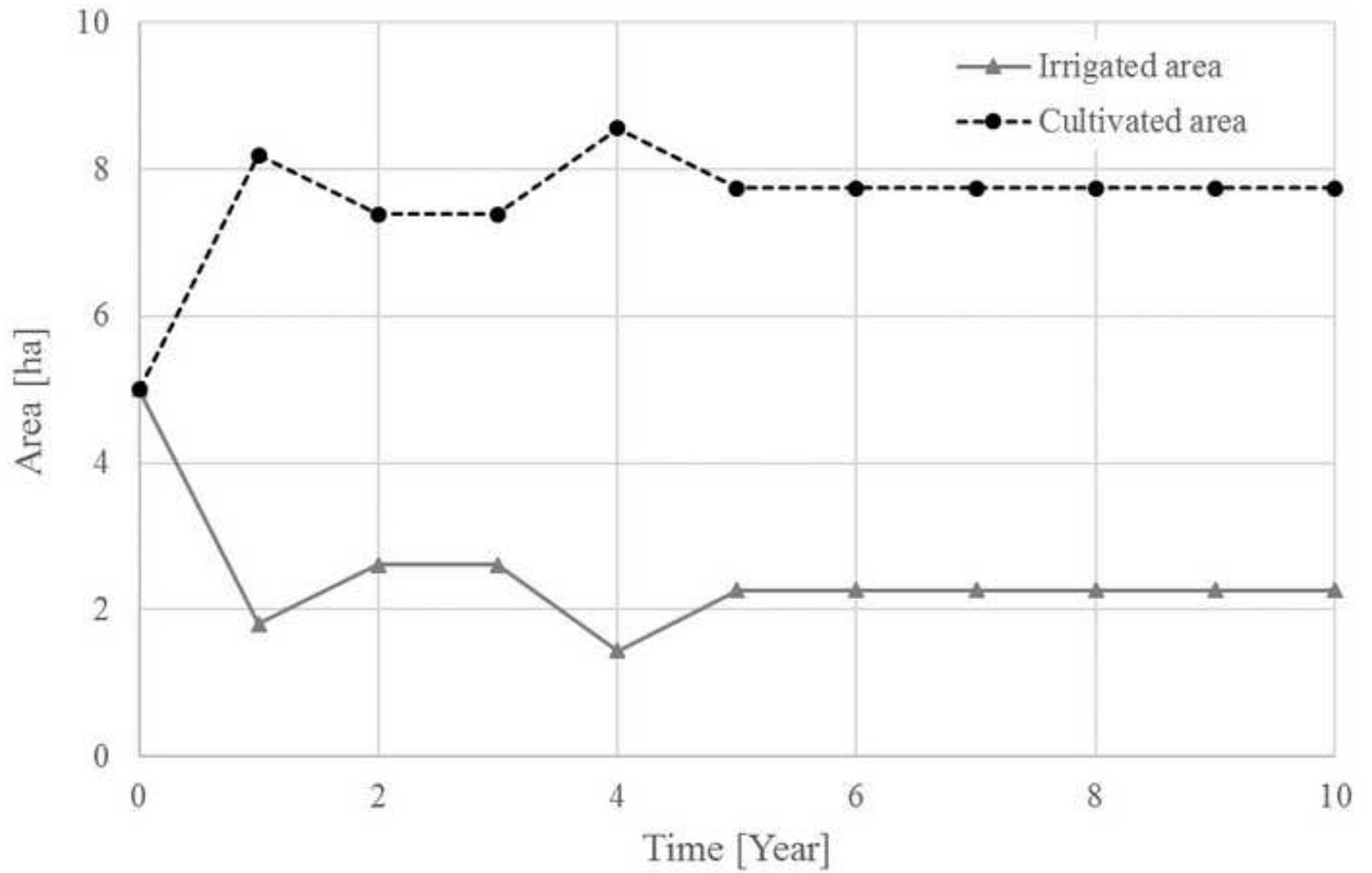


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