Modelling farmland dynamics in response to farmer decisions using an advanced irrigation-related agent-based model

Lang, Dengxiao; Ertsen, Maurits W.

DOI
10.1016/j.ecolmodel.2023.110535

Publication date
2023

Document Version
Final published version

Published in
Ecological Modelling

Citation (APA)
Lang, D., & Ertsen, M. W. (2023). Modelling farmland dynamics in response to farmer decisions using an advanced irrigation-related agent-based model. *Ecological Modelling*, *486*, Article 110535. https://doi.org/10.1016/j.ecolmodel.2023.110535

Ecological Modelling 486 (2023) 110535

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Modelling farmland dynamics in response to farmer decisions using an advanced irrigation-related agent-based model

Dengxiao Lang [*], Maurits W. Ertsen

Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands

ARTICLE INFO

Keywords:
Agent-based model
Water availability
Harvest memory
Decision-making
Common pool resource

ABSTRACT

Often, individual, communal, regional, or even national conflicts arise when water resources are shared and used. For equitable water-sharing strategies to be implemented, adequate collective action is required to allocate water – not limited to, but specifically in irrigation systems. In this research, we develop an Advanced Irrigation-Related Agent-Based Model (AIRABM) to explore issues of unequal access to water in relation to water use on farm and system levels. By simulating farmer activities and system management decisions within an irrigation system, our research aims to explore farmland dynamics in response to different levels of decision-making according to water availability. We incorporate both individual and collective decision-making processes to explore patterns in farmers' yields and the dynamics of farmlands. Our results show that (1) within a prevailing trend of increasing yields for higher river discharge and gate capacity, (2) the influence of water availability is characterized by nonlinear changes in yields in response to variations in river discharge and gate capacity, revealing thresholds and tipping points, with (3) strategies for water redistribution partially alleviate inequitable water allocation between upstream and downstream farmers, although considerable variation persists in individual farmers' and system-wide harvest outcomes. The AIRABM emphasizes individual and collective decision-making processes, encapsulating the uncertainty stemming from water availability and harvests of individual farmers. The modeling framework serves as a valuable tool to explore cooperative approaches in shared (water) resource management. Our findings provide meaningful suggestions to study and promote communication and (conditional) cooperation measures between farmers and management, thereby enhancing the effectiveness of irrigation water distribution.

1. Introduction

With a developing global economy and growing population, water use competition may increase, as allocating water between competing users may become increasingly difficult (Nandalal and Simonovic, 2003; Tilmant et al., 2009). As water is a common source shared by many users, decisions about water management or allocation can typically affect a large group of water users (Berglund, 2015). Water management is crucial for reaching equitable water distribution, given conflicts of interest with multiple decision-makers (Daniell et al., 2016; Pluchinotta et al., 2018). Actual irrigation water management resulting in water availability for users is created by complex interactions between stakeholders, with distribution and use of water resources possibly creating conflicts at different levels. For instance, the Lingmuteychu Watershed in Bhutan saw strong water conflicts between upstream and downstream communities, with upstream holding water longer than downstream, resulting in planting practice upstream having significant impacts on downstream's water supply and crop production (Gurung et al., 2006). In Zimbabwe, different irrigators along the Manjirenji-Mkwasine irrigation canal suffered from irrigation water conflicts (Svubure et al., 2010). Tanzanian farmers in Mufindi district also faced the situation that upstream farmers could use water excessively (D'Exelle et al., 2012). To implement equitable water-sharing strategies, researchers indicate the need for adequate collective actions on water allocation (D'Exelle et al., 2012; Meinzen-dick et al., 2002; Ray and Williams, 2002). It is challenging to allocate water between upstream and downstream users, as the latter rely on the former through the canal infrastructure.

In modeling coupled human-water systems, like irrigation systems, there is a growing recognition for sustainable irrigation management that not only considers farmers' benefits, but also incorporates relationships among farmers and with hydraulic infrastructures. Traditional hydrological modeling approaches have difficulties in effectively

---

[*] Corresponding author.
E-mail address: D.Lang-1@tudelft.nl (D. Lang).

https://doi.org/10.1016/j.ecolmodel.2023.110535
Received 18 July 2023; Received in revised form 11 September 2023; Accepted 6 October 2023

capturing system user heterogeneity, which can limit the model's ability to represent the interactions among the agents (Khan et al., 2017; Yang et al., 2019). Involving stakeholders (e.g. hydrologists, policy makers, water managers, farmers) in the modeling process could improve model system performance and allow stakeholders to understand how their actions (can) affect other agents. As such, collective modeling can open a discussion how systematic patterns emerge from collective actions. However, these hydrological models could be unfriendly to non-tech stakeholders. For instance, the process-based model Soil and Water Assessment Tool (SWAT) has been used broadly to explore agents' interventions in water resource management (Daloğlu et al., 2014; Khan et al., 2017). The input data of SWAT is divided into static data (soil, elevation, land-use data, etc.) and dynamic elements (water flow, meteorological data, water quality, etc.). However, availability and complexity of these data is usually less accessible to non-tech stakeholders, making their involvement more challenging (Muste et al., 2013). The Sobek hydrodynamic model is broadly utilized for irrigation network simulations, like water conveyance and water distribution (Afrasiabikia et al., 2017; Ibrahim, 2022; Seyed Hoshiyar et al., 2021). However, in addition to similar challenges for not-tech stakeholders identified above, it cannot easily include farmers' irrigation actions on farmland or crop yield simulations.

In irrigation (and other ecological settings) humans and their environment together form an intricate system, where humans are not only capable of interacting with each other, but can also exert an impact on the local environment while simultaneously responding to the outcomes of those actions. These interconnected systems hold significance in grasping the repercussions of human activities and the system's potential to avert instances of vulnerability (Ghani and Mahmood, 2023; Pal and Ghosh, 2023). An agent-based model (ABM) offers an integrated approach for complex system simulation (Aghaie et al., 2020; An et al., 2021; Chen et al., 2023). It can model the heterogeneity of individuals and mimic the actions of these individuals. ABMs can be developed in a user-friendly platform with an interface that provides realistic representations of human and non-human actions. We can use simplified, but realistic hydrological processes and empirical data to build an ABM. Therefore, ABMs are especially interesting for non-tech stakeholders to play a role in the modeling work. Although we have not included real-life stakeholders yet in our modeling procedures and development, we can show how the (un)equal distribution of water in an irrigation system using an ABM-approach based on farmers' decision-making according to water availability and harvest memory can be studied in a meaningful and yet accessible way to stakeholders.

In this paper, we propose the Advanced Irrigation-Related Agent-Based Model (AIRABM), which explores interactions between human and non-human agents in an irrigation system driven by water supply. Our previous research developed the Irrigation-Related Agent-Based Model (IRABM) to study how barley yields patterns emerged from human and non-human agents interacting in an irrigation system (Lang and Ertsen, 2022). IRABM showed potential water conflicts between upstream and downstream farmers due to location priority – upstream farmers have higher yields, especially when there is water scarcity in the irrigation system – but did not include communication or decision-making among farmers, we modelled non-human agents to express human agents' actions. We improved IRABM by adding (1) options to learning and make decisions for individual water users and (2) collective actions responding to specific situations on system level. The basic design logic is the same for the two versions, like the water movement through the model system and the yield response mechanism to water that becomes available. In the current research, we explore yield patterns resulting from (un)equal irrigation water distribution and management options, as a proxy for potential water conflicts among upstream and downstream farmers when there is unequal water distribution in the system. To do this, model farmers have memories about their harvest situation and water availability: they can learn from their own experience. Based-on farmers' memory, they can make decisions on sowing choices, which can generate dynamics in terms of the use of fields on model farms. As individual farmers focus on their own business first and do not necessarily care about what other farmers' decisions are, water conflicts will easily come to the system with an increasing water demand. Then, the modelled systematic management of farm gates attempts to act to help solve these water conflicts – by reducing the capacity of upper gates and letting more water flows to the lower area, which hopefully solves distribution problems without hampering upstream farmers. As such, we developed the model to mimic activities by individual farmers and actions on system level in an irrigation system to explore how system agents learn by themselves and interact with each other under equal and unequal water distribution situations.

2. Methods

2.1. Model outline

The AIRABM design is structured according to the ODD + D protocol, which stand for Overview, Design concepts, Details + Decision Making (Grimm et al., 2020, 2010, 2006; Müller et al., 2013). The elements of the ODD + D for AIRABM are briefly explained in Table 1. As AIRABM shares much with its predecessor IRABM, many basic elements and details described in Lang and Ertsen (2022)) are relevant as well. The first main difference between AIRABM and IRABM can be found in the number of canals and farmers, and the number of fields per farmer. IRABM includes more canals (16) and farmers (8 per canal), with each farmer having one field (farmland). With this setup, we tested the model's capability to mimic an irrigation system. Our successful first step allowed us to explore decision-making processes in irrigation with AIRABM, with one canal with 10 farmers having more farmlands (up to five per farm). As such, farmers can make decisions on farmland dynamics. With different individual farmers' decision possibly leading to a variation of yields among farmers, AIRABM includes system level (management) decision-making mechanisms to potentially limit this variation – especially when it results in unequal yields. This is the second difference between the versions, as IRABM did not include such decision dynamics yet. In this section and the subsequent one, a multitude of scientific terminology is employed. To facilitate comprehension, we have compiled an overview of frequently utilized terms and their corresponding abbreviations in Appendix A.

Table 1
The brief ODD protocol of the AIRABM.

Elements	Explanation
1. Purpose	Analysing farmland dynamics in response to farmer decisions, with system level decisions creating more equal conditions.
2. Entities, state variables, and scales	There are ten farmers (each having a maximum of 5 farmlands to be cultivated); one river; and one canal. Water Units are used to present water volume (WU/tick).
3. Process overview and scheduling	Barley yields and farmlands status are reported annually.
4. Design concepts	In the 1^{st} year, farmland 1 is cultivated by all farmers; subsequently, farmers decide to keep, expand, or abandon farmlands according to yields and water availability. Interaction between farmers' are expressed in adjusting gate capacities to increase lower yields.
5. Initialization	All farmers can cultivate farmland 1 in the 1^{st} year.
6. Input data	No input data.
7. Submodels	Irrigation schedule; irrigation sequence; the response of barley yields to supplied-water; and farmland dynamics.

