Agent-based modelling to understand irrigated farmland dynamics and farmer decision-making

Lang, Dengxiao; Ertsen, Maurits W.

DOI
10.1016/j.ifacol.2022.07.633

Publication date
2022

Document Version
Final published version

Published in
IFAC-PapersOnline

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 55-5 (2022) 18–24

Agent-based modelling to understand irrigated farmland dynamics and farmer decision-making

Dengxiao Lang * Maurits W. Ertsen *

* Delft University of Technology, Stevinweg 1, 2628, CN, Delft, the Netherlands (e-mail: D.Lang-1@tudelft.nl, M.W.Ertsen@tudelft.nl).

Abstract: An Advanced Irrigation-Related Agent-Based Model (AIRABM) of farmers' decision-making mechanism and feedback among farmers is developed. The model explores the interactions among human and non-human agents in the irrigation system. In this paper, we discuss harvest patterns as they result from more equal or unequal water distribution in the system. In a baseline model run, farmers are not restricted in their water use. For those situations that yields are low on the system or farmer level, we allow gate settings to be adjusted to improve poor harvest situations. Our model results show that 1) in the baseline scenario, upstream farmers generally receive more water and gain higher yields compared to downstream farmers; 2) gate capacity adjustments of upstream and middle stream farmers can push more water to downstream farmers, but those specific variations are considerable. We observe unexpected emerging system performance. The AIRABM model offers options for how combinations of individual farmers' decisions on water use and farming create (un)equal yield patterns in irrigation systems.

Keywords: Agent-based model, irrigation system, water availability, yields, decision-making, feedback

1. INTRODUCTION

Global socio-economic developments, especially a growing population, could increase pressure on water use in agriculture. Water managers may increasingly face difficult situations when allocating water to competing users (Nandalal and Simonovic, 2003; Tilmant et al., 2009). This applies particularly to irrigation water management, as the diversity of claims and increased competition on irrigation water among farmers is a common phenomenon worldwide (Gurung et al., 2006; Svubure et al., 2010; D'Exelle et al., 2012). The distribution and use of the limited, shared water resources can create conflicts between individuals, communities, regions and countries. Adequate collective actions to arrange water allocation are required to implement equitable water sharing strategies (D'Exelle et al., 2012; Meinzen-dick and Raju, 2000; Ray and Williams, 2002).

In this paper, we discuss our research approach as it focuses on issues of equal or unequal water distribution in irrigation systems. We build on previous research, when we introduced the Irrigation-Related Agent-Based Model (IRABM). IRABM expresses how non-human agents in irrigation (gates, fields, etcetera) can express human agents' actions. The model set-up does include neither communication among the farmers nor decision-making in the system, but it is clear that the model can show how upstream and downstream farmers compete for water due to their location (Lang and Ertsen, submitted).

Our Advanced Irrigation-Related Agent-Based Model (AIRABM), which we introduce in this contribution, is the second version of IRABM. We developed it to further explore the interactions among human and non-human agents in a supply-driven irrigation system. Compared to IRABM, we added learning behaviour, decision-making mechanisms, and farmers' feedback mechanisms – all of which will be explained in the Methods section. In this research, we explore yields' pattern as they result from more equal and unequal irrigation water distribution setups, that aim to manage water availability conflicts between upstream and downstream farmers.

We have built the model with a specific overarching research question in mind. Our larger project aims to study how irrigation systems in ancient south Mesopotamia may have coped with water distribution issues under water stress when farmers share the same water resource. The region of southern Mesopotamia has been seen by researchers as one of the earliest civilisation (Adams, 1981; Rothman, 2004). The landscape of this region can be regarded as a hydraulic landscape: the history of the region is actually the history of the complex water systems structured by natural and man-made channels, irrigation canals, levees, marshes, and swamps (Altaweel, 2019; Wilkinson et al., 2015). Research also shows how the history of irrigation management in southern Mesopotamia has to be explained as evolving from simple, small-scale to large-scale, from short-term to longer-term, from locally to centralised management (Adams, 1965; Jacobsen and Adams, 1958; Rost, 2017; Wilkinson et al., 2015; Wilkinson and Jotheri, 2017). Overall, the development of the irrigation systems would result from both natural water system evolution and human activities – flood feedbacks, population growth, and food demand etc.