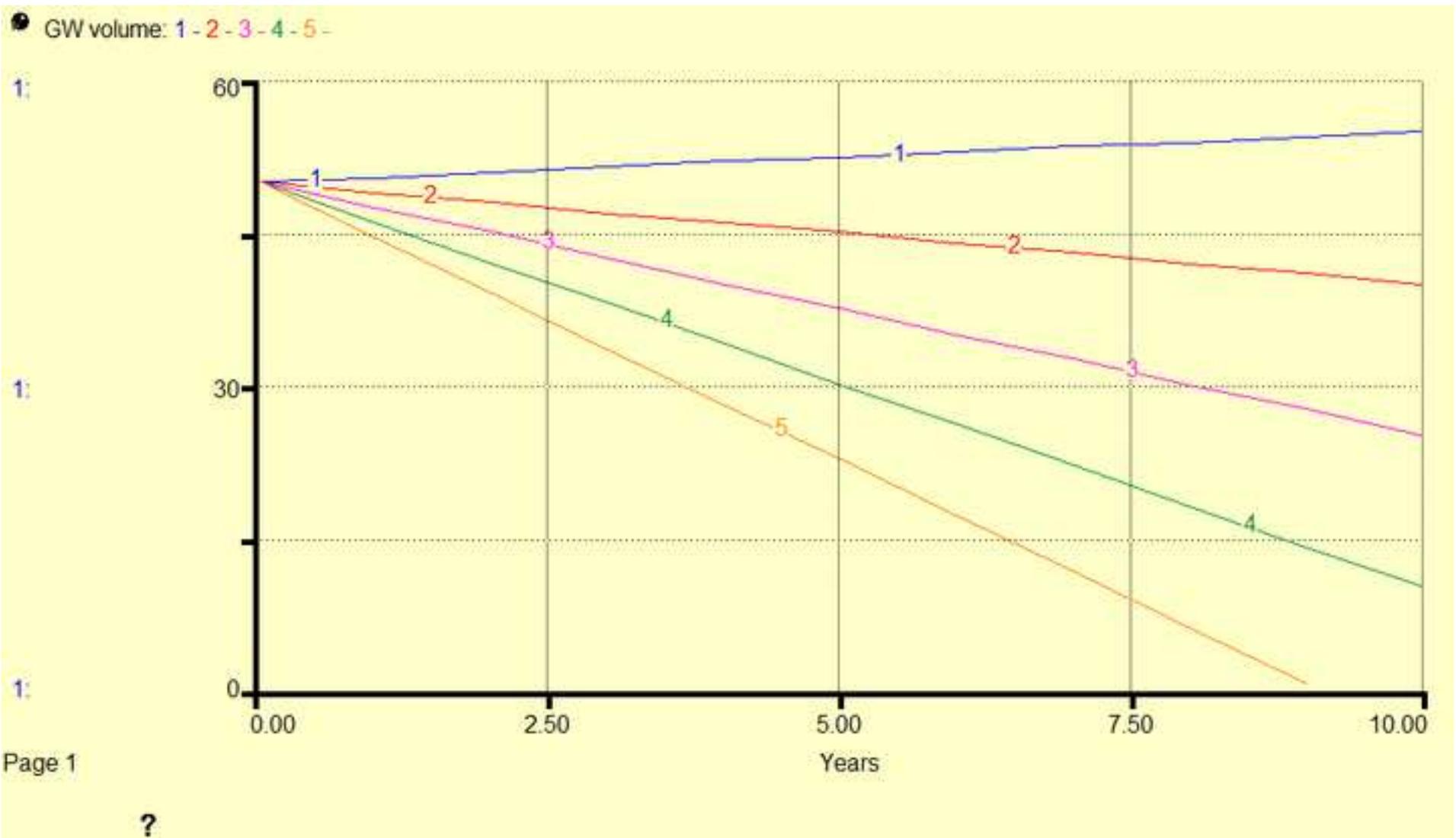
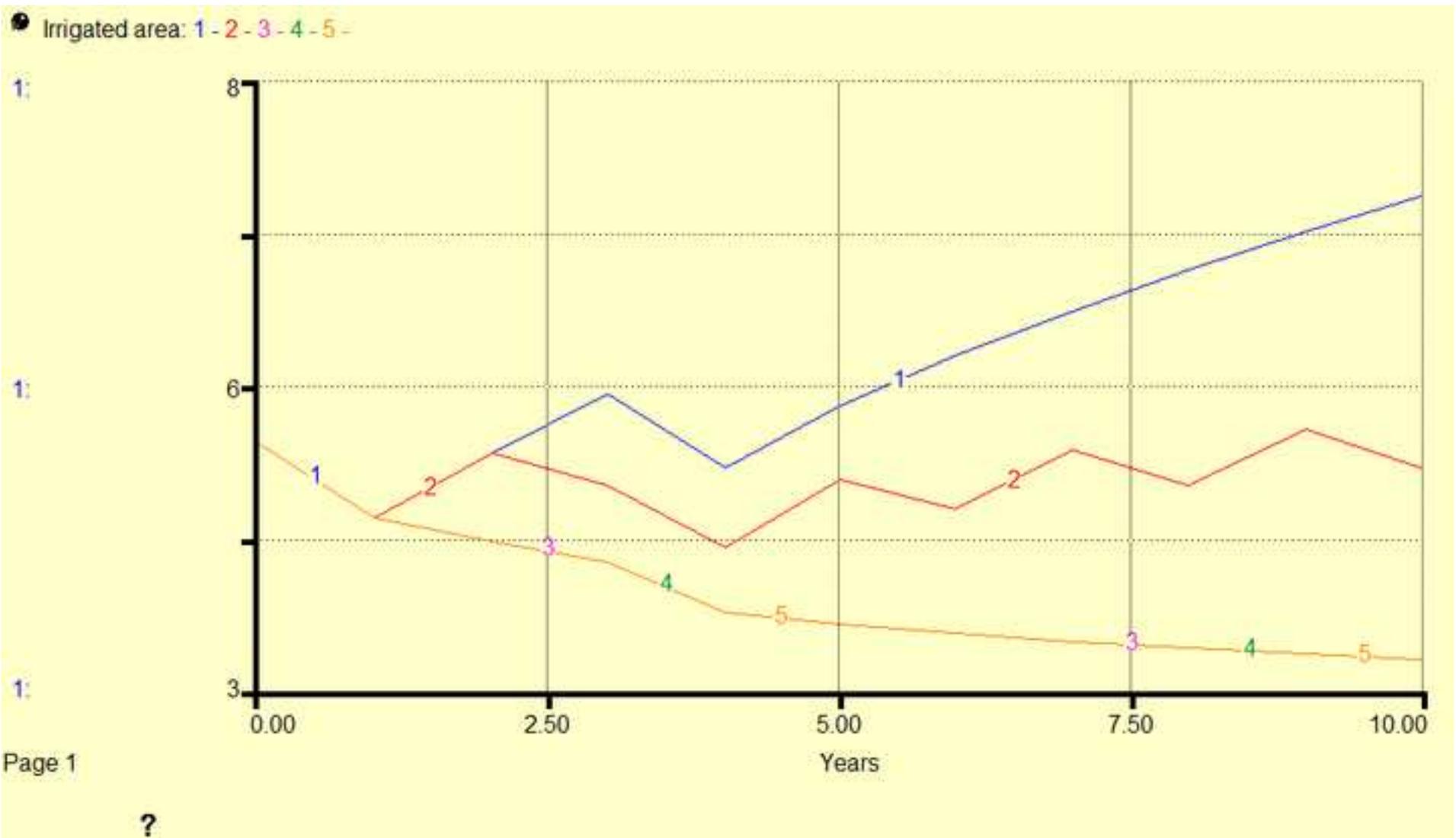