Note: One farmer has one farm, with five farmlands that potentially could be cultivated on this farm.

2.2. Process overview and scheduling

AIRABM explores farmland dynamics resulting from individual farmers' decision-making. This model considered two processes: one is the evaluation of annual yields and received water, for next year's planting choice; the other one is the evaluation of the yield situation which is used to determine if GC adjustment is needed or not (Fig. 1).

2.3. Model design concepts

The simplified irrigation system layout and the model design concept are shown in Figs. 2 and 3: one river feeds 10 farmers along one canal, each farmer has 5 fields that can be potentially planted with the model crop barley. A daily time step is applied, with barley growing status and water dynamics being updated daily as well. The total simulation time is 20 years. In the current model, we use the so-called Irrigation Memory (IM) in farmlands, which refers to the interval between two irrigation actions – if there is irrigation water on the field, the IM procedure will start. The IM is set at 36 days in the current version and is calculated according to a relatively simple calculation method (Brouwer et al., 1989). The IM decreases with 1 day when the model goes 1 tick further. As soon as the IM is lower than 1 day, the irrigation procedure will start, which will depend on the availability of water resources. However, if the IM is reaching −24 days (thus when water is not available to irrigate for many days), the barley will die. If two or more farmlands are cultivated, the irrigation sequence within the farm starts with farmland1, followed by farmlands 2, 3, 4, and 5 respectively. According to farmers' location in a gravity-based system, we defined farmers 1, 2, and 3 as upstream farmers (F1, F2, and F3); whereas middle stream farmers are farmers 4, 5, 6, and 7 (F4, F5, F6, and F7); and downstream farmers are farmers 8, 9, and 10 (F8, F9, and F10).

2.4. The response of barley yields to water supply

According to empirical irrigation data for Mesopotamia (see Lang and Ertsen (2022) for explanation of that regional choice) and a relatively simple calculation method for irrigation scheduling, our modelled irrigation demand and the barley yields response to the water supplied are presented in Table 2 and Fig. 4 (Brouwer et al., 1989; Charles, 1988). The stage-wise ratio of barley yields to supplied water was determined with the logic discussed in Burton (1989). Stage I consists of land preparation and the first irrigation, stage II consists of the second and the third irrigation, while stage III only includes the last irrigation. The highest barley yields shown in Fig. 4 were calculated based on the literature (Wilkinson et al., 2007).

2.5. Learning and memory

Every year, for each farm, the model calculates the average available water (AAW) and average harvest of barley (AHB). These two variables are based on water availability and barley yields in all past growing season. These variables are used in the model to track water and yields and use the historical record (memory) to allow our model farmers to make decisions based on their own agriculture experience. AHB and AAW are calculated as:

$$AHB = \frac{HBY_1 * 1 + \ HBY_2 * 2 + \ HBY_3 * 3 + \cdots + HBY_n * n}{1 + 2 + 3 + \cdots + n} \tag{1}$$

$$AAW = \frac{AW_1 * 1 + \ AW_2 * 2 + \ AW_3 * 3 + \cdots + AW_n * n}{1 + 2 + 3 + \cdots + n} \tag{2}$$

Where HBY_n is harvest barley in the n^{th} year, Kg; AW_n is available water in the n^{th}year, WU (water units).

In calculating AHB and AAW, we consider both the weight of harvest barley and water availability. Specifically, years closer to the upcoming planting year carry a higher weight in the calculations.

2.6. Individual farmers' decision-making mechanism

Fig. 5 describes the decision-making mechanism of farmland management. This decision-making flow is the general routine in each model year. The AHB and AAW provide farmers with the opportunity to keep the last season's cultivation choice (Keep), or make change to expand one farmland, or to abandon one or two farmlands. The expansion sequence is expanding farmland 2 first, then expanding farmlands 3, 4, and 5, while the abandonment sequence is the opposite. In their decisions to expand or not on their farmlands, our model farmers disregard other farmers' cultivation choices.

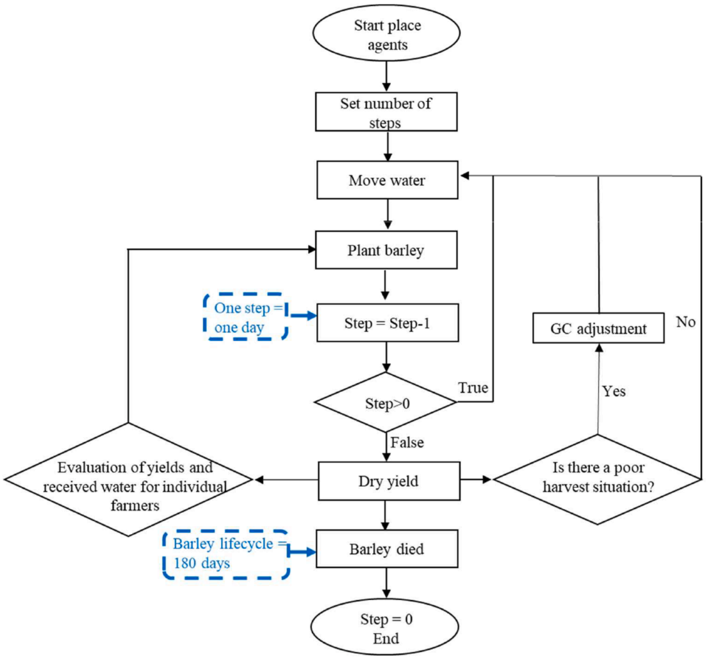

Fig. 1. Process overview of the AIRABM.

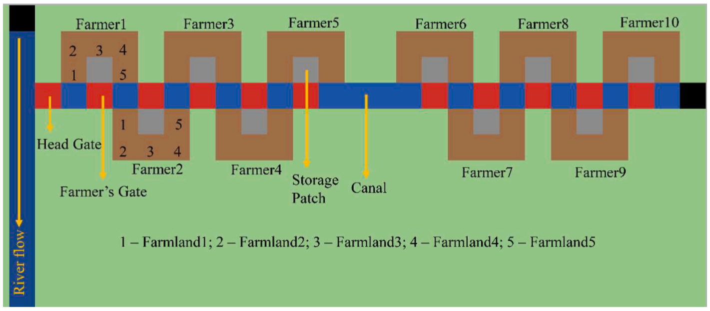

Fig. 2. The layout of the modelled irrigation system.

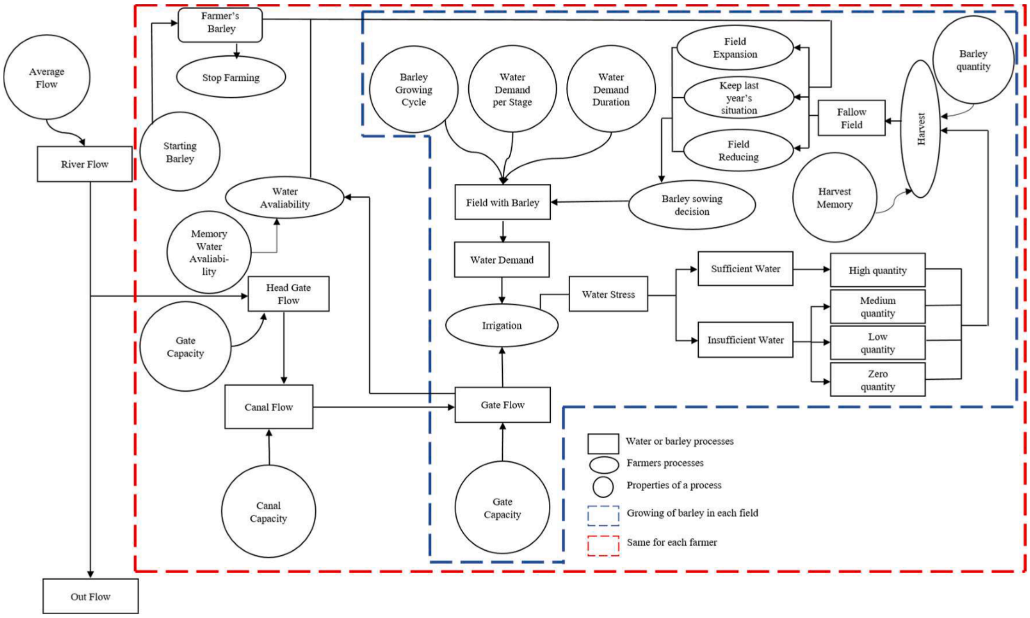

Fig. 3. The overview of the AIRABM design concept.

Table 2
Simplified irrigation demand of barley at each stage.

Irrigation demand (mm)	Stage I	Stage II	Stage III
Ideal	200	150	60
Good	100 – 200	75 – 150	30 – 60
Medium	\	30 – 75	\
Poor	0 – 100	0 – 30	0 – 30
None	0	0	0

2.7. *Irrigation system level management decision-making*

As is known in gravity-based irrigation systems, whatever the relatively upstream farmers do will affect the more downstream farmers. This means that individual decisions of these farmers can influence other farmers. To study such interactions and what can be done at system level, the current model version has explored collective decision-making mechanisms. At the end of each growing season, farmers' harvest situations are evaluated by comparing the barley yields and the harvested farmlands of each farmer. Here, yields refer to the amount of barley that farmers or the irrigation system could obtain at the end of the barley growing season. We define the overall results of the evaluation as "harvest situation". In scenarios with unequal yields among farmers, both the upstream gate capacity (UGC) and middle stream gate capacity (MGC) of farmers will decrease (with different decreasing levels) while the downstream gate capacity (DGC) will remain constant at the initial gate capacity (IGC). This gate capacity (GC) adjustment pushes more water to the downstream farmers. The actual values we applied to decrease GCs are shown in Table 3. It is possible that after one GC adjustment in a year, the harvest situation still creates another GC adjustment in the next year(s). With this procedure, the modelled water distribution can represent farmers' communication and/or represent irrigation management decisions that were taken at the (collective) system level.

