Simulating Irrigation Systems (Landscapes) in Ancient and Modern Times
Developing an Irrigation-Related Agent-Based Model Framework

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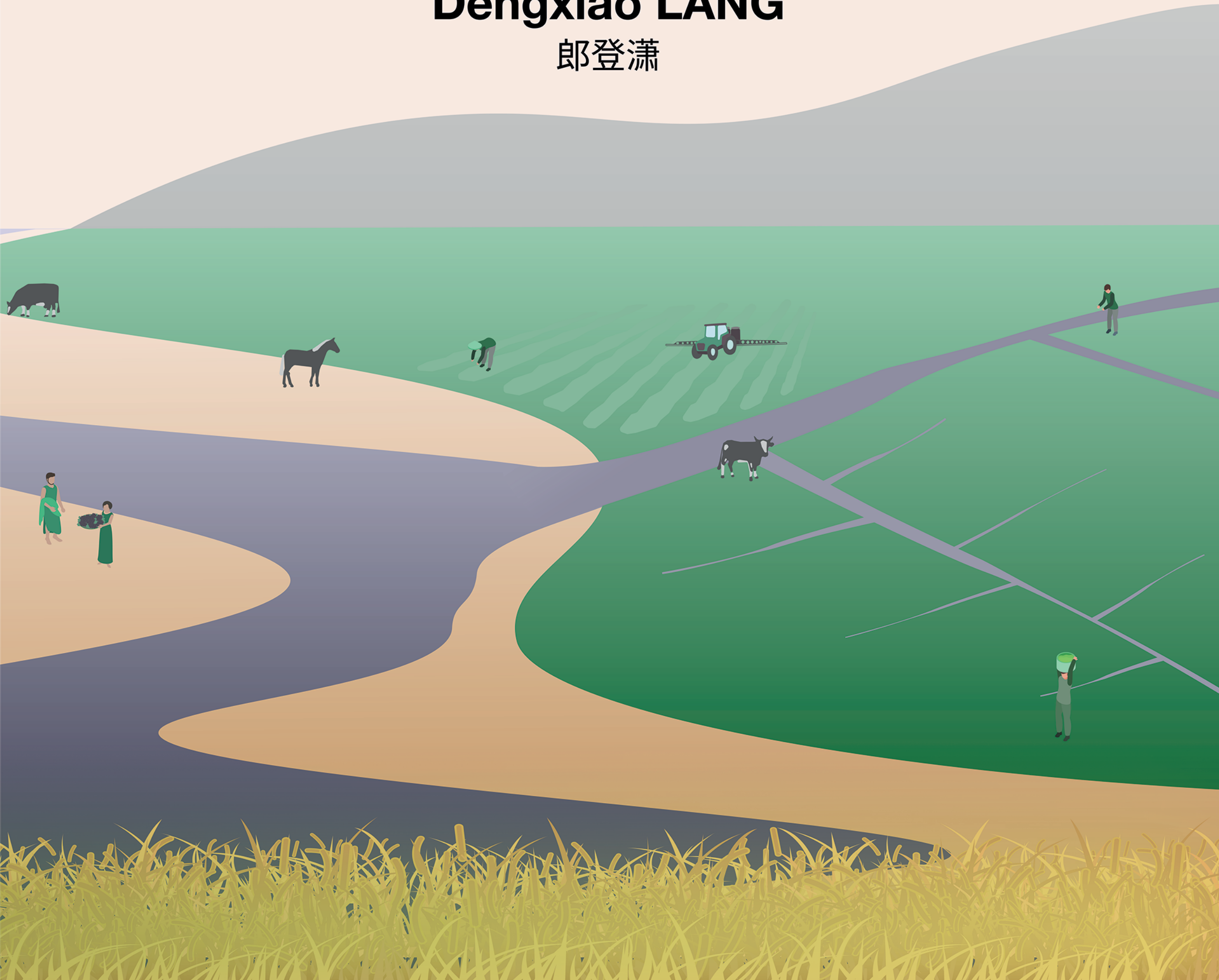
Simulating Irrigation Systems (Landscapes) in Ancient and Modern Times

Developing an Irrigation-Related Agent-Based Model Framework

Dengxiao LANG
郎登潇



SIMULATING IRRIGATION SYSTEMS (LANDSCAPES) IN ANCIENT AND MODERN TIMES

DEVELOPING AN IRRIGATION-RELATED AGENT-BASED MODEL FRAMEWORK

SIMULATING IRRIGATION SYSTEMS (LANDSCAPES) IN ANCIENT AND MODERN TIMES

DEVELOPING AN IRRIGATION-RELATED AGENT-BASED MODEL FRAMEWORK

Dissertation

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chair of the Board for Doctorates,
to be defended publicly on
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To my father Mingsong Lang

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SUMMARY

The human-water system, exemplified by irrigation systems, can be viewed as a highly intricate adaptive system that emerges from the dynamic and continuous interplay of environmental and societal elements over time and space. A thorough examination of the interconnections between humans, water resources, crops, and hydraulic infrastructure in the practice of irrigation management could yield profound insights into how irrigation systems function. Southern Mesopotamia boasts renowned, advanced irrigation systems that have supported the development of vast urban centers. Nevertheless, the historical workings and evolution of these irrigation systems in Southern Mesopotamia remain shrouded in mystery. It is imperative to explicitly address the interplay between human activities and the water system when investigating the development of irrigation systems and the landscapes they nurture.

In this thesis, I propose that a systematic exploration of the evolution of irrigation systems, progressing from small-scale to large-scale, from short-term to long-term, and from individual to collective, can provide a deeper comprehension of the intertwined environmental and societal dimensions of irrigation systems in Southern Mesopotamia. This exploration offers invaluable insights into understanding the co-evolutionary history of the environment and human society. To this end, I have developed an Agent-Based Model Framework with three model versions from the vantage points of human agents, hydrology, and hydraulics to simulate the irrigation systems in Southern Mesopotamia.

The first model version, the Irrigation-Related Agent-Based Model (IRABM), simulates the key functions of irrigation actions across various scenarios, infusing water realism and human realism into the agent-based model (ABM), thereby representing human-water interactions. This study primarily focuses on water distribution through the manipulation of hydraulic infrastructure and human-made strategies. The IRABM serves as a platform for the integration of human and non-human agents, facilitating actions and interactions among model agents. Furthermore, this theoretically and empirically informed computer model can offer fresh insights into the simulation of human-water systems, elucidating the emergence of irrigation patterns and yields from a dynamic environment.

The second model version, the Advanced Irrigation-Related Agent-Based Model (AIRABM), in contrast to the IRABM, incorporates learning behaviors, decision-making processes, and mechanisms at both the individual farmer and irrigation system levels. This model contributes to our understanding of the decision-making processes and mechanisms at both individual and collective levels, particularly concerning water conflicts among farmers in irrigation management. It also guides efforts to enhance communication and cooperation among farmers to optimize irrigation system performance. The model retains flexibility in the parameters, enabling its application to various irrigation systems worldwide.

In comparison to the IRABM and AIRABM, the third version of Irrigation-Related Agent-Based Model (IRABM^3) maintains the core components of individual decision-making regarding farmland dynamics and collective decision-making in irrigation management. Through a comprehensive computational approach, including sensitivity analysis and Gini coefficient evaluation, I investigate the emergence of patterns in irrigation systems under diverse scenarios of water availability and the decisions made by heterogeneous agents. This allows for the discussion of the potential processes involved in the development of ancient societies in Southern Mesopotamia. Moreover, the IRABM^3 offers adaptability to accommodate spatial and temporal variations within the irrigation system. This adaptability permits the exploration of irrigation-based societies in ancient Southern Mesopotamia on a larger scale, contributing to a broader understanding of the intricate dynamics at play in these societies. Furthermore, IRABM^3 forms a foundation for future research by incorporating additional agents into the irrigation system, facilitating a more comprehensive grasp of the evolutionary dynamics of irrigation systems in ancient Southern Mesopotamia and providing researchers with a powerful tool for further investigation.

These three models, presented in this series, demonstrate the potential and reliability of using ABM to simulate the operation of irrigation systems. They enable the interaction, adaptation, and decision-making of agents in response to changing parameters, such as river discharge, gate capacity, various water allocation strategies, and learning behaviors. They make a significant contribution to the study of the development of irrigation systems, both in Southern Mesopotamia and in irrigation systems worldwide.

SAMENVATTING

Zogenaamde mens-water systemen, zoals irrigatiesystemen, kunnen worden beschouwd als uiterst ingewikkelde, adaptieve systemen die voortkomen uit de dynamische en continue wisselwerking tussen milieu- en maatschappelijke elementen in tijd en ruimte. Een grondige analyse van de verbanden tussen mensen, waterbronnen, gewassen en hydraulische infrastructuur in irrigatiebeheer kan diepgaande inzichten opleveren hoe irrigatiesystemen functioneren. Historisch Zuid-Mesopotamië kan trots zijn op gerenommeerde, geavanceerde irrigatiesystemen die de ontwikkeling van uitgestrekte stedelijke centra hebben ondersteund. Desalniettemin blijven de historische werking en evolutie van deze irrigatiesystemen in Zuidelijk Mesopotamië gehuld in mysterie. Het is noodzakelijk om expliciet de wisselwerking tussen menselijke activiteiten en het watersysteem centraal te stellen bij het onderzoeken van de ontwikkeling van irrigatiesystemen en de landschappen die ze mogelijk maken.

In dit proefschrift stel ik voor dat een systematische verkenning van de ontwikkeling van irrigatiesystemen, gaande van kleinschalig naar grootschalig, van korte termijn naar lange termijn, en van individueel naar collectief, een beter begrip kan creëren van de verweven milieu- en maatschappelijke dimensies van irrigatiesystemen in Zuidelijk Mesopotamië. Deze verkenning biedt waardevolle inzichten in het begrijpen van de co-evolutionaire geschiedenis van omgeving en menselijke samenleving. Hiervoor heb ik een Agent-Based Model Framework ontwikkeld met drie model varianten vanuit het perspectief van menselijke actoren (agents), hydrologie en hydraulica om de irrigatiesystemen in Zuidelijk Mesopotamië te simuleren.

De eerste modelversie, het Irrigation-Related Agent-Based Model (IRABM), simuleert de belangrijkste functies van irrigatiehandelingen in verschillende scenario's, waarbij water en mens worden geïntegreerd in het agent-gebaseerde model (ABM), waardoor mens-water interacties worden gerepresenteerd. Deze studie richt zich met name op waterverdeling door middel van de manipulatie van hydraulische infrastructuur en door mensen ontwikkelde strategieën. Het IRABM dient als platform voor de integratie van menselijke en niet-menselijke actoren, waarbij acties en interacties tussen modelagenten worden vergemakkelijkt. Bovendien kan dit theoretisch en empirisch onderbouwde computermodel nieuwe inzichten bieden in de simulatie van mens-water systemen, waarbij de opkomst van irrigatiepatronen en opbrengsten uit een dynamische omgeving worden toegelicht.

De tweede model variant, het Advanced Irrigation-Related Agent-Based Model (AI-RABM), bevat – in tegenstelling tot het IRABM - leeropties, besluitvormingsprocessen en mechanismen op zowel het niveau van de individuele boer- als van het irrigatiesysteem. Dit model draagt bij aan ons begrip van de besluitvormingsprocessen en mechanismen op zowel individueel als collectief niveau, met name met betrekking tot waterconflicten tussen boeren in irrigatiebeheer. Ook helpt het model inspanningen om communicatie en samenwerking tussen boeren te verbeteren om de prestaties van irrigatiesystemen te optimaliseren Het model behoudt flexibiliteit in de parameters, waardoor het toepasbaar is op verschillende irrigatiesystemen wereldwijd.

In vergelijking met het IRABM en AIRABM heeft de derde variant Irrigation-Related Agent-Based Model (IRABM^3) de kerncomponenten van individuele besluitvorming met betrekking tot landbouwdynamiek en collectieve besluitvorming in irrigatiebeheer behouden. Door middel van een uitgebreide aanpak, inclusief gevoeligheidsanalyse en evaluatie van de Gini-coëfficiënt, onderzoek ik de opkomst van patronen in irrigatiesystemen onder diverse scenario's van waterbeschikbaarheid en de beslissingen van heterogene agenten. Hierdoor wordt een discussie mogelijk van potentiële processen in de ontwikkeling van oude samenlevingen in Zuidelijk Mesopotamië. Bovendien kan IRABM^3 aangepast worden om ruimtelijke en temporele variaties binnen het irrigatiesysteem op te vangen. Deze aanpasbaarheid maakt de verkenning mogelijk van op irrigatie gebaseerde samenlevingen in het oude Zuidelijk Mesopotamië op grotere schaal, wat bijdraagt aan een breder begrip van de complexe dynamiek in deze samenlevingen. Bovendien vormt IRABM^3 een basis voor toekomstig onderzoek door aanvullende agenten in het irrigatiesysteem op te nemen, waardoor een meer alomvattend begrip van de evolutionaire dynamiek van irrigatiesystemen in het oude Zuidelijk Mesopotamië mogelijk wordt en onderzoekers een robuust instrument krijgen voor verder onderzoek.

Deze drie modellen, gepresenteerd in deze reeks, tonen het potentieel en de betrouwbaarheid van het gebruik van ABM om de werking van irrigatiesystemen te simuleren. Ze maken interactie, aanpassing en besluitvorming van agenten mogelijk in reactie op veranderende parameters, zoals rivierafvoer, capaciteit van sluizen, verschillende waterallocatiestrategieën en leergedrag. Ze leveren een significante bijdrage aan de studie van de ontwikkeling van irrigatiesystemen, zowel in Zuidelijk Mesopotamië als wereldwijd.

1

INTRODUCTION

1.1. IRRIGATION, IRRIGATION SYSTEM, IRRIGATION LANDSCAPE

Farmers utilize water in two primary methods for cultivating crops: rain-fed agriculture and irrigation-based agriculture. Rain-fed agriculture refers to the process of water seeping into the soil within the root zone through direct rainfall, facilitating crop growth (Rockström et al., 2010). In contrast, irrigation is the artificial application of water to the soil through various hydraulic infrastructures typically employed in situations when rainfall cannot sustain the cultivation (Kelly, 1983; Lucke et al., 2019). Irrigation serves as a means for humans to adapt and manipulate the environment, particularly in arid and semi-arid regions (Lucke et al., 2019; Small and Svendsen, 1990). Irrigation is of major importance in many countries as it has enabled food production for the growing population in the world (Elshaikh et al., 2018; Small and Svendsen, 1990). Various water sources can be used for irrigation, including surface water from rivers, lakes, or reservoirs, groundwater from springs or wells, as well as alternative sources like treated wastewater or desalinated water.

An irrigation system is defined as a set of natural and human-made components employed to utilized to transport water from sources, like rivers, in order to facilitate and regulate the movement of water from these sources to agricultural lands (Small and Svendsen, 1990). The notion of “human-made components” encompasses hydraulic infrastructures designed to store, divert, channel, or otherwise manipulate water from its source to specific fields. These components also include the rules that manage the actions of individual farmers, households, and groups, their relationships, and the control of water movement in both temporal and spatial dimensions (Small and Svendsen, 1990; Ertsen, 2010; VanderMeer, 1968).

Irrigation involves a complex interplay among humans, land, and water, encompassing both temporal and spatial dimensions, collectively constituting the irrigated landscape. I argue that a detailed exploration of the short-term interactions between humans, water, crops, and hydraulic infrastructures in irrigation management practices leads to a deeper understanding of the long-term functioning of irrigation systems. This exploration provides invaluable understanding for comprehending the co-evolutionary history of the environment and human society.

1.2. AGENT-BASED MODEL (ABM)

1.2.1. GENERAL DESCRIPTION OF ABM

Agent-Based Modelling (ABM) is a type of computational modelling that focuses on the interactions, actions, and communication protocols among agents within a shared model environment (Abar et al., 2017). ABM employs a bottom-up approach to model complex systems, starting from individual agents or collective agents such as organizations or groups (Shook et al., 2013; Moon, 2017; Abar et al., 2017). The general structure of ABM is shown in Figure 1.1. The agents in the system are situated within an environment where they interact with one another and their surroundings. The interactions among agents and their related environment shape the (adaptive) strategies of agents, with their actions capable of generating or modifying the states of agents and influencing the decision-making processes. The actions by which the agents operate vary depending on their nature, whether they are physical or human processes. The objective

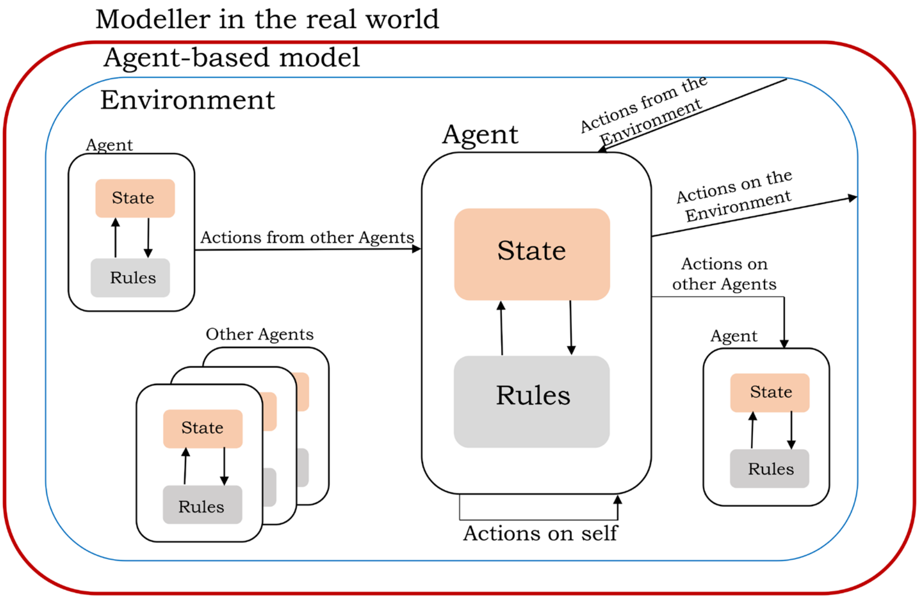

Figure 1.1: Structure of the agent-based model (Van Dam et al., 2012).

of this ABM approach is to evaluate the design and effectiveness of these agents and understand the interactions among agents, while also extracting valuable insights into their emergent actions and patterns at both the individual and system levels.

1.2.2. PLATFORM FOR DESIGNING ABM

There are plenty of platforms to implement ABM. NetLogo and GAMA offer universal and repeatable software, without asking users to familiarize themselves with the specific programming language employed by the framework (Tisue and Wilensky, 2004; Grignard et al., 2013; Cardinot et al., 2019); MASON and Repast are written in Java (Lucke et al., 2019; North et al., 2013); the web platform AgentBase uses JavaScript (Wiersma, 2017); Python is the language used by the platform Mesa (Masad and Kazil, 2015). NetLogo is chosen for this PhD project because 1) it is user-friendly, and stakeholders could play with the parameters within the designed graphical environment and see the dynamics in the built environment; 2) it is especially suitable for modelling complex systems that evolve over time; 3) it provides an authoring environment for students and researchers to create their own models, even without extensive programming expertise (North et al., 2013; Tisue and Wilensky, 2004; Gooding, 2019).

1.2.3. ABM APPLICATION

The use of ABMs for research and management is growing rapidly in various disciplines, including biology, social sciences, economics, architecture, urban planning, and archaeology, etc. Yang et al. (2022) developed an ABM in the bioenergy and bioproduct community for effective communication among stakeholders and researchers. In a comparison between ABM and four other models that integrated environmental assessment and management, the conclusion was that ABM was highly relevant for social learning in a wide range of settings, as it can consider individual and/or aggregated effects (Kelly et al., 2013). Farmer and Foley (2009) developed economics needs ABM to analysis the financial crisis. The application of ABM in architecture is not only focused on the design and planning process but also explores the interactions between individuals in design and construction processes (Achten et al., 2004; Watkins et al., 2009; Stieler et al., 2022). In order to investigate the effects of heterogeneity in residential preferences of urban sprawl, an ABM was developed to represent the process of residential development (Brown and Robinson, 2006). Archaeological ABMs have been developed to simulate social interactions, for example, inter-agent social learning, group formation, and the emergence of societal development (Premo and Scholnick, 2011; Premo, 2012; Kohler et al., 2012; Brughmans et al., 2019).

1.3. ABM IN IRRIGATION MANAGEMENT

The human-water system can be conceptualized as a complex adaptive system created by environmental and social agents that interact dynamically and continuously with each other in time and space. ABMs can be employed to simulate this complexity, offering a valuable tool to address challenges such as water conflicts or shared water management (Eyni et al., 2021; Darbandsari et al., 2020; Meinzen-Dick et al., 2018; Nhim et al., 2019), water contamination problems (Araya et al., 2021), water supply and water demand management (Xiao et al., 2018; Lin et al., 2020), flooding (Dubbelboer et al., 2017), water reuse (Kandiah et al., 2019), food–energy–water resources management (Ding et al., 2021), and evaluation of crop pattern and water management policies (Nouri et al., 2019; Huber et al., 2019).

ABMs are also utilized for irrigation water management, allowing for the portrayal of natural, economic, and societal dynamics. These ABMs achieve this by integrating and connecting various models, such as hydrology and crop models, while also accounting for social activities such as decision-making and communication. Moreover, they function across a wide range of spatial and temporal dimensions, offering a holistic comprehension of the intricacies involved in irrigation water management. Aghaie et al. (2020) explored the hydrological and economic efficiency of groundwater-based irrigation water markets by using ABM; Bahrami et al. (2022) applied an ABM framework to model the interactions between reservoir operating policy and farmers' irrigation demand; ABM was also used to explore efficient irrigation strategies under different climate scenarios (Himanshu et al., 2019); Hyun et al. (2019) introduced an ABM to analyse the decision-making processes of prominent irrigation districts in the New Mexico section of the San Juan River; Anthony and Birendra (2018) developed an ABM irrigation management tool to allocate water in farmlands. There are many applications of ABM in irrigation based on irrigation games as well (Bouziotas and Ertsen, 2017; Janssen et al., 2015; Janssen and Baggio, 2017; Gurung et al., 2006).

Ertsen (2011) and Ertsen et al. (2014) discussed the capability of applying ABMs to irrigation systems, and pointed out that agent-based analysis and modelling in irrigation is more challenging than in rain-fed agriculture. This challenge arises from the intricate interactions between humans and the environment inherent in irrigation activities, in which the irrigation infrastructure is a crucial component as it connects other agents. Beginning with irrigation game theory as its foundation, this project utilizes ABM with empirical data from Southern Mesopotamia to showcase practical irrigation water management strategies according to water availability. It explores the irrigation system evolutionary processes, dynamics of the irrigated landscapes, and decision-making mechanisms at various levels. By designing irrigation-related agent-based models in NetLogo and incorporating real-world data, the project aims to support a comprehensive understanding of irrigation system (landscape) management in Southern Mesopotamia.

1.4. SOUTHERN MESOPOTAMIA

1.4.1. ENVIRONMENTAL BACKGROUND

Southern Mesopotamia is located in a flat alluvial plain between the modern Tigris and Euphrates rivers (Figure 1.2). The Tigris and Euphrates rivers come from Turkey, where the Taurus Mountains provide both rivers with a continuous water supply from precipitation and meltwater. This flat alluvial plain has been shaped and reshaped by complex water systems that consist of natural and human-made channels, hydraulic infrastructures, swamps, and levees. Through a process of human niche construction, human-driven irrigation practices and the hydrological characteristics of watercourses and hydraulic structures mutually evolved, ultimately giving rise to a hydraulic landscape characterized by the well-known herringbone systems (Wilkinson et al., 2015; Rost, 2015).

Southern Mesopotamia has the most fertile agricultural soil in the wider region, and two-thirds of the regional population is settled in this part of Iraq (Jotheri and Hamzah, 2016). Much earlier, the region was the home of early urban settlements such as Uruk, Girsu, Kish, and others (Altaweel, 2019). In ancient times, the climate exhibited somewhat higher and more consistent levels of precipitation compared to the current-day conditions. However, the contemporary climate still adheres to the prevailing weather patterns of Southern Mesopotamia (Rost, 2015; Bar-Matthews et al., 1999; Lemcke and Sturm, 1997). The annual precipitation is less than 100 mm in most years, and rainfall is unevenly distributed throughout the year (Rost, 2015). River water levels are low in September/October and peak just prior to April/May. The main crops are winter crops: wheat and barley, both in the past and present environment. The crop rhythms are opposite to the water regime: when the water is high, the water demand is low, and vice versa. Southern Mesopotamia lies outside the rain-fed agriculture zone and it is a semi-arid zone with hot and dry summers but cooler winters, thus, irrigation has been imperative for agricultural production in this area for 6000 years (Hritz, 2010).

Irrigation in ancient Southern Mesopotamia is typically conceptualized as a process that started with individual irrigation actions and gradually developed into collective management of irrigation highly centralized and water distribution centrally managed (Rost, 2015) over millenia. The farmers may have been grouped by institutions to irrigate the agricultural land, but they probably could trade (crops or water) among themselves and with other people outside the system (Rost, 2015; Altaweel, 2019). Khan et al. (2006) claim that irrigated agriculture in Mesopotamia met problems in its development including silting of canals, soil salinity, water conflict, over-exploitation of water, and institutional failure.

Whatever the case, interactions between human activities, hydrology, and the physical characteristics of both natural and human-made watercourses have mutually shaped and advanced the development of irrigation systems and irrigated landscapes within this area. Delving into these interactions in depth is crucial, as it allows us to comprehend irrigation activities at both the individual farmer and community levels and to explore how individual activities can promote collective actions. This understanding then paves the way to grasp the intricacies underlying the dynamics of irrigation systems (landscapes) and, ultimately, to attain insights into the evolutionary journey of irrigation-based societies in Southern Mesopotamia. Moreover, there exists a notable absence of comprehensive and detailed historical records concerning irrigation management within the framework of an evolving irrigated landscape in this region. My investigation entails an examination of different levels of decision-making and irrigation activities in response to water situations. Specifically, my focus will be on unraveling the process through which simple structures gradually evolved into fully developed irrigation systems (landscapes) through the mechanism of human niche construction (Wilkinson et al., 2015).

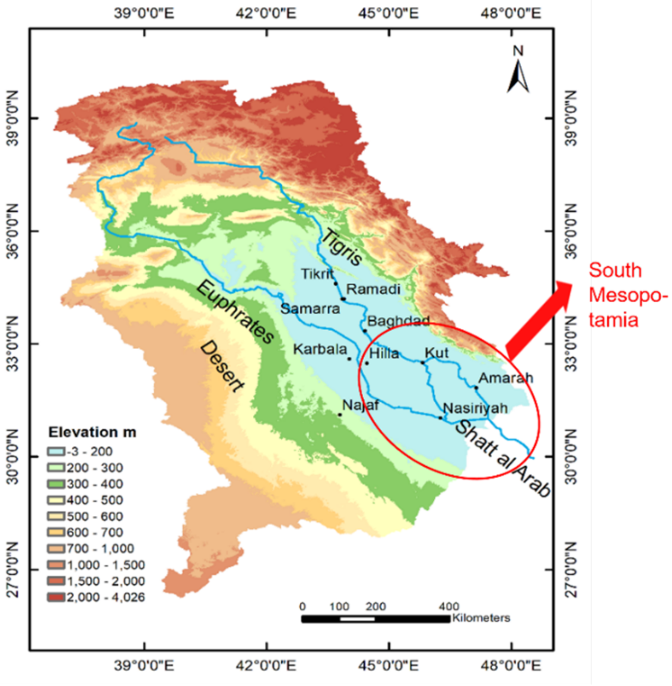

Figure 1.2: The map of Mesopotamia.