Irrigation water management plays a crucial role in the development of irrigation systems in this region. As such, we have used empirical archaeological data for Mesopotamia in this model. The issues we study, however, are general and relate to how decision making on irrigated farmland in different locations in an irrigation system affects decision making elsewhere in the same system.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2022.07.633

2. METHODS

2.1 Model Outline

The AIRABM outline is based on the ODD + D (Overview, Design concepts, Details + Decision Making) protocol for multi-agent systems (Grimm et al., 2020; Müller et al., 2013). Table 1 shows the brief explanation of each element of the ODD for AIRABM (please note that many basic elements and details are in Lang and Ertsen (Submitted).

Table 1 AIRABM ODD protocol

Elements	Explanation
1. Purpose	To explore farmland dynamics in response to farmer decision-making in an irrigation system
2. Entites, state variables, and scales	Entities are 10 farmers; each farmer can farm on 5 farmlands; one river; irrigation water flows from the river, through the head gate, to the canal, through the farmer's gate, to end on the farmlands (WU/tick, where WU means Water Unit).
3. Process overview and scheduling	Yields and growth status of farmlands are described every year.
4. Design concepts	In year1, all farmers cultivate farmland1; in year2 and further, farmers decide to keep, expand one, or abandon one or two farmlands based on yields and water availability in all seasons. Farmers' interaction is expressed in adjusting gates of upstream and/or middle stream farmers to increase lower harvests.
5. Initialization	Each farmer has a certain amount of barley seed at the start to ensure he/she can sow on farmland1.
6. Input data	There is no additional external input data
7. Submodels	Irrigation schedule; irrigation sequence; response of barley yields to water supply; and farmland expansion sequence.

2.2 The response of barley yields to water supply

Levels of supplied water relate to the level of barley yields: in IRABM, with supplied water going down (eg one level), the potential yields will be reduced (eg by 50%). Figure 1 shows the simplified relations between water supplies to barley at each of three growing stages, divided into four levels: Ideal, Medium, Poor, and None. These levels represent four levels of barley yields response to the four levels of water availability.

2.2 Farmers' decision-making mechanism

The layout of the virtual irrigation system is shown in Figure 2 and a flow chart of the decision-making mechanism of farmland management is shown in Figure 3. In the model, this decision-making is a general routine each year. Comparing average harvests of barley (AHB) and average available water (AAW) of earlier years suggests to farmers whether they should keep their last season's planting choice (Keep), or change it – with as options to expand one farmland, decrease one farmland, or decrease two farmlands. The expansion sequence is fixed – farmland 2 is first to expand, followed by farmland 3, 4, and 5, while the decrease sequence is the other way around.