3. Some representative results

Our modeling efforts have resulted in many results, which cannot be represented entirely in this paper. We have selected two representative sets of results of our model setup, distinguished by whether the GC remains unaltered or is adjusted. With the first set (the baseline), there is no gate control: regardless of how the harvest situation changes, all farmers (continue to) have the same gate capacity. The GC adjustment procedure is not applied yet. In the second set, all farmers start with the same GC (also known as IGC), but GCs are adjusted as explained above when there is a poor harvest situation.

3.1. *Harvest situations without gate capacity control*

3.1.1. *Harvest situations for irrigation system's level*

Fig. 6 shows the total yields on system level for all combinations of RD and GC over the 20 model years of the system. Total yields generally

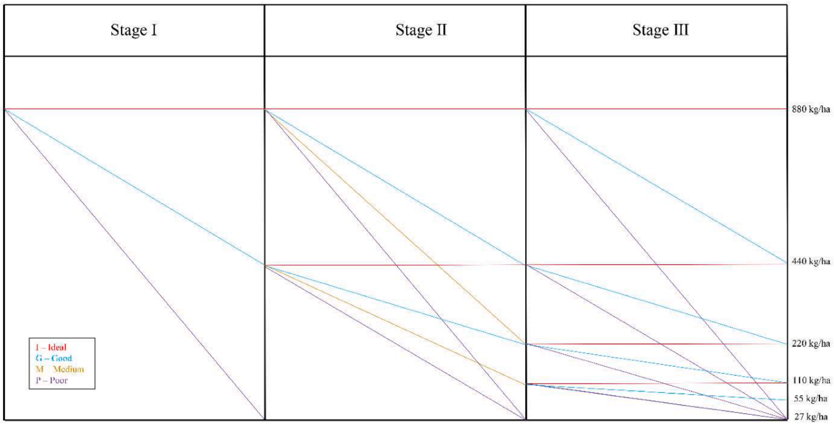

Fig. 4. Simplified barley yields response to supplied water diagrams.

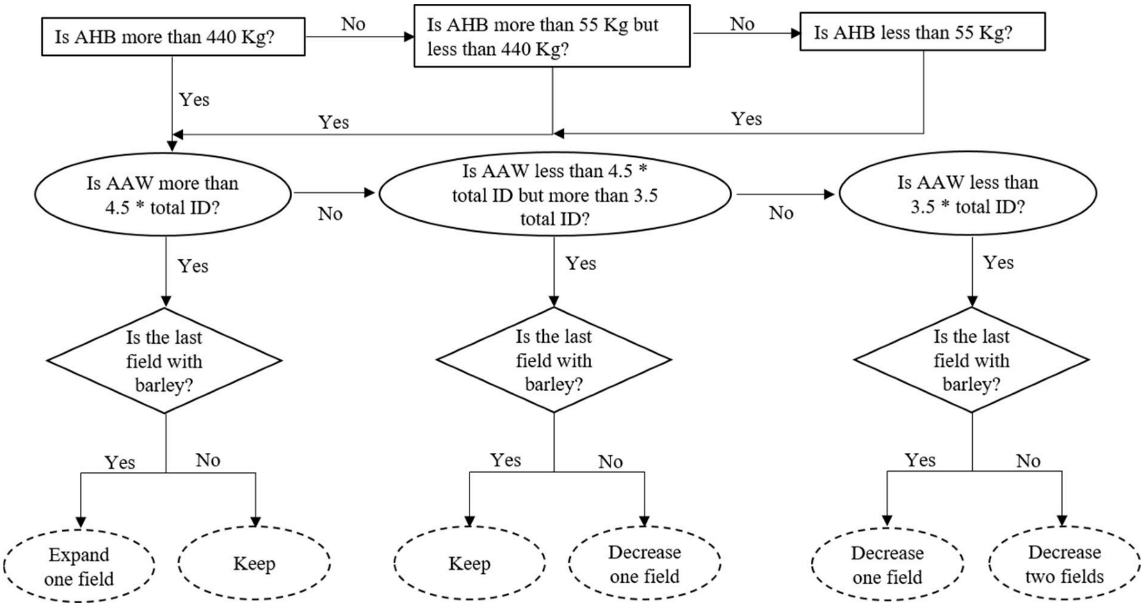

Fig. 5. The processes of individual farmers' decision-making on farmlands dynamics. ID – irrigation demand. This is a decision-making example of when there are 4 harvested fields in the last year.

increase as RD increases – which is not surprising, given that higher water availability typically promotes higher crop production (Aliyari et al., 2021; Dinar et al., 2019; Rehman et al., 2019). Each GC column shows a clear threshold value for RD in terms of total yields with increasing RD. When the RD threshold is reached, total system yields will remain the same no matter how much RD is increased. For most GCs, the RD thresholds are higher than 150 WU/tick. In the case of GC = 50 WU/tick, there is no yield threshold: water availability shifts without a clear direction with this GC per field. This result is somewhat artificial, as it is a direct consequence of the combination of the numerical values of water needs per farmland and the GC settings as defined in the model. Furthermore, some GCs show the general increasing trend but not the fluctuations per step of increased RD before the general trend is resumed. Again, the model settings, particularly those for water transport between cells, are responsible for this. These setup issues do not affect the overall pattern though.

Next to thresholds per GC column, GC tipping points have been found when measuring total system yields between increasing GC and constant RD. Once the GC tipping point is reached, regardless of how the GC changes, the total yields decrease to a certain value and remain unchanged until the highest simulated GC is reached. There is a trend for the value of GC tipping points – they increase with increasing RD when RD <160 WU/tick. For RD > 160 WU/tick, GC tipping points decrease and then stabilize. That is because the modeling RD is higher than the highest modeling GC: there is sufficient water in the system. This means that only relatively low GC will affect yields. As farmlands start the IM procedure at different times (depending on when they were irrigated), the relatively lower GC brings little water to the fields and then leads to lower yields due to the time limitation caused by the IM. Therefore, if there is sufficient water, increasing GC could gradually offset the IM limitation both for upstream and downstream farmers. When GC reaches the threshold, yields are always maximum.

3.1.2. Harvest situations for individual farmers' level

We will discuss the yields of individual farmers in this section while the details of the farmland expansion years of individual farmers are described in Appendix B. At the end of the barley growing season, individual farmers' harvest situations are arranged into two main categories. We refer to the first category as a "good harvest situation" when the yield pattern of all farmers and the expansion pattern of all farmlands are the same (see Appendix C for further details). As a second category, we have farmers with different yield patterns, with in general,

Table 3
Gate capacity adjustment strategy.

Initial Gate Capacity (WU/ tick)	Gate capacity adjustment		
	Upstream Gate Capacity (WU/ tick)	Middle stream Gate Capacity (WU/tick)	Downstream Gate Capacity (WU/tick)
10	5	5, 10	10
20	5, 10	10, 15, 20	20
30	10 – 20	10 – 30	30
40	10 – 30	10 – 40	40
50	10 – 40	10 – 50	50
60	10 – 50	10 – 60	60
70	10 – 60	10 – 70	70
80	10 – 70	10 – 80	80
90	10 – 80	10 – 90	90
100	10 – 90	10 – 100	100
110	10 – 100	10 – 110	110
120	10 – 110	10 – 120	120
130	10 – 120	10 – 130	130
140	10 – 130	10 – 140	140
150	10 – 140	10 – 150	150
160	10 –150	10 – 160	160

Note: if the initial GC is higher than 20 WU/tick, the increments of upstream and middle stream GC is 10 WU/tick.

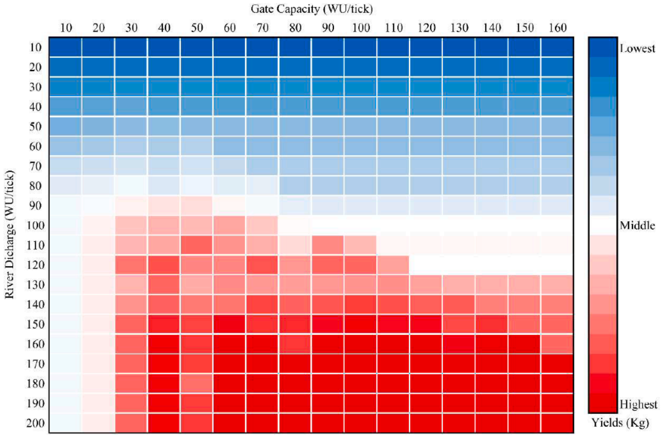

Fig. 6. Total system yields with the varied RD and GC.

relatively upstream farmers having higher yields than relatively downstream farmers – which is why we refer to this as a "poor harvest situation".

Table 4 lists a summarizing overview of the second category, with yields or water availability being less and/or unequal for F1–10. A pattern with increasing RD can be observed:

- For RD = 10 WU/tick, only F1 and F2 have yields. Water does not reach the other farmers.
- For RD = 20 WU/tick, F1–6 can potentially harvest while F7–10 remain without yields.
- For RD = 30 – 80 WU/tick, all farmers harvested, but their yields and amounts of harvested farmlands varied.
- For RD > 90 WU/tick, there are scenarios with equivalent water distribution resulting in good harvest situations. There are also scenarios with unequal harvests.