1.4.2. FOCUS ON BARLEY

Although there was a wide range of cultivated grains in ancient Southern Mesopotamia, sufficient evidence indicates that agricultural production was strongly based on winter crops such as barley and wheat (Rost, 2015). We selected barley as our modelling grain because 1) barley is more drought-resistant and tolerant of alkaline soils, and it is more productive in drier conditions; and 2) barley plays a vital role in politics and society through its universal distribution in society, including trade (Alexander and Violet, 2012; Edens, 1992; Ellison, 1981; Foldvari and Van Leeuwen, 2012; Helback, 1959; Rost, 2015; Smith, 1995). As we will model the development of irrigation (the irrigated landscape) in Southern Mesopotamia, barley appears to be the perfect crop to start a model. The details of barley growth and yield response to supplied water can be found in Lang and Ertsen (2022a, 2022b).

1.5. RESEARCH OVERVIEW

1.5.1. RESEARCH OBJECTIVES

To investigate the evolution of irrigation systems in Southern Mesopotamia from the perspectives of humans, hydrology, and hydraulics, I propose to develop agent-based computational simulations. These simulations model the functioning of irrigation systems and examine the interactions among human agents, non-human agents, and their environment, analyzing how they respond to varying levels of decision-making.

The initial focus of this research is to test the capability of an ABM in simulating irrigation systems, the objective is to demonstrate how the resulting Irrigation-Related Agent-Based Model (IRABM) can effectively represent and study human-water system interactions without predetermined assumptions.

Building upon IRABM, I incorporate both individual and collective decision-making processes to explore patterns in farmers' yields and the dynamics of farmlands within the individual farms. As such, I developed the model – Advanced IRABM (AIRABM) to mimic farmer activities and system management actions in an irrigation system, to explore how farmland dynamics respond to farmer decisions according to the water situations.

Furthermore, I enhance the AIRABM by introducing the third model version IRABM^3, which integrates collective decision-making of system dynamics. By considering the dynamics of individual farmers and the irrigation system, I argue that the third model has the potential to simulate the evolutionary patterns of irrigation systems in Southern Mesopotamia. This research offers valuable insights into how human decision-making influenced the development and configuration of the irrigated landscape.

In this PhD project, I utilize ABM on the NetLogo platform to simulate the interactions between human agents and non-human agents in an irrigation environment, and then virtually reconstruct selected irrigation landscapes in the Southern Mesopotamia region. This research aims to enhance our understanding of the evolution of irrigation systems under the combined influence of nature and human activities. Understanding the past irrigation systems and their landscape context is crucial for assessing ancient social economies and their environmental connections. Ultimately, this research will provide new insights to re-evaluate the current irrigation management practices and predict future trajectories of irrigation systems.

1.5.2. RESEARCH QUESTIONS

The main research question (RQ) is:

How can we use agent-based modeling to mimic the evolution processes of irrigation systems (landscape) in Southern Mesopotamia?

To fully understand the main research question, there are three sub-questions that should be addressed first:

RQ1: How can agent-based modeling as an approach be used to design an irrigation-related agent-based model? (Chapter 3)

RQ2: How can ABM with different levels of decision-making reflect the farmland dynamics and yields pattern according to the farmers' experience? (Chapter 4)

RQ3: How could small-scale processes of irrigation activities contribute to large-scale irrigation system development when modelling irrigation-based society in Southern Mesopotamia? (Chapter 5)

1.5.3. RESEARCH APPROACH

ABM is used as the main method in this PhD project. The key steps in developing an ABM are (Macal and North, 2006; Akhbari and Grigg, 2013):

1. Identifying agents relevant to the objective of the research and the potential processes that may affect it;
2. Accurately specifying the agents' distinct activities;
3. Defining the environment the agents live in and interact with;
4. Identifying the agents' relationships and developing a theory about their interactions with each other and the environment;
5. Developing essential agent-related data;
6. Appropriately representing agent-to-agent interactions as well as agent-environment interactions;
7. Validating the agent-based model.

ABM Framework

In ABM, the central elements are the individual agents which act independently while also engaging in interactions with one another based on specific rules and/or decisions (Klabunde and Willekens, 2016). There are two challenges when building an ABM framework. Firstly, how can activities or decision-making of human agents be included in this model; secondly, how can one meaningfully incorporate the environment – with elements providing the model context and other elements acting as model agents? The modelling framework version of this research is elaborated and presented as an overview in Figure 1.3. Our irrigation-related ABM will start with five agents, which are human agents (farmers and virtual water managers) and non-human agents (river, hydraulic infrastructures, and crop). Each agent has different and complex interactions with others.

ABM cycle

As shown in Figure 1.4, the standard ABM cycle can be broken down into three steps (Wilensky and Rand, 2015): 1) Initialization of the world and agents, setting the initial

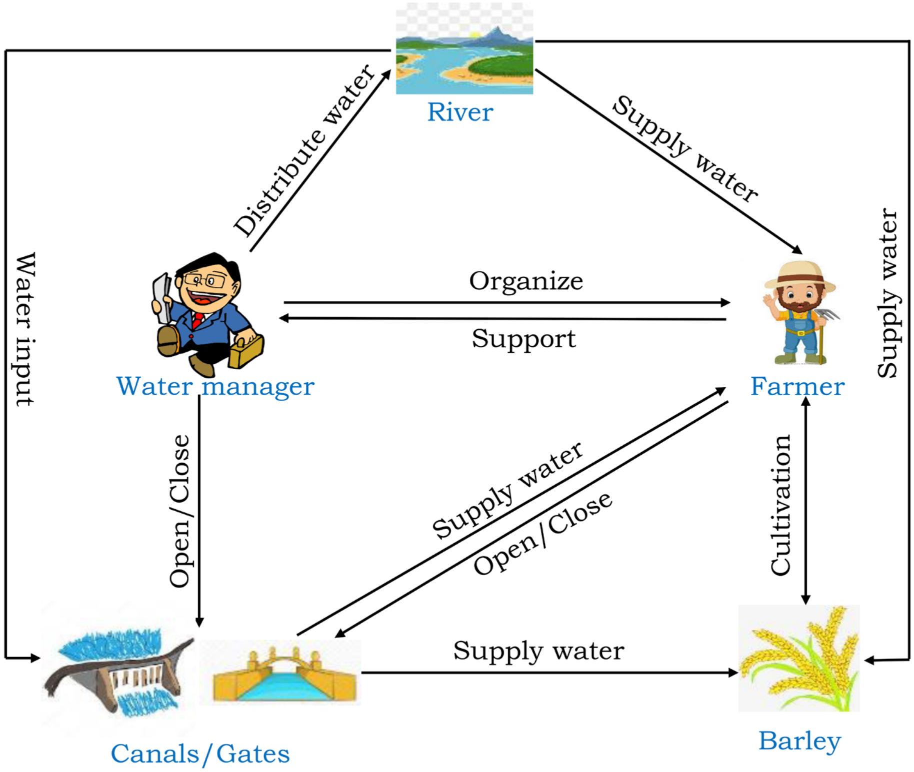

Figure 1.3: Overview of the ABM framework.

conditions for the simulation; 2) Each agent observes the current state of the world, gathering information about their environment and the actions of other agents; 3) Agents make decisions and take actions based on their observations, influencing the state of the world. The cycle then repeats by returning to step 2. By introducing an additional step between observation and action, the model transitions into an adaptive ABM. In this adaptive model, agents have the capability to update their internal model of the world based on their observations. This updated internal model guides their decision-making process, determining the actions they will undertake. I have included this updating step in my own ABMs.

Model Validation

Validation is the process of ensuring that the implemented model accurately represents the “real world”. It involves assessing whether the designed model performs well within its intended scope and aligns with the modelling objectives (Balci, 1997). The ABMs capture the intricate interactions between individual agents and their environment, guided by predefined rules. While the structure of the model itself may be simple and straightforward, the simulations generated by the agents can exhibit highly complex and dynamic actions. Consequently, traditional model validation methods may

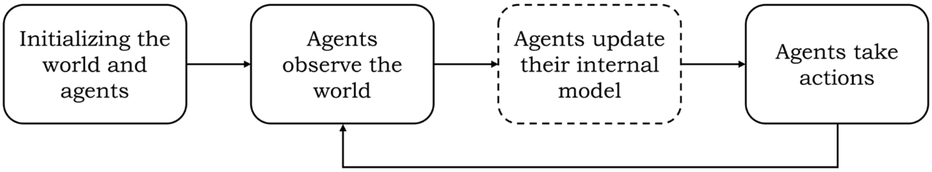

Figure 1.4: The ABM cycle (Wilensky and Rand, 2015).

face challenges when applied to ABMs. Recognizing this complexity, validation of ABMs goes beyond assessing the model outcomes alone and encompasses the various components of the model itself. Researchers have categorized ABM validation into three levels (Ligtenberg et al., 2010; Anand et al., 2016):

- Level 1 Knowledge validation: also known as ontology validation, focuses on evaluating the effectiveness of the ontology in accurately representing the real world in terms of entities and their relationships. This is particularly relevant in ABMs as they are constructed based on real-world entities and their interactions. Developing an ontology is often the initial step in building an ABM (Livet et al., 2010).

- Level 2 Process validation: process presents the actions taken by the agents. Behavioural attributes define the actions performed by agents or their responses to other agents or the environment. Interaction protocols refer to how agents determine their interactions with other agents and the environment based on observations. Validation at this level is crucial as it determines the extent to which the actions of the agents align with the intended process.

- Level 3 System validation: this level validates how well the ABM represents the real world based on the global outcomes. If the empirical data is available, the traditional method should be used to validate the ABM. When no or insufficient empirical data is available, expert validation should be used.

In this project, due to limited data availability, our primary approach to validation is Level 1 Knowledge validation. We gauge the efficacy and outcomes of the models by comparing them with conclusions derived from parallel research within the same domain. Furthermore, we substantiate the models' outputs by aligning them with actual scenarios in the real world, affirming their authenticity and realism.

1.5.4. RESEARCH SCOPE

The layout of the virtual irrigation systems is based on the human niche construction of irrigation canal layouts in Southern Mesopotamia. Empirical data like irrigation schedules and barley yields responses to supplied water are considered in this research. Due to data scarcity on the hydraulic characteristics of the two rivers, and ways of direction communication among farmers and water managers, the traditional method for validating the ABM are not considered in this research.

1.6. THESIS LAYOUT

In this thesis, a series of irrigation-related agent-based models (IRABMs) were developed and tested based on the situations of Southern Mesopotamia, aiming at a better understanding of the operation of irrigation systems based on the interactions of human and non-human agents, and the evolution process of irrigation systems from 3H – human, hydrology, and hydraulics (Ertsen, 2010) in Southern Mesopotamia. As shown in Figure 1.5, the thesis contains seven chapters. The outline of each chapter is as follows:

Chapter 1 serves as an introduction to the research background, research overview, and thesis outline.

Chapter 2 provides the comprehensive ODD + D protocol for executing ABM, encompassing essential components utilized in constructing all three versions of the model.

Chapter 3 presents an Irrigation-Related Agent-Based Model (IRABM) to mimic the human-water systems in the NetLogo environment. The model explores the interactions between humans, water, crops, and hydraulic infrastructures and indicates how crop yields patterns emerge from the varied water availability in an irrigation system. This theoretical and empirical modelling framework provides the potential ability to solve socio-hydrological questions from a new perspective.

Chapter 4 introduces an Advanced Irrigation-Related Agent-Based Model (AIRABM) to simulate farmland dynamics in an irrigation system within the NetLogo environment. The model explores processes and mechanisms of decision-making on individual farmers' and system's levels, based on past water availability and harvest realized (expressed as "memories"). This study offers directions on how to improve irrigation system performance by managing communication and cooperation among stakeholders.

Chapter 5 proposes the final version IRABM^3, with model parameters contributing to the generation of various patterns of yields and expansion of farms and system according to individual and collective decision-making. Additionally, the Gini coefficient (based on yields) was applied to estimate the level of inequality among farmers. This model is a suitable base for further study, by incorporating additional agents into the irrigation system and expanding the spatial-temporal scales of the irrigated landscapes, to reach a more comprehensive understanding of the evolutionary dynamics of irrigation systems in Southern Mesopotamia.

Chapter 6 builds on previous chapters and aims to summarize the key contributions of this PhD research, the knowledge generated, and the limitations, to answer the research questions, and to show the main findings of this project.

Chapter 7 brings the perspective for future research, as it addresses the significance of the PhD project and recommendations for extending the current research.

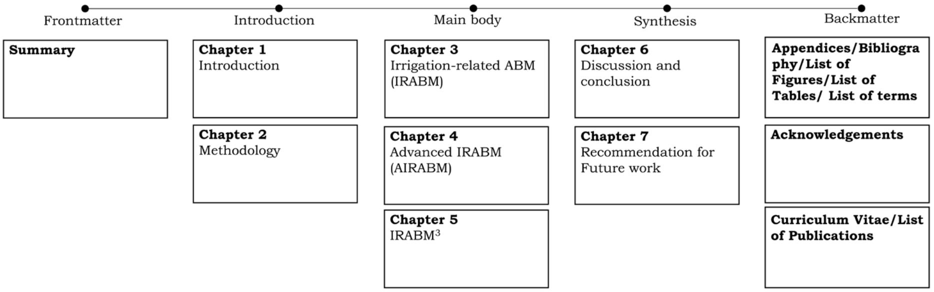

Figure 1.5: Chapter outline of this thesis.

2

AN IRRIGATION-RELATED AGENT-BASED MODEL OVERVIEW, DESIGN CONCEPTS, DETAILS + DECISION MAKING (ODD + D) PROTOCOL

This chapter is about the methodology of this dissertation, encompassing essential components utilized in constructing three versions of IRABMs.

The conception or description of the three models presented in this thesis follows the structure of the ODD + D protocol, which stands for Overview, Design concepts, Details + Decision Making (Grimm et al., 2006; Grimm et al., 2010; Grimm et al., 2020; Müller et al., 2013).

- The "Overview" consists of three elements (purpose and patterns, state variables and scales, process overview, and scheduling), which provide an overview of the overall purpose and structure of the model.
- The section titled "Design Concepts" does not provide a description of the model itself, but instead focuses on explaining the fundamental concepts that form the basis of the model's design. The objective of including this element in the protocol is to establish a connection between the design of the model and the broader concepts recognized in the field of Complex Adaptive Systems (Grimm and Railsback, 2005; Railsback, 2001). These concepts encompass questions related to emergence, the interactions among individuals, whether individuals take into account past experiences and predictions about future conditions, and the rationale behind considering and incorporating stochasticity.
- The "Details", which is the third part of ODD + D, consists of four elements (implementation, initialization, input, sub-models) that provide the specific information that was not covered in the overview.
- Regarding "Decision-making", the focus is primarily on human decision-making, encompassing both the empirical and theoretical foundations that underpin the choices of decision-making processes within the model (mostly in Chapter 4 for AIRABM and Chapter 5 for IRABM^3).

The rationale behind the ODD + D sequence is to present context and general information first (Overview), followed by strategic considerations (Design concepts), then with technical details (Details), and concluding with human consciousness (Decision-making). By applying this structure, we can assist readers in understanding our ABMs by providing a standardized protocol that presents information in a logical order, enabling readers to progressively enhance their understanding based on prior knowledge. The IRABM, AIRABM, and IRABM^3 were created on the NetLogo platform. The details of the ODD + D protocol can be found in the following sections.

2.1. PURPOSE AND PATTERNS

What are the purpose and pattern of the model?

This research project develops agent-based computational simulations to explore the operation of irrigation systems through the interactions among agents and the related environment. The purpose of the series of IRABMs is to 1) explore how the irrigation-related agents and their related environment interact with each other; 2) test the decision-making mechanisms from individual level and collective level in an irrigation system; and 3) study how short-term irrigation management actions create long-term irrigation system patterns. The IRABMs simulate parameters like river discharge (RD), gate capacity (GC), irrigation controls (demand control and time control), and decision-making from individual and collective levels over time as functions of water (re-)distribution strategies. It builds an understanding of how barley yield patterns, farmland dynamics, and system dynamics are generated from the supplied water:

- Barley yields and farmland dynamics at farms (the smallest spatial scale, representing individual farmers or families) are used to check the results of water distribution, individual farmers' planting choices, and the collective decision-making on water redistribution to upstream, middle stream, and downstream farmers.

- The system dynamics – farmers/canals movement or expansion is used to explore how the short-term actions promote longer-term patterns.

- Aggregating yields at the levels of individual farmers, canals, or whole system allows for exploring how specific irrigation strategies create patterns in water availability and yields.

These patterns reflect the results of interactions among the agents in this model. Barley yields are directly dependent on water distribution, as crop yields respond to changing irrigation measures (Anthony and Birendra, 2018; Hu and Beattie, 2019; Tamburino et al., 2020). The patterns emerged as a result of establishing a water system in NetLogo, aimed at simulating the water movement through the hydraulic lands, the irrigation activities, the barley growth, and the decision-making of human agents.

For whom is the model developed?

I designed the IRABMs with the empirical data of ancient Southern Mesopotamia. The IRABMs allow archaeologist to increase their understanding of the socio-hydrological reality of the irrigation landscape in Southern Mesopotamia in a specific time period. It can also help decision-makers to design irrigation management based on limited supplied water. Moreover, to make this modelling framework more accessible to stakeholders, especially for non-tech stakeholders, a user-friendly interface has been developed in NetLogo where stakeholders can play with and build model simulations with differently specified agent rules.

2.2. ENTITIES, STATE VARIABLES, AND SCALES

What kinds of entities are in the IRABMs?

The environment of this simulation is a water system: one main river brings water to an irrigation system with farmers, canals, gates, and farmlands. Canals are built along the river, which is used as the transfer tool of water. Gates allow water to flow from the river into irrigation canals, and from canals to farm(s). There are gates at the junction of the river and canals or two canals (head gates), and at the junction of canals and farms (farmers' gate).

The model consists of the following entities: river, canals, gates, farmlands, barley, virtual water managers, and farmers. More details follow later.

By what state variables are these entities characterized?

The entities and their state variables are defined as follows:

- The river is the origin of the water resource. Water agents start from the river and move one cell per time step, whatever the inflow. The relevant variable is varied river discharges.
- Canals are transfer tools of water, transporting water from the river to farmers. Water moves one cell per time step, organized with canal capacity.
- Gates control the water flow – either from the river to canals or from canals to farmers. Water moves one cell per time step, arranged by gate capacity.
- Farmlands have two states in IRABMs: one farmland state is with barley; another one is fallow – preparing for the next crop season. The farmlands with barley have the variables: water demand, water stress, start barley, barley yields, harvest cycle, barley alive or not. The fallow farmlands have the variables: available for barley sowing, pre-irrigation demand when they are ready for the next cultivation.
- Virtual water managers propose water (re)allocation strategies. Water allocation control, or irrigation water control, to canals, can be done in two ways – time control and demand control (IRABM). In AIRABM, water managers can redistribute water among farmers along the same canal, while water managers can control the irrigation system dynamics based on the harvest situation in IRABM^3 as well. Water distribution strategies are shaped through river discharge, gate capacity, the number of canals irrigated simultaneously, and barley water demands.
- The farmers make choices on crop growing and sowing choices in the next year (farmlands dynamics). Farmers will support the water allocation strategies when there are poor harvest situations in the system. They have the variable: irrigation demand.
- Barley yields update annually and are based on the supplied water throughout the season.

How is scale included in the model?

The overview of the agents in these three models is listed in Table 2.1. All these entities are stationary, and water is the only agent that can move through the model environment. The scale in NetLogo is 38×18 cells. The time step of IRABM is hourly and we simulate it for 1 year, while the time step for AIRABM and IRABM^3 are daily and the simulation years are 20 years and 100 years, respectively.

Table 2.1: Number of agents in these three models.

Agents in three models	IRABM	AIRABM	IRABM^3
River	1	1	1
Canals - Primary Canal	16	1	1
Canals - Secondary Canal	0	0	1
Farmer	128	10	22
Farmlands per farmer	2	5	5
Head Gates	16	1	3
Gates of farmers	128	10	22

2.3. PROCESS OVERVIEW AND SCHEDULING

What entities do what in which order?

IRABM simulates the interactions of irrigation-related non-human agents – which represents human choices, and as such human agents as well. There are two main processes: the irrigation procedure and the water allocation procedure. Barley growth and water dynamics are updated at an hourly time step (Figure 2.1). At the end of the simulation, the dry yields of barley for all farms are given.

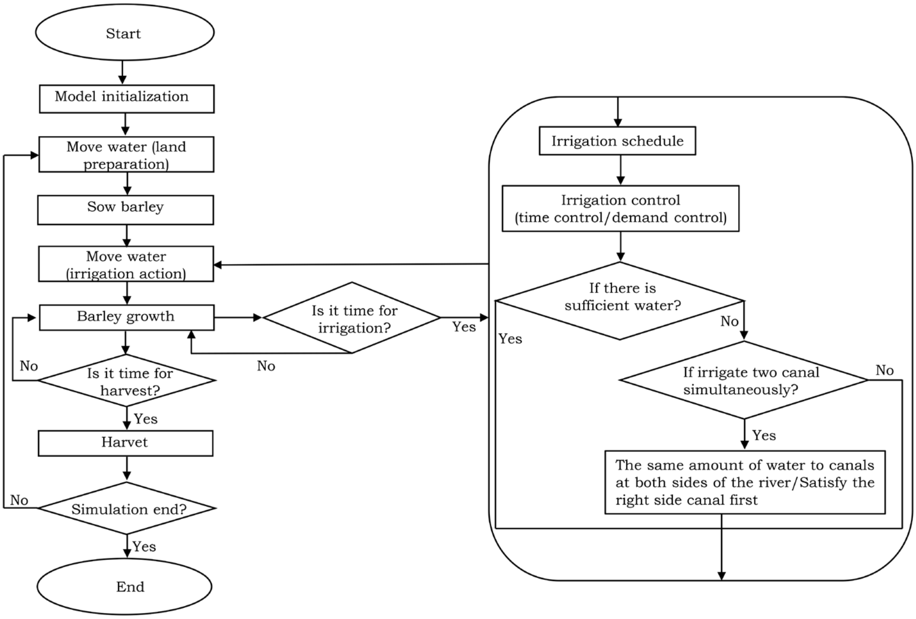

Figure 2.1: Process overview of the IRABM.

AIRABM explores the response of farmland dynamics to individual farmers' decision-making. This model considers two processes: the evaluation of the situation of the yield which is used to determine if GC adjustment is needed or not; and the evaluation of annual yields and received water, for next year's planting choice (Figure 2.2).

Figure 2.3 shows the process overview of IRABM^3, which studies not only the dynamics of the farmlands of a single farmer, but also the dynamics of the system. These processes are 1) yields and available water memory evaluation for individual farmers planting decisions; 2) annual yields evaluation for GC adjustment; and 3) evaluation of harvest situations among farmers for decision-making of system dynamics.

2.4. DESIGN CONCEPTS

2.4.1. THEORETICAL AND EMPIRICAL BACKGROUND

Which general concepts, theories, or hypotheses underlie the model's design?

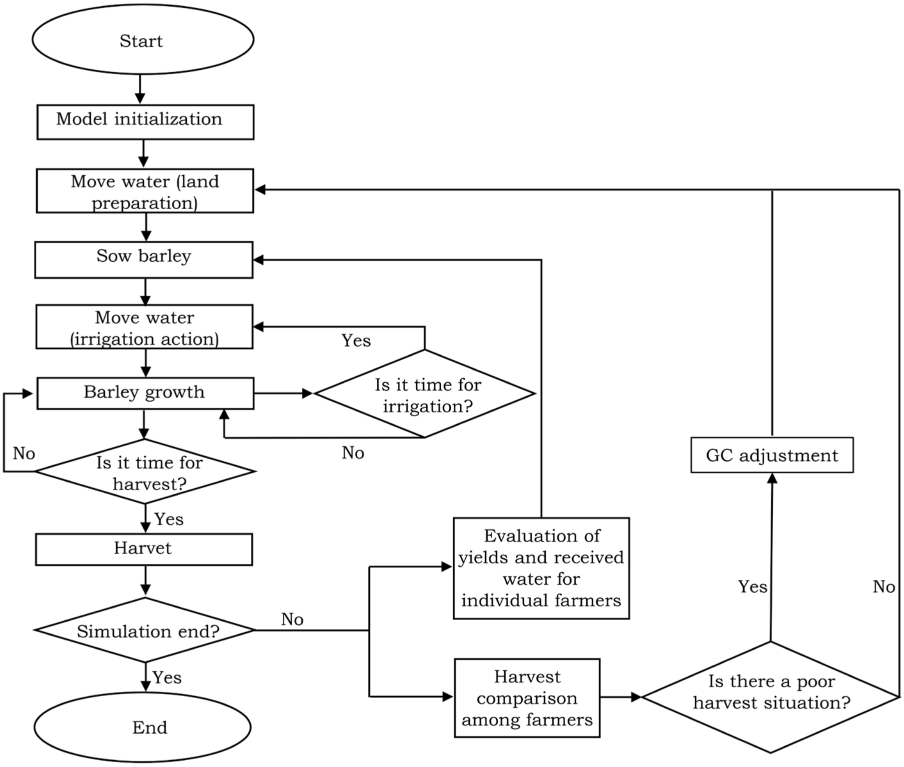

Figure 2.2: Process overview of the AIRABM.

IRABM

Figure 2.4 shows the entire modelling concept. Water from the main river flows through canal head gates and flows via these canals through farmers' gates to the farms. For each time step, farms have a current water demand, based on their history of receiving water. If there is not enough water to fulfill the water demand, barley will have water stress. Too much water stress results in reduced harvest quantities. After harvesting, farmlands remain fallow until the start of the next planting season.

AIRABM

The model design concept for AIRABM is shown in Figure 2.5. In comparison to IRABM, there are two distinct decision-making processes in this model. The first decision-making process occurs at the individual farmer level, where farmers make decisions regarding the dynamics of their own farmlands. The second decision-making process takes place at the collective level, involving all farmers in the system. In this process, farmers may adjust the GC to achieve a more equal distribution of water throughout the system.

IRABM^3

IRABM^3 actually has the same initial layout and design concept as the IRABM and

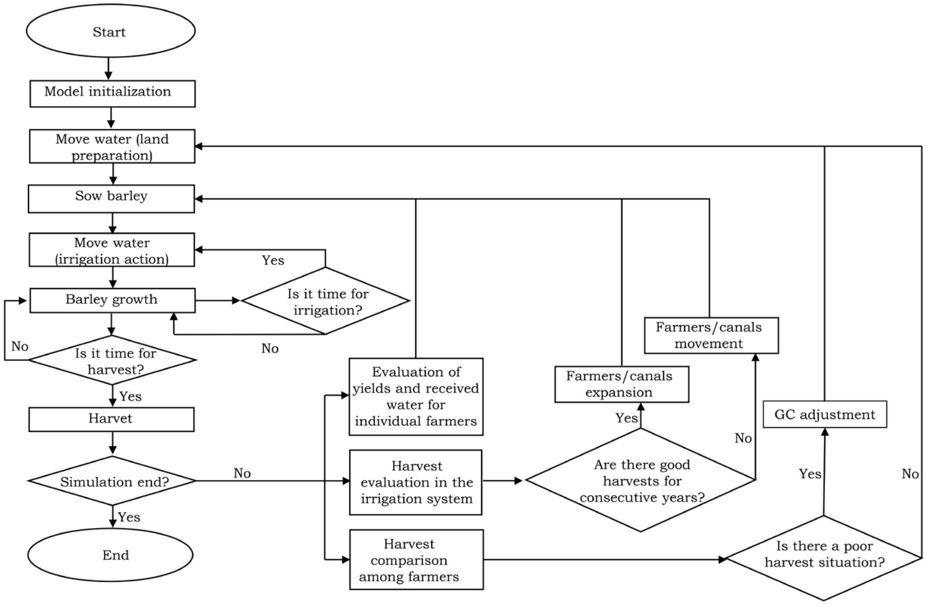

Figure 2.3: Process overview of the IRABM^3.