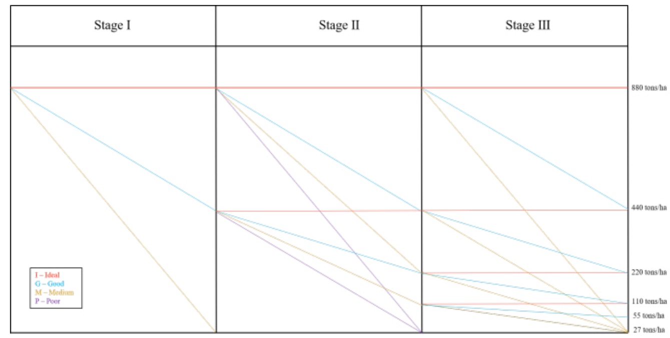

Figure. 1 Simplified barley yield responses to supplied water

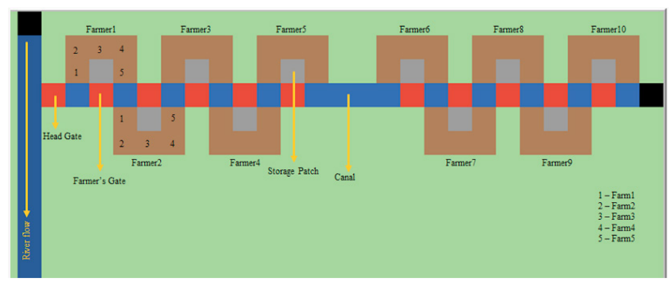

Figure. 2 The layout of the irrigation system

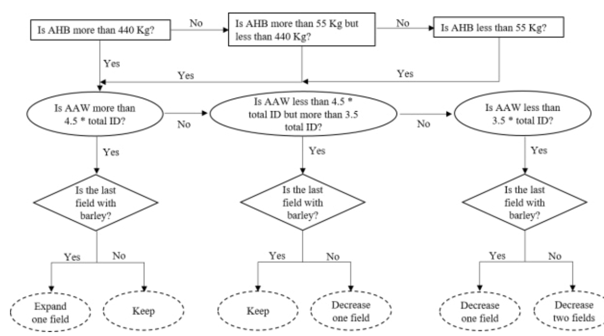

Figure. 3 Decision-making mechanism for farmlands dynamics

2.3 Farmers' feedback mechanism

As is known in irrigation systems, water availability plays an important role in the interactions between upstream, middle stream, and downstream farmers, since whatever the relative upstream farmers do, will have an effect on the more downstream farmers. In the current version of the model, the farmers do not yet communicate, cooperate or compete directly with each other. For example, the farmers disregard how many farmlands other farmers are growing. They cannot communicate either about how much water they would like to use and the water consumption of other farmers. In the current model concept, farmers' interactions are indirectly modelled. At the end of each growing season, the yields per farmer per year and the number of harvested farmlands per farmer per year are evaluated. If there is evidence for unequal water availability between upstream, middle stream, and downstream farmers, the gate capacity (GC) of upstream (UGC, Farmer1-3) and middle stream (MGC, Farmer4-7) farmers will decrease, while the gate capacity of downstream (DGC, Farmer8-10) farmers will be kept at the initial gate capacity (IGC). As such, the modelled water flows represent cooperation, competition, and communication among the farmers indirectly.

3. RESULTS

This setup creates two sets of results, in which different scenarios combining different river flows and gate capacities are created. Both sets of results are based on model runs of 20 years per scenario. In a first set, gate control is not possible: all farmers have the same gate capacity per run. Per run, each farm uses that gate capacity to water their farm with the potential five fields, with each farmer starting with a single field. In the second set, gate capacities are adapted when yields are lower, either on system level or for farmers, at the end of simulation.

3.1 System without gate capacity control

3.1.1 Barley yields pattern from varied river discharge and gate capacity

The total yields for the whole system in the 20 model years of the system are shown in Figure 4 for all combinations of river discharge (RD) and GC. Generally, total yields increase with increasing RD. Looking at the GC column, the changes in total yields with increasing RD show a clear RD threshold value per GC. When the RD threshold is reached, total system yields stay the same up to the highest RD scenario. The RD threshold for GC = 10 – 160 WU/tick are 90, 110, 150, 160, \, 170, 180, 170, 170, 160, 160, 160, 170, 170, 160, and 170 WU/tick, respectively. The only exception is GC = 50 WU/tick, which does not show any threshold in yields: with this GC per farm, combinations of water availability in the canal and on the farm easily shift – which is a direct result of the water needs per field as defined in the model. While higher RD increases yields in general, there are only a few actual GC settings that show this pattern without (minor) changes for increasing RD – GC = 10, 20, and 110 WU/tick. Most GCs show some fluctuations per step of increased RD. For several GCs, we observe fluctuations in the range when RD = 100-130 WU/tick – with higher total yields reached for a lower RD followed by an immediate decreasing yield for the next higher RD. Total yields increase again for higher RD. For GC = 50 and 80 WU/tick, we observe two of those fluctuations. This is again a result of the model settings for water transport between cells.

When studying the total yields pattern for increasing GC and constant RD, GC tipping points were found: when the tipping point is reached, no matter how the GC changes, total system yields decrease to a certain value and then keep the same up to the highest GC. For RD < 160 WU/tick, GC tipping points increased with increasing RD. GC tipping points decreased with increasing RD for RD > 160 WU/tick.