Considering the given location priority, it makes sense that upstream farmers have better harvest situations than middle-stream farmers, and downstream farmers have the worst harvest situations. Once more, the challenge of how to equitably distribute the "common pool water resource" emerges (Ostrom and Gardner, 1993). Within the model reality, it is still possible that middle stream farmers have better performance compared to upstream farmers, whereas downstream farmers can perform better than middle stream farmers. This is at least partially because of the model settings, with each farmer having a different sowing time in the first year. This means that the procedure of their irrigation memory starts at different times, allowing farmers to take water from the canal at different times. With different water volumes in the canal being available in different time steps (partially resulting from upstream decisions), a lower canal discharge can flow to a farmer at his/her irrigation time, and cannot meet the irrigation demand. As a result, this farmer will have lower yields than other farmers. There could also be a higher flow, which explains why occasionally yields of downstream farmers are high.

Table 4
The summary of poor harvest situations.

River Discharge (WU/tick)	Gate Capacity (WU/tick)	Description
10	10 – 160	F1 with 3 harvest fields, F2 with 2 harvest fields, F3–10 without harvest fields
20	10 – 160	Upstream and middle stream farmers with different number of harvest fields, downstream farmers without harvest fields
30 – 80	10 – 160	Upstream farmers always have 4 or 5 harvest fields while middle stream farmers and downstream farmers have a maximum of 5 and a maximum of 4 harvest fields respectively and sometimes lower yields per field.
90	20 – 160	GC = 80, F10 without harvest fields; while all farmers have harvest but with different number of harvest fields with other situations
100 – 140	30 – 160	All farmers have harvest but with different number of harvest fields with other situations
150	40,70 – 90,110 – 150	All farmers have harvest but with different number of harvest fields with other situations
160	80, 130, 160	All farmers have harvest but with different number of harvest fields with other situations

3.2. *Adaptive irrigation system with gate capacity control*

In the second sets of results, when we allow system-level decisions in the model sequence, there is a considerable number of combinations of adjusted GCs for upstream and middle stream farmers. Considering the initial yield patterns shown in Table 4, our focus will be on some representative cases of GC adjustment for poor harvest situations, using the RD levels of 30, 90, and 160 WU/tick respectively. We will present the harvest situations when RD = 90 WU/tick in detail in this subsection, the details of the harvest situations for RD = 30 and 160 WU/tick are provided in Appendix D.

RD = 90 WU/tick, with IGC = 20 – 90 WU/tick

Fig. 7 illustrates that relatively low UGCs and MGCs could create higher total yields when RD = 90 WU/tick with IGC = 20 – 90 WU/tick, especially with relatively low MGCs. In contrast, lower total yields always occur with higher UGCs and MGCs. The highest yields are always found with the lowest MGC. Generally, the combination of UGC = 40 WU/tick and MGC = 10 WU/tick shows the highest yields in each subfigure. Moreover, most of the IGC scenarios resulted in decreased total yields after GC adjustment while only the scenario of IGC = 80 WU/tick shows an increment of total yields. Nearly half of the combinations show decreased yields when IGC = 20 and 50 WU/tick. Furthermore, the relationship between changing UGC or MGC and the overall system yields pattern remains unclear.

When studying yields of individual farmers, only for the scenario of

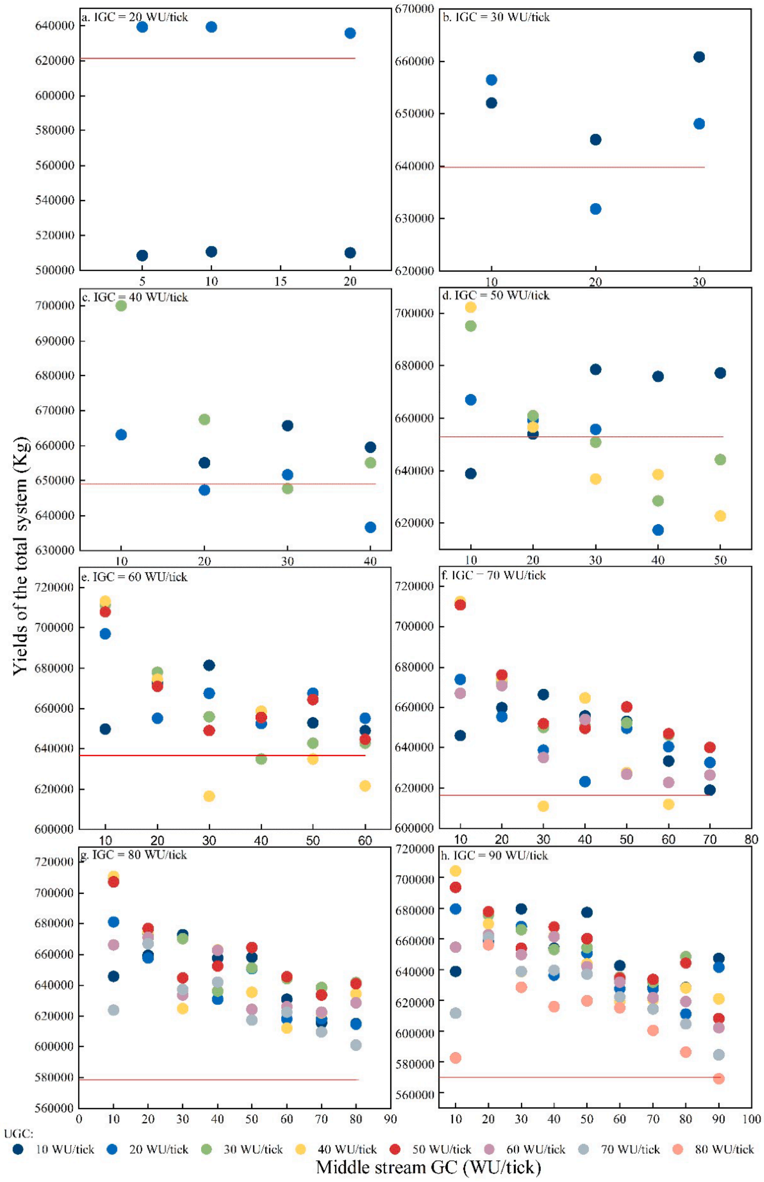

Fig. 7. Total system yields with varied UGC and MGC when RD = 90 WU/tick (red line shows the initial total system yields). The y-axis has different scales due to the significant differential of the yields; the x-axis has different scales due to different MGCs, which are based on the IGC.

IGC = 90 WU/tick we can find situations demonstrating that all farmers are satisfied with the adjustment: poor harvest situations improved without sacrificing anything for other farmers. However, even with increased total yields, GC changes for IGC below 90 WU/tick may not be equally satisfying for farmers. For relatively upstream farmers, there are sacrifices like delayed farmlands expansion, abandoned farmland(s), and decreased yields. Farmers located relatively downstream did not always benefit, with specific situations even potentially being worse. Again, when there is an improvement in relatively downstream farmers' harvest situations, the upstream farmers' profit will be affected. Based

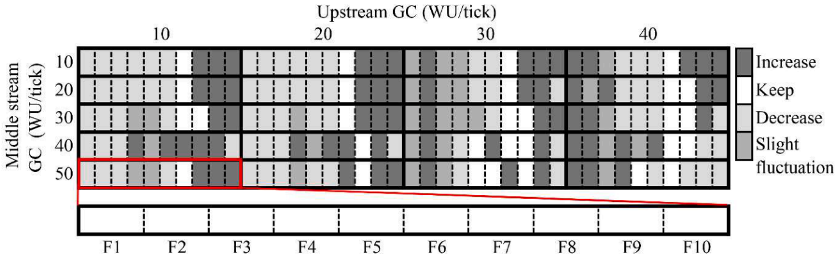

Fig. 8. Harvest situation of individual farmers after GC adjustment (RD = 90 WU/tick, IGC = 50 WU/tick). After GC adjustment, Increase – the farmer has higher yields; Keep – the farmer has the same harvest situation; Decrease – the farmer has lower yields; Slight fluctuation – the farmer has lower yields in the first few years of the GC change and then back to the initial situation (the same in Figs. 9 and D3).

on the total system yields, two examples of individual farmers' harvest situations after GC adjustment will be indicated in detail below.

The first example of individual farmers' yields is based on IGC = 50 WU/tick and RD = 90 WU/tick. After GC adjustment, nearly half of the combinations of UGC and MGC show a decreased trend of total system yields. The harvest situations for F1–10 after GC adjustment, when compared to the initial harvest situation, are shown in Fig. 8. The initial situation is F1–6 having five harvested fields, while F7–8 and F9–10 have 4 and 2 harvested fields, respectively. The GC controls are aiming to improve the yields of F7–10. Fig. 8 illustrates that the improvement of F7–10 is always accompanied by yield sacrifices of upstream and middle stream farmers. F7–10 cannot improve at the same time either. There are farmers with better yields while other farmers end up with worse yields under each combination of changed GC. Combining the results of total system harvest, it is easily found that the amount of decreased yields is higher than the increased yields in some scenarios, which explains those scenarios when total yields decreased after GC adjustment. When UGC and MGC values are closer to the IGC, it is harder to help F7–10 to improve yields as depicted in Fig. 8. For instance, for UGC = 40 WU/tick and MGC = 40 and 50 WU/tick, F7–10 are left without increment in yields. Both lower UGCs and MGCs (10, 20 WU/tick) show that the increased yields of F8–10 are based on the loss of other farmers' profit – F1–6 have lower yields. For UGC >= 30 WU/tick or MGC = 40 WU/tick, there are situations showing not only downstream farmers having higher yields, but also (part of) the upstream and (part of) middle stream farmers having a better harvest.

In the second example, with IGC = 80 WU/tick and RD = 90 WU/tick, total system yields increased under all scenarios. The initial situation is that F1–6 have the same expansion pattern and finally realize the same yields with five harvested fields, while F7–8 and F9–10 have two and one harvested fields, respectively. Again, the GC adjustment was expected to help F7–10 gain more yields. Figs. 7g and 9 show that even when the total system has increased yields no matter how the GC is changed, there are worse situations for some individual farmers under most combinations of UGC and MGC. The hypothesis was that GC adjustment could help poor harvest farmers to have better harvests without decreasing others' profits. There are two combinations that meet the hypothesis – UGC = MGC = 10 WU/tick and UGC = MGC = 70 WU/tick. The first indicates F7–10 having better harvests while the second combination can help F7, 8, and 10, without yields changing for the remaining farmers. However, the total system harvest of these two combinations is not the highest. The upstream farmers are more vulnerable when both UGC and MGC are relatively low, yet the total system harvest is higher indicating that increased profits of F7–10 are higher than decreased profits of F1–6.