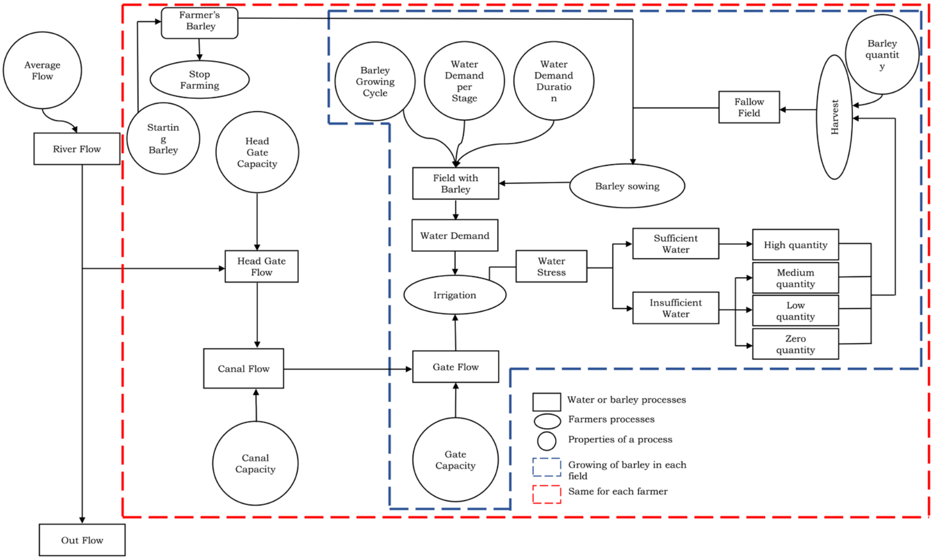

Figure 2.4: The overview of the IRABM design concept.

AIRABM. The model design concept for IRABM^3 is shown in Figure 2.6. In addition to

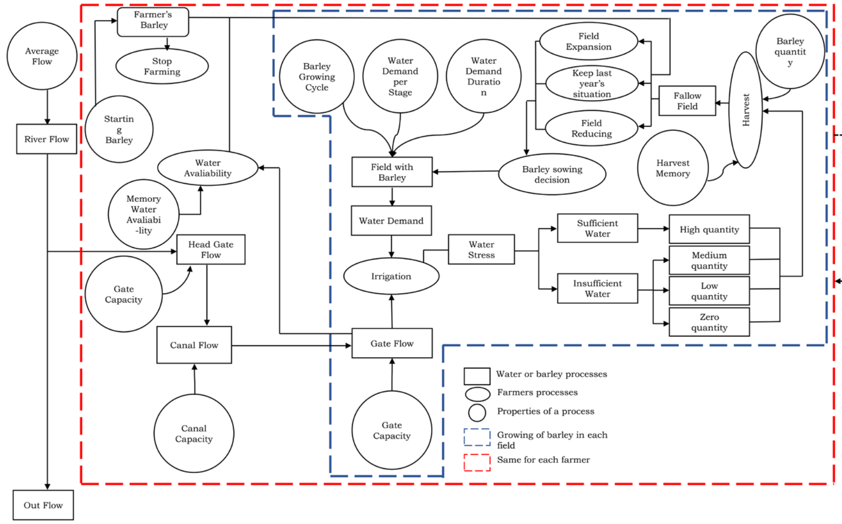

Figure 2.5: The overview of the AIRABM design concept.

the previous two versions, the system dynamics specifically focus on the expansion of farmers/canals and the movement of farmers/canals, according to the continuous evaluation of harvests over multiple years.

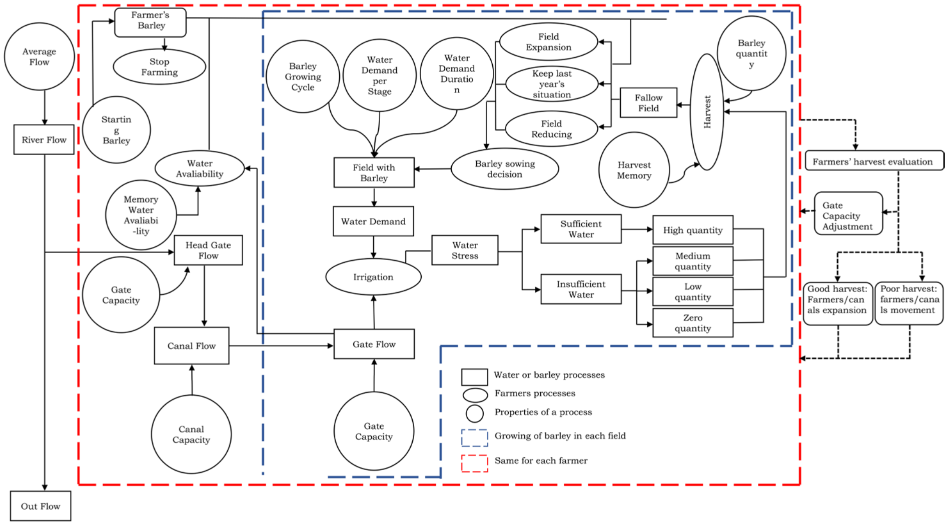

Figure 2.6: The overview of the IRABM^3 design concept.

2.4.2. EMERGENCE

Which system-level phenomena truly emerge from individual traits, and which phenomena are merely imposed?

The main focus of these models is to predict the barley yields of farm(er)s. The patterns of barley yields, dynamics of farmlands, and overall system dynamics are influenced by factors such as water availability, past harvest memories, and the decision-making of stakeholders. These outcomes arise from the interactions between nature and humans within the irrigation system. As we delve into later chapters, it will become apparent that this approach to modelling allows for the emergence of realistic patterns without predetermined constraints on which specific patterns or relationships to consider.

2.4.3. ADAPTATION

What adaptive traits do the model individuals have which directly or indirectly can improve their potential fitness, in response to changes in themselves or their environment?

Two approaches are employed to facilitate the adaptation of virtual water managers to meet water requirements and availability. Firstly, a water allocation strategy can be determined based on the river discharge. Secondly, the decision of whether to open the gate or not, potentially in response to farmers' irrigation demands, plays a crucial role. Barley yields are adjusted based on the amount of water received. The model encompasses three different versions, each representing diverse strategies employed by farmers to adapt to the circumstances:

- IRABM – Farmers' adaptive actions depend on the irrigation demands of barley and the water distribution facilitated through various irrigation controls.

- AIRABM – Farmers have two options for adaptation: 1) they can choose to expand their farmland by planting additional areas, maintain their current sowing choices, or reduce one or two farmlands - however, farmers' decisions regarding their farmlands influence each other's choices; 2) farmers are also required to adhere to water managers' recommendations regarding the adjustment of gate capacity. They may be advised to lower the gate capacity or maintain the initial gate capacity based on the prevailing conditions.

- IRABM^3 – Farmers have three adaptation options: 1) they adapt to the consequences of each other's decisions regarding farmland choices; 2) farmers must adhere to water redistribution advice, which may involve adjusting the gate capacity to ensure a more equitable distribution of water; 3) farmers adapt to the outcomes of decision-making related to system expansion or relocation.

2.4.4. OBJECTIVES

What are the objectives of the agents in the model?

There are three primary objectives in these models. Firstly, water managers aim to meet the water requirements of farmers while maximizing the crop yields in the irrigation system. Secondly, farmers strive to ensure the growth of high-quality barley and irrigate their own farmlands adequately. Lastly, the objective of barley is to fulfill its water demand. The models conducted thus far demonstrate the outcomes concerning these objectives.

2.4.5. LEARNING

Is individual or collective learning implemented in the model?

IRABM

No learning is included in this model version.

AIRABM

The AIRABM simulation spans a period of 20 years, with each farmer having the potential to cultivate up to 5 farmlands. I incorporated the concept that farmers can learn from their past experiences with barley yields and the amount of water received in previous years to inform their decision-making regarding the choice of farmlands cultivation for the upcoming year. GC adjustment is another learning activity, grounded in the yearly harvest comparison among farmers situated alongside a common canal. This ongoing adjustment process enables GC to continually refine water distribution, providing support to farmers facing subpar harvests, up to the point of reaching the modelled minimum GC threshold (IRABM^3 has this learning activity as well).

IRABM^3

This model incorporates two learning activities. The first one involves individual farmers learning from their personal experiences with barley yields and water received in previous years. Based on this knowledge (as in AIRABM), they decide whether to increase or decrease the number of farmlands they plant. The second learning option involves the entire irrigation system evaluating the farmers' harvest outcomes over multiple years. Based on this evaluation, the system decides whether to expand by adding more farmers or canals, or to relocate farmers with consistently lower yields to a different location.

2.4.6. PREDICTION

Which data is used to predict future conditions?

IRABM

There is no prediction in this model.

AIRABM and IRABM^3

The individual farmers and the collective system explicitly evaluate water availability and barley yields, for the prediction of cultivation choice and system landscape dynamics. These measures serve as key predictors to assess the performance and outcomes of both individual farmers and the overall system.

2.4.7. SENSING

What are individuals and collectives assumed to sense and consider in their decisions?

IRABM

The primary sensing behaviour in this model revolves around the water flow pattern. The model focuses on the movement of water, which originates from the river and flows through the canal system, ultimately reaching the farms.

AIRABM and IRABM^3

Of their own state variables, individual farmers are aware of the amount of water and barley that they need for managing their farmlands; the irrigation system is conscious of the amount of water and the situation of farmer harvest that it needs for irrigation management – both benefitting each farmer and the whole system.

2.4.8. INTERACTION

Are interactions among agents direct or indirect?

IRABM

The decision-making by the human agents is configured in the different gate settings, which influence water flows and barley production. Virtual water managers and farmers interact with each other, in the sense that different gate settings result in different options to realize barley yields. At the moment, there is no real decision-making available to model agents on water allocation strategies and gate openings (but decisions are represented by the performance of non-humans), nor is there an option for farmers to respond. As such, the implicit interaction in the model is that farmers accept the water managers' decisions that come to them in terms of water input.

AIRABM and IRABM^3

While direct communication, competition, or cooperation among farmers is not present in the model, there are indirect interactions between them. Upstream farmers have priority access to water and can naturally take as much water as they need. Consequently, the decisions of upstream farmers regarding water allocation can significantly impact the barley yields of downstream farmers. If upstream farmers expand their farmlands, it exacerbates the situation for downstream farmers. Additionally, interactions occur between farmers and the irrigation system. There are collective actions for adjusting gate capacity in both the AIRABM and IRABM^3 models. In the case of IRABM^3, there are also collective decisions regarding system dynamics. Throughout these processes, model farmers consistently support the collective decision-making process.

2.4.9. STOCHASTICITY

What processes are modelled by assuming they are random or partly random?

There is no stochasticity in this model.

2.4.10. COLLECTIVES

Do the individuals form or belong to aggregations that affect and are affected by the individuals? How are collectives represented?

The irrigation system functions as a collective entity comprising the actions of all agents involved. In this context, individual farmers are considered as individual agents, while groups of farmers form collectives. The purpose of studying these collectives is to investigate how actions undertaken at individual farmers within the system influence the overall outcomes.

2.4.11. OBSERVATION

What data are collected from the ABM for testing, understanding, and analysing it, and how and when are they collected?

The ultimate purpose of this model is to explore how the irrigation-related agents interact with each other, resulting in barley yields. Accordingly, the key output of the model is the barley yield of each farmer – which is closely related to another primary output, the amount of received water from each farm. At the end of each simulation year, the barley yields of each farmer will be collected and used for pattern analysis.

What key results, outputs, or characteristics of the model?

This project's primary outcomes encompass barley yield patterns, farmland dynamics (mainly in AIRABM), and system dynamics (mainly in IRABM^3). These aspects are articulated through the annual yields of individual farmers and the overall yields of the system according to water availability and decision-making, spanning both the individual farmer and system levels.

2.5. DETAILS

2.5.1. IMPLEMENTATION

How has the model been implemented?

The model is coded in NetLogo, which is able to provide a user-friendly interface for stakeholders to play with the model with specified rules.

Is the model accessible, and if so where?

Yes. The model is opened to the public at https://github.com/mess-nlesc.

2.5.2. INITIALIZATION

What is the initial state of the model world, i.e. at time t = 0 of a simulation run?

At the initial stage, each farmer has a certain amount of barley seed to ensure he/she can sow. The barley farm is brown at first, but it will change to green after sowing barley. Each patch is empty at the beginning. When the model is running, the patches will be occupied by water volume, irrigation volume, or barley. I designed a simplified layout for the irrigation system of IRABM: one river feeds sixteen canals, with 8 farmers along each canal, and each farmer manages one farm (Figure 2.7). The simplified initial irrigation system layout for AIRABM and IRABM^3 is shown in Figure 2.8: one river feeds 10 farmers along one canal, and each farmer has 5 fields that can be potentially planted with the model crop barley.

Is the initialisation always the same, or is it allowed to vary among simulations?

During model execution, diverse factors such as river discharge, gate capacity, irrigation controls, memories, and decision-making will be implemented. These variables will be incorporated dynamically to simulate the changing conditions and interactions within the system.

Are the initial values chosen arbitrarily or based on data?

The initial values in the model are derived from empirical data, which includes information on the irrigation schedule as well as the response of barley yields to the amount of water supplied. These empirical data serve as the foundation for setting the starting conditions in the model, enabling a realistic representation of the system dynamics.

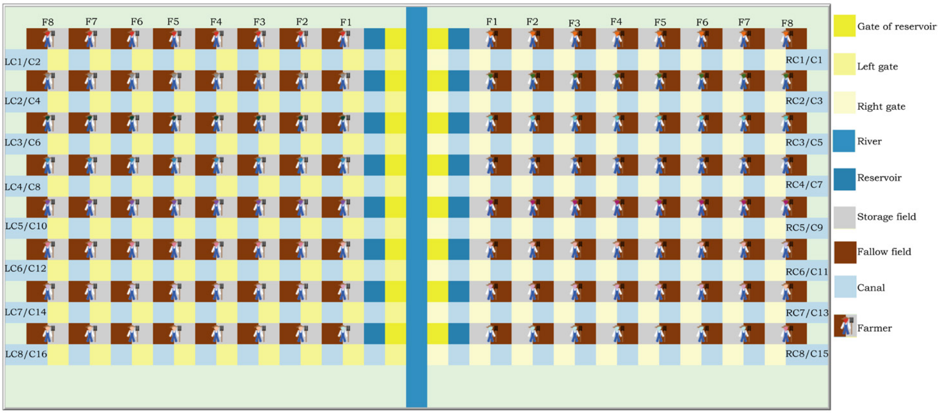

Figure 2.7: The layout of the artificial irrigation system in IRABM. The figure's legend includes the reservoir patch and storage field (patch); however, they do not contribute to the construction of the model. Instead, their functions involve the temporary storage of water and barley yields during model execution.

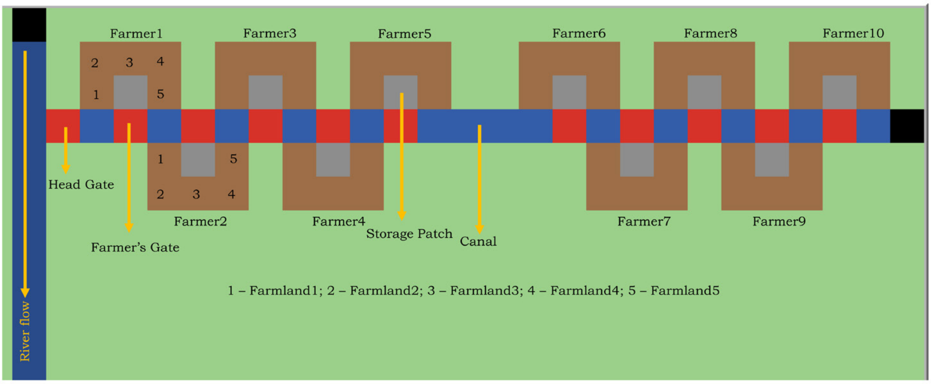

Figure 2.8: The initial layout of the modelled irrigation system in AIRABM and IRABM[3].

2.5.3. INPUT DATA

Does the model use input from external sources such as data files or other models to represent processes that change over time?

There is no external input data.

2.5.4. SUB-MODELS

What, in detail, are the sub-models that represent the processes listed in "Process overview and scheduling"? What are the model parameters, their dimensions, and reference values? How were the sub-models designed or chosen, and how were they parameterised and then tested?

The sub-model applied in this study is the irrigation schedule (same as IRABM, AIRABM, and IRABM^3) and the response of barley yields to supplied water (same as AIRABM and IRABM^3).

Irrigation Schedule

Irrigation schedule was calculated through the following logic:

Estimating net irrigation (d_{net}) and gross irrigation (d_{gross}) – The dominant soil type in Mesopotamia is clay/loam. Barley is a deep rooting crop. According to Brouwer et al. (1989), this results in a d_{net} of 60 mm. The gross irrigation depth can be estimated using the following equation:

$$d_{\text{gross}} = \frac{d_{\text{net}}}{E_a} * 100 \tag{2.1}$$

Where E_a is the field application efficiency (%), 60% was chosen in this research (Brouwer et al., 1989).

Estimating the IN over the total growing season – IN can be computed as follows:

$$\text{IN}_i = \text{ET}_{c,i} - P_{e,i} \tag{2.2}$$

where $\text{ET}_{c,i}$ is the crop water demand for the i^{th} growing period (mm) and $P_{e,i}$ is the effective rainfall during the i^{th} period (mm). The total net IN during the total growing period is developed as:

$$\text{IN} = \sum_{i=1}^{\text{ND}_c} \text{IN}_i \tag{2.3}$$

where ND_c is the number of days in the total growing period.

Estimating the number of irrigation applications over the total growing season – The number of irrigation applications N_i over the total growing season can be calculated as follows:

$$N_i = \frac{\text{IN}}{d_{\text{net}}} \tag{2.4}$$

Estimating the irrigation interval (INT) – The INT is calculated in days and can be obtained as follows:

$$\text{INT} = \frac{\text{ND}_c}{N_i} \tag{2.5}$$

The response of barley yields to water supply

IRABM

Table 2.2 and Figure 2.9 show the simplified water supplies to barley at each of the three growing stages and divided into four levels: Ideal, Medium, Poor, and None, which present four levels of barley yields. From a simplification of reality: stage I includes irrigation rounds 1 and 2 (crop initial growing stage), stage II includes irrigation rounds 3 and 4 (crop middle growing stage), and stage III includes irrigation round 5 and 6 (crop late growing stage). Calculation ratios of supplied water are taken from (Burton, 1989): Ideal is 1.0; Medium is from 0.5 to 1.0; Poor is from 0.2 to 0.5; and None is from 0.0 to 0.2. This ratio of supplied water is based on the Simple Calculation Method of Irrigation Scheduling (Brouwer et al., 1989). At the end of the growing season, barley yields will be generated according to the total received water of each farm. Previous studies suggest that 3.00 tons/ha set is a realistic ideal yield of barley (Steduto et al., 2012), but this quantity can easily be adjusted when needed. Levels of supplied water relate to the level of yields: in IRABM, with supplied water going down one level, the potential yields will be reduced by 50%.

Table 2.2: Simplified supplied water amount to the barley at each stage.

Irrigation demand (WU/tick)	Stage I	Stage II	Stage III
Ideal	120	140	130
Medium	60-48	70-140	52-130
Poor	\	28-70	\
None	0-48	0-28	0-52

Note: \- means this situation is not applicable. In Stage I and Stage III, there are three levels of irrigation demand: Ideal, Medium, and None. There are four levels of irrigation demand in Stage II: Ideal, Medium, Poor, and None.

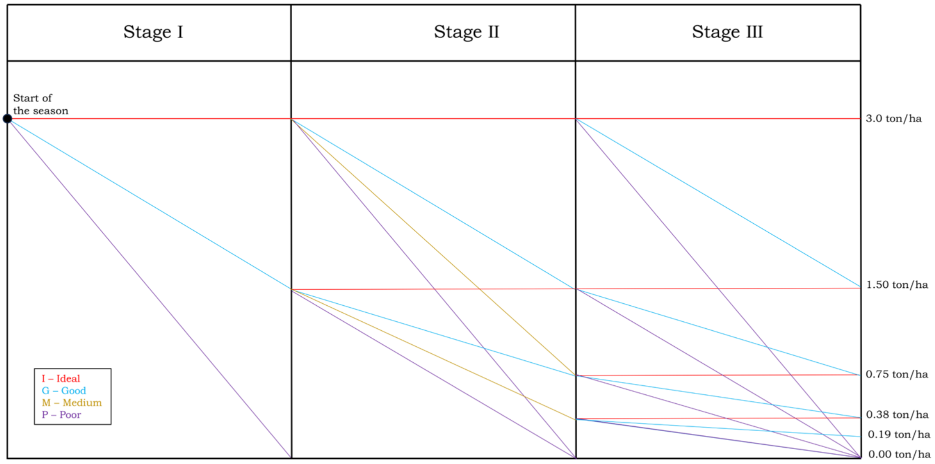

Figure 2.9: Simplified barley yields response to supplied water diagrams.

AIRABM and IRABM[3]

According to empirical irrigation data for Mesopotamia (see Lang and Ertsen (2022b) for an 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 2.3 and Figure 2.10 (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 Figure 2.10 were calculated based on the literature (Wilkinson et al., 2007).

Table 2.3: Modelled irrigation demand of barley along the growing season.

Irrigation demand (WU/tick)	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

Note: \- means this situation is not applicable. In Stage I and Stage III, there are four levels of irrigation demand: Ideal, Good, Poor, and None. There are five levels of irrigation demand in Stage II: Ideal, Good, Medium, Poor, and None.

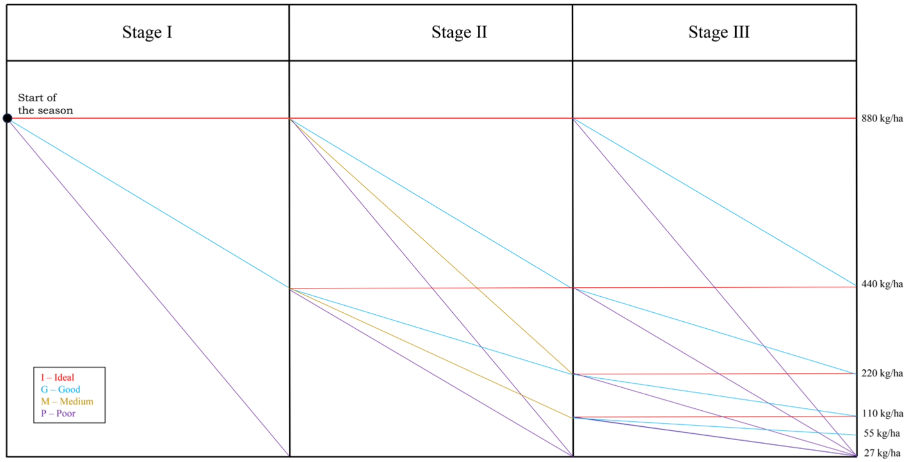

Figure 2.10: Simplified barley yields response to supplied water along the growing season.

2.6. DECISION-MAKING OF INDIVIDUAL FARMERS AND THE COLLECTIVE SYSTEM – AIRABM AND IRABM^3

What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision-making included?

In both AIRABM and IRABM^3, individual farmers make decisions regarding the yields and received water of their farmlands; at the irrigation system level, there is collective decision-making involved in adjusting the gate capacity to support farmers with poor harvests and enable them to improve their yields. However, in IRABM^3, there is an additional collective decision-making process. This involves considering the expansion of the irrigation system or relocating farmers based on evaluations of multiple years of harvest outcomes.

What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?

Farmers typically aim to minimize the risk of water scarcity and, as a result, strive to maximize their barley yields under conditions of limited water availability. They utilize their capacity to adopt adaptive decisions, both from each other and from the irrigation system, in order to achieve this goal.

How do agents make their decisions?

There are different levels of decision-making in these ABMs:

- Regarding individual decision-making on farmland dynamics, farmers assess their previous barley yields and the amount of water received in past years at the end of the growing season. Based on this evaluation, they decide whether to increase the number of farmlands planted for the next year, maintain the current planting choice, or reduce the number of farmlands (shown in AIRABM and IRABM^3).
- As for the first collective decisions regarding gate capacity adjustments, the system evaluates the harvests of farmers located along the same canal on a yearly basis. Using this evaluation, the system determines whether it is necessary to make adjustments to the gate capacity (shown in AIRABM and IRABM^3).
- The collective decision-making regarding system dynamics involves the continuous evaluation of multiple years' harvests from farmers. Based on this evaluation, decisions are made to expand the current system (by adding more farmers and more canals) or relocate poor-harvested farmers (by moving these farmers to a new secondary canal) (shown in IRABM^3).

Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?

Both exogenous and endogenous variables play a role in influencing adaptation decisions in AIABM and IRABM^3. These variables include the historical data on barley yields and water availability, and the decisions made by other farmers. The farmer's perception of farmland management is influenced by the barley yields they have achieved and the amount of water received in the past. Additionally, decisions made by upstream farmers to expand their operations can adversely affect the harvest of downstream farmers. Moreover, collective decisions concerning irrigation management can have a profound impact on both individual farmers and the overall system. These decisions shape the allocation and distribution of water resources, thereby influencing the performance of individual farmers as well as the entire system.

Do social norms or cultural values play a role in the decision-making process?

No, these are not included in these models.

Do temporal aspects play a role in the decision process?

Yes. The dynamics of farmlands and the system are influenced by two types of memory. The first is the memory of individual farmers, which incorporates their past experiences with barley yields and the amount of water received. This memory guides their decisions and actions regarding farmland management. The second type of memory is the collective memory of the system, which involves the continuous evaluation of harvest situations among farmers. This memory captures the overall performance and outcomes of the system over time, allowing for informed decision-making regarding system dynamics.

Do spatial aspects play a role in the decision process?

Yes. The location of farmers significantly influences their yields, particularly due to the water distribution dynamics. Upstream farmers are given priority in accessing water, allowing them to take as much water as they require. Consequently, this can result in unequal water distribution among farmers, ultimately impacting their yields.

To which extent and how is uncertainty included in the agents' decision rules?

It is not included in the model.

3

CONCEPTUALIZING AND IMPLEMENTING AN AGENT-BASED MODEL IN AN IRRIGATION SYSTEM

This chapter is based on

Lang, D., Ertsen, M. W. (2022). Conceptualising and Implementing an Agent-Based Model of an Irrigation System. Water, 14(16), 1-23. [2565].