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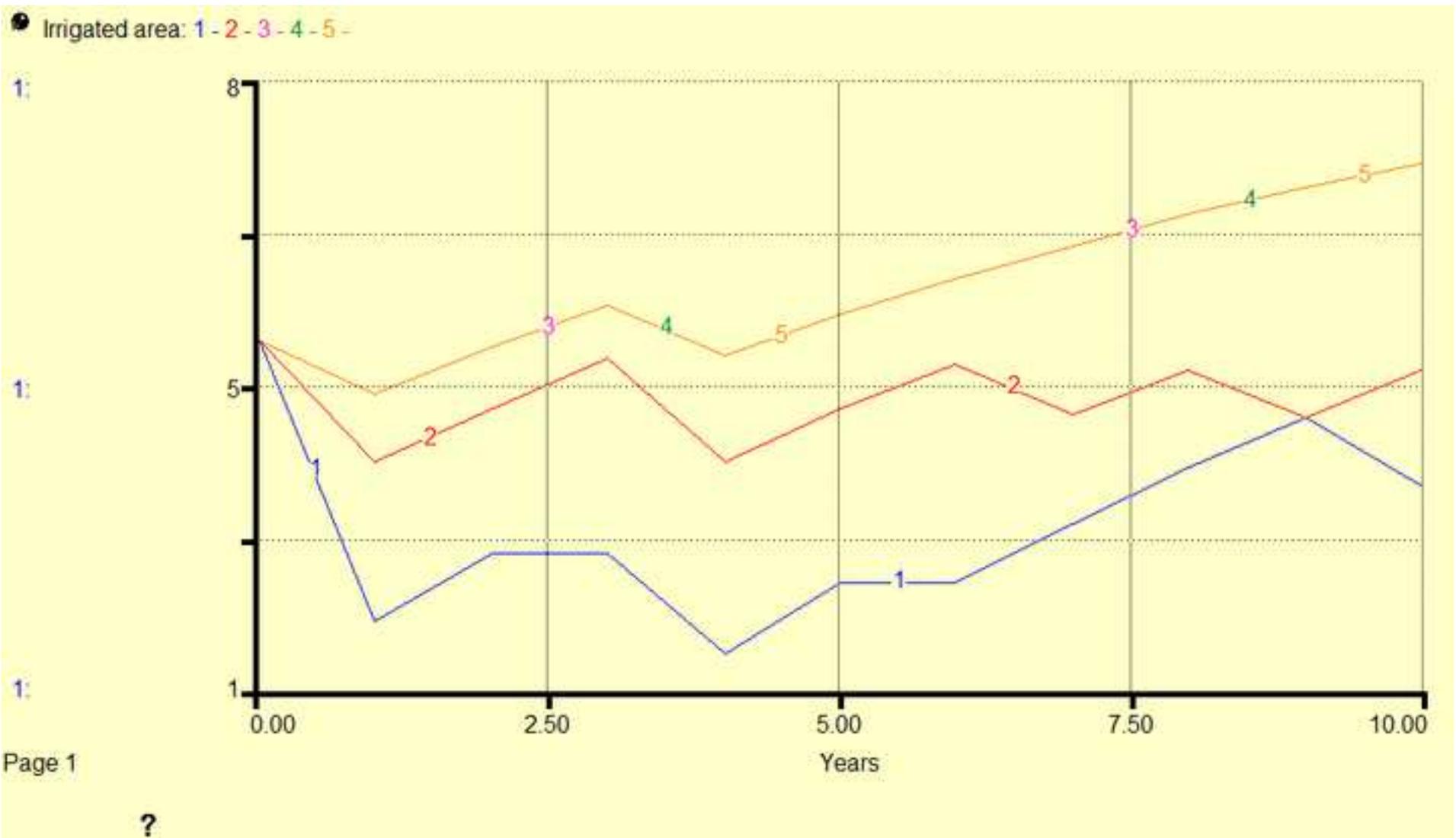


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