4. Discussion

In this research, we use AIRABM to simulate the complex interactions between farmers, irrigation infrastructure (especially gates), and water availability in an irrigation system. With this model, we incorporate both river discharges and gate capacities, as well as decision-making processes and mechanisms at the level of individual farmers and irrigation system. The results indicate how farmers' harvest situations respond to water availability, how farmers adapt and learn from their own experiences, and explore the influence of incorporating other farmers' decisions into water distribution activities. Our research shows how unequal water distribution may promote actions to get more equal distribution later, which indicates a synergy between equitable and inequitable water distribution.

4.1. Temporal and spatial dynamics of this model

The modeling framework described in this paper evaluates the harvest situation and water availability on an annual time step. Both the farmlands expansion decision of farmers and the (virtual) exchange of harvest situations among farmers take place before the new cultivation year. With or without GC control, even with fluctuations in annual yields, farmlands expanded step by step based on their harvest and water availability memory. Eventually, yields and the number of farmlands of each farmer are stabilized. We considered harvest memory and available water memory as the main factors to determine the expansion dynamics of the farmlands. From the 20 years simulation, we could see many farmers cannot cultivate 5 farmlands at the end of the simulation period. If the simulation time is long enough, there will be more accumulated harvest and water memories, which are likely to finally reach the benchmark to expand the farmlands. Thus, it is possible to have higher yields or more farmlands when the model runs for more years than 20. The current model setup suggests that our model farmers use learning skills, offering the possibility of getting higher yields or more farmlands, at least partially with longer simulation times. This is especially relevant for our future study on Mesopotamian irrigation development (see Lang and Ertsen(2022)), which is assumed to have taken centuries if not millennia (Altaweel, 2019; Rost, 2017; Wilkinson et al., 2015).

The physical locations of farmers when they share the same water sources play a vital role in the irrigation system, as shown in our model as well. Given their location-oriented water extraction priority, upstream farmers have the priority to benefit from the system. Our model setting without any gate controls indicates relatively upstream farmers having higher yields than relatively downstream farmers. That is exactly what Olson (2000) and Janssen et al. (2012) have observed in their 'stationary bandit' theory setting, with the bandit capturing more benefits when people share common resources. The "irrigation dilemma" (Ostrom and Gardner, 1993) was also found in our model irrigation system: the situations of head farmers and tail farmers who share the same water resources reflect different levels of influence on the collective irrigation actions when re-allocating water. It is important to note that these model results reflect the complexity of real-world irrigation systems closely, including system dynamics and interactions among related agents. According to Janssen et al. (2012), when distribution rules are enforced there is more equal sharing of the common resources – as is also observed when GC adjustment strategies are applied in our

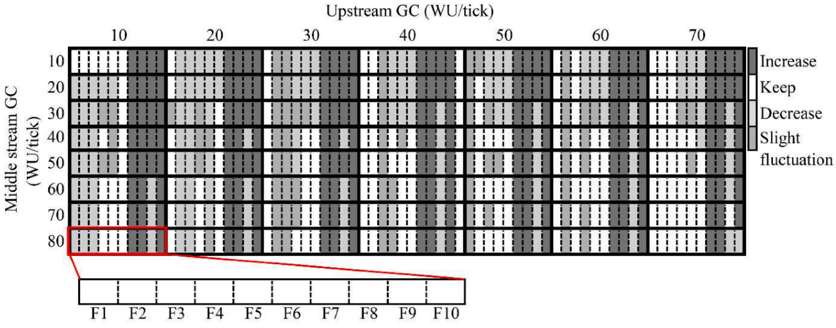

Fig. 9. Harvest situation of individual farmer after GC adjustment (RD = 90 WU/tick, IGC = 80 WU/tick).

model. After changing GCs, the model shows that upstream farmers can leave some water for the downstream farmers so that the downstream farmers can gain more yields and also can contribute to the collective profits.

4.2. Harvest situations from the level of individual farmers and the irrigation system

Farmers can achieve better profits for themselves as well as the community through collective actions (Arias et al., 2013; Bean and Nolte, 2018; Silvert et al., 2021). It is therefore important to understand the performance of irrigation systems with or without collective actions. We estimated the harvest situation according to water availability, firstly providing all farmers with the same GC. As soon as the model manager observed a poor harvest situation, GCs of relatively upstream farmers were lowered to allow more water to flow further downstream. We could argue that if farmers prefer to work alone, or in cases where system management cannot enforce certain actions on water distribution, it is easy to find unequal water distribution in a water-scarce irrigation system, leading to better harvest upstream and worse harvest downstream. This in itself is not a revolutionary insight, but our model manages to capture the phenomenon in quite some detail, thus opening up the possibility to study both how inequality is created in irrigation systems and how it can be dealt with.

Our expectation was that GC adjustments could save poor harvest situations without (huge) yield sacrifices of other farmers. However, we have observed rather complex farmers' harvest situations related to adjustments (Table 5) – sometimes upstream farmers have lower yields. A complex water system can be characterized by unexpected system performance due to the interactions among water users as suggested by Berglund (2015). Tilmant et al. (2009) point out that upstream users would have to give up some potential benefits if water resources were equally shared with all water users who face common pool recourses dilemmas. Indeed, this was also confirmed in our research, with farmers with good harvest situations sacrificing yields to improve poor harvest situations on system level, which was indeed related to water being more equally distributed in the system. The sacrifices made by upstream farmers can provide a theoretical insight into how important it is for priority water users to understand that their decisive role in irrigation management can promote cooperation and collective actions to increase the possibility of system success (Heinz et al., 2022).

Our model supports insight into cooperative human agents with the potential to communicate and monitor others' actions. Behavior theory experiments are broadly studied by researchers (DeCaro, 2019; DeCaro et al., 2021; Janssen et al., 2022; Ostrom, 1998), focusing on collective actions and indicating that communication plays an important role to facilitate cooperation and trust when facing inequal resource distribution. Our model observations cannot be explained without including inequality in water distribution and (indirect) communication in farmers' decision-making through adaptations of GCs. Whereas our findings cannot provide insights in issues like trust and communication efficiency yet, bringing in these issues in the ABM is possible. Further research is needed to offer a complete chain of collective actions to see how communication and trust could facilitate cooperation – which can be done by including additional rules in our ABM setup.

Table 5
The harvest situation of the irrigation system and individual farmers.

System	Individual
Increase	PHS improve, GHS keep
	PHS improve, GHS decreased
	PHS partly improve and partly keep, GHS keep
	PHS partly improve and partly decrease, GHS keep
	PHS partly improve and partly decrease, GHS partly keep and partly decrease
	PHS partly improve, partly keep, and partly decrease, GHS partly keep and partly decrease
Decrease	PHS improve, GHS decrease
	PHS partly improve, partly keep, and partly decrease, GHS keep
	PHS partly improve and partly decrease, GHS keep
	PHS partly improve and partly decrease, GHS partly keep and partly decrease
	PHS partly keep and partly decrease, GHS partly decrease
Keep	No change

Note: PHS – Poor harvest situation; GHS – Good harvest situation.

That being said, sometimes the total system harvest would also decrease, creating a situation in which more equality between farmers would be accompanied with less overall yields. In practice, decision-makers should consider the balance of individual farmers' benefits and the community's profits. Moreover, yields always fluctuated in the first few years after GC changes or among higher farmlands expansion. Eventually the harvest situations of the ten farmers (partly) returned to the initial situation, (partly) with better harvest, (partly) with even worse harvest. This not only shows how farmers' and managers' decision-making on GC variation could lead to greater differences between farmers no matter the location of the farmer, but also that interventions could result in short-term redistribution of benefits before more stable (improved) distributions are reached – which would have effects on interventions being accepted and evaluated in real-life practices. Those phenomena demonstrate the capability of (our) ABM to capture the complexity of decision-making processes and results (Ng et al., 2011).

4.3. Specific properties of the advanced irrigation-related agent-based model

Our proposed model AIRABM is an updated version of our earlier modeling framework IRABM, which was based on ODD + D protocols to describe decision-making in ABM (Lang and Ertsen, 2022; Müller et al., 2013). Our new model builds on IRABM by adding details on both individual farmers' and irrigation system perspectives. Although this is an experimental model, the dynamics of the farmlands and reactions among farmers when facing water stress allows this model to come close to realistic irrigation systems and indeed helps us to better understand the operation of irrigation systems and farmers' decision-making processes. Moreover, to make this modeling framework more accessible to stakeholders, especially for non-tech stakeholders, an user-friendly interface has been developed in NetLogo where stakeholders can play with and build model simulations with differently specified agent rules.

This study attempted to quantify the impact of farmers' decision-making on crop yields to inform better irrigation water resources management. However, we acknowledge several limitations that require further evaluation in future studies. Here we discuss two limitations of the current study: data availability and model structure. The lack of data forced (or allowed) us to simplify hydrological and hydraulic processes. Coupling more hydrological data, land use data, and other data might result in a more detailed model. Hydrologic/hydraulic models like SWAT and Sobek are extensively used to simulate the water distribution, hydraulic structures, soil characters, and landscape change, etc. (Afrasiabikia et al., 2017; Bishehgahi et al., 2022; Seyed Hoshiyar et al., 2021; Xie et al., 2021). Including such models in coupled hydrology/hydraulic-agent-based models would open up even more options to explore complex irrigation systems with detailed hydrological processes and irrigation actions. Including such models would potentially sacrifice some of the user-friendliness though. Another limitation is how to fully validate the model with historical data. Our current validation is based on comparing our model with other research and with realistic irrigation management settings. This comparison suggests that our model is realistic in its dynamics and as such can be used as a possible direction for future work when suitable data is available. Regarding model design limitations, the phenomenon of farmer's interactions on model system level is currently using one single parameter – gate capacity adjustment. This reflects possible system management, but does not cover possible direct communication between and among farmers yet. Furthermore, the effects of other farmers' decision, potential water availability, and landscape dynamics are currently not considered in the model.