ABSTRACT FOR CHAPTER 3

The literature on irrigated agriculture is primarily concerned with irrigation techniques, irrigation water-use efficiency, and crop yields. How human and non-human agents co-shape(d) irrigation landscapes through their activities and how these actions impact long-term developments are less well studied. In this study, we aim to (1) explore interactions between human and non-human agents in an irrigation system; (2) model the realistic operation of an irrigation system in an agent-based model environment, and; (3) study how short-term irrigation management actions create long-term irrigation system patterns. An agent-based model (ABM) was used to build our Irrigation-Related Agent-Based Model (IRABM). We implemented various scenarios, combining different irrigation control methods (time versus water demand), different river discharges, varied gate capacities, and several water allocation strategies. These scenarios result in different yields, which we analyse on the levels of individual farmers, canals, and systems. Demand control gives better yields under conditions of sufficient water availability, whereas time control copes better with water deficiency. As expected, barley (Hordeum vulgare, Poaceae) yields generally increase when irrigation time and/or river discharge increase. The effect of gate capacity is visible with yields not changing linearly with changing gate capacities, but showing threshold behaviour. With the findings and analysis, we conclude that IRABM provides a new perspective on modelling the human-water system, as non-human model agents can create the dynamics that realistic irrigation systems show as well. Moreover, this type of modelling approach has a large potential to be theoretically and empirically used to explore the interactions between irrigation-related agents and understand how these interactions create yield patterns according to water availability. Furthermore, the developed user-interface model allows non-technical stakeholders to participate and play a role in modelling work.

Keywords: agent-based model; irrigation system; barley yields; water availability

3.1. INTRODUCTION

The need for a more complete understanding of complex water issues, and the associated requirement to build relations between different academic disciplines, and between academic and other societal practices, is widely recognized in the hydrological community. The key question concerning what counts as "good" or "useful" knowledge, as illustrated by Junier (2017), is highly relevant for hydrological models (see also Ertsen (2018)). Better understanding must include better capturing of interactions between humans and hydrological system(s). Recent studies discuss how different disciplines can collaborate and develop analytical tools to do so (Di Baldassarre et al., 2018; Rangecroft et al., 2021; Pramana and Ertsen, 2022). It is clear that computational models provide an opportunity to investigate the relationships between and among human and non-human agents in water systems. Traditional hydrology models can be unfriendly to non-water stakeholders, even when they are developed to support policy making Junier (2017). These models also cannot easily deal with water users' heterogeneity and how these users interact with their surroundings (Ertsen et al., 2014; Blair and Buytaert, 2016; Khan et al., 2017). However, humans are the dominant agents in hydrological systems, and well-represented their actions in models is necessary to investigate how interactions happen among agents and their related environment (O'Connell and O'Donnell, 2014).

In simulating interactions between individuals and their environment, Agent-Based Modelling (ABM) is an interesting approach. ABM retains the heterogeneity of individuals when it mimics the actions of these individuals. ABM provides a cross-level analysis: it is used to study what happens to a setting because of individuals' actions and what happens to individuals because of the actions taken by (other agents in) the setting. ABM could be created in a platform with a user interface and provide realistic representations of human and non-human actions. When appropriately designed, stakeholders can directly use such models to discuss the interactions of human agents with hydrological processes (Ertsen et al., 2014; Khan et al., 2017). Baggio and Janssen (2013), and Janssen et al. (2015), and Janssen and Baggio (2017) tested well-known behavioral theories in irrigation systems through irrigation games in an ABM. Holtz and Pahl-Wostl (2012) showed that ABM can be used to explore the impact of farmers' characteristics on land-use change and their behavior of overuse of groundwater. Anthony and Birendra (2018) proved that an ABM can simulate water-saving strategies in crop production. Hu and Beattie (2019) developed an ABM to optimize farmers' decision-making on crop choice and groundwater irrigation. Tamburino et al. (2020) explored a collective action problem: the choice of the water source in a smallholder farming system.

Irrigation is an activity which typically develops in situations when available rainfall does not support the cultivation of crops or meet humans' irrigation water expectations – either because of low amounts of rainfall (important in arid and semi-arid regions (Lucke et al., 2019)) or because the rainfall is not distributed according to the preferences of (the growers of) crops (which is also relevant in more humid climate zones) (Ertsen, 2010). An irrigation setting can be defined as a landscape with river courses and hydraulic infrastructures that store, divert, channel, or otherwise move water from a source to some desired farms for the purpose of producing crops (VanderMeer, 1968). Irrigation systems support processes of water transfer and distribution, which combines the dynamics of hydrology, hydraulics, and humans on different temporal and spatial scales (Ertsen, 2010; Ertsen et al., 2014).

Much of the available irrigation literature focuses on irrigation techniques and (improving) water use efficiency (Bonfante et al., 2019; Cai et al., 2021; Kothari et al., 2019; Mattar et al., 2021; Sadiq et al., 2019). Many other texts discuss anthropological and other issues in irrigated agriculture (Bentzen et al., 2017; Chaoua et al., 2019; Karthikeyan et al., 2020). In both categories, papers do not typically mobilize the notion that irrigation links humans, water, hydraulic infrastructures, and crops beyond simply mentioning it, let alone study processes of water transformation through the many interactions between humans and water, humans and hydraulic infrastructures, infrastructures and water, water and crops, agriculture land and crops, as well as humans and crops (Ertsen, 2010). An irrigation system can be conceptualized as a complex adaptive system created by environmental and social agents (water resources, stakeholders, hydraulic infrastructures, crop productivity) that interact dynamically and continuously with each other in time and space. We claim that exploring those interactions between humans, water, crops, and hydraulic infrastructures in detail builds a better understanding of the long-term functioning – and as such development – of irrigation systems, both old and new.

In their discussion on applying ABMs to irrigation systems, Ertsen et al. (2014) point out that agent-based analysis and modelling in irrigated agriculture is more challenging than in rain-fed agriculture. In irrigation systems, actions (e.g. different gate states and irrigation controls) and uncertainties are not confined to individual farmers, but are spread through the water infrastructure to other farmers across temporal and spatial scales. Furthermore, Zhu et al. (2018) show how important it is to consider different hydraulic representations of (ancient) irrigation systems, as these can detail the different (emerging) irrigation options for irrigators. Varied temporal and spatial options connect directly to the short-term (daily) irrigation management actions that affect long-term irrigation system viability. Building further on this logic, we designed and developed our virtual irrigation system as an alternative to real-world laboratories by using ABM – in our case the NetLogo platform.

Our Irrigation-Related Agent-Based Model (IRABM) explores the relationships among irrigation-related agents. The Irrigation Management Game (IMG) could provide a very useful foundation for ABM applications, but does not offer yet options for realistic water flows and hydraulic infrastructure details (Ertsen, 2011; Burton, 1989, 1993). Our modelling framework was built to represent the realistic operation of an irrigation system, without details of specific hydraulics, but with sufficient hydraulic realism in NetLogo. Typically, ABMs have human agents in a given environment, with water being included as a stock, which is simply described as water demand or supplied water (Linkola et al., 2013; Perello-Moragues et al., 2021; Berglund, 2015). In our model, we focus on the non-human agents – the entities that typically constitute "the environment". In our case, the environment is not static, but produces the way the system functions. Preferences of human agents are expressed through the non-human model agents. Therefore, not the relations between water managers and farmers are modelled, but the performance of gates, canals, barley, and farms which represent humans' actions. Water managers' actions are represented by the capacity of the head gates and canals, while farmers' actions are expressed by the capacity of farms' gates, the amount of received water, and yields of barley. Moreover, we did not define adaptation strategies (yet) in this model. Instead, we study options for adaptation actions in the setting of the scenarios. As such, we designed the model to mimic key activities of an irrigation system (opening and closing gates in the real world) while remaining both concise and meaningful in the model to explore and build the secrets of the real world (especially the effects of opening and closing gates at one location on other locations) (compare with Allison et al. (2018) and Sun et al. (2016)).

Our longer-term aim is to use this ABM setup to study the longer-term evolution of irrigation in ancient Mesopotamia, in line with the ideas set in (Sun et al., 2016). This explains for example why our initial model has barley as the object crop. Although we built the model with the flexibility to accommodate different crops and their water demands, allowing the modelling framework to be modified to any irrigation system, ancient Mesopotamia was the main setting we had in mind. Mesopotamia is known to the world as the cradle of civilization, with agricultural technology appearing more than 6 millennia ago (Horton et al., 2013; Rost, 2015). Its sophisticated irrigation systems that supported the formation of larger urban areas, especially in the south, are well known. However, the history of how irrigation systems functioned and evolved in South Mesopotamia is still unclear. Currently, ideas of the emergence of irrigated agriculture in the region focus more on the gradual development of agriculture shaping the options for exchange and trade between communities, which would have led to elite formation and as such state formation. The irrigation landscape of south Mesopotamia is likely to have developed through a process of human niche construction (Wilkinson et al., 2015). Even though state-induced irrigation would require a detailed explanation of actions too, the more gradual perspective on Mesopotamian irrigation development emphasizes even stronger that we need to study how human and non-human agents co-shaped the irrigation landscape through their short-term activities, and how these short-term actions impacted long-term development (Ertsen, 2016) – hence the logic of IRABM.

This paper discusses our theoretically and empirically informed, flexible IRABM framework. It analyses the effects of actions of and between agents in the model system. We show the capability of IRABM to simulate local-specific irrigation actions that together produce the operation of an irrigation system, and detail methodological issues related to the construction of this IRABM and its application. The remainder of the paper is organized as follows. Section 2 provides an overview of IRABM and its key components. Section 3 presents the results, divided into three sub-sections – representing different water availabilities – and focusing on the barley yields. Section 4 offers the conclusions and relates our work to previous studies. We close this paper by exploring possibilities for future research.

3.2. MATERIALS AND METHODS

The model conception (or description) presented here follows the logic of the Overview, Design Concepts, Details (ODD) protocol for characterizing ABM and other simulation models (Grimm et al., 2006; Grimm et al., 2010; Grimm et al., 2020). Additional details of the ODD can be found in Chapter 2.

3.2.1. MODEL DESIGN CONCEPTS

We designed a simplified layout for the irrigation system: one river feeds sixteen canals, with 8 farmers along each canal, and each farmer manages one farm (Figure 2.7). Hydrological processes like rainfall, evaporation and evapotranspiration are reflected in water demands at farm level and water availability in the river. Drainage is not included either. River, canals, and gates are assumed to have constant shapes or profiles. Artificial water units (WU) were used in order to mimic these physical processes. Water units flow through the river and canals with constant velocity: water units move one cell per time step (tick). The main river flows along the head gates of the canals until eventually the river passes the last canal and remaining water flows out. The canal flows along the gates of the farmers, until water finally passes the last farmer and flows out. At the head gates, water has the possibility to flow to the canal; at the gates, the farmers have the possibility to withdraw water from the canal. We set a range of capacities for the river, head gates, canal, and farm gates. We gave all farms a size of 1 hectare, with farms next to each other sharing similar soils.

3.2.2. IRRIGATION SCHEDULE

An irrigation schedule is important to link irrigation water management to (improvement of) crop productivity. A relatively simple calculation method (Brouwer et al., 1989) was applied, linking the depth of irrigation application and the calculated irrigation water need (IN) of barley over the growing season (please refer to Chapter 2: 2.5.4 Submodels). Based on the calculation, we defined six irrigation applications (irrigation rounds) over one complete barley growth period – 180 days, with an irrigation interval of 30 days. We also calculate the irrigation demand at each application as 60 WU, 60 WU, 80 WU, 60 WU, 60 WU, and 70 WU respectively. The irrigation schedule represents farmers' decisions when to open and close their gates according to their irrigation requests. The irrigation time per farm will impact barley yields on the farm, as irrigation time is directly linked to the water volume that crops receive. At the same time it may influence other farms, when bringing water to one farm lowers the available time for other farms. With our 30 days irrigation period, 1.5 days of irrigation time per canal is a realistic maximum time to irrigate one canal without disturbing others, when all 16 canals are to be irrigated one after the other. In the model, irrigation time IT is set at 1 day, 1.5, 2, 3, and 3.5 days respectively when irrigating two canals per tick.

3.2.3. SCENARIOS

Modelling of interactions between human agents and hydraulic variables can improve our understanding of how irrigation systems emerge within a specific human-water environment. As we aimed to compare how different irrigation controls can influence barley yields, we defined two types of possible water flow control. Time Control (TC) allocates to each canal a certain irrigation time, while Demand Control (DC) moves the water from one canal to the next only after the last farmer of the upper canal has satisfied the water demand. Furthermore, if water is scarce and RD cannot meet the water demand of the canals at both sides of the river simultaneously, a distinction is made between allocating the same amount of water to canals at the two sides of the river or satisfying the demand of canals on one side (right) first.

Given our available varied river discharges (RD), number of canals being irrigated at the same time, two types of irrigation control (TC and DC), and a series of farmers' gate capacities (GC), there are 840 possible scenarios in IRABM's current version. The hydraulic characteristics of the scenarios were reflected in water agents (water units) and may indicate the coordination of farmers' irrigation requests and water availability. For all scenarios, water availability was expected as sufficient water and insufficient water on the levels of the whole system, canal, and farmer. These scenarios show the potential adaptation options for users in this model. Each scenario has been run for a single season of barley. With procedures predefined, following the design routine, scenarios have been repeated 3 times in order to estimate the outputs' variability. For stochastic models, 3 replications seem rather low, but with each procedure being predefined, we argue that 3 runs are enough for this study. Table 3.1 provides an overview of the parameters used in each scenario.

3.3. RESULTS

Given the rather high number of scenarios, this paper provides a set of representative results to demonstrate IRABM's potential. This will show how the original features of this model, through the use of scenarios, can be used (as a realistic modelling basis) to explore irrigation performance. In terms of water availability for the whole system, the threshold of available RD is 160 WU/tick for scenarios irrigating two canals per time step, whereas it is 80 WU/tick when water is provided to one canal per time step. If the amount of available water for each canal is above or equal to the threshold, all farmers receive a certain amount of water to produce yields; if not, some or even all farmers will face water stress. It is useful to mention that the maximum yields of each canal and each farmer are 24 TON and 3 TON in these simulations, respectively.

3.3.1. ABUNDANT WATER AVAILABILITY

Irrigation demand control

When enough water is available, most farmers and canals gained optimal yields both when irrigating one canal and irrigating two canals simultaneously. Practically all canals gained optimal yields for GCs above 2 WU/tick. However, downstream canals and some middle-stream canals gain lower yields (or even did not have yields) for low GCs of 2 and 1 WU/tick (Figure 3.1). Irrigating two canals per tick resulted in canals and farmers gaining optimal yields for all GCs, except for GC = 1 WU/tick – with the farmers along the last two canals gaining half of the optimal yield (1.5 TON). When only one canal is irrigated, middle-stream canals also start to be affected by the relatively low GC. Some farmers cannot even survive – as in not gain yields at all.

There is no difference in yields in the system under DC when irrigating two canals simultaneously or one canal at the time for higher gate capacities. Apparently, the available RD can be transferred to all canals and farms. There is a difference, however, between canals, with downstream canals gaining lower yields – and occasionally even no yields at all – with lower GCs of 1 and 2 WU/tick, when most of the upstream canals still gained the optimal yields. Comparing irrigating two canals and one canal per tick, the former one results in higher and more constant yields for farmers located in the middle-

Table 3.1: Overview of the scenarios and parameter settings per scenario.

River Discharge (WU/tick)	Number of canals irrigated simultaneously	Irrigation control method	Head Gates (WU/tick)	Farmers' Gates (WU/tick)
200	One canal	TC (1 and 1.5days)	80	1-10
		DC		
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)		
		DC		
160	One canal	DC	80	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)		
		DC		
120	One canal	DC	40-80	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)		
		DC		
80	One canal	DC	80	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)	0-80	
		DC		
40	One canal	DC	40	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)	0-40	
		DC		
20	One canal	DC	20	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)	0-20	
		DC		
10	One canal	DC	10	
	Two canals	TC (1, 1.5, 2, 3, and 3.5 days)	0-10	
		DC		

stream and downstream canals for GC at 1 and 2 WU/tick. No matter how many canals are irrigated at the same time, there is almost no difference in yields among farmers located along the same canal.

Irrigation time control

The results make it obvious that barley yields increased with the extension of IT and higher GC – again with sufficient RD (Figure 3.2). All farmers' yields are shown in this figure: given the fixed time period, it is expected and easily observed that all canals have

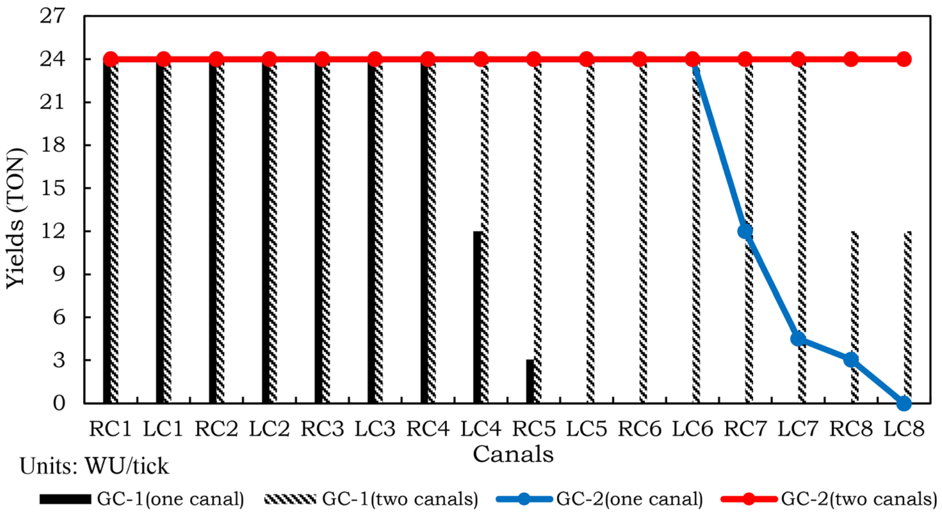

Figure 3.1: Yields per canal with sufficient water under Demand Control and low Gate Capacity. RC = Right Canals; LC = Left Canals; Number indicates position along the canal – see Figure 2.7.

the same yields and yield distribution per farm under each combination of IT and GC. The most upstream farmer is the most productive one throughout, except for when GC = 1 WU/tick and IT= 1 day, when no farmer has a harvest. Irrigating two canals per tick creates more IT per canal and as such higher yields. With IT above one day, higher GCs resulted in very stable yields – with most farmers gaining optimal yields. The longest IT (3.5 days) resulted in high yields in general, but above all in a more equal yield distribution among farmers.

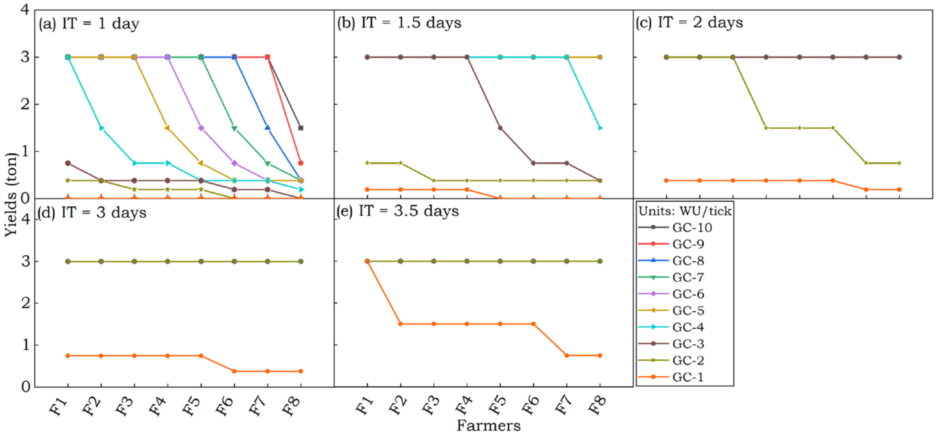

Figure 3.2: Yields per farmer with sufficient water under Time Control with different irrigation times.

3.3.2. INSUFFICIENT WATER AVAILABILITY

When the irrigation system is facing water stress, results become more diverse. Within the two canals' perspective, we tested two water allocation strategies. Strategy one allocates the same flow to both canals, strategy two fulfils the gate capacity of the right canal first and sends the remaining water to the left canal.

Irrigation demand control

With insufficient water, results show that either all canals had yields or only a few canals had yields – with yields only existing along the first two canals, or only found along the first right canal. When canals have yields, they are always the same for all canals. Therefore, Figure 3.3 only shows yields of the first two canals. Actually, in most scenarios many canals could not produce yields. This is a consequence of the experiment model design: if water cannot flow to the last farmer in the first right canal – which means that the demand of that canal is not met – (farmers along) the next canals never receive water, even there is plenty of time left.

Under the strategy of prioritizing the right canal and with CD <= 80 WU/tick, only the first right canal can produce yields. If water is delivered to farms (farmers), most of them receive the desired water, which results in ideal yields. In case the last farmer along the upper canal stays without yields, however, no farmer along the lower canals can produce yields. Different GC thresholds were observed for different canal discharges in terms of yields for all irrigation strategies: either all canals gained yields with GCs below the threshold, or only the RC1 and LC1 canals gained yields when the GC was equal to or higher than the threshold. Generally, yields of RC1 and LC1 are lower than 24 TON means the GC threshold was reached, which also demonstrates that the remaining canals are without yields. Figure 3.3 illustrates GC thresholds are 9, 6, 3, 2, and 1 WU/tick for canal discharges of 60, 40, 20, 10, and 5 WU/tick, respectively. Moreover, for GCs equal to or above the threshold, the total yield of each canal decreases, and the number of farmers gaining yields declines. Higher GCs result in water not reaching the most downstream farmer of a canal, and in the demand setting of the model this blocks the flow going through. If the GC is lower than the threshold – when water can flow to downstream and the full irrigation time can be used – the results of each canal or each farmer are similar to those for settings with sufficient water. In other words, reducing water use by upstream farmers is beneficial for everyone in the system when water is scarce.

Allocating the same amount of water to two sides – splitting the available RD – gave better results in terms of yields, as the GC threshold is higher and more canals and farmers gain yields. The most important observation, however, when comparing the results of demand control for settings with sufficient and insufficient water, is that the demand setting of the model brings a typical irrigation dilemma to the front. For lower RDs with higher GCs, water could be kept from flowing further than the first canal(s), which results in downstream canals having no yields – unless the upstream farmers limit their water use, which does not necessarily lower their own yields. Furthermore, in DC scenarios, the main difference in yields exists between canals, not between farmers. Both for canals and farmers, the main factors affecting yields are RD, GC, and canals' location.

Irrigation time control

The GC threshold is also observed for TC with insufficient water: higher GCs generate relatively lower yields. The pattern is that shorter ITs generate a higher GC threshold,

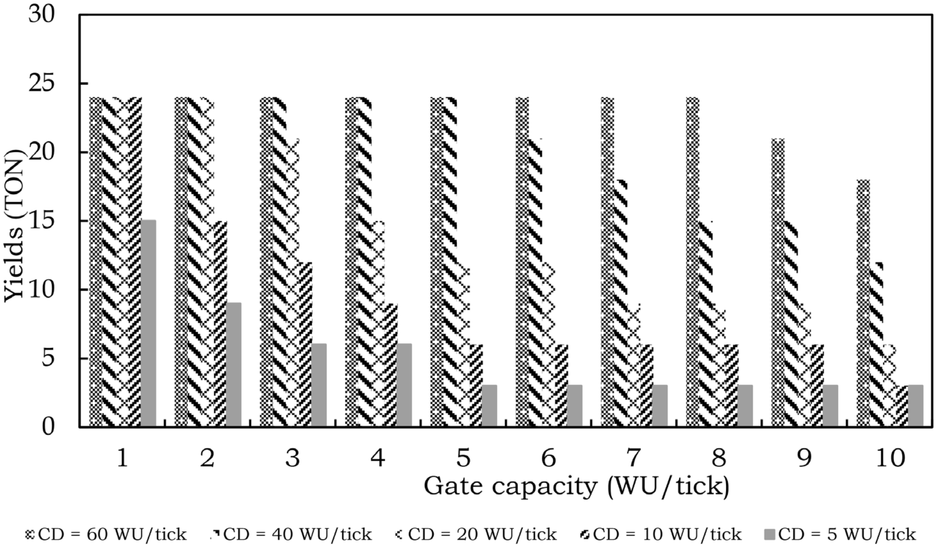

Figure 3.3: The yields of RC1 and LC1 with insufficient water under Demand Control.

while longer ITs generate a lower threshold (Figure 3.4). GC thresholds decreased with decreasing RD and varied with different IT. In addition, tipping points for GCs are observed: yields decrease rather dramatically with specific decreases in GC. Usually, the tipping point is lower than 5 WU/tick, and decreases with extended IT. If GC = 1 WU/tick and IT = 1 day, barley yields zero TON, no matter how RD varies. Concerning different water distribution strategies, all canals act the same when distributing the same amount of water to each side. Prioritizing right canals' demands results in all right canals and all left canals respectively realizing similar yields – with the second strategy leaving all left side canals without harvest for RD <= 80 WU/tick – as there is no water left for them.

As one example, Figure 3.5 shows farmers' yields when CD = 60 WU/tick, which is the best harvest situation among the insufficient water scenarios. In Figure 3.5, we see that water cannot flow to the downstream farmers with GC = 9 and 10 WU/tick for all ITs. Furthermore, longer IT and higher GC (excluding 9 and 10 WU/tick) can generate higher yields, but extremely low GC, especially with shorter IT, can lead to the collapse of farmers. The number of farmers gaining yields declines and yields of each canal decrease with rising GC, but at least each canal has yields. For lower GCs, the (bad) results of canals and farmers are similar to situations with sufficient water supply. Overall, most downstream farmers, some middle-stream farmers, and even several upstream farmers stay without harvest at all – even in scenarios with the longest IT time and higher GC, which results in no yields for farmers relatively downstream and reduced canals' yields. Whatever the combination of factors, it is apparent that the downstream farmers along a canal are affected the most, followed by the middle-stream and upstream farmers.

In summary, similar dynamics can be observed for time control scenarios that irrigate one canal and two canals per tick, both for yields of canals and farmers. When canal

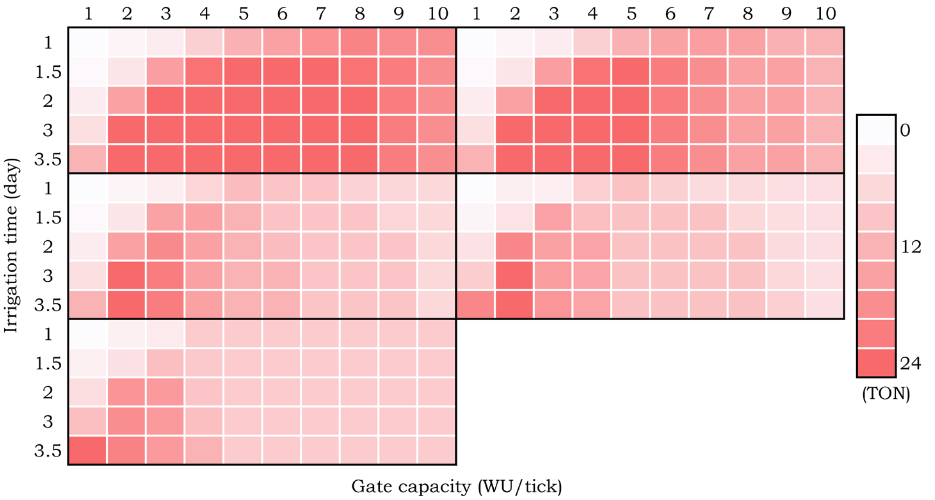

Figure 3.4: Yields per canal with insufficient water and Time Control (canal discharge of upper left, upper right, middle left, middle right, and low at 60, 40, 20, 10, and 5 WU/tick respectively).