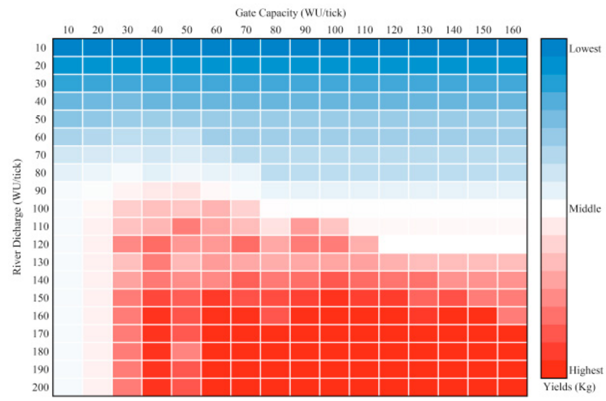

Figure. 4 Total system yields with the varied RD and GC

3.1.2 Harvest situation for each farmer

There are two main types of patterns for farmers' and farmlands' yields when taking each combination of RD and GC at the end of simulation season into account. The first type includes those results when all farmers and all farmlands have the same yield pattern. The second type includes those results when upstream, middle stream, and downstream farmers have different yield pattern under each combination of RD and GC.

Type 1 shows all farmers and farmlands showing the same farmland expansion and yields under certain combinations of RD and GC: 1) with finally all farmers having four active farms - farms1-3 expand in the same year while farm4 expands in a different year; 2) all farmers have five harvested farmlands, but not necessarily with the same expansion rhythm - for F1-10, farmlands1-4 expanded in the same year, but farmland5 expanded in different years.

Patterns of the second type are more complex, although they typically occur when RD is lower. Different combinations of RD and GC create different ways how harvests or water availability are less on system level and/or unequal between F1-10 at the end of the simulation period. We observed the following generalized results:

- For RD = 10 WU/tick, only upstream farmers have harvests.
- For RD = 20 WU/tick, upstream and some middle stream farmers have harvests.
- For RD = 30 to 80 WU/tick, all farmers have harvests, but with varying numbers of farmlands and yields per farmland.
- For RD = 90 to 160 WU/tick, the equivalent water availability situation appears, with yields only depending on GC.

Apart from the last subset, F1-10 have different yields and expansion patterns for all subsets. Theoretically, in terms of the number of harvested farmlands and the yields of each farmland, one would expect an order of upstream farmers > middle stream farmers > downstream farmers, because of the location priority rule. The model reality is that upstream farmers can perform worse compared to middle stream farmers (sometimes even worse than downstream farmers), whereas middle stream farmers can have worse performance than downstream farmers. This is a result of the way the model settings transport water between cells. As such, it can be representative of localized hydraulic conditions on real-life irrigation settings.

3.2 Farmers adaptation with gate capacity control

There are many possible combinations of adjusted upstream and middle stream GCs for each subset from the second type. Therefore. we will focus on a few representative results of adjustment for lower harvests, using a selection of options from the different categories: when RDs are 30, 90, and 160 WU/tick respectively.

3.2.1 RD = 30 WU/tick, IGC = 10, 20, 30 WU/tick

The total system yields after GC adjustment for RD = 30 WU/tick are shown in Figure 5. The initial total yields are shown with a red line in this figure. The results show that with this RD, GC changes cannot satisfy all farmer simultaneously.

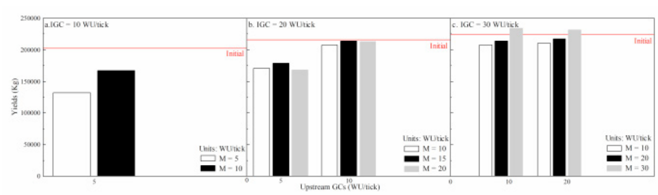

Figure. 5 Total system yields with varied UGC and MGC (RD30)

The model results suggest that for IGC = 10 and 20 WU/tick, the adjustments create even lower yields than the initial total yields (Fig. 5a and 5b). The adjustment actually helps middle stream and downstream farmers to improve their yields, but the price of the improvements are lower yields per farmland and a lower number of farmlands for upstream farmers.

For IGC = 20 WU/tick, harvests of upstream farmers decreased dramatically when UGC = 5 WU/tick, as the expansions to farmland3 and farmland4 are delayed. Typically, total yields increased with an increasing UGC and keeping MGC, or with an increasing MGC and keeping UGC. For MGC = 15 WU/tick, highest yields occurred when the IGC = 20WU/tick was kept upstream.

For IGC = 30 WU/tick, total yields increased only after changing the MGC to 30 WU/tick (Fig. 5c). The adjustment delayed the expansion time of farmland3 and farmland4 for F1-3. The number of farmlands for F1-2 also reduced. The yields F4 became less, but the situation of F5-8 improved. F3, F9, and F10 saw hardly any change.