5. Conclusion

With our Advanced Irrigation-Related Agent-Based Model that includes farmers' cultivation decisions and gate adjustment decisions in an irrigated setting, our main findings are:

- River discharge, gate capacity, and farmers' location can significantly affect harvest situations.
- With an increase in river discharge and gate capacity, yields generally increase.
- The barley yields pattern created by combinations of water availabilities is nonlinear, and river discharge thresholds and gate capacity tipping points were identified.
- To some extent, gate capacity adjustments address inequitable water allocation issues.
- Adjustments to gates may result in unexpected system performance, illustrating the complex nature of irrigation systems.

In this research, further methodological and case-related suggestions were provided to understand the importance of (conditional) cooperation when facing common pool resources, which enables us to (1) describe farmers' decision-making processes, (2) assess the decision uncertainty associated with harvest memory and water availability, and (3) explore adaptive water management strategies. As part of our ongoing research, we are examining how system expansions may be a reflection of ancient Mesopotamian development processes. The current AIRABM indicates how farmland dynamics and water distribution strategies can affect individual farmers' yields and overall system yields – resulting in varied yield patterns. Moreover, stakeholders could experience how their decisions could constrain the actions of others, and how the decisions of others are consequences of their situations. These experiences and actions create specific conditions for sharing water in irrigation systems, which is an issue that will only grow in importance in the next few decades of increased stress on irrigated production in a changing climate.

CRediT authorship contribution statement

Dengxiao Lang: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Maurits W. Ertsen:** Supervision, Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by China Scholarship Council with the project reference number of 201806910044.

Appendix

A. *A list of abbreviations*

Agent-Based Model (ABM): an integrated approach for complex system simulation.
Irrigation-Related Agent-Based Model (IRABM): the first version of agent-based model in irrigation systems
Advanced Irrigation-Related Agent-Based Model (AIRABM): the further developed agent-based model in irrigation systems
Irrigation Memory (IM): it refers to the interval between two irrigation actions.
Average Available Water (AAW): it refers to the average received water for each farmer in the past growing seasons.
Average Harvest of Barley (AHB): it refers to the average barley for each farmer in the past growing seasons.
Harvest Barley in the n^{th} year (HBY_n): it refers to the barley yields in a specific year.
Available Water in the n^{th}year (AW_n): it refers to the received water in a specific year.
Water Units (WU): it refers to the water agents in AIRABM and it is used as units for river discharge, gate capacity, irrigation demand, and available water.
Irrigation Demand (ID): the irrigation demand of barley.
Gate Capacity (GC): gate structure belongs to individual farmers and is used to transfer water from canals to farmlands. Each gate has its own capacity, WU/tick.
Initial Gate Capacity (IGC): all the GCs start at the same value for the model initialization, even with the newly expanded farmers, WU/tick. The IGC of this model is 200 WU/tick.
Upstream Gate Capacity (UGC): the GC of upstream farmers after the GC adjustment, WU/tick.
Middle stream Gate Capacity (MGC): the GC of middle stream farmers after the GC adjustment, WU/tick.
Downstream gate capacity (DGC): the GC of middle stream farmers after the GC adjustment, WU/tick.
River Discharge (RD): the capacity of the main river, WU/tick.

B. *Expansion pattern of the farmlands*

Table B1 summarizes the results in terms of the expansion year of each farmland for the many scenarios that are created when the river discharge (RD) changes from 10 to 200 WU/tick and the GC ranges from 10 to 160 WU/tick. In general, scenarios allowing expansion from one farmland to five for all farmlands do exist. However, given irrigation sequence and water availability, the expansion time can be quite different between farmlands depending on the actual combination of RD and GC in the respective scenario. As was to be expected, expanding all farms to the fifth field (farmland) proves to be the most difficult – but not impossible, as a few examples below illustrate.

- The optimal expansion series for all farmers is when the five farmlands expand in the first five modeling years, but this only happens when RD is over 160 WU/tick.
- With extremely low RD (10 WU/tick), expansion options are generally challenging and not equally distributed between F1–10. After 20 years, F1 has three harvested farmlands, with farmland 1 starting in year 1, farmland 2 becoming in use in the fifth year and farmland 3 in the thirteenth year. In contrast, F2 has two farmlands, with these farmlands having the same expansion pattern as F1. F3 ends up with only one farmland, and F4–10 stay without any harvested farmlands.
- When RD = 70 WU/tick and GC = 40 WU/tick, expansion patterns are more complex. F1–5 have five harvested farmlands, F6 has four, F7 could expand to four farmlands during the period, but ended with only two in the end. Similarly, F8 had three farmlands along the way but finally ends with two. F9 could reach three but kept only one, while F10 expanded to two, but kept one in the end. The expansion years of farmlands for the different farmers are too complex to mention, but these changing farmlands in farms reflect the complex interactions between expansion decisions upstream and downstream in the model system.

Table B1
Possible expansion year of each farmland.

Expansion year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Farmland1	×	✓	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Farmland2	×	\	✓	✓	\	✓	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Farmland3	×	\	\	✓	✓	✓	\	✓	\	\	\	\	\	\	\	✓	\	\	\	\	\
Farmland4	×	\	\	\	✓	✓	✓	✓	✓	✓	\	\	\	\	\	✓	\	\	\	\	\
Farmland5	×	\	\	\	\	✓	✓	✓	✓	✓	✓	✓	✓	✓	\	✓	✓	✓	\	✓	\

Note: × - the farmland never expands; ✓ - the farmland expands in this year; \ - the farmland does not expand in this year.

C. Good harvest situations

Fig. C1 summaries category 1 – good harvest situations under all scenarios at the end of the simulation period of 20 years.

- Fig. C1a and C1b show the expansion time of each farmland is the same for F1–10, with finally all farmers having four harvested fields – the first three fields expand in the same year while the expansion year of field 4 is different.
- Fig. C1c – j indicate scenarios when all farmers have five active farmlands, but with different expansion years. F1–10 have the same expansion years for farmlands 1–4 but different expansion years for farmland 5. The earliest and the latest expansion year of farmland5 are the fifth year and the twelfth year, respectively.
- It is worth noting that each harvested farmland gained 880 kg of barley for all scenarios. Although at the end of the simulation period of 20 years, all farmers have the same number of fields with equal yields, some scenarios show that farmers can increase their farmland earlier compared to others – which means that their total yields in the simulation period is higher.

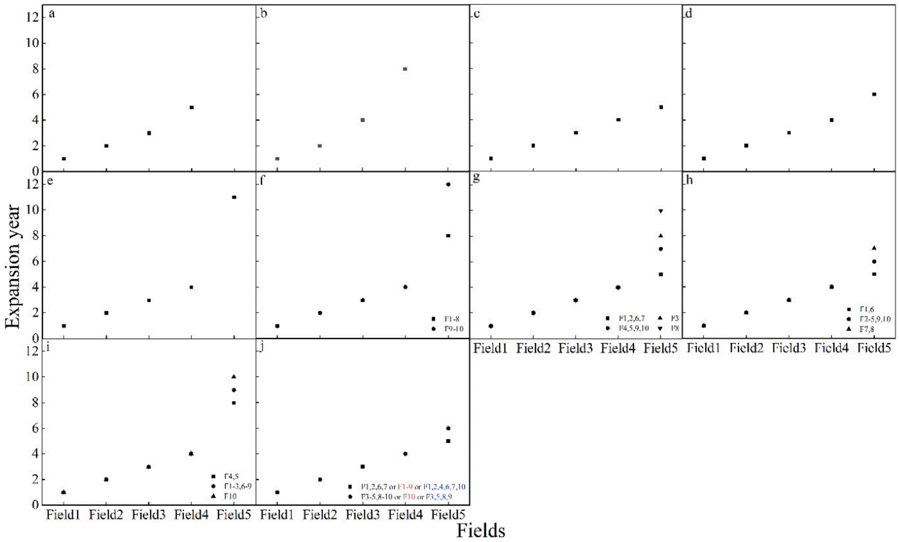

Fig. C1. Expansion year of farmlands when farmers have good harvest situation.

D. Harvest situations with gate capacity control for RD = 30 and 160 WU/ tick

D.1. RD = 30 WU/tick, IGC = 10, 20, 30 WU/tick

Fig. D1 shows the total system yields when RD = 30 WU/tick with IGC at 10, 20, and 30 WU/tick. The initial total yields before GC adjustment are 202,605, 215,573, and 224,948 Kg for corresponding IGCs of 10, 20, and 30 WU/tick. Even lower total system yields are created by GC adjustments compared to the initial total yields when IGC = 10 and 20 WU/tick (Fig. D1a and D1b). For IGC = 20 WU/tick, upstream farmers' yields decreased dramatically when UGC decreased to 5 WU/tick, due to the delayed expansion of farmland 3 and farmland 4. These results suggest that with these low

RDs, total system yields increase with increasing UGC or increasing MGC. However, the highest yields occurred when the MGC decreased to 15 WU/tick (Fig. D1b). For IGC = 30 WU/tick, only keeping the MGC at 30 WU/tick created increased total yields while total yields decreased under other combinations of UGC and MGC (Fig. D1c). With these low RDs, the GC adjustment did benefit farmers suffering from poor harvest situations, but the prices of it are on systems level in the shape of lower yields, delayed farmland expansion, and less harvested upstream farmlands. F9 and (especially) F10 saw hardly any change. In summary, GC adjustment is not able to satisfy all the farmers at the same time with RD at 30 WU/tick.