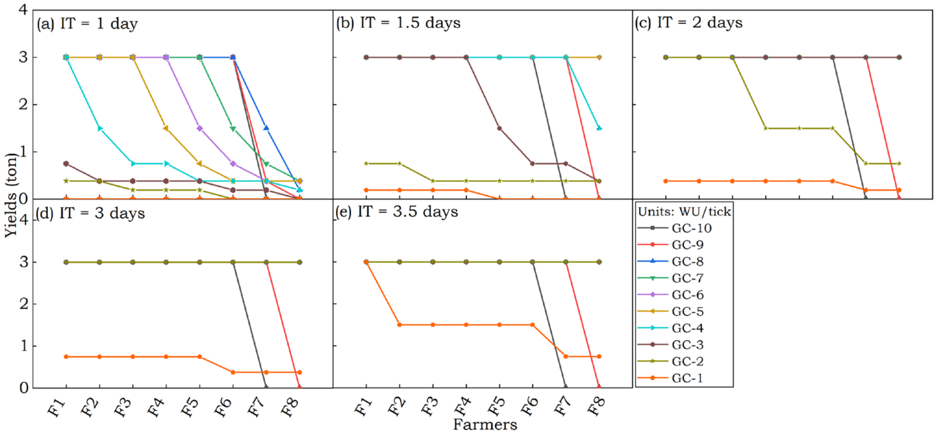

Figure 3.5: Yields per farmer with CD = 60 WU/tick under different irrigation time controls.

discharges are at least 80 WU/tick, barley yields increase with prolonging IT and rising GC. Both for canals and farmers, yields are high and stable when IT is above 1.5 days. However, and second, with insufficient water, but GCs stay relatively high, downstream farmers along a canal have no yields and the total yield of a canal is reduced. Moreover, irrigating two canals simultaneously will further reduce the canal discharge. This suggests that irrigating one canal at the same time could be better than irrigating two canals at the same time, when prioritizing the benefits of the community above the individuals. Third, it can be easily observed that there is no difference between canals under each sub-scenario, but there are differences between the upstream, middle-stream, and downstream farmers along a canal. These results indicate that IT, GC, and RD are factors that affect canals and farmers' yields, while farmers' location also affects farmer's yields.

3.3.3. WATER CONTROL PATTERNS

When the irrigation system is facing water stress, results become more diverse. Within the two canals' perspective, we tested two water allocation strategies. Strategy one allocates the same flow to both canals, strategy two fulfills the gate capacity of the right canal first and sends the remaining water to the left canal.

The comparison of all sub-scenarios suggests that if the irrigation system has sufficient water supply, DC and irrigating two canals per time step is the best choice. In case of water deficiency, TC would be the better choice, as at least more canals and farmers gained yields, and yields could be managed by managing irrigation time. For DC, some differences in yields are created between upstream, middle-stream, and downstream canals, but there is not much difference between farmers located at the same canal. In contrast, with TC, there is no difference in yields between canals, but there are differences between the upstream, middle-stream, and downstream farmers within the same canal.

When the irrigation system is facing severe water stress, GC could be the most important factor affecting yields. Higher GCs bring benefits to the upstream farmers only. To benefit more farmers, which also would be beneficial for the whole irrigation system in terms of yields – and does not go against the benefit for upstream farmers at all – lower GCs should be used. The number of canals irrigated per tick is also a major factor, which could affect irrigation decisions when facing water deficiency. To create benefits for more farmers, irrigating one canal per time step would work better. In order to create higher profits for some individuals, irrigating two canals simultaneously works better.

Lower RDs with GCs result in lower yields per canal and fewer farmers gaining yields, because of the water flow patterns that are created to both irrigation controls. Table 3.2 summarizes when water can flow to which farmer for all CD situations under all RD scenarios. If CD is lower than 80 WU/tick, there is a GC threshold that blocks water from flowing to farmers downstream along a canal. GCs above the threshold block water flowing to downstream. The gate thresholds are 9, 6, 3, 2, and 1 WU/tick for CDs at 60, 40, 20, 10, and 5 WU//tick, respectively. The threshold value decreases with lower canal discharges. This implies that if water availability is lower, only low GCs make water flow downstream.

3.3.4. PATTERNS OF YIELD

There are 840 sub-scenarios in this experimental model. 153 sub-scenarios gain the optimal barley yields of 384 TON, or 3 TON per farmer, whereas 12 sub-scenarios gain no yields at all. In terms of total yields for the irrigation system, 8% of the sub-scenarios gain exactly half of the maximum yields, or 192 TON. Over 50% of the sub-scenarios give total yields below 192 TON, while 35% gain yields over 192 TON. Sub-scenarios that result in the same total yields, however, have different underlying interactions between canals and farms/farmers. Only the total yields of 384 and 0 TON respectively, indicate automatically that the whole irrigation system – all canals and farmers – did the same things

Table 3.2: The furthest farmer that the water flow reaches.

River Discharge (WU/tick)	Canal Discharge (WU/tick)	Gate Capacity (WU/tick)									
		10	9	8	7	6	5	4	3	2	1
200/160/120/80	80	F8	F8	F8	F8	F8	F8	F8	F8	F8	F8
120	60	F6	F7	F8	F8	F8	F8	F8	F8	F8	F8
120/80	40	F4	F5	F5	F6	F7	F8	F8	F8	F8	F8
40	20	F2	F3	F3	F3	F4	F4	F5	F7	F8	F8
20	10	F1	F2	F2	F2	F2	F2	F3	F4	F5	F8
10	5	F1	F1	F1	F1	F1	F1	F2	F2	F3	F5

Note: F-farmer; number - the location of each farmer along a canal, the larger the number, the more downstream of the farmer.

in terms of water distribution. Table 3.3 shows some examples of different water distribution activities that resulted in the same total yields for the system as a whole. Even for these low overall yields, different scenarios can be identified.

Table 3.3: Examples of the sub-scenarios when they had the same total system yields.

Case	Number of canals	River discharge (WU/tick)	Water allocation	Irrigation control	Gate capacity (WU/tick)	Yields of irrigation system(TON)
1	1	200	\	1.5days	1	12.16
2	2	120	S	1.5days	1	12.16
3	2	120	R	1.5days	1	12.16
4	2	10	S	1 day	2	12.16
5	2	20	S	2 days	10	48
6	2	20	R	3days	10	48
7	2	80	S	DC	7	36
8	2	10	R	1 day	6	36

Note: S - allocating the same amount of water to the canals at both sides of the river; R - satisfying the right side canals first.

- Cases 1-4: the same low total yields are the result of different results per canal and between farmers: canals have the same yields, but farmers not. In case 4, the first two farmers along each canal harvest 0.38 TON barley, but the last six farmers gain nothing. In cases 1 to 3, the first four farmers along canals yield 0.19 TON, with the rest of the farmers harvesting nothing.

- Case 5-6: in case 5, each canal yields 3 TON, because each first farmer could gain 3 TON barley, while the others are left without harvest. For case 6, each right canal gains 6 TON barley, but the left canals gain nothing. Actually, the first two farmers along each right canal gain 3 TON barley, while the other farmers harvest nothing.

- Case 7-8: in case 7, only the first two canals gain yields (18 TON), whereas the other canals remain without yields. Case 8 shows each right canal gaining 4.5 TON, but the left canals have no yields. In terms of difference between farmers, case 7 allows the first six farmers yields of 3 TON each, but the last two farmers gain nothing. Case 8 shows yields of 3 and 1.5 TON for the first and second farmers along the right canals, respectively, but the left-canal farmers are bankrupted.

3.4. SUMMARY AND DISCUSSION

The founding principle of the IRABM model is the irrigation cycle being divided into 6 irrigation rounds, according to barley growth stages, with irrigation options being simulated separately in each round with varied scenarios combining available water, canal and gate settings and control methods. The results clarify how and why irrigation patterns (can) emerge when agents act in an irrigation setting. The way(s) the different model agents (model parameters) influence barley yields can be analysed. The model outputs have allowed several main findings to be defined:

- Demand control gives better results in terms of yields than time control, when there is sufficient water in the river.
- Time control should be the first choice when our irrigation system faces water deficiency.
- Barley yields generally increase when irrigation time and/or river discharge are extended.
- Tipping points of gate capacity resulting in yields differences can be observed.
- Yields do not change linearly with changing gate capacities but show threshold behaviour.

Some results can be understood as artifacts of our own model settings. For example, in a situation with irrigation demand control, a relatively high gate capacity, and insufficient water in the river, it can be easily observed that yields only exist along the first-level canals. This is the direct consequence of the current model design settings, with the control rule only allowing water to flow to the next canal when the last farmer along the upstream canal receives the required water. This may be seen as the extreme version of an expected outcome that, in terms of locations along the canals, downstream farmers run much more risk of being negatively affected in their water availability – especially those farmers that are downstream in the more downstream canals. Similarly, the downstream farmers along a canal are affected the most in the case of time control.

There is a rather important aspect, however, concerning the effect of the position of farmers in relation to how water moves from upstream to downstream. Through changing gate capacities – the management of flows to the farms – we showed that in situations with sufficient water in the system, higher gate capacities generate higher yields for farmers in the whole system. When there is insufficient water in the river, however, higher gate capacities only benefit upstream farmers, whereas lower gate capacities could benefit both upstream and more downstream farmers – and as a consequence the whole system.

Therefore, this experimental model generates an emerging setting that we did not explicitly build in, but that relates closely to real-world irrigation systems. In real irrigation management, upstream farmers often take more water than allowed, even when there is insufficient water on system level – resulting in downstream farmers facing further water stress. But if every farmer's gate capacity is kept low enough, water could probably be allocated to each farmer, which should result in everyone at least receiving a certain amount of water.

3.4.1. IRABM'S ENGAGEMENT WITH OTHER STUDIES

IRABM aims to construct an ABM framework to explore varied scenarios to mimic the operation of an irrigation system and the longer-term emergence of irrigated settings. Obviously, we are not the first to build an irrigation-related ABM to do just that. As already mentioned in the Introduction, Tamburino et al. (2020) built an ABM to mimic a small-holder farming system with conditional environmental attributes to explore the interactions between water courses, humans, and crops. One of their main focus issues was farmers' behaviour in relation to group activities. Hu and Beattie (2019) developed an ABM using a two-stage optimization strategy to guide farmers to make an optimal decision on choosing crop and groundwater irrigation. Their results proved the viability of strategies resulting in higher crop yields and slower groundwater depletion – an issue similar to the canal-sharing dilemma we mentioned earlier. Anthony and Birendra (2018) developed an ABM to explore its ability to manage water distribution strategies in New Zealand, which suggested that significant water savings were possible. Barreteau et al. (2004) built the SHADOC model, a multi-agent simulation of the dynamics of an irrigation system in the Senegal River Valley. With scenarios defined as an environment plus a set of individual and group rules, their results suggest that their simulations can be used to evaluate the viability of irrigation systems, as well as provide a new approach to the study of such systems.

The current IRABM version was built to analyse the interactions among non-human model agents that could both represent human activity and non-human realism: river discharge, gate capacity, irrigation time, farmers' location, and barley yields. This digital experiment model provides opportunities to study complex irrigation system dynamics from a new perspective. One of the main problems of the "irrigation dilemma" is the inequality between upstream and downstream farmers' ability to access water when they share a common water resource (Ostrom and Gardner, 1993). Janssen et al. (2015) used an experiment with constrained communication and limited information to study inequalities of water access. Their research illustrates that lack of communication among farmers could cause an imbalance between upstream and downstream farmers' investments and earnings. Our model experiments, with model farmers that have no means of feedback (communication) yet, confirm that the "irrigation dilemma" can be caused by upstream farmers simply responding to water availability – they do not need to steal water, just not knowing what happens downstream would be sufficient to leave downstream farmers with less possibilities to access water, especially when there is water scarcity, resulting in downstream farmers – and the system as a whole – gaining less earnings.

As already mentioned, this phenomenon is a genuine emerging result of the model setup, as we did not built-in this kind of "emergence" using something like the ODD protocol. We did not specify that upstream users had to take water, we studied what happened when they did. We did not define what type of emergence our model should be based upon, as emergence that is already known is not really emergence. What we did find, however, when applying a model setup that was realistic enough to catch water flow behaviour and yet simple enough to run multiple scenarios, was threshold behaviour in the system – which is exactly what one would expect in realistic irrigation settings. With much of the ABM work available explicitly defining the expected results or key outputs beforehand through the ODD protocol (Grimm et al., 2006; Grimm et al., 2010; Grimm et al., 2020; Cai and Xiong, 2017; Pacilly et al., 2019), we would like to argue that "emergence" should be a new phenomenon in a model. Results like upstream farmers taking water at the cost of downstream farmers, predictable as it may be, should always be surprisingly ("naturally") emerging from a reliable and robust ABM – without being pre-defined in the ODD protocol. Similarly, there is no specific adaptation in this model as all settings are predefined, although the performance of irrigation-related non-human agents already represents potential adaptations. Different water allocation strategies show the adaptation of varying river discharging, the settings of the gate (capacity) reflect the adaptation of water supply and irrigation schedule, and the yields of barley represent the adaptation of different water distribution strategies. Consequently, potential adaptation phenomena can go through model agents, even in a model with predetermined settings.

One could argue that IRABM goes against the trend that current ABMs of the human-environmental systems, become increasingly complex (Sun et al., 2016). For instance, Bithell and Brasington (2009) developed a coupled modelling system which consists of several sub-models (ABM, individual-based and hydrological) to simulate land-use change. Arnold et al. (2015) coupled an ABM with a hydrological model in a multi-agent farm decision and production simulation to quantify the economic importance of irrigation water reuse. Jaxa-Rozen et al. (2019) combined ABM with MODFLOW/SEAWAT geo-hydrological modelling to study Aquifer Thermal Energy. The interesting results notwithstanding, we would suggest that irrigation systems are complicated and dynamic systems, because of interactions between (non)human agents on small temporal and spatial scales. As the effects of these small steps can be approached with relative certainty, IRABM only needs to involve simplified hydrological and hydraulic processes, including synthesized data, instead of using coupled ABM with crop or hydrology/hydraulic simulations on larger temporal or spatial scales. The objective of this study was to show how IRABM can represent and study relevant human-water system interactions without predefining them. We think we have shown that IRABM provides the flexibility required to allow dynamical agents' actions. As such, we plan further model steps, which both involve more complicated feedback mechanisms and more accurate methodologies to represent certain agencies.

3.4.2. IRABM'S NEXT STEPS

The experimental model discussed is to be developed for further studies, especially focusing on how agents' actions can change when results (like yields) become known to model agents and key model parameters are varied. The base model was designed using the principles laid out in Ertsen (2010) and Ertsen (2016): the non-human agents, like canals, gates, and crops, shaped the temporal and spatial options of the human agents. As mentioned in the Introduction, we are particularly keen to use our model setup to study longer-term irrigation development in ancient Mesopotamia. Communication and cooperation were crucial in Mesopotamia to create successful and efficient irrigation works (Altaweel, 2019; Nieuwenhuis, 2012), but how such cooperation and communication emerged is less certain. In the current setup, human agency is represented by setting the amount of water flowing through gates. While not including human decisions as such in the model, we have been able to illustrate how the interactions among IRABM model agents show possible effects of agent interactions and tensions between the goals of individuals versus the overall community. There is no communication and cooperation in the current IRABM setup, but upstream and downstream farmers already compete for the water according to their location.

Building options for interactions among farmers is a way to increase the benefit of the downstream farmers and even the whole system in the model. Real-world decision-making is influenced by many complicated factors that must be simplified in any modelling approach. The next IRABM setup will allow for the consideration of irrigation decisions on crop choice, irrigation forecast, and water allocation. IRABM's barley irrigation schedule is divided into six irrigation rounds, with each round having a regular time period. As our running periods remained short, this level of detail could be used. We consider condensing the whole barley growing period into one irrigation season, as this may provide a quicker computation routine which would be beneficial for multiple-year runs – but this would lose the effect of decision-making and water distribution within a season. Whatever seasonal setup we will work with, multiple-year runs bring us to the issue of memory in the model, for example in the shape of "irrigation memory" or "available water memory". We are looking into options to create possible feedbacks between farmers based on these memories – possibly in different combinations, including knowing the results of other farmers. We could extend this work by considering more irrigation-related factors or adding different crops to optimize water allocation strategies and crop yields to simulate farmers' decision-making.

With these inputs, we move closer to the coupled models that we mentioned earlier. These models might face challenges like modelling design, processes of data change, and results interpretation, but these models can capture complex behaviours and be friendly to decision-making support, scenarios analysis, and forecasting capacity (Sun et al., 2016; Jaxa-Rozen et al., 2019; Bakhtiari et al., 2020). We could still decide to move towards a coupled model, with IRABM being enhanced with a crop-growth model and hydrological/hydraulic model, but for the moment we plan to stay within the NetLogo environment.

We showed the flexibility of the IRABM framework of using non-human agents to present human agents and demonstrated its ability to simulate the interactions of irrigation-related agents in an irrigation system. It provides an alternative perspective to simulate the human-water system and is friendly for non-technical stakeholders. The IRABM already is able to simulate the effects of decisions, and decisions can be directly linked to current model elements (canals, gates and farms), it is a promising tool that could be used as a framework to study both the operation of irrigation systems and the longer-term effects of this. We are planning to apply an extended IRABM to irrigation development in Mesopotamia. The IRABM is ready for more.

4

MODELLING FARMLAND DYNAMICS IN RESPONSE TO FARMER DECISIONS USING AN ADVANCED IRRIGATION-RELATED AGENT-BASED MODEL

This chapter is based on

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Lang, D., and Ertsen, M. W. (2023). Modelling farmland dynamics in response to farmer decisions using an advanced irrigation-related agent-based model. Ecological Modelling, 486, 110535.

ABSTRACT FOR CHAPTER 4

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.

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

4.1. 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 the 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 relies 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 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 of 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 are 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, 2022b). 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 making 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 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.

4.2. METHODS

4.2.1. MODEL OUTLINE

The AIRABM design is structured according to the ODD + D protocol, which stands for Overview, Design Concepts, Details + Decision Making (Grimm et al., 2006; Grimm et al., 2010; Grimm et al., 2020; Müller et al., 2013). The elements of the ODD + D for AIRABM are briefly explained in Table 4.1. As AIRABM shares much with its predecessor IRABM, many basic elements and details described in Lang and Ertsen (2022b)) 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' decisions 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.

Table 4.1: The brief ODD protocol of the AIRABM.

Elements	Explanation
1. Purpose	Analysing farmland dynamics in response to farmer decisions
2. Entities	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 1st year, farmland 1 is cultivated by all farmers; subsequently, farmers decide to keep, expand, or abandon farmlands according to yields and water availability. The interaction between farmers' is expressed in adjusting gate capacities to increase lower yields.
5. Initialization	All farmers can cultivate farmland1 in the 1st 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.

4.2.2. MODEL DESIGN CONCEPTS

The simplified irrigation system layout and the model design concept are shown in Figure 2.8 and Figure 2.5: 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 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 – if possible, as this depends on water availability. 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 farmland 2, 3, 4, and 5 respectively. We used farmers' location as indication of their easy access within a gravity-based system. We defined upstream farmers are farmers 1, 2, and 3 (F1, F2, and F3); 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).

4.2.3. 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 barley yields and water availability in all past growing seasons. 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:

$$\mathrm{AHB} = \frac{\mathrm{HBY}_{1} * 1 + \mathrm{HBY}_{2} * 2 + \mathrm{HBY}_{3} * 3 + ... + \mathrm{HBY}_{n} * n}{1 + 2 + 3 + ... + n} \tag{4.1}$$

$$\mathrm{AAW} = \frac{\mathrm{AW}_{1} * 1 + \mathrm{AW}_{2} * 2 + \mathrm{AW}_{3} * 3 + ... + \mathrm{AW}_{n} * n}{1 + 2 + 3 + ... + n} \tag{4.2}$$

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.

4.2.4. INDIVIDUAL FARMERS' DECISION-MAKING MECHANISM

Figure 4.1 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), make changes to expand one farmland, or to abandon one or two farmlands. The expansion sequence is expanding farmland 2 first, then expanding farmland 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.

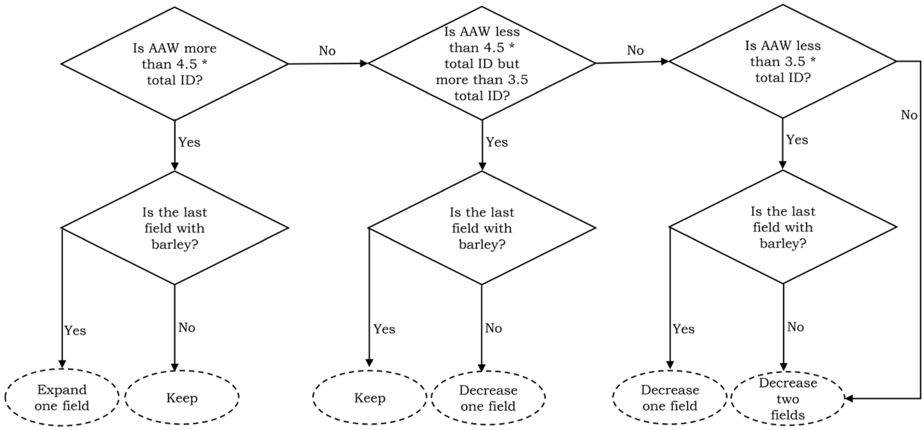

Figure 4.1: The processes of individual farmers' decision-making on farmlands dynamics. ID – irrigation demand. This is a decision-making example of when there were 4 harvested fields in the last year.

4.2.5. 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 the 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 4.2. 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.

4.3. SOME REPRESENTATIVE RESULTS

Our modelling 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

Table 4.2: Gate capacity adjustment strategy.

Initial Gate Capacity (WU/tick)	Gate capacity after 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 after adjustment is 10 WU/tick

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.

4.3.1. HARVEST SITUATIONS WITHOUT GATE CAPACITY CONTROL

4.3.1.1 Harvest situations for irrigation system's level

Figure 4.2 shows the total yields on the system level for all combinations of RD and GC over the 20 model years of the system. Total yields generally 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 modelling RD is higher than the highest modelling 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.

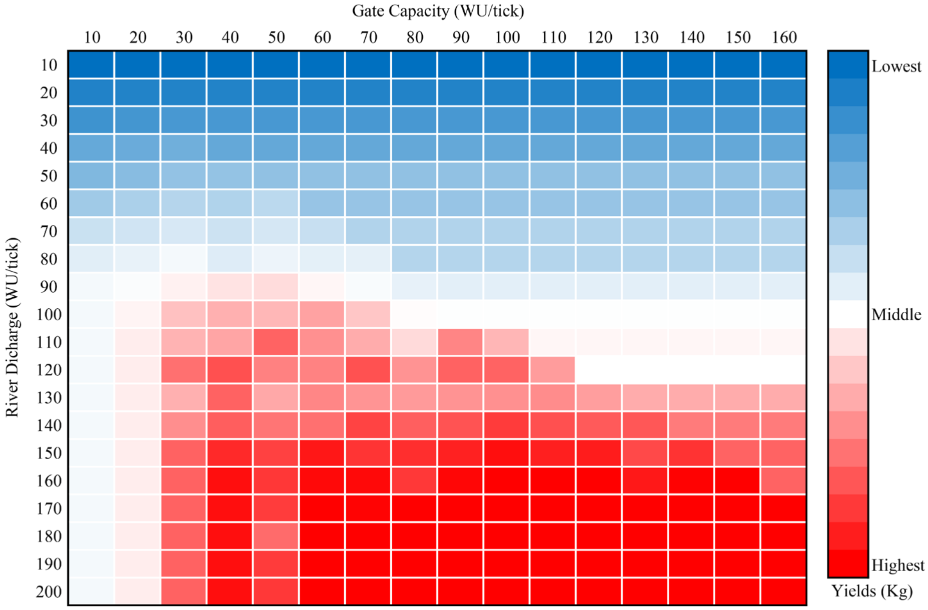

Figure 4.2: Total system yields with the varied RD and GC.

4.3.1.2 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 Supplementary Material A.1. 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 Supplementary Material A.2 for further details). As a second category, we have farmers with different yield patterns, with in general, relatively upstream farmers having higher yields than relatively downstream farmers – which is why we refer to this as a “poor harvest situation”.

Table 4.3 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.

4.3.2. 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 4.3, 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 sub-section, the details of the harvest situations for RD = 30 and 160 WU/tick are provided in Supplementary Material A.3 and A.4.

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

Figure 4.3 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

Table 4.3: 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 numbers 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 numbers 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

= 40 WU/tick and MGC = 10 WU/tick shows the highest yields in each sub-figure. 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 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 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

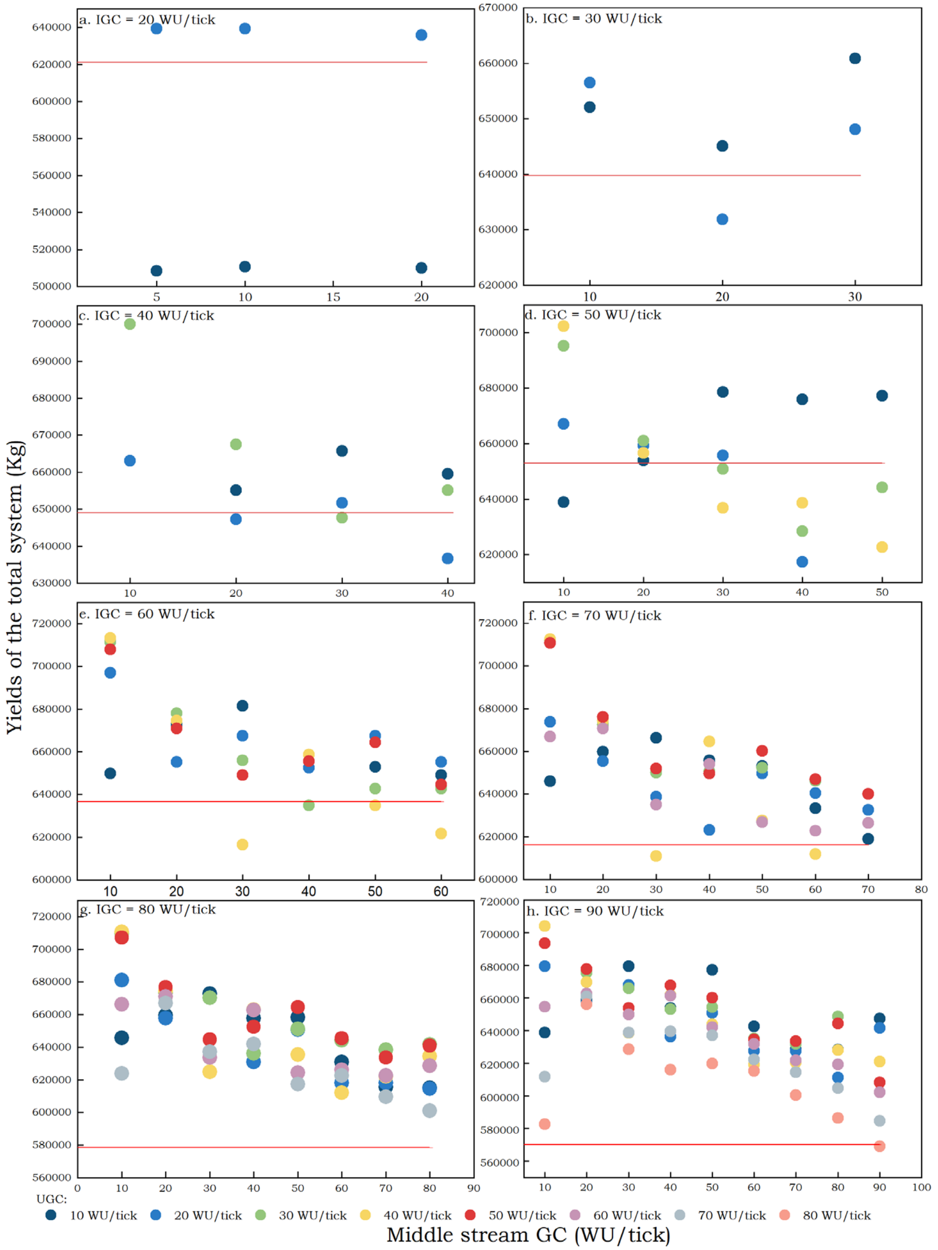

Figure 4.3: Total system yields with varied UGC and MGC when RD = 90 WU/tick (red line shows the initial total system yields). The y-axis has different scales due to the significant differential of the yields; the x-axis has different scales due to different MGCs, which are based on the IGC.