3.2.2 RD = 90 WU/tick, with IGC = 20 - 90 WU/tick

Figure 6 shows the total system yields after adjustments when RD = 90 WU/tick. The figure shows the total system yields relative to the highest UGCs as initial total yields in each sub-figure in the black reference frame on the right. It is easy to see that higher total yields always occur when UGC and MGC are relatively low, especially for relatively low MGCs.

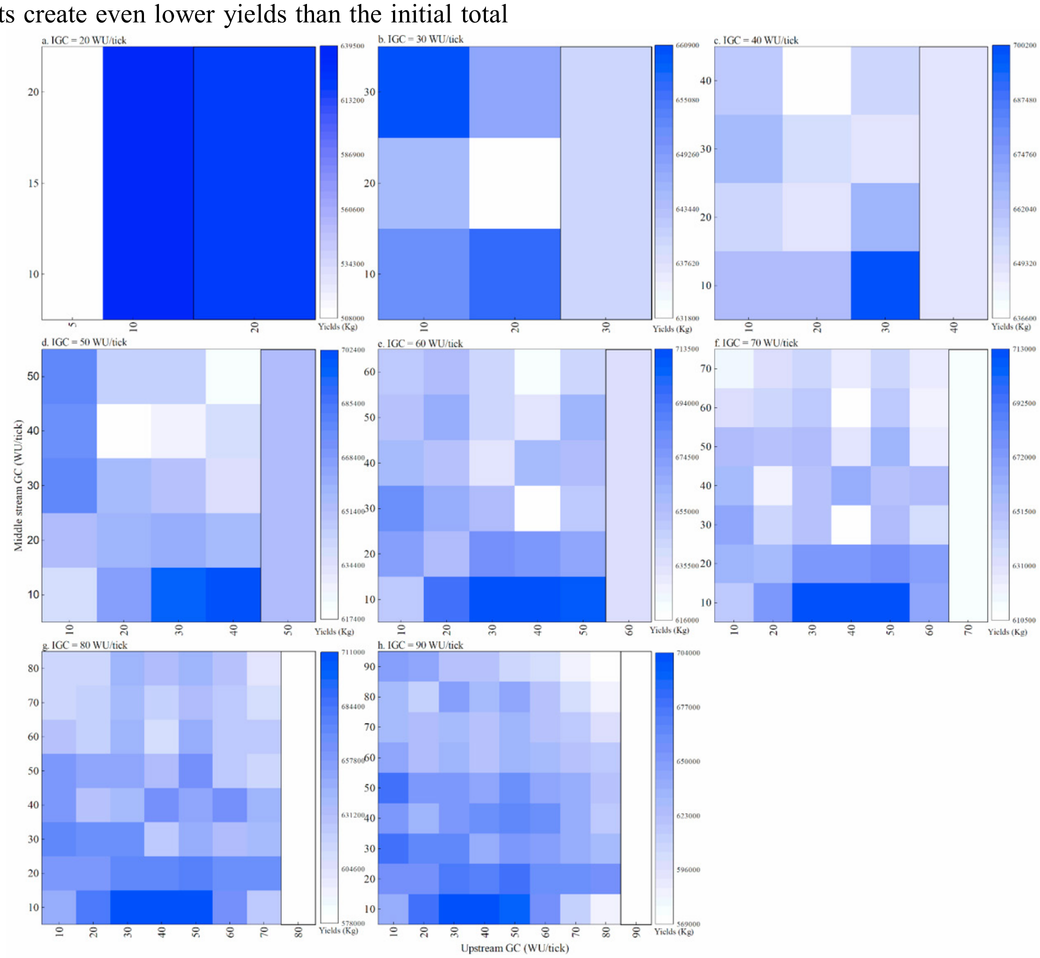

Figure. 6 Total system yields with varied UGC and MGC (RD90)

In contrast, higher UGCs and MGCs show lower total yields. Moreover, adjustments increased total yields for all combinations with IGC = 80 WU/tick, but decreased total yields for some combinations with all other IGCs. Furthermore, there is no clear pattern of total yields with increasing UGC or MGC. When comparing harvests of individual farmers, it can be observed that only when IGC = 90 WU/tick, we can find situations when all farmers are equal or better off with the adjustment: poor harvests improved and no sacrifices were needed.