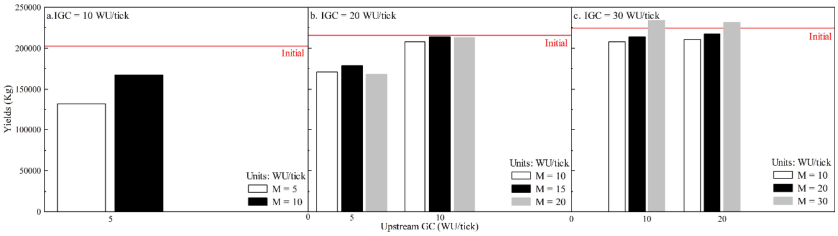

Fig. D1. The comparison of total system yields before and after GC adjustment when RD = 30 WU/tick (red line shows the initial total system yields).

D.2. RD = 160 WU/tick, with IGC = 80, 130, 160 WU/tick

Fig. D2 shows a comparison of the total yields after and before GC adjustment when RD = 160 WU/tick with IGC = 80, 130, and 160 WU/tick. Changing GCs in these three IGC cases clearly results in lower total yields when UGC is 10 WU/tick or when MGC is 10 WU/tick. However, relatively high UGC and MGC resulted in lower total yields for IGC = 160 WU/tick. The lowest total yields occurs when both UGC and MGC are 10 WU/tick.

For IGC = 80 WU/tick, the GC change generated higher total yields, except for MGC = 10 WU/tick (Fig. D2a). The higher yields are concentrated in combinations of higher UGC and MGC. The case of IGC = 130 WU/tick shows a decrease in total yields when UGC or MGC is 10 WU/tick respectively (Fig. D2b). The higher yields are mainly located in the area with lower MGC or higher UGC, while in the area with both higher UGC and MGC total yields tend to remain at the initial value. For IGC = 160 WU/tick, most of the UGC and MGC combinations show increased total yields (Fig. D2c). However, total yields are lower than the initial value when both UGC and MGC are 10 WU/tick. The harvest situations are more discrete, but the highest values are always found in the area with higher UGC or lower MGC. Thus, we will take this example to describe the individual farmers' harvest situations in detail.

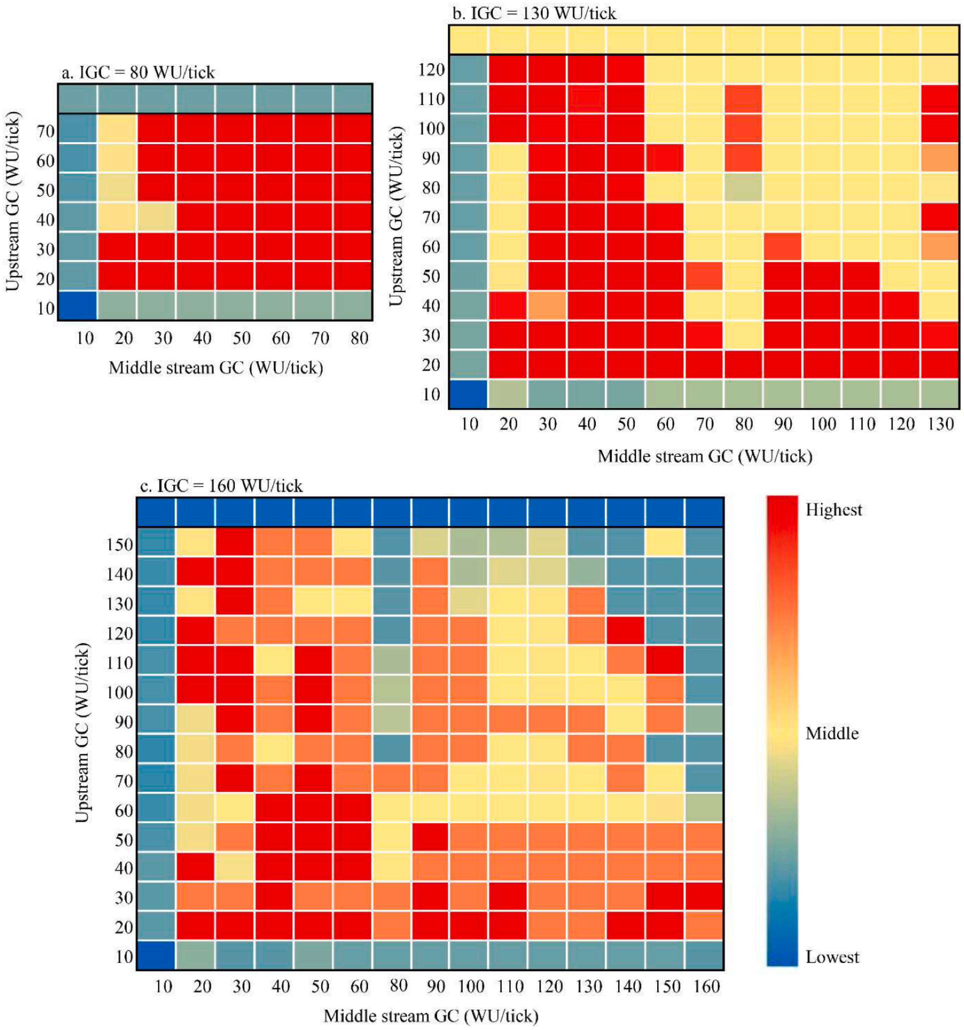

Fig. D2. Total system harvest with varied up and middle stream GC (RD160) (the initial total system yields shown in the black frame on the top for reference). Fig. D2a, D2b, and D2c share the same legend but the color scale means different values. We use the heatmap to show the yield trend instead of the exact value. Moreover, there is no comparison between the three sub-figures.

For individual farmers' yields after GC changing when RD = IGC = 160 WU/tick and before GC changing, F1–8 have the same farmland expansion pattern and yields pattern. These eight farmers harvested five fields in the end, whereas F9 finally has three or four fields and F10 has two fields. Therefore, the GC is adjusted to boost the yields of F9 and F10. Fig. D3 shows individual farmers' harvest situations after changing the GC with IGC = 160 WU/tick. According to the figure, F9 and F10 have higher yields in all combinations and the majority of combinations show no loss of yields for F1–8. Mostly, the decreased harvests of upstream and middle stream farmers occurred when UGC = 10 WU/tick or MGC = 10 WU/tick – this is consistent with the tendency of total system yields. It is difficult for F9 and F10 to gain higher yields when UGC and MGC are close to the initial GC, which make F10 having an even worse harvest.

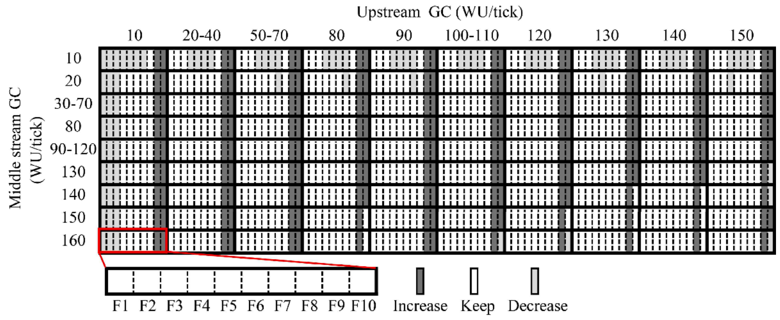

Fig. D3. Harvest situation of individual farmer after GC adjustment (RD = 160 WU/tick, IGC = 160 WU/tick).

References

Afrasiabikia, P., Parvaresh Rizi, A., Javan, M., 2017. Scenarios for improvement of water distribution in Doroodzan irrigation network based on hydraulic simulation. Comput. Electron. Agric. 135, 312–320. https://doi.org/10.1016/j.compag.2017.02.011.

Aghaie, V., Alizadeh, H., Afshar, A., 2020. Emergence of social norms in the cap-and-trade policy: an agent-based groundwater market. J. Hydrol. 588, 125057 https://doi.org/10.1016/j.jhydrol.2020.125057.

Aliyari, F., Bailey, R.T., Arabi, M., 2021. Appraising climate change impacts on future water resources and agricultural productivity in agro-urban river basins. Sci. Total Environ. 788, 147717 https://doi.org/10.1016/j.scitotenv.2021.147717.

Altaweel, M., 2019. Southern mesopotamia: water and the rise of urbanism. Wiley interdiscip. Rev. Water, e1362. https://doi.org/10.1002/wat2.1362.

An, L., Grimm, V., Sullivan, A., TurnerII, B.L., Malleson, N., Heppenstall, A., Vincenot, C., Robinson, D., Ye, X., Liu, J., Lindkvist, E., Tang, W., 2021. Challenges, tasks, and opportunities in modeling agent-based complex systems. Ecol. Modell. 457 https://doi.org/10.1016/j.ecolmodel.2021.109685.

Arias, P., Hallam, D., Krivonos, E., Morrison, J., 2013. Smallholder Integration in Changing Food Markets. Food and Agriculture Organization of the United Nations (FAO).

Bean, C., Nolte, G.E., 2018. Annual report: peru's Coffee production continues recovering.

Berglund, E.Z., 2015. Using agent-based modeling for water resources planning and management. J. Water Resour. Plan. Manag. 141, 04015025 https://doi.org/10.1061/(asce)wr.1943-5452.0000544.

Bishehgahi, H.B., Rizi, A.P., Mohammadi, A., 2022. Rehabilitation of operation regimes in aged irrigation schemes based on hydraulic simulation. Water Supply 22, 3617–3627. https://doi.org/10.2166/ws.2022.004.

Brouwer, C., Prins, K., Heibloem, M., 1989. Irrigation water management: irrigation scheduling. Train. Man. 66.

Burton, M.A., 1989. Experiences with the irrigation management game. Irrig. Drain. Syst. 3, 217–228. https://doi.org/10.1007/BF01112806.

Charles, M.P., 1988. Irrigation in lowland Mesopotamia. Bull. Sumer. Agric. 4, 39.