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 Figure 4.4. 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. Figure 4.4 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 Figure 4.4. 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.

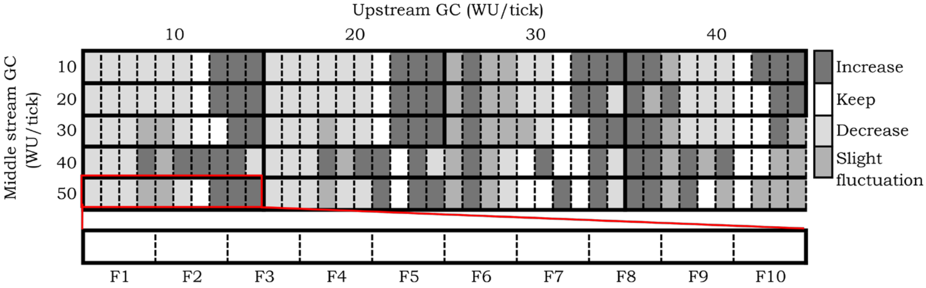

Figure 4.4: Harvest situation of individual farmers after GC adjustment (RD = 90 WU/tick, IGC = 50 WU/tick). After GC adjustment, Increase – the farmer has higher yields; Keep – the farmer has the same harvest situation; Decrease – the farmer has lower yields; Slight fluctuation – the farmer has lower yields in the first few years of the GC change and then back to the initial situation (the same in Figure 4.5 and Figure A.4).

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. Figure 4.3g and Figure 4.5 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 have 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 the increased yields of F7-10 are higher than the decreased yields of F1-6.

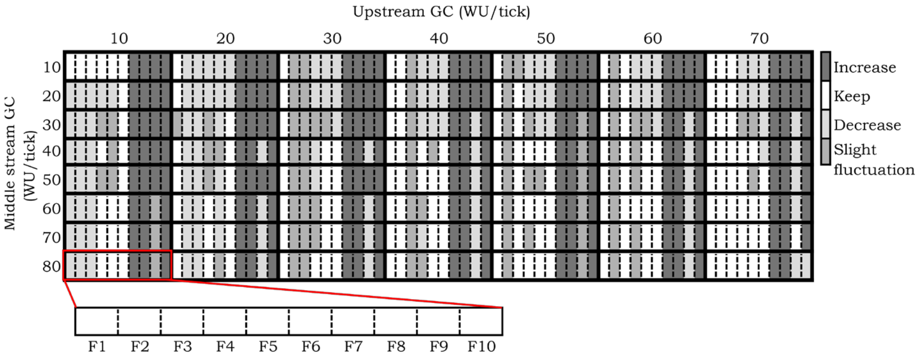

Figure 4.5: Harvest situation of individual farmer after GC adjustment (RD = 90 WU/tick, IGC = 80 WU/tick).

4.4. 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.

4.4.1. TEMPORAL AND SPATIAL DYNAMICS OF THIS MODEL

The modelling 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 (2022b)), 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 (2002) 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 reallocating 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 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 contribute to the collective profits.

4.4.2. 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 4.4) – 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 in facilitating 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.

That being said, sometimes the total system harvest would also decrease, creating a situation in which more equality between farmers would be accompanied by 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).

4.4.3. SPECIFIC PROPERTIES OF THE ADVANCED IRRIGATION-RELATED AGENT-BASED MODEL

Our proposed model AIRABM is an updated version of our earlier modelling framework IRABM, which was based on ODD + D protocols to describe decision-making in ABM (Lang and Ertsen, 2022b; 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 allow this model to come close to realistic irrigation systems and indeed help us to better understand the operation of irrigation systems and farmers' decision-making processes. Moreover, to make this modelling framework more accessible to stakeholders, especially for non-tech stakeholders, a user-friendly interface has been developed in NetLogo where stakeholders can play with and build model simula-

Table 4.4: 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.

tions 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 the 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' decisions, potential water availability, and landscape dynamics are currently not considered in the model.

4.5. CONCLUSIONS

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.

5

MODELLING SOUTHERN MESOPOTAMIA IRRIGATED LANDSCAPES, OR HOW SMALL-SCALE PROCESSES CONTRIBUTE TO LARGE-SCALE SOCIETAL DEVELOPMENT

This chapter is based on

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ABSTRACT FOR CHAPTER 5

Early Southern Mesopotamia shows a complex history of expansion of (irrigated) farming in relation to urban developments and changing landscapes. As a first step to studying expanding irrigated farming system, an irrigation-related agent-based model was developed to explore farm(land)s and irrigation systems in relation to decision-making processes, both of farms and their farmlands (an agriculture unit) and collective decision-making processes for irrigation system management – especially sharing water between farms. The decision-making processes include options to move farms, expand the system, or start a new system, as these would be options available for Mesopotamian farmers as well. In this text, we report how model parameters contribute to the generation of various patterns of yields and the expansion of farms and system. Additionally, the Gini coefficient (based on yields) is applied to estimate levels of inequality among farmers. Our results show how 1) human decision-making determines the level of influence of and benefits for farms, as well as the overall irrigation system; 2) Gini values effectively capture the degree of inequality in yields among farms based on water availability; and 3) our model is a suitable base for further study, by incorporating additional agents into the irrigation system and expanding the spatial-temporal scales of the irrigated landscapes, to reach a more comprehensive understanding of the evolutionary dynamics of irrigation systems in Southern Mesopotamia.

Keywords: Agent-based modelling, irrigation, harvest situations, decision-making, ancient Mesopotamia

5.1. INTRODUCTION

The region of Southern Mesopotamia is generally considered as setting for one of the earliest civilisations (Adams, 1981; Rothman, 2004). The landscape of this region comes to the observer 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; Pournelle, 2003; Wilkinson et al., 2015). This history of irrigation management in Southern Mesopotamia needs to be explained as “evolving”, in the sense that an earlier, relatively empty landscape with (irrigated) farming most probably being relatively small-scale, did transform into a relatively intensively used landscape, with identifiable centralised management of irrigated farming and yields (Adams, 1965; Jacobsen and Adams, 1958; Rost, 2017; Wilkinson et al., 2015; Wilkinson and Jotheri, 2021). Buringh (1960) argues that the first step of irrigation probably involved cutting the river banks, which gradually became a canal system and finally developed into larger irrigation systems on the floodplain. Wilkinson et al. (2015) suggest that the management of crevasse splays from the (elevated) channels could act as triggers for artificial cuts providing water to irrigated fields along the levees. Groups of fields would eventually be structured along irrigation canals with associated management by local communities in succeeding generations. Rost (2017) indicates that irrigation management could not only provide subsistence to small communities but also could be the economic basis of states or empires when management was taken over by specific groups. However, an overarching, yet detailed history of irrigation management in a developing irrigated landscape in Southern Mesopotamia has not been written yet. We have good developmental models for earlier periods, and we have data from later periods, but we lack a clear trajectory between the two. In this manuscript, we suggest that systematically exploring how irrigation systems could evolve from small-scale to large-scale, from short-term to longer-term, and from independent to collective could build further understanding of the co-development of environmental and socio-political aspects of irrigation systems in ancient Mesopotamia – and as such in other regions and periods as well.

Our own baseline, systematic exploration builds on applying an Agent-Based Model (ABM), as ABMs have shown to be valuable tools for investigating human-water systems, facilitating the exploration of the intricate interactions between human activities and hydrological characteristics (Alam et al., 2022; Hyun et al., 2019; Streefkerk et al., 2023). Moreover, ABMs have been broadly applied to archaeological research in different sub-fields, including simulating Roman tableware trade procedures and economic history (Brughmans et al., 2019; Brughmans and Poblome, 2016; Carrignon et al., 2020; Graham et al., 2022), modelling networks in archaeology (Collar et al., 2015), exploring the evolution of human language (Ruland et al., 2023), reconstructing past human-environment interactions (Perry and O’Sullivan, 2018), and studying the long-term implications for individuals’ preference of local Jerash products (Romanowska et al., 2022), etc. The suitability of ABMs is closely linked to their inherent capability to represent (non)human decision-making in a heterogeneous and flexible manner, accommodating the diverse nature of data available on decision-making outcomes at individual, local, and larger scales (An, 2012; DeAngelis and Diaz, 2019; Murphy et al., 2019). ABMs have been recognized as important tools for designing, evaluating, and operating water allocation processes (Murphy et al., 2015; Murphy et al., 2019; Ozik et al., 2014). ABMs for irrigation management incorporate various sub-modelling routines, like hydrological and crop models, as well as social factors such as decision-making and interactions, to accurately portray the interplay of natural, economic, and societal dynamics across different temporal and spatial scales (Aghaie et al., 2020; Altaweel and Watanabe, 2012; Altaweel and Watanabe, 2012; Anthony and Birendra, 2018; Bahrami et al., 2022; Hyun et al., 2019). Irrigation systems are examples of complex systems, with their changeable stakeholders' decision-making, complicated hydraulic characteristics, and complex water distribution rules among canals and farmers. These features together create interactions between humans and water through the infrastructure, with human actions affecting water availability of other humans, creating reasons for changes in the irrigated landscape by human interventions, that will affect water availability etcetera (De Bruijn et al., 2023; Davies et al., 2014; Ertsen, 2010; Pluchinotta et al., 2018). These interactions between human activities and the water system need to be explicitly addressed when studying the development of irrigation systems and irrigated landscapes.

With this in mind, the design logic of our research approach focuses on the dynamic layout of a virtual irrigation system, taking inspiration from the evolving irrigation landscape in Southern Mesopotamia over time. Before the current study, we had already developed the Irrigation-Related Agent-Based Model (IRABM) and the Advance Irrigation-Related Agent-Based Model (AIRABM) (Lang and Ertsen, 2022a, 2022b). IRABM offers a theoretical and methodological framework for examining the interactions among irrigation-related agents and gaining insights into how these interactions can shape water and yield patterns. AIRABM applies a similar design logic to explore the dynamic behaviour of farmlands and yields through decision-making by independent farms as well as collective decision-making processes. Building upon these two models, we have further advanced the model series to the current IRABM^3. In IRABM^3, we maintain the mechanisms for water movement, irrigation scheduling, barley yield response to water supply, farmland dynamics, and decision-making processes at farm and system levels, from the previous two versions. IRABM^3 expands the decision-making process on the farm level: next to incorporating choices within the existing canal, the current model includes decision-making in relation to the expansion of farming activities in the same irrigation system or by creating a new system. In order to illustrate how dynamics in irrigation systems can emerge from decisions made by heterogeneous agents, three key decisions on two levels of decision-making are included in IRABM^3:

1. Decisions are made on "farms" concerning farmland dynamics (without specifying which entity exactly makes these decisions), which may lead to

2. Collective decision-making on water distribution between those farms, as in cases with lower yields along the canal, upstream and middle stream farms will gradually lower their gate capacity to distribute water more equally among farms. The result of these adaptations may

3. Trigger a final farm-related or collective decision-making process, based on the realized yields, affecting the overall dynamics of the irrigation system: expansion of farms and/or canals when yields are good or movement of farms when yields are low.

With these three decision processes, offering insights into how human decision-making influenced the development and configuration of the irrigated landscape, we argue that our model presents a useful basic approach to simulate evolutionary patterns of irrigation systems in Southern Mesopotamia on extensive temporal and spatial scales. We will return to this potential in the discussion, after presenting the modelling setup in much more detail further below.

As one of our underlying concepts related to decision-making concerns yields, we added one additional concept to our analysis: the Gini coefficient. Originally, this coefficient was introduced by Gini (1912) to evaluate income inequalities within the realm of economics, and it continues to be commonly utilized in this domain (Campano and Salvatore, 2006; De Maio, 2007; Piketty and Saez, 2014). It is now employed in various research fields, including both modern and ancient contexts. For instance, Harch et al. (1997) employed the Gini coefficient to compare bacterial soil communities, Zheng et al. (2013) developed the land Gini coefficient (LGC) to evaluate the rationality of land use structure in China, and Sueyoshi et al. (2021) investigated technology diffusion inequality among Chinese provinces. The Gini coefficient has also found application in agricultural research for estimating crop yields at various levels (Vesco et al., 2019; Vesco et al., 2021). It is also been utilized in in archaeology recently, for instance, Kohler et al. (2017) utilized a house size Gini coefficient to represent post-Neolithic household wealth and wealth disparities, and studies from Baker (2023) and Basri and Lawrence (2020) have related archaeological evidence of increasing inequality to the Gini coefficient. These applications have demonstrated the universality of the Gini coefficient, and the positive results obtained in evaluating crop yields have further encouraged its continued usage in this field. We did not include the Gini coefficient in the modelling itself (yet), but employed the coefficient to analyse modelled inequalities of barley yields among farms, utilizing annual values of yields and farms' population. This allowed us to examine the spatial-temporal patterns of barley yields among farms and explore the correlation between farms' cooperative tendencies and the Gini coefficient values.

This paper is structured as follows. Section 5.2 presents the theoretical framework and the analytical approach of IRABM^3, where we present the foundation and outline of the analytical methodology employed. Section 5.3 presents the findings obtained from our analysis and discusses the empirical outcomes. Section 5.4 delves into a comprehensive discussion of the research, examining its implications and potential avenues for further exploration. We will close this paper with Section 5.5, which summarizes the key findings and highlights the significance and outlook of our research.

5.2. MODEL AND DESIGN DESCRIPTION

The current model is built upon the IRABM and AIRABM models, both of which were extensively described in previous papers utilizing the ODD + D (Overview, Design concepts, Details + Decision-Making) protocol (Lang and Ertsen, 2022a, 2022b). Moreover, the Model Design Concepts, the Response of Barley Yields to Water Supply, the Learning and Memory Behaviour, and the Farm's Decision-making Mechanism remain consistent with the logic presented in the aforementioned papers. In contrast to the previous two versions, that focused on farmlands dynamics within one farm (including decisions 1 and 2 mentioned in the Introduction), the current version IRABM^3 incorporates both farms and system dynamics, applying all three decisions mentioned. This section will outline how we construct the model system dynamics, specifically the expansion of farms/canals and the movement of farms/canals.

5.2.1. IRABM^3 DESIGN CONCEPTS

The IRABM^3 setup has the same initial layout has the AIRABM design shown in Figure 2.8. We gave each farmland a constant size of 1 hectare, with farms next to each other sharing similar soils.

The model design concept for IRABM^3 is shown in Figure 2.6. We do not predefine which entity is making decisions on farms or system, as we focus on the reasons for and results of decisions. Obviously, in future studies such nuances of decision-making will need to be included (see Discussion).

5.2.2. COLLECTIVE DECISION-MAKING ON IRRIGATION MANAGEMENT

Within our latest model, we introduce two primary system dynamics: 1) relocating farms with poor harvests to new areas in – or outside the irrigation system and 2) expanding the irrigation system with extra farms. Both responses can be related to longer-term changes in the irrigated landscape, as relocations will mainly increase the number of irrigated areas, whereas expansions would increase the number of irrigation systems and irrigated areas simultaneously (see details in the paragraphs below). These changes in the irrigated landscape entail adjustments in the number of farms or in the size/number of canals. Following these modifications, we take into account water distribution among the canals. To achieve a more equitable distribution of water among canals, our model controls and adjusts the head gate diversion rates based on the ratio of the number of farms along a particular canal to the total number of farms in the entire system. This ensures that water is distributed more evenly among the various canals in the current model setup – which is obviously a feature that needs further study as well.

System movement decision-making processes

Irrigation water can be considered as “common pool resource”, with unequal access to water between upstream and downstream farmers posing a significant challenge in the “irrigation dilemma” when farmers share the common water resource (Albiac et al., 2020; Ostrom and Gardner, 1993). Generally, unequal access to water easily causes inequality of crop yields among farmers. With these concepts, we can move to the collective decision-making process which involves the movement of farms and canals in response to poor harvest situations. The initial configuration of our model consists of 10 farms. We define “poor harvest situation” as upstream farms having successfully harvested five farmlands while downstream farms have fewer than three harvested farmlands (for details on these farmlands’ dynamics in the model see Lang and Ertsen (2022a)). In other words, we consider barley yield inequality between farms as key for decisions on movement and/or expansion. When such a poor harvest situation arises and continues for at least five years, the model system decision procedure contemplates relocating downstream farms to a new secondary canal branching off from the original canal – thus effectively redesigning the tail area of the canal. In case these farms continue to experience poor harvests along the new secondary canal for at least five years, the system further considers relocating them to a new primary canal along the river (as illustrated in Figure 5.1). Thus, there can be up to two movements to address poor harvest situations: when the first internal move does not result in higher yields, farms decide to start a new system themselves elsewhere. Movement is a response to water scarcity on farms.

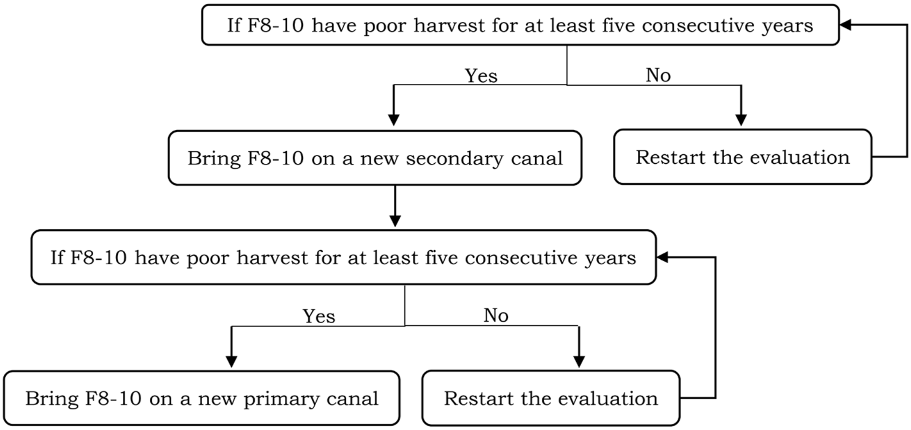


Figure 5.1: The movement design logic of farms (F - farm).

System expansion decision-making processes

The expansion of the model irrigated system is triggered when farms achieve good yields for a consecutive period. If a good harvest situation – determined as upstream farms having five successfully harvested farmlands, while midstream and downstream farms have at least three harvested farmlands each – persists for a minimum of five years, the model considers expanding irrigation activities by introducing additional canals and farms. In total, there are eight expansion stages in sequence (Figure 5.2). The maximum development of our model entails a total of 22 farms (from the initial amount of 10) along two primary canals and one secondary canal (from one original primary canal). Our model does not define where these new farms come from and how many farmers work on each farm – these new farmers could be migrants or family members of current farmers.

Farmland reduction and/or abandonment

Our study did not explicitly include the option for model farms to be abandoned – largely because our major interest in this paper is to discuss how to study under which conditions the (observed) expansion of irrigation in ancient Southern Mesopotamia may have occurred. Our modelling of the internal dynamics of farmlands did allow farms to return to and/or stay with the fallow status of fields within each respective farm, with this option depending on water resource availability. In situations with insufficient water resources within the system, downstream farms would confront the risk of having water shortages, which can potentially lead to diminished barley yields or, in severe cases, crop failure. As a proactive measure to mitigate these adverse consequences, farms may reduce the number of cultivated farmlands, essentially allowing some fields to revert to fallow status. It is important to underscore that this practice does not constitute farm

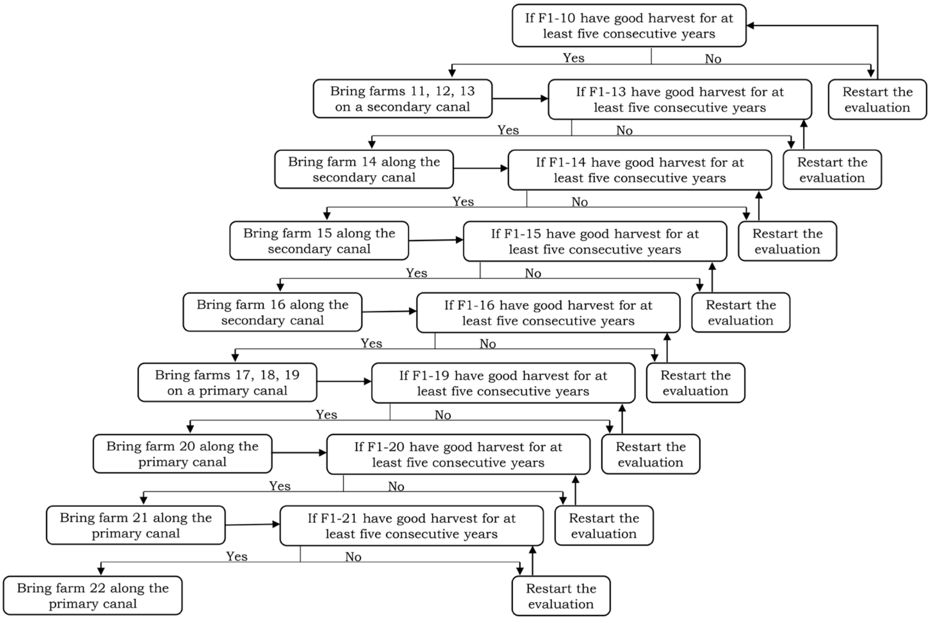


Figure 5.2: The expansion design logic of canals and farms.

abandonment as such, but would have a similar effect on how the water resources are used. As we suggest in the outlook at the end, it is indeed the abandonment of farms that would fit in scenarios that require further study – as those cultivators that abandoned their fields may have become the producers of other important societal objects and services (like pottery, as may have occurred in the Hohokam area in modern Arizona (Zhu et al., 2018).

Gate capacity adjustment

According to Lang and Ertsen (2022a), farms are categorized as upstream, midstream, and downstream based on their respective locations along the same canal. In this research, the expansion scenario permits the inclusion of one secondary canal and one new primary canal. Consequently, the classification of upstream, midstream, and downstream farms determined by their positions along the same canal can change depending on the changes in the system size and farm locations. Since the expansion occurs gradually and the number of farms along a given canal increases over time, the composition of upstream, midstream, and downstream farms will vary as well. Table 5.1 provides a detailed description of the farms within these three groups.

Barley yields of farmers at the farm level are evaluated every model year at the end of the growing season for farms located along the same canal. The harvest situation is determined based on this evaluation. Initially, all farms have the same initial gate capacity (IGC) for their irrigation needs. In the event of a poor harvest situation, collective decision-making comes into play for adjusting the gate capacity (GC) of upstream and midstream farms, while downstream farms maintain the original IGC. The adjustment

Table 5.1: The list of upstream, midstream, and downstream farms.

Canals	Expansion times	Farms	Upstream farms	Middle-stream farms	Downstream farms
Primary canal 1	Initial	F1-10	F1-3	F4-7	F8-10
Secondary canal	The first expansion (from F10 to F13)	F11-13	F11	F12	F13
	The second expansion (from F13 to F14)	F11-14	F11	F12-13	F14
	The third expansion (from F14 to F15)	F11-15	F11	F12-14	F15
	The fourth expansion (from F15 to F16)	F11-16	F11-12	F13-14	F15-16
Primary canal 2	The fifth expansion (from F16 to F19)	F17-19	F17	F18	F19
	The sixth expansion (from F19 to F20)	F17-20	F17	F18-19	F20
	The seventh expansion (from F20 to F21)	F17-21	F17	F18-20	F22
	The eighth expansion (from F21 to F22)	F17-22	F17-18	F19-20	F21-22

of GC can occur continuously over multiple years, as it is driven by potentially persistent lower yields experienced by downstream farms, rather than being a one-time adjustment. The equations of GC adjustment were calculated as:

$$UGC = IGC - (CPHY + 1) * 10 \tag{5.1}$$

$$MGC = IGC - CPHY * 10 \tag{5.2}$$

Where UGC means the gate capacity of upstream farms; CPHY means the continuous lower yields years for downstream farms; and MGC means the gate capacity of midstream farms. The lowest value of UGC and MGC is 30 WU/tick (WU: water units, which are used to represent water volumes), which is also the lowest boundary of GC in this research.

5.2.3. SCENARIOS

Considering the combinations of 1) varied river discharge (RD) and gate capacity (GC), 2) the adjustment year of GC, 3) the continuity of good or poor harvests, and 4) the memory of harvest barley and water availability, the current model encompasses a total of 2880 possible scenarios (Table 5.2). The GC adjustment or variation (GCV) indicates whether the gate capacity is adjusted annually or every two years. The memory (M) of harvesting barley and available water is based on the past 10 years or 20 years, which influences the actual decision-making process. These variations in scenarios allow for a comprehensive exploration of the dynamics within the model, providing a wide range of possibilities for analysing the interactions and outcomes of the model irrigation system. The sheer amount of results also forces us to select a few specific scenarios to discuss the results of IRABM[3] (see below).

5.2.4. GINI COEFFICIENT AND LORENZ CURVE

The distribution of barley yields among farms in response to model system dynamics was analysed using the Lorenz curve and Gini coefficient – with the Gini coefficient derived from the Lorenz curve (Lorenz, 1905). To construct the Lorenz curve, we plotted the cumulative fraction of total yields (y) from lowest to highest against the cumulative fraction of the number of farms (x) from lowest to highest. This curve provides a visual representation of the distribution of yields among farms. The Gini index is calculated as the ratio of the area between the perfect equality line and the Lorenz curve (A) divided

Table 5.2: The overview of the parameters and scenarios.