However, for IGC < 90 WU/tick, farmers cannot be satisfied equally with the change, even when total yields increased. Relatively upstream farmers saw delayed expansion of fields, or even abandoned farmland and decreased yields per farmland. Relatively downstream farmers do not benefit all together or their situation might be even worse. These situations may happen separately or together. Again, when there is an improvement of farmers' harvests relatively downstream, the upstream farmers have lower yields.

3.2.3 RD = 160 WU/tick, with IGC = 80, 130, 160 WU/tick

Total yields after adjustment when RD = 160 WU/tick and IGC = 160, 130, and 80 WU/tick, are shown in Figure 7 (with initial total system yields shown in the black reference frame on the right). The figure shows that after changing GCs, lower total yields were realized with UGC = 10 WU/tick or MGC =10 WU/tick. Lower total yields were also found with higher UGC and MGC for IGC = 160 WU/tick. When both UGC and MGC are 10 WU/tick, the lowest total yields occur.

For IGC = 160 WU/tick, total yields increased under each combination, except for UGC = 10 WU/tick and MGC = 10 WU/tick (which is lower than the initial value). For IGC = 130 WU/tick, total yields decreased when UGC = 10 WU/tick or MGC = 10 WU/tick, while 34% of the situations kept the total yields and 48% even increased. For IGC = 80 WU/tick, total yields increased, except for MGC = 10 WU/tick.

When comparing the satisfaction of individual farmers, we observed that 78%, 47%, and 66% of all combinations show that all farmers can be satisfied with the changes when IGC = 160, 130, and 80 WU/tick, respectively. Similarly, situations that do not result in higher total yields represent sacrifices of upstream farmers in exchange for downstream improvement, although not all farmers have higher harvests.

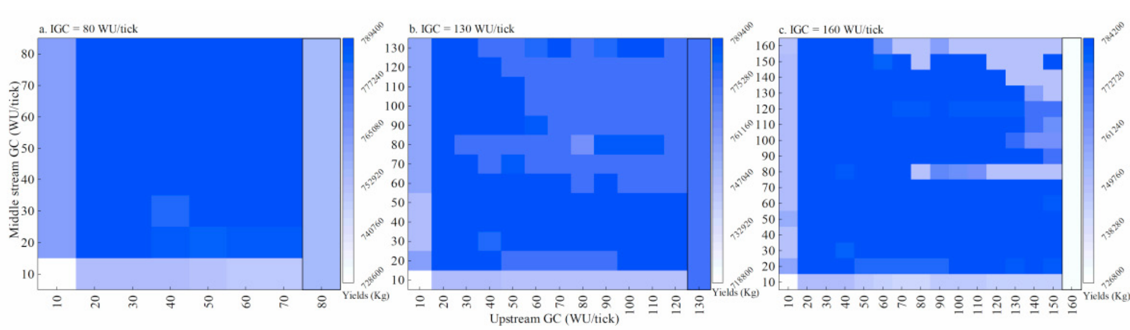

Figure. 7 Total system yields with varied UGC and MGC (RD160)

4. DISCUSSION

4.1 Temporal and spatial variation of this model

In this study, we used the AIRABM model to simulate interactions among human and non-human agents in irrigation systems to analyse resulting (distribution of) yields. Varied river discharges and gate settings were applied in the simulation, and we considered farmers' decision-making process and feedback mechanisms too. The results indicate how barley yields response to supplied water and how farmers can react to their own yields and those of others. We confirmed that farmers' location and gate interventions can have significant effects on the (distribution and amount of) farm yields. Our analyses illustrate a synergic process between inequity and equity in water distribution and yields.

Physical locations in the irrigation system when facing common pool resources play a vital role. Upstream farmers are typically able to capture a substantial share of the benefits from the system, because of their location-oriented water extraction priority. If there is no water extraction limitation, they can take as much water as they want to earn high yields or to expand farmlands earlier. Olson (2000) and Janssen et al. (2012) tested the 'stationary bandits' theory, with the bandits capturing more benefit when a group of members share the resources. That is exactly what we observed in our first round – relatively upstream farmers have better harvests when gate controls are absent in the system. The harvest situation in this system also shows the "irrigation dilemma" (Ostrom and Gardner, 1993), which captures those situations where farmers at the head or end of a system reflect different levels of influence on the collective actions related to the allocation of irrigation water. These situations are also closely related to the complexity of real-world irrigation situations, including system dynamics and feedbacks.