Chen, Y., Xu, L., Zhang, X., Wang, Z., Li, H., Yang, Y., You, H., Li, D., 2023. Socio-econ-ecosystem multipurpose simulator (SEEMS): an easy-to-apply agent-based model for simulating small-scale coupled human and nature systems in biological conservation hotspots. Ecol. Modell. 476, 110232 https://doi.org/10.1016/j.ecolmodel.2022.110232.

D'Exelle, B., Lecoutere, E., Van Campenhout, B., 2012. Equity-efficiency trade-offs in irrigation water sharing: evidence from a field lab in rural Tanzania. World Dev. 40, 2537–2551. https://doi.org/10.1016/j.worlddev.2012.05.026.

Daloğlu, I., Nassauer, J.I., Riolo, R.L., Scavia, D., 2014. Development of a farmer typology of agricultural conservation behavior in the american corn belt. Agric. Syst. 129, 93–102. https://doi.org/10.1016/j.agsy.2014.05.007.

Daniell, K.A., Morton, A., Ríos Insua, D., 2016. Policy analysis and policy analytics. Ann. Oper. Res. 236, 1–13. https://doi.org/10.1007/s10479-015-1902-9.

DeCaro, D.A., 2019. Humanistic rational choice: understanding the fundamental motivations that drive self-organization and cooperation in commons dilemmas. Routledge Handbook of the Study of the Commons. Routledge, pp. 117–132.

DeCaro, D.A., Janssen, M.A., Lee, A., 2021. Motivational foundations of communication, voluntary cooperation, and self-governance in a common-pool resource dilemma. Curr. Res. Ecol. Soc. Psychol. 2, 100016 https://doi.org/10.1016/j.cresp.2021.100016.

Dinar, A., Tieu, A., Huynh, H., 2019. Water scarcity impacts on global food production. Glob. Food Sec. 23, 212–226. https://doi.org/10.1016/j.gfs.2019.07.007.

Ghani, L.A., Mahmood, N.Z., 2023. Modeling domestic wastewater pathways on household system using the socio-MFA techniques. Ecol. Modell. 480, 110328 https://doi.org/10.1016/j.ecolmodel.2023.110328.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecol. Modell. 198, 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Modell. 221, 2760–2768. https://doi.org/10.1016/j.ecolmodel.2010.08.019.

Grimm, V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., Deangelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A.S.A., Milles, A., Nabe-Nielsen, J., Polhill, J.G., Radchuk, V., Rohwäder, M.S., Stillman, R.A., Thiele, J.C., Ayllón, D., 2020. The ODD protocol for describing agent-based and other simulation models: a second update to improve clarity, replication, and structural realism. Jasss 23. https://doi.org/10.18564/jasss.4259.

Gurung, T.R., Bousquet, F., Trébuil, G., 2006. Companion modeling, conflict resolution, and institution building: sharing irrigation water in the Lingmuteychu watershed, Bhutan. Ecol. Soc. 11 https://doi.org/10.5751/ES-01929-110236.

Heinz, S., Otto, I.M., Tan, R., Jin, Y., Glebe, T.W., 2022. Cooperation enhances adaptation to environmental uncertainty: evidence from irrigation behavioral experiments in South China. Water 14. https://doi.org/10.3390/w14071098 (Switzerland).

Ibrahim, A.S., 2022. Improving irrigation system management: a case study: bahr Sanhoor Canal, Fayoum, Egypt. J. Water L. Dev. 53 https://doi.org/10.24425/jwld.2022.140774.

Janssen, M.A., Bousquet, F., Cardenas, J.C., Castillo, D., Worrapimphong, K., 2012. Field experiments on irrigation dilemmas. Agric. Syst. 109, 65–75. https://doi.org/10.1016/j.agsy.2012.03.004.

Janssen, M.A., Decaro, D.A., Lee, A., 2022. An agent-based model of the interaction between inequality, trust, and communication in common pool experiments. Jasss 25. https://doi.org/10.18564/jasss.4922.

Khan, H.F., Yang, Y.C.E., Xie, H., Ringler, C., 2017. A coupled modeling framework for sustainable watershed management in transboundary river basins. Hydrol. Earth Syst. Sci. 21, 6275–6288. https://doi.org/10.5194/hess-21-6275-2017.

Lang, D., Ertsen, M.W., 2022. Conceptualising and implementing an agent-based model of an irrigation system. Water 14, 2565. https://doi.org/10.3390/w14162565 (Basel).

Meinzen-dick, R., Raju, K.V., Gulati, A., 2002. What affects organization and collective action for managing resources? Evidence from canal irrigation systems in India. World Dev. 30, 649–666. https://doi.org/10.1016/S0305-750X(01)00130-9.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol. Environ. Model. Softw. 48, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003.

Muste, M.V., Bennett, D.A., Secchi, S., Schnoor, J.L., Kusiak, A., Arnold, N.J., Mishra, S.K., Ding, D., Rapolu, U., 2013. End-to-end cyberinfrastructure for decision-making support in watershed management. J. Water Resour. Plan. Manag. 139, 565–573. https://doi.org/10.1061/(asce)wr.1943-5452.0000289.

Nandalal, K.D.W., Simonovic, S.P., 2003. Resolving conflicts in water sharing: a systemic approach. Water Resour. Res. 39, 1–11. https://doi.org/10.1029/2003WR002172.

Ng, T.L., Eheart, J.W., Cai, X., Braden, J.B., 2011. An agent-based model of farmer decision-making and water quality impacts at the watershed scale under markets for carbon allowances and a second-generation biofuel crop. Water Resour. Res. 47, 1–17. https://doi.org/10.1029/2011WR010399.

Olson, M., 2000. Power and Prosperity. Basic Books.

Ostrom, E., 1998. A behavioral approach to the rational choice theory of collective action : presidential address, american political science association, 1997 Author (s): elinor Ostrom Source: the American Political Science Review, Vol . 92, No . 1 (Mar., 1998). Am. Polit. Sci. Rev. 92, 1–22.

Ostrom, E., Gardner, R., 1993. Coping with asymmetries in the commons: self-governing irrigation systems can work. J. Econ. Perspect. 7, 93–112. https://doi.org/10.1257/jep.7.4.93.

Pal, S., Ghosh, I., 2023. Dynamics of a coupled socio-environmental model: an application to global CO2 emissions. Ecol. Modell. 478, 110279 https://doi.org/10.1016/j.ecolmodel.2023.110279.

Pluchinotta, I., Pagano, A., Giordano, R., Tsoukiàs, A., 2018. A system dynamics model for supporting decision-makers in irrigation water management. J. Environ. Manage. 223, 815–824. https://doi.org/10.1016/j.jenvman.2018.06.083.

Ray, I., Williams, J., 2002. Locational asymmetry and the potential for cooperation on a canal. J. Dev. Econ. 67, 129–155. https://doi.org/10.1016/S0304-3878(01)00180-8.

Rehman, A., Chandio, A.A., Hussain, I., Jingdong, L., 2019. Fertilizer consumption, water availability and credit distribution: major factors affecting agricultural productivity in Pakistan. J. Saudi Soc. Agric. Sci. 18, 269–274. https://doi.org/10.1016/j.jssas.2017.08.002.

Rost, S., 2017. Water management in Mesopotamia from the sixth till the first millennium B.C. Wiley Interdiscip. Rev. Water 4, e1230. https://doi.org/10.1002/wat2.1230.

Seyed Hoshiyar, S.M., Pirmoradian, N., Ashrafzadeh, A., Parvaresh Rizi, A., 2021. Performance assessment of a water delivery canal to improve agricultural water distribution. Water Resour. Manag. 35, 2487–2501. https://doi.org/10.1007/s11269-021-02843-1.

Silvert, C., Diaz, J., Warner, L., Ochieng, W., 2021. To work alone or with peers: examining smallholder coffee farmers' perceptions influencing collective actions. Adv. Agric. Dev. 2, 1–14. https://doi.org/10.37433/aad.v2i2.95.

Svubure, O., Soropa, G., Mandiregа, S., Rusere, F., Ndeketeya, A., 2010. Water conflicts on the Manjirenji-Mkwasine irrigation water supply canal. Masvingo Province 2, 219–227. Zimbabwe.

Tilmant, A., Goor, Q., Pinte, D., 2009. Agricultural-to-hydropower water transfers: sharing water and benefits in hydropower-irrigation systems. Hydrol. Earth Syst. Sci. 13, 1091–1101. https://doi.org/10.5194/hess-13-1091-2009.

Wilkinson, T.J., Gibson, M.G., Christiansen, J.H., Widell, M., Schloen, D., Kouchoukos, N., Woods, C., Sanders, J., Simunich, K.L., Altaweel, M., Ur, J.A., Hritz, C., Lauinger, J., Paulette, T., Tenney, J., 2007. Modeling settlement systems in a dynamic environment: case studies from mesopotamia, the model-based archaeology of socionatural systems. Edited by Timothy A. Kohler and Sander E. van der Leeuw.

Wilkinson, T.J., Rayne, L., Jotheri, J., 2015. Hydraulic landscapes in Mesopotamia: the role of human niche construction. Water Hist. 7, 397–418. https://doi.org/10.1007/s12685-015-0127-9.

Xie, H., You, L., Dile, Y.T., Worqlul, A.W., Bizimana, J.C., Srinivasan, R., Richardson, J.W., Gerik, T., Clark, N., 2021. Mapping development potential of dry-season small-scale irrigation in Sub-Saharan African countries under joint biophysical and economic constraints - an agent-based modeling approach with an application to Ethiopia. Agric. Syst. 186 https://doi.org/10.1016/j.agsy.2020.102987.

Yang, J., Yang, Y.C.E., Chang, J., Zhang, J., Yao, J., 2019. Impact of dam development and climate change on hydroecological conditions and natural hazard risk in the Mekong River Basin. J. Hydrol. 579, 124177 https://doi.org/10.1016/j.jhydrol.2019.124177.