Parameters	Value	Increment	Units	Scenarios
Simulation years	100	\	year	\
RD	50-600	50	WU/tick	20
GC	30-200	10	WU/tick	18
GC adjustment variation	1-2	1	year	2
Continuously poor harvest years	5	\	year	1
Continuously good harvest years	5	\	year	1
Harvest memory	10-20	\	year	2
Available water memory	10-20	\	year	2
Total	\	\	\	2880

Note: 1. Gate capacity adjustments are commonly influenced by factors such as crop rotation, crop varieties, water availability, climate variability, changes in irrigation system, soil conditions, and environmental regulations (Zhang et al., 2021). However, it's important to note that these factors exhibit a relatively stable pattern and/or are not within the scope of consideration in our current research, specifically within our study area. Moreover, our research exclusively focuses on the cultivation of barley, and our decisions regarding GCV are predicated on the comparison of yields among farms. As a result, we have chosen to implement an annual basis for GCV adjustments in our study. Initially, we conducted model runs using GCV values of 1, 2, 3, 4, and 5 years. However, when analysing the outcomes for GCV values of 3, 4, and 5 years, it became evident that these adjustments offer minimal benefit to farms experiencing poor harvests – their yields remain largely unaffected, or any improvements are marginal at best. Notably, a trend emerges where higher GCV values correspond to diminishing assistance. Consequently, we have opted to exclusively present GCV values of 1 and 2 years in this paper. 2. We have opted for the M of 10 years and 20 years for our analysis based on the following considerations: 1) Farming decisions are often informed by past experiences, such as weather patterns, soil conditions, crop performance, pest and disease occurrences, and other elements influencing agricultural outcomes; 2) While some farmers possess traditional knowledge handed down through generations, offering insights spanning decades or even centuries, others might have a more limited historical perspective due to being newer to farming practices; 3) It is important to acknowledge that rapid shifts in agricultural systems can constrain the depth of historical experience, owing to changes in methodologies and technologies; 4) Notably, there is a lack of detailed historical records pertaining to agricultural practices in Southern Mesopotamia, further affecting the scope of available evidence; 5) We aimed to provide a substantial historical perspective which allows to capture long-term trends and patterns in factors such as climate, crop, and water. It is important to note that the choice of a 10 and 20-year period for farmers' memory years is context-dependent. The specific length of the memory period is determined by the research objectives, the nature of the agricultural system under study, and the availability of reliable historical data. We aim to strike a balance between capturing meaningful trends and maintaining practical relevance for farmers' decision-making. 3. \ - The parameter associated with this category lacks a specified value.

by the total area under the perfect equality line (A + B) (Figure 5.3). Per definition, the Gini coefficient ranges from 0 to 1, with a coefficient closer to zero indicating a more equal distribution of yields among farms. Often, a Gini coefficient value of 0.4 is considered a "warning line" for income (or yields in our research) distribution gaps, indicating a significant level of inequality in the distribution of wealth among users (Sitthiyot and

Holasut, 2020). The calculation equation of the Gini coefficient is as follows (Harch et al., 1997; Sadras and Bongiovanni, 2004):

$$G = 1 - \int_0^1 \mathrm{L}\mathrm{d}_x \tag{5.3}$$

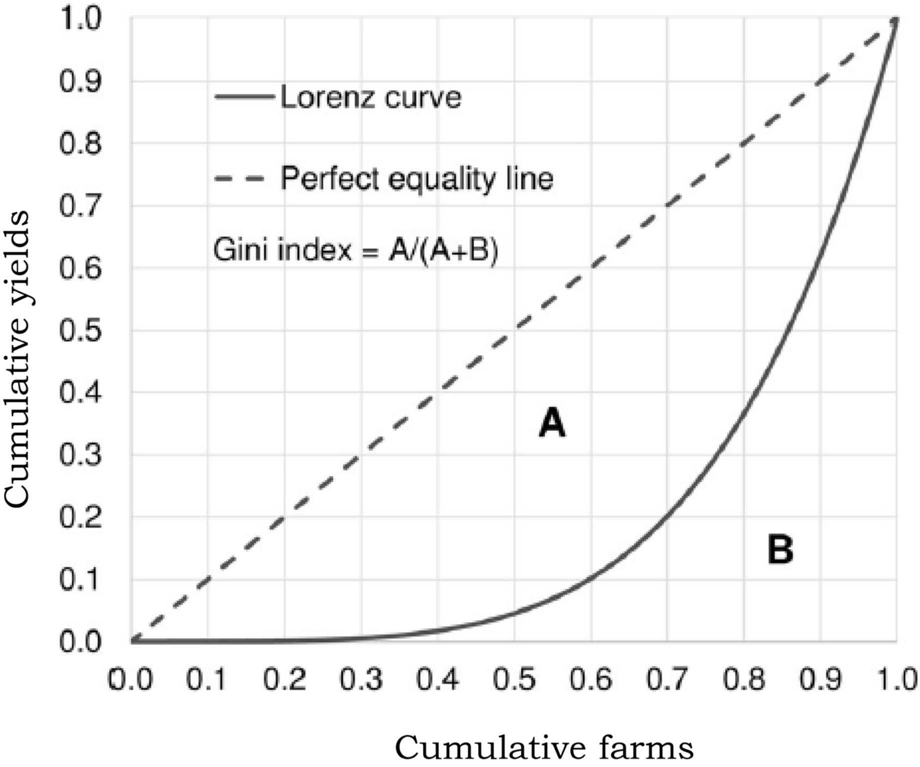


Figure 5.3: Lorenz curve.

5.3. RESULTS

5.3.1. THE MOVEMENT PATTERNS OF FARMS AND CANALS

The movement year of F8-10

As mentioned, the design of IRABM[3] allows for a maximum of two movements in case yields are low, depending on water availability. The first movement involves relocating F8-10 from the initial primary canal to a newly established secondary canal when their yields along the original primary canal prove to be inadequate. Regrettably, should F8-10 continue to experience poor harvest even after transitioning to the new secondary canal, the second movement will be initiated. This involves relocating F8-10 from the secondary canal to a new primary canal 2 (Figure 5.4). Depending on water and time controls, the movement time of F8-10 varied considerably in the different scenarios (Table 5.3).

- For RD = 50 WU/tick, the two movements are always completed by the model (agents). For each movement, the movement year varies with increasing GC: the year increases first before decreasing to a value, that is kept until the highest simulated GC. Harvest memory and available water memory create differences in the movement year, with the combination of lower GC – higher M creating an earlier movement year.

- For RD = 100 WU/tick, the first movement occurs only when the GC is higher – indicating that in many cases the yields are not too bad. When GCV is set to 1 year, the movement occurs when the GC exceeds 140 WU/tick. When GCV is set to 2 years, the movement takes place when the GC is above 110 WU/tick. Moreover, the movement year increases as the GC increases for M = 10 years, whereas the movement year remains constant regardless of the GC levels when M = 20 years. The table also suggests that expansion occurs for RD = 100 WU/tick when GC < 60 WU/tick or GC > 110 WU/tick.

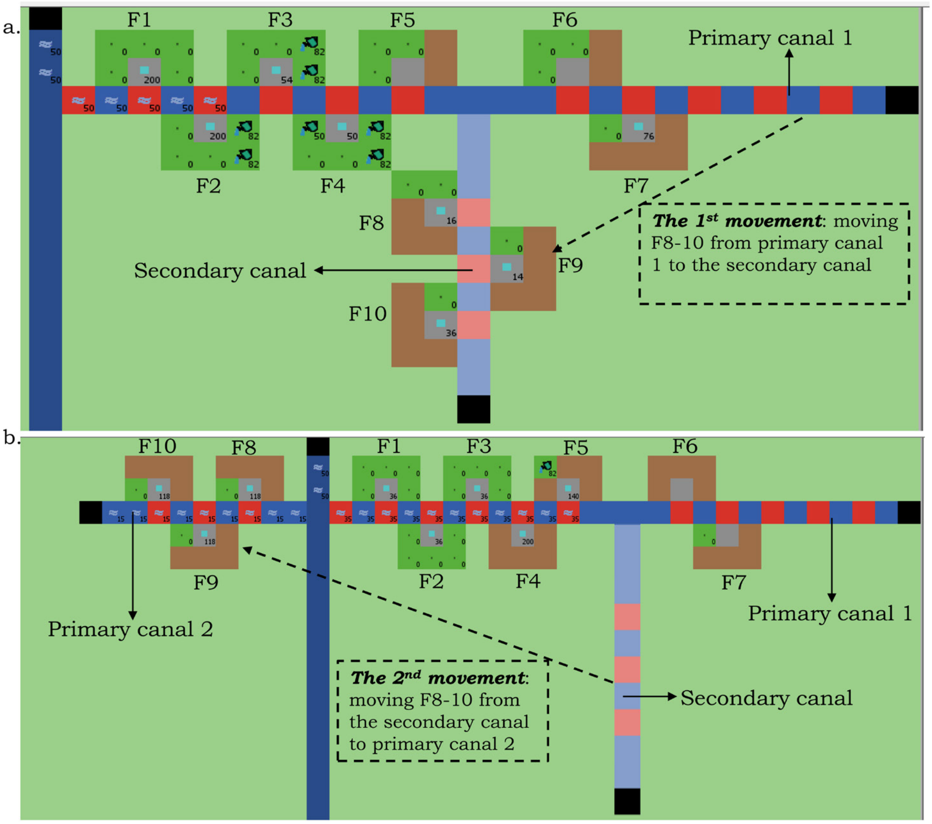
- An intriguing discovery for M = 20 years is that in several situations farms first relocate due to poor harvest situations, after which the system expands as a result of the substantial profits generated by F8-10 (in the table indicated with "E"). This indicates the success of the F8-10 movement, as it did not only benefit farms but also benefit the entire system leading to an increase in total yields and attracting more farms to join the system. We discuss expansion because of good harvests further below.

Table 5.3: The movement year of F8-10 when there is poor harvest situation.

Controls	RD (WU/tick)	Two movements	GC (WU/tick)														
			30	40	50	60	70	80-110	120	130	140	150	160	170	180	190	200
M = 10 years, GCV = 1 year	50	1st	18	39	39	39	17	14	14	14	14	14	14	14	14	14	14
		2nd	28	49	49	49	27	24	24	24	24	24	24	24	24	24	24
	100	1st	16E	17E	17E	\	\	\	\	\	\	10	11	12	13	14	15
		2nd	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\
M = 10 years, GCV= 2 years	50	1st	18	39	39	39	13	14	14	14	14	14	14	14	14	14	14
		2nd	28	49	49	49	23	24	24	24	24	24	24	24	24	24	24
	100	1st	16E	17E	\	\	\	\	10	11	12	13	14	15	16	17	18
		2nd	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\
M = 20 years, GCV= 1 year	50	1st	33	33	33	20	20	20	14	14	14	14	14	14	14	14	14
		2nd	43	43	43	30	30	30	24	24	24	24	24	24	24	24	24
	100	1st	16E	17E	17E	\	\	\	\	\	\	10	10	10	10	10	10
		2nd	\	\	\	\	\	\	\	\	\	30E	32E	32E	33E	33E	35E
M = 20 years, GCV = 2 years	50	1st	33	33	33	20	13	14	14	14	14	14	14	14	14	14	14
		2nd	43	43	43	30	23	24	24	24	24	24	24	24	24	24	24
	100	1st	16E	17E	\	\	\	\	10	10	10	10	10	10	10	10	10
		2nd	\	\	\	\	\	\	35E	36E	38E	40E	43E	44E	47E	49E	50E

Note: E – expansion of the farms and canals after the movement. \ - movement situations are not applicable.

In summary, for RD = 50 WU/tick, the variation of M and GCV have little influence on the movement year. For RD = 100 WU/tick, the variation of memory influences the



The 1st movement: moving F8-10 from primary canal 1 to the secondary canal

The 2nd movement: moving F8-10 from the secondary canal to primary canal 2

Figure 5.4: The layout of irrigation system regarding the two movements. The figure illustrates two sequential movements: a, The 1st movement, occurs when unfavourable harvest situations persist for at least 5 years among farmers situated upstream, midstream, and downstream along the initial primary canal. At this point, the system contemplates initiating a secondary canal and relocating downstream farmers (F8-10) to this secondary canal in order to assist them in enhancing their crop yields. b, The 2nd movement, If F8-10 still experience poor harvests at the new location in comparison to F1-7 who stay along the initial primary canal, the system will consider establishing a new primary canal. This would involve transferring F8-10 from the secondary canal to the new primary canal, thereby aiding them in improving their yields.

movement situations – farms tend to move earlier with a longer memory, with subsequent expansions along the secondary canal after the initial movement.

The influence of movement to farms

The influence of movement on all modelled farms is shown in Figure 5.5. The figure may be a little complex, but demonstrates that the movements have a more intricate impact on farms for RD = 50 WU/tick compared to when RD = 100 WU/tick. To start with the higher RD, for this RD = 100 WU/tick, the movement had no impact on F1-5. In contrast, F6 experienced lower yields and F7 initially had lower yields for the first few years but then returned to initial levels. However, the movement proved beneficial for F8-10, as they could increase yields. For RD = 50 WU/tick, the impact on the farms that did not move (F1-7) exhibits many more variations:

- F1 and F2 consistently maintain their barley yields, unaffected by the movements.
- The first movement has no effect on F3, but the second movement reduces yields for this farm.
- Starting from F4, the impacts of movements on farms become more complicated. For certain GCs, F4 manages to maintain yields after the first movement but experiences a decrease after the second movement – especially in scenarios with M = 20 years. For other GCs, F4 consistently experiences a decline in yields.
- Starting from F5, farms are no longer able to retain their initial yields after the first movement of more downstream farms. For GCV = 1 year, there are two situations regarding the impact on F5: either yields decrease twice or they increase after the first movement but decrease after the second movement. For GCV = 2 years, in one situation F5's yields decrease after the first movement and increase after the second.
- Yields of F6 and F7 decreased twice due to the movements under all scenarios. F6 always had no yields after the second movement, while for F7, the first movement reduced its yields to zero.

According to Figure 5.5, the movements influenced F8-10 (the farms that actually moved) differently as well. F8 benefitted the most from the decision to move, as its yields increased after both movements. The movements also helped F9 achieve higher yields – either maintaining initial yields and then increasing or increasing twice. However, the two movements did not lead to an increase in yields for F10. While F10 experienced an increase in yields in the first few years, the successful movement and expansion of F8 and F9 resulted in these two farms acquiring more water for their own farmland expansion. Consequently, after a promising start, F10 continued to experience what most downstream farms in a gravity system may face: less water for irrigation and eventually having no yields.

The influence of movement on the irrigation system

Figure 5.6 illustrates the comparison of total system yields before and after the movements for RD = 50 and 100 WU/tick. In the case of RD = 100 WU/tick, it is evident that total system yields increase following the movement – with a generally decreasing trend in total yields as GC increases. In contrast, for RD = 50 WU/tick, the situation is more diverse. Under certain GCs with GCV = 1 year, there is a decrease in total yields after the first movement. Furthermore, when GCV = 2 years, total system yields are lower after the first movement when GC exceeds 130 WU/tick. However, regardless of the scenarios, total system yields increase after the second movement. The movements had less influence on the head farms, but affected tail farms. Initially, movements were able to address poor harvest situations, but once the farms relocated and settled in new areas, the issue of how to share the common pool water resource Ostrom and Gardner, 1993 arose once again. As a result, the improvement in yields for farms did not align consistently with the improvement of the overall system. These sensitivity analyses indicate that factors

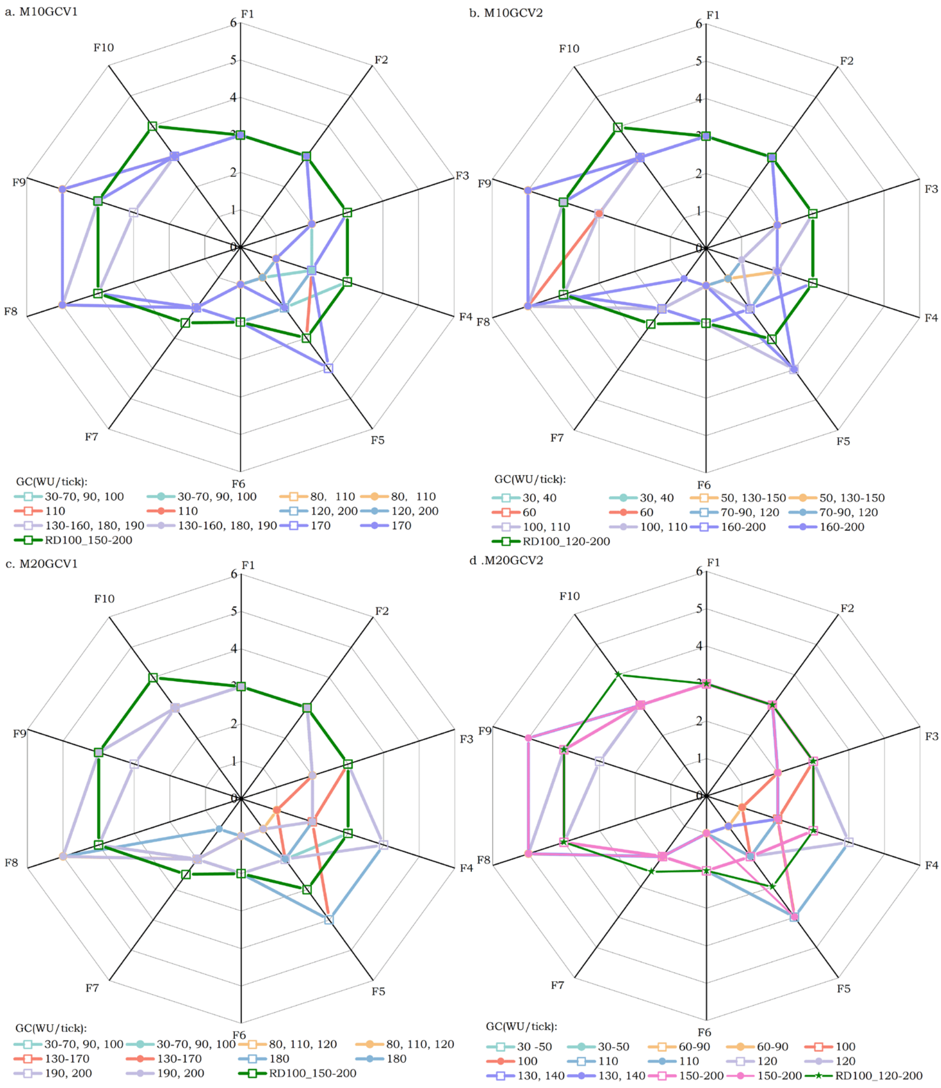


Figure 5.5: The influence of movement to farms. Numbers 1-5 were used to present the yields change of farms after the two movements: where 5-further increase (yields increased again after the second movement); 4-increase (yields increased after the first movement); 3-keep (yields remained the same after two movements); 2.5-decrease after the first movement and then increase after the second movement; 2-decrease (yields decreased after the first movement); 1-further decrease (yields decreased again after the second movement). M10, M20 – memory of 10, 20 years; GCV1, GCV2 – adjust GC every year, every two years. Line + square shows the influence of the first movement while line + dot shows the influence of the second movement. For RD = 100 WU/tick, there is only one movement shown with deep green. All of the other colors show the situation of RD = 50 WU/tick and are sorted with different GC groups.

such as the location of farms along the same canal, GC, RD, and the time of movements have a significant impact on farms' yields. On the other hand, the memory years and GC variation years have a relatively minor influence on farms' yields.

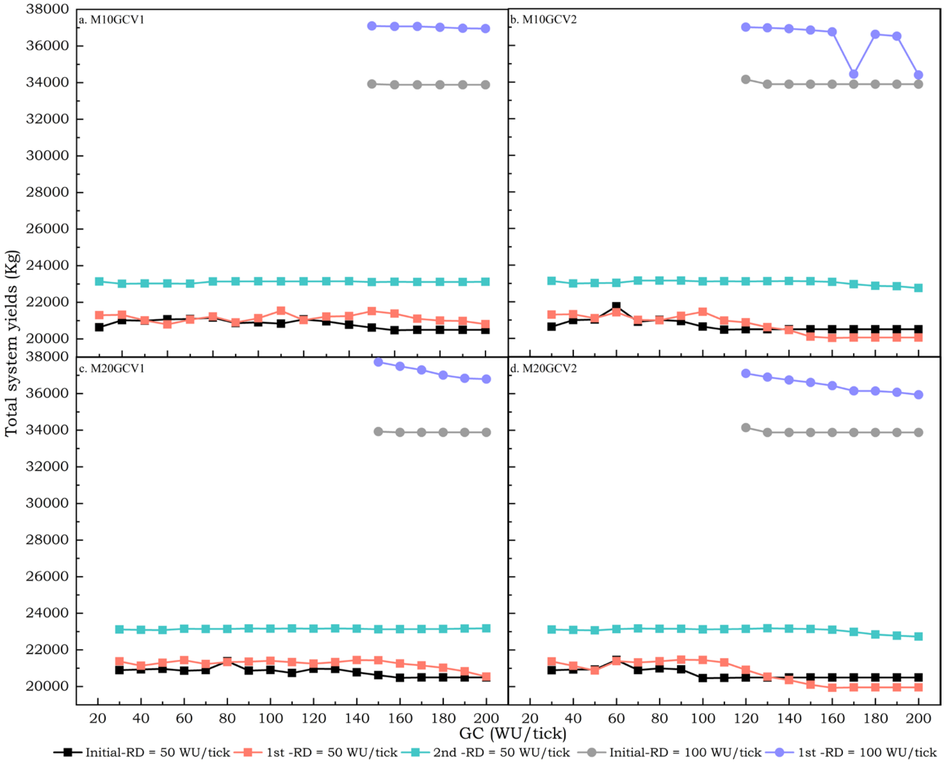


Figure 5.6: The influence of movement to the total system (10 farms).

5.3.2. THE EXPANSION OF FARMS AND CANALS

The eight consecutive expansion decisions implemented in this model (Figure 5.2) contribute to the gradual growth of the irrigation system. For the largest model area that we can reach in IRABM^3, F1-10 are situated along the original primary canal 1, F11-16 are along the new secondary canal, and F17-22 are along the new primary canal 2 (see Figure 5.7). Each expansion resulted in an overall increase in total system yields, although the impact on farms varied.

The expansion year of new farms (F11-F22)

Overall, our model results indicate that combinations of RD and GC have the potential to trigger expansions in any given year, but that actual expansions of new farms exhibit notable variation depending on the combinations of RD and GC. To simplify the visualization and explanation in this section, we categorized expansion years into five levels. In this text, we will introduce the farms' expansion year patterns with M = 10

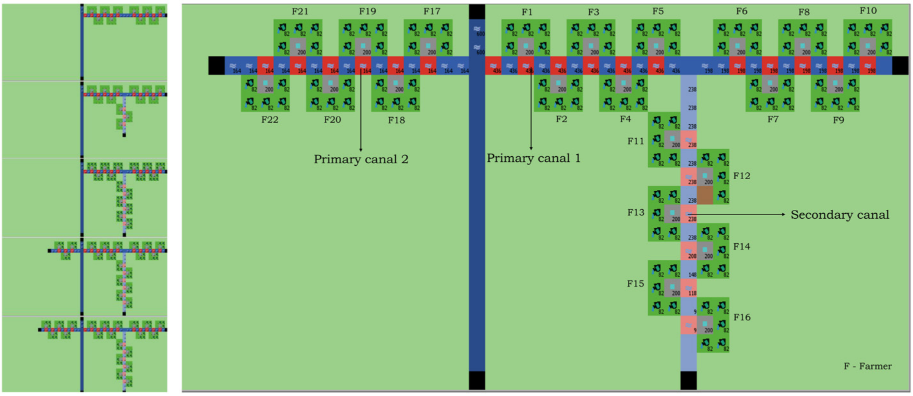


Figure 5.7: The sequence of expansion (left) and the fully expanded irrigation system (right).

years and GCV = 1 year in detail (Figure 5.8). Details for the other three M and GCV combinations can be found in Figures B.1, B.2, and B.3 in Supplementary Material B.1.

When RD = 150 and 200 WU/tick (the lowest two rows in Figure 5.8), the system could not fully expand:

- For RD = 150 WU/tick, only F11-13 expanded, finishing in Expansion Year Level 1 (EYL1 – for definitions of this and other terms used in this overview see Figure 5.8).
- For RD = 200 WU/tick, the system could be expanded to F21: F11-13 expanded in EYL1 under all GCs scenarios; F14-21 expanded under some GCs scenarios – F14 and F15 expanded in EYL2, EYL3, and EYL5, F16 expanded in EYL3, EYL4, and EYL5, F17-19 expanded in EYL3 and EYL5, while F20 and F21 only expanded in EYL5.

When RD >= 250 WU/tick, the system could fully expand, but not for all GCs:

- EYL1: F11-13 could expand in this level under all combinations of RDs and GCs, while F14 could also expand in this level except for when GC = 30 and 50 WU/tick.
- EYL2: when RD = 250 WU/tick, F15 expanded with most GCs, while F16 finished expansion with three GCs; when RD > 250 WU/tick, F15-19 could finish the expansions except for some combinations of GC > 110 WU/tick and RD = 300-450 WU/tick.
- EYL3: when RD = 250 WU/tick, F16-19 expanded with most GCs; when RD > 250 WU/tick, F20-21 could finish the expansions except for some combinations of GC > 110 WU/tick and RD = 300-450 WU/tick.
- EYL4: only 7 scenarios show that farms expanded in this level: F16 (RD = 200 WU/tick and GC = 150 WU/tick); F17-19 (RD = 250 WU/tick and GC = 180-200 WU/tick), F21 (RD = 300 WU/tick and GC = 60 WU/tick), and F21 (RD = 350 WU/tick and GC = 70-80 WU/tick).

- EYL5: F20-22 expanded in this level when RD = 250 WU/tick with most GCs; when RD > 300 WU/tick, F20-21 expanded in this level with GC = 30-50 WU/tick, while both of higher RD and GC show more F22 expanded situations in this level.

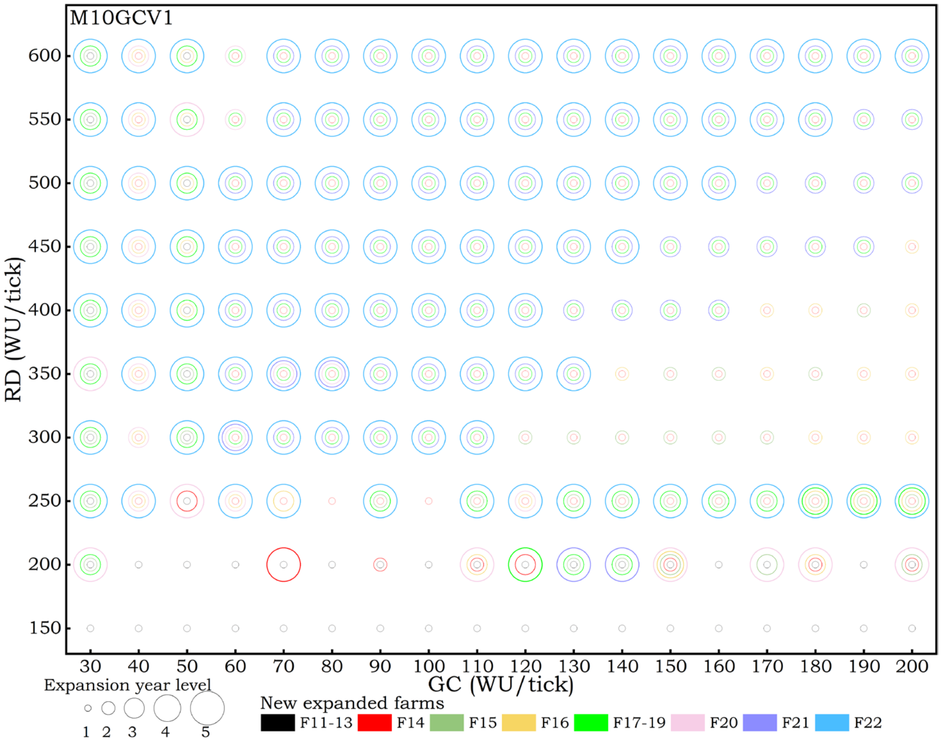


Figure 5.8: The expansion year of new farms when there is a good harvest situation. For Expansion Year Level: 1-expansion in years 10-27; 2-expansion in years 28-45; 3-expansion in years 46-63; 4-expansion in years 64-81; 5-expansion in years 82-100. There is no relation between the size of the expansion year level and the id of the new farms. The farms could be expanded in any year, for instance, when GC = 70 WU/tick, F14 expanded in level 5 with RD = 200 WU/tick while F14 expanded in level 1 with RD = 250 WU/tick. The combinations of RD and GC could bring all possible expansion years for all new farms.