We can also observe that with adjustment strategies applied, the results differ quite substantially – which is similar to the "stationary bandit" theory, which showed to be less prevalent when distribution rules are enforced (Janssen et al., 2012). We observed many possible combinations after adapting GCs. Upstream farmers kept initial harvests, or reduced harvested farmlands, delayed farmland expansion time, or dropped production per farmland. We observed as well how middle stream and downstream farmers increased production per farmland, or could at least keep the initial harvests, but also how they could end up with even lower yields per farmland.

4.2 Harvests of individuals versus harvests in the system

We estimated the different resulting harvests according to water availability. We found that the adjustment of gate capacities can create quite different impacts for farmers, with the consistency of total system yields and individual yields being very different before and after adjustments. Before adjustment, the harvest patterns we observe are quite simple - good harvest situations mean that all farmers have good yields; most of the poor harvest situations show that upstream farmers have better harvests than lower farmers – especially the downstream ones. We tested to what extent adjustments in water availability could improve the poor harvest situations without any individual sacrifices. We did observe that such improvement is possible, but the results after adjustment are quite complex. This is exactly in line with Berglund's (2015) theory, that interactions among water users may lead to unexpected system performances characteristic of the complexity of water systems. Tilmant et al. (2009) indicate that if water is equally shared between water users who have to solve the common pool recourse sharing dilemma, upstream users will have to abandon some potential benefits. Our research confirmed this: situations with lower system harvests improved when upstream sacrifices were made – changing their good harvests to lower ones. We also observed that such sacrifices can result in more equal water and yield distribution over the system, but with a lower total system yield.

5. CONCLUSION

The irrigation-related agent-based AIRABM model simulates farmers' crop-growing decision and gate adjustment decision. Its main findings are:

- Yield patterns are not linear: gate capacity tipping points and river discharge thresholds were found.
- Gate capacity adjustments address issues associated with equitable water allocation to some extent.
- Facing extremely water scarce situations, the adjustments might further reduce actual yields.
- Adjustment creates emerging system performance, illustrating the complexity of irrigation systems.

These findings provide further methodological and case-related suggestions for understanding the importance of (conditional) cooperation when sharing common resources like water. Our focus will expand to (1) extending farmers decision-making processes, (2) quantifying the associated decision uncertainty caused by water availability and harvest memory, and (3) examining options for adaptive water management in response to gate capacity variability. We are still working on these expansions, including how they may reflect development processes in ancient Mesopotamia. With the current version of AIRABM, we can already show how different land and water use strategies can affect yields of farmers and the overall system – resulting in different yield patterns, creating specific conditions for sharing water.

REFERENCES

Adams, R.M., 1981. Heartland of Cities, Technology and Culture. Chicago, IL: University of Chicago Press.

Adams, R.M., 1965. Land behind Baghdad: A History of Settlement on the Diyala Plains. Chicago, IL: University of Chicago Press.

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

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

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

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

Jacobsen, T., Adams, R.M., 1958. Salt and silt in ancient mesopotamian agriculture. Science (80-.). 128, 1251–1258. https://doi.org/10.1126/science.128.3334.1251

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

Lang, D., Ertsen, M.W., 2022. An advanced agent-based model for analysing farmland dynamics in response to farmer decision-making in an irrigation system, Hydrol. Earth Syst. Sci., submitted.

Meinzen-dick, R., Raju, K. V, 2000. What Affects Organization and Collective Action for Managing Resources? Evidence from Canal Irrigation Systems in India. Food Policy 30, 1–26.

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

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

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

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

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

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

Rothman, M.S., 2004. Studying the development of complex society: Mesopotamia in the late fifth and fourth millennia BC. J. Archaeol. Res. 12, 75–119. https://doi.org/10.1023/B:JARE.0000016695.21169.37

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

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., Jotheri, J., 2017. The Origins of Levee and Levee-Based Irrigation in the Nippur Area– Southern Mesopotamia. Cycles Stages Jeeps Passats Stud. Anc. Near East honour McGuire Gibson 1–17.

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.