For different M and different GCV, there were no clear differences observed in terms of the expansion year or the number of farms involved in the expansion. A more or less consistent pattern can be detected from the figures (Figures 5.8, B.1, B.2, and B.3):

- Across all RDs, the expansion of F11-13 was completed before the 28th model year, categorizing it as EYL1. However, only one expansion took place when RD was set to 150 WU/tick.
- More expansions commenced when RD increased to 200 WU/tick, although the first fully expanded irrigation system was only achieved when RD reached 250 WU/tick.

- With more farms or more farmlands in the system, the expansion years occur later.
- To be fully expanded, both RD and GC played vital roles. The combinations of higher RDs and low to upper-medium-range GCs had a higher likelihood of achieving full expansion. These combinations actually resulted in a more equitable distribution of water in the irrigation system as well (which may also be an important factor for successful societal development, see further below).

The influence of expansion to farms

Due to the complexity of the different aspects of farms expansion and the effects, it is difficult to present the results through figures. Therefore, in this section, we provide a simplified explanation of the findings. Throughout the expansion process, F1-6 consistently achieved the highest yields, regardless of the progression of the expansion. When analysing the original dataset of farm yields after the expansions, it was observed that expansions had an impact on the yields of F7-20. As the expansions were implemented gradually, the farms who expanded earlier were inevitably impacted by those who expanded later. Among the impacted ones, F9-12 were most affected by expansions. However, it is important to note that the yields of the affected farms did not drop to zero. There was still some yield despite the (influence of the) expansions. This general observation brings us to the (in)equalities in annual barley yields within the model farms' communities.

5.3.3. BARLEY YIELDS INEQUALITY

In total, we have 18 GCs to analyse for potential unequal yields with a series of RDs. As values in the ranges of GC = 30-50 WU/tick, 60-140 WU/tick, and 150-200 WU/tick show similar patterns for each range, we focus on three specific cases: (GC = 30, 120, and 200 WU/tick) to clearly illustrate the Gini variations (Figures 5.9, 5.10, and 5.11). As demonstrated earlier, the dynamics of the irrigation system were minimally affected by M and GCV. Therefore, for these GCs, the Gini variation is presented for different RDs for the combination of M = 10 years and GCV = 1 year. For information regarding the Gini values for other GCs, please see Supplementary Material B.2 (Figure B.4).

The fluctuations of Gini values over time are readily observable in each figure. Fluctuations align with the expansion periods of farms and canals. Gini values tend to be higher in the years directly following an expansion or movement, and gradually decrease over time afterwards. This indicates an initial increase in inequality of yields during the early stages of expansion or movement, which subsequently decreases until the next expansion or movement occurs. The new farms initially cultivated one field on their model farmland and then expanded their farmlands based on their experienced successes. Consequently, the yields of farms exhibited significant variation in the early years, but gradually became more similar over time. This trend may illustrate the potential tension in irrigated landscapes, when individuals decide to change something to improve their position, with potential negative effects on the short term for equal distribution of benefits. It is not automatically given that the farms whose actions are affected will accept such a change, even when on the longer term the larger group might benefit. This example illustrates the importance of taking short-term interactions into account:

what might become beneficial on the longer term may not become reality because of inequalities and consequent struggles on the short term.

The highest Gini values are observed for the lowest RD (50 WU/tick). These values often exceed 0.4, which surpasses the warning threshold for inequality. This assertion is further supported by Basri and Lawrence (2020), who highlighted the relationship between house size inequality and urbanism. Their research indicates that Gini values for rural agricultural settlements below 5 hectare consistently remain below a Gini value of 0.4. For RD exceeding 50 WU/tick, the Gini values remain below 0.4, indicating a more equitable (but not equal) distribution of annual yields. For each higher RD, Gini values gradually have fewer fluctuations over time and stay at lower values. For RD = 600 WU/tick, which is also the highest simulated RD in our research, Gini values are consistently low with only slight fluctuations. These observations support the obvious observation that expansion is easier when sufficient water is available, as a more equal distribution of yields among farms reduces competition for resources. It also creates a potential opportunity to share the surplus with new members of the system. Sufficient resources facilitate a more equitable distribution of resources. However, when systems expand even further – beyond our modelled maximum area – it is to be expected that relative scarcity of water will put pressure on the equal sharing of wealth – possibly leading to some actors shifting activities, like trade or crafts, as for example discussed in Zhu et al. (2018) for the Hohokam irrigated areas (located in modern Arizona).

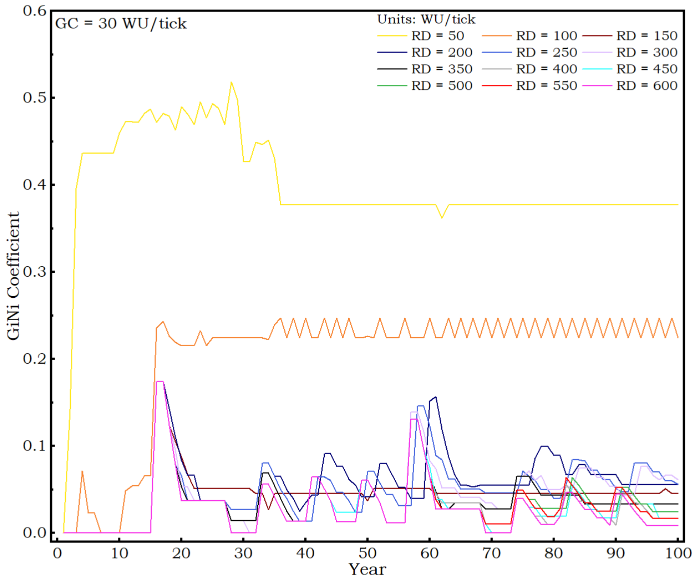


Figure 5.9: Barley yields Gini coefficient through 100 years (GC = 30 WU/tick).

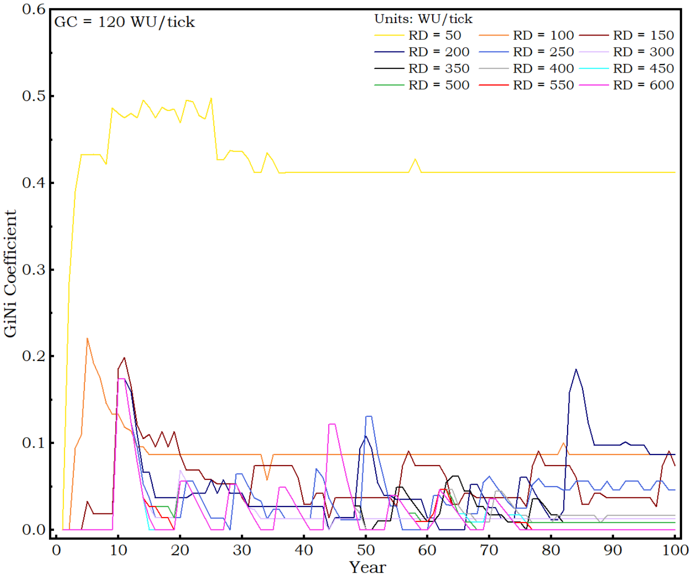


Figure 5.10: Barley yields Gini coefficient through 100 years (GC = 120 WU/tick).

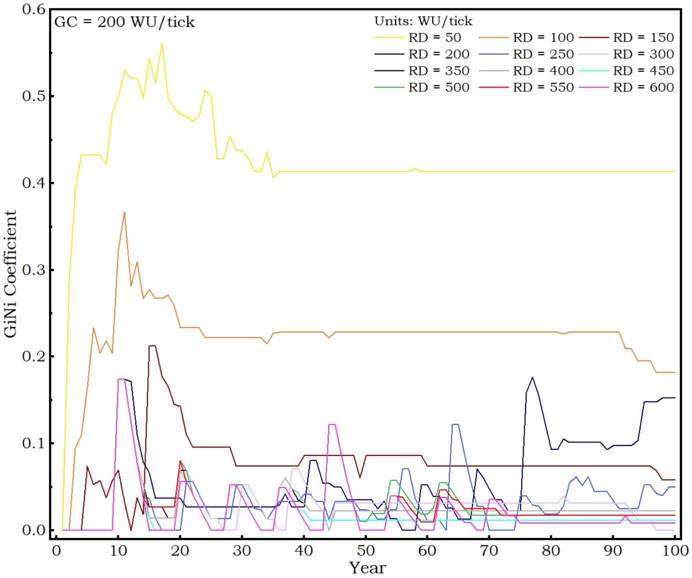


Figure 5.11: Barley yields Gini coefficient through 100 years (GC = 200 WU/tick).

5.4. DISCUSSION

5.4.1. DECISION-MAKING MECHANISMS IN IRABM^3

The findings of this study highlight the capabilities of IRABM^3 in capturing the complexities of decision-making in irrigation system use and management. The results emphasize that key factors influencing barley yields in response to farms' decisions include RD, GC, farms' location, and the independent or collective outcomes arising from those decisions. These factors are closely connected to (the distribution of) water availability, aligning with the inherent nature of irrigated agriculture and corroborating existing literature in the field (D'Odorico et al., 2020; Gomez-Zavaglia et al., 2020; Rosa et al., 2019). These factors contribute to the complexity of irrigation systems, including the dynamics of farmlands and the expansion or movement of canals and farms. This indicates that the current model effectively captures decision-making mechanisms operating at different levels, as per the objectives of the agents involved. Decision-making is a multifaceted process that involves both independent and collective dimensions. Commonly, initial decisions made at lower levels have the potential to develop into decisions at higher levels. These collective decisions can have varying degrees of impact on the agents involved, shaping the dynamics of the system (Ertsen et al., 2014; Holman et al., 2019; Wens et al., 2019). Please note again that we did not specifically assume who would make these decisions: we did include decisions related to different locations in the model system.

Generally, one could expect stakeholders in irrigation systems to be willing to share limited water resources (D'exelle et al., 2012; Geertz, 1972; Li et al., 2019; Tilmant et al., 2009). However, when farm(er)s make decisions, they often prioritize their own goals without considering to directly the demands of others. These actions exacerbate the issue of "common pool resource management" (Albiac et al., 2020; Ostrom and Gardner, 1993). Through more collective (or coordinated) decision-making processes, such as adjusting the GC for water reallocation in our model, it is possible to partially improve the yields of farms experiencing poor harvests. We propose that incorporating direct social interactions among farms in the modelling, such as neighbourhood effects, can create further options to study the effects of addressing unequal water distribution by model agents (Bell et al., 2016; Rasch et al., 2016).

From a broader perspective of irrigation systems (Ertsen et al., 2014; Merot et al., 2008; Robertson and Wang, 2004), we argue that the intricate relationship between irrigation activities and water availability, the heterogeneity with collective system and farms characteristics, the relevance of short and long-term decisions, and the uncertainty associated with crop production, are important properties of decision-making. Understanding and accounting for these properties are crucial in comprehending and analysing decision-making dynamics in the context of irrigation systems. The framework proposed in this research for structuring irrigation-related ABM is the third version, which is built upon two previously introduced frameworks (Lang and Ertsen, 2022a, 2022b). Additionally, it incorporates elements of the Overview, Design concepts, and Details + Decision-making (ODD + D) protocols to comprehensively describe decision-making processes within ABMs. This framework provides a holistic approach to understanding irrigation systems by considering both farms and collective irrigation system perspectives, thus enhancing the overall descriptive capacity of the IRABM^3 model.

5.4.2. THE DYNAMICS OF FARMLANDS, FARMS, AND CANALS

The IRABM^3 effectively captures the processes of expansion/reduction of farmlands and the expansion/movement of canals/farms. Furthermore, the model extensively explores the dynamic interactions arising from decision-making across different levels. In gravity-based irrigation systems, it is observed that upstream farms tend to achieve higher yields and can consider expanding their farmlands, whereas downstream farms experience lower or no yields and may contemplate reducing (part of) the farmlands. These findings highlight the presence of "common pool resource" issues, wherein conflicts arise due to the sharing of limited water resources when the irrigation management decisions of upper farms impact the agricultural productivity of lower farms (Becu et al., 2003).

It is important to note that achieving one's personal goals in this context may come at the expense of sacrificing the profits of others (Murphy et al., 2019). However, in cases where collective action, such as water redistribution, is implemented in the system, farms have the opportunity to keep maximizing yields within a farm while also assisting farms – with lower yields – apparently sharing water does not automatically reduce yields of upstream users. Our results show the complexity of yields pattern and farmlands pattern – the (partial) improvement of poor harvest situations with 1) the increase of total system yields; 2) the sacrifice of upper farms and an increase of total system yields; 3) the sacrifice of upper farms and a decrease of total system yields; and 4) the expansion or reduction of farmlands, which aligns with the corresponding changes in yields.

The expansion and movement patterns of farms and canals in our model environment can be simplified as follows: if the annual decision-making regarding farmland dynamics and GC adjustment leads to a mutually beneficial outcome for farms and the irrigation system, and this situation persists over time, the model system will prioritize the inclusion of more farms, construction of new canals, and gradual development towards a more fully established irrigation landscape. Conversely, if the annual decision-making fails to improve the poor harvest situation, the model system will consider relocating the affected farms to a different canal. These patterns reflect the ongoing efforts to optimize the irrigation system based on the outcomes of continuous decision-making processes – in our model based on annual results. These phenomena support the theory that short-term, farm-level decision-making has the potential to drive long-term, community-level development (Ertsen et al., 2014; Ertsen, 2016). The decisions made by farms in the short term, such as optimizing their own yields and addressing immediate challenges, can collectively contribute to the overall progress and development of the irrigation system over time. This highlights the interconnectedness between actions at farm level and the broader community outcomes, emphasizing the importance of considering both short-term and long-term perspectives in decision-making processes. Please note that both (or a combination of) the expansion of successful system and the movement of unsuccessful farms to new systems may have created an expanded irrigated area as it would have developed in ancient Southern Mesopotamia. It is likely that the distribution of benefits would have been a key factor in Mesopotamia's history.

5.4.3. YIELDS INEQUALITY IN THE DEVELOPING IRRIGATION SYSTEM

Actually, many archaeologists have put forward the notion that water availability was never a limiting factor impeding the growth of the irrigation system in Southern Mesopotamia as water regimes of Tigris and Euphrates could support the diachronic development of irrigation management from dispersed, small-scale to large-scale, and finally to empires-scale (Adams, 1981; Rost, 2017; Wilkinson et al., 2015; Wilkinson and Jotheri, 2021). The application of the Gini coefficient to barley yields has allowed us to analyse the distribution of yields among farms and examine the degree of inequality within the system. These findings not only support current narratives and knowledge about the region but also shed light on additional aspects that can be explored in future studies. Our analysis of Gini values reveals that the distribution of barley yields within the growing irrigation system was relatively equal. This implies that while river discharge is a significant factor influencing the harvest situation and decision-making, the same water supply does not seem to create unequal development of/within the irrigated areas.

One intriguing finding from the analysis of the Gini coefficient is the correlation between its fluctuation and the dynamics of the irrigation system. The Gini values consistently exhibited a pattern of increasing to a peak value in the first year of expansion/movement, followed by a gradual decrease to a certain level that was maintained for several years. Subsequently, the values exhibited a cycle of periodic increase and decrease until the end of the simulation period. Remarkably, this pattern of Gini values increasing at the initial stage after expansion aligns with archaeological evidence that highlights the occurrence of increasing inequality during the early stages of urbanization or the transition from small-scale to large-scale communities, with the formulations of new social, economic, and political arrangements (Baker, 2023; Basri and Lawrence, 2020). However, our study exclusively concentrates on the expansion of farmlands and canals, as opposed to delving into the unconstrained expansion of farmlands. Taking this perspective, it becomes conceivable that larger farmland sizes could lead to higher Gini values. This conjecture totally aligns with earlier research that has demonstrated a consistent rise in Gini values corresponding to larger house sizes (Basri and Lawrence, 2020; Squitieri and Altaweel, 2022). If we can include measuring Gini values with the agricultural land size, our research would furnish and endorse a viewpoint concerning the urbanization of societal development.

5.4.4. MODELLING ADVANTAGES AND CHALLENGES

Our IRABM^3 framework offers several notable advantages. One key advantage lies in its ability to integrate essential concepts such as the willingness to on individual (farm) and collective (system) levels (Mezgebo et al., 2022), decision-making (Elsawah et al., 2015), and different agent types (Kaiser et al., 2020). By combining these elements, the framework provides a comprehensive approach that captures the complexity and interplay of factors involved in the decision-making processes within an irrigated agricultural context. According to our model design, the irrigation decision-making takes place on three-time scales: 1) the decision-making process for farmland dynamics occurs on an annual basis, 2) the GC adjustment is considered either annually or every two years, and 3) system expansion or movement is evaluated based on at least five years of harvest data. Meempatta et al. (2019) summarized the temporal scales of irrigator decision-making into three categories: tactical (decisions made within a short-term time frame of less than one year), strategic (decisions considering medium-term goals and objectives that span one to five years), and structural (decisions with a long-term perspective, extending beyond five years). Various studies have employed qualitative, quantitative, and mixed methods to model and analyse irrigators' decision-making processes on irrigation water management, farmlands management, and crop management (Arnall, 2014;

Dury et al., 2013; Gras, 2009; Marques et al., 2006; Meempatta et al., 2019; Navarrete and Le Bail, 2007; Niles et al., 2015). Related to these studies, the IRABM^3 framework demonstrates its robustness and reliability in simulating irrigator decision-making in irrigation management. The flexibility and generality of the framework can be extensively applied to irrigated agricultural systems worldwide, allowing for the investigation of long-term perspectives, such as the evolution of the irrigation system in Southern Mesopotamia. Another advantage of the framework is the incorporation of sensitivity analysis, which allows for the identification of influential factors affecting yields and decision-making. This could help to enhance the model's performance and policy relevance (Ligmann-Zielinska et al., 2014).

Obviously, we still face challenges in terms of data availability. Future research should aim to address these limitations and explore additional perspectives: 1) incorporating direct communication and interaction among farms into the model to provide a deeper understanding of different levels of patterns in irrigation systems that may have been previously overlooked; 2) acquiring additional relevant crop and water data for model validation to strengthen the model, and also contribute to the validation challenges of ABM in general (Filatova et al., 2013; Heppenstall et al., 2021).

We designed our virtual irrigation system with a maximum of 22 farms, two primary canals, and one secondary canal within a 100-year simulation. The outcomes of our model indicate the potential for further expansion of farmlands, an increase in the number of farms, and the construction of additional canals under conditions of higher water availability, enhanced communication among farms, or extended simulation time. This insight aligns with the historical development of irrigated landscapes in Southern Mesopotamia. Over time, these irrigated (hydraulic) landscapes underwent a transformation, progressing from areas along levees to areas natural or human-made canals, transitioning from small-scale to large-scale systems, eventually culminating in the establishment of systems under central management – including but not necessarily limited to the famous herringbone patterns (Altaweel, 2019; Rost, 2017; Wilkinson et al., 2015; Wilkinson and Jotheri, 2021). The Gini coefficient, when applied to farms' production, appears a promising tool for characterizing the development of an agricultural-based society. It is conceivable that by factoring in diverse forms of collective engagement, such as community-level administration, state oversight, and imperial patronage in the management of irrigated agriculture, the measurement of Gini values for yields could substantially contribute to research on societal structuring. Our study provides valuable insights into the progression and transformation of irrigation practices, as well as their influence on the development of irrigated societies in the region of ancient Southern Mesopotamia.

5.5. CONCLUSION AND OUTLOOK

We presented our irrigation-related agent-based model IRABM^3 to illustrate how patterns in irrigation systems can emerge from decisions made by heterogeneous agents. We demonstrate how various factors such as irrigation demand, river discharge, and gate capacity can shape the dynamics of these systems. Importantly, our model is designed to be flexible and adaptable, enabling its application to a wide range of irrigation systems, both historical and contemporary. Through our computational approach, we contribute to discussions surrounding the development of ancient societies in Southern Mesopotamia. Our sensitivity analysis demonstrates that the most influential factors affecting yields and decision-making are river discharge, gate capacity, farms' location, and the consequences resulting from decisions. Furthermore, our analysis suggests that the actions on farms and along canals may tend more toward realism than boldness for systems that have a longer-term existence. These findings align with intuition and illustrate the feasibility and robustness of using agent-based modelling to simulate an irrigation system.

The outcomes of our research on expansion patterns and movement patterns shed light on the varying impacts on farms and the irrigation system as a whole. We observed how farms located upstream and downstream can engage in checks and balances due to disparities in water availability resulting from decision-making at different levels. Our findings emphasize that while farms may prioritize their own interests when making decisions, these choices can have adverse effects on other farms. Similarly, collective decision-making regarding irrigation management can yield benefits for the overall system or part of farms but may also affect yields at the farm level. We also demonstrated how agents' decision-making and interactions contribute to the evolution of the irrigation system (or irrigated landscape). We applied the Gini coefficient to assess the yields inequality among farms, with Gini values exhibiting fluctuations that correspond to the progression of the irrigation system over a span of 100 years. When considering a larger time frame spanning thousands of years, the irrigation system in Southern Mesopotamia experienced gradual growth. The area underwent cycles of formulation, establishment, stability, and subsequent rounds of formulation, establishment, and stability. Our findings offer a reflection of the inequality in barley yields among farms and can provide valuable insights into the evolutionary trajectory of irrigation-based societies in Southern Mesopotamia, when further developed.

Southern Mesopotamia witnessed an expanding irrigated landscape, characterized by an increasing number of agricultural units over a long period of time. In our forthcoming research, we aim to extend the time scale of the irrigation system's evolution from one century to several millennia and also extend the spatial scale from 22 farms to fully developed irrigated landscapes with thousands of farms, enabling a deeper understanding of societal development. Specifically, we will investigate how the irrigated landscapes originated from smaller areas (associated with simple crevasses) and gradually transformed into larger areas (associated with fully developed hydraulic landscapes). To enhance the realism of our irrigation-related agent-based model, we propose incorporating additional (empirical) data, such as direct communication among farms, family cereal consumption, and farms' adaptive measures. We also aim to introduce communication between farms and areas/canals in terms of trade. This approach would not only improve the simulation of farms' activities but also facilitate the validation process. Abandonment of farms may have occurred because of the challenges that cultivators faced, for example in terms of water availability. Furthermore, over the course of time, farms encountered challenges such as soil salinization and silting in both canals and farmlands during their irrigation endeavours. Our subsequent studies could incorporate such issues that farms confronted by providing additional constraints on crop growth in the model, offering valuable insights into the resilience of irrigation agriculture within this region – as salinity and sediments may possibly affect movement decisions as well. Hydrological data and meteorological data could also be considered to understand how water and humans interacted, shaped, and influenced each other in ancient Southern Mesopotamia. Farm abandonment may actually also result from successful irrigation: as soon as yields of irrigated agriculture are higher than required to feed a population, some (groups of) cultivators may decide to abandon farming and focus on other productive activities (like pottery) and/or societal services (like religious activities). Such choices would have been especially possible in circumstances with well-developed trade relations between areas. Thus, the study of irrigated landscapes' dynamics in Mesopotamia necessitates the exploration of both farm expansion and farm abandonment, which are intricate decisions shaped by a multitude of factors encompassing economic, environmental, and social dimensions. The comprehensive consideration of these factors is pivotal for facilitating a thorough exploration of farm dynamics to further develop our understanding of ancient Southern Mesopotamia.

6

DISCUSSION AND CONCLUSION

6.1. MAIN FINDINGS

This doctoral project developed a sequence of agent-based models focused on irrigation (IRABM → AIRABM → IRABM^3) within a framework emphasizing the interactions of human agents, non-human agents, and their related environment. The aim is to investigate interactions between irrigation-related agents and their decision-making processes, while also replicating the evelution processes of the irrigation systems (landscapes) in Southern Mesopotamia. These models encompassed various elements such as decision-making at different levels, interactions between human and non-human agents, diverse irrigation strategies, and agents' learning activities. The main conclusions corresponding to the research questions are as follows:

RQ1: How can agent-based modelling as an approach be used to design an irrigation-related agent-based model?

In Chapter 3, I introduced the IRABM, the first model designed to test the feasibility of simulating irrigation systems using ABM. My approach involved using non-human agents to represent human actions, enabling us to explore various scenarios such as different river discharges, varied gate capacities, diverse irrigation control methods, and multiple water allocation strategies. By incorporating water-realism and human-realism, I aimed to support the understanding of human-water interactions within the ABM.

The IRABM demonstrated how parameters such as river discharge, gate capacity, irrigation time, and farmers' locations are the main factors influencing barley yield patterns. My study primarily focused on water distribution through the control of hydraulic infrastructures and human-made strategies. By integrating both human and non-human agents and facilitating their actions and interactions, the IRABM served as a platform for investigating the dynamics of human-water systems. This theoretically and empirically informed computer model not only provides new insights into simulating human-water systems but also reveals how and why irrigation and yield patterns emerge within a dynamic environment. Additionally, I developed the model with an accessible user interface, enabling non-expert stakeholders to actively participate in the simulation process.

RQ2: How can ABM with different levels of decision-making reflect the farmland dynamics and yields pattern according to the farmers' experience?

In order to address RQ2, Chapter 4 introduces AIRABM, an enhanced version of the original IRABM. Compared to IRABM, AIRABM incorporates learning activities and decision-making processes and mechanisms. The model consists of two settings: the baseline model, which simulates varied river discharge and farm gate capacity without any interventions; and the second setting, where gate capacity adjustment strategies are implemented in response to poor harvest situations. The key findings of this study are as follows: 1) upstream farmers consistently achieve higher yields compared to relatively downstream farmers due to location priority without human intervention; 2) river discharge, gate capacity, and farmers' location have a significant impact on harvest situations; 3) both individual decisions (farmland dynamics) and collective decisions (gate capacity adjustment) greatly influence the variability of harvest situations.

AIRABM emphasizes farmers' decision-making processes and the associated uncertainties arising from water availability and harvest outcomes. This model provides insights into studying cooperation strategies for managing shared water resources among farmers. My research contributes to understanding the decision-making processes and mechanisms at both individual and collective levels, particularly in relation to water conflicts in irrigation management. It also highlights the importance of strengthening communication and cooperation among farmers to enhance the performance of irrigation systems. Once again, the model maintains flexibility by allowing for the adjustment of nearly all parameters, enabling its application to various irrigation systems worldwide and it serves as a platform for non-technical stakeholders to experiment with and experience different irrigation rules.

RQ3: How could small-scale processes of irrigation activities contribute to large-scale irrigation system development when modelling irrigation-based society in Southern Mesopotamia?

In Chapter 5, I addressed RQ3 by introducing IRABM^3, which builds upon the advancements of AIRABM. This model takes into account the dynamics within individual farmers and the larger system, considering both individual decision-making and collective decision-making processes. I investigated how various model parameters, such as river discharge, gate capacity, gate adjustment strategies, and the memory of water and yields, contribute to the emergence of different yield patterns, the expansion of farmlands, and overall system dynamics.

Through sensitivity analysis, I could say that river discharge, gate capacity, farmers' location, and the consequences resulting from decisions are the main factors affecting yields patterns and decision-making. The Gini coefficient analysis enabled me to assess the inequality in barley yields among farmers and gain valuable insights into the evolutionary trajectory of irrigation-based societies in Southern Mesopotamia. Moreover, the IRABM^3 offers flexibility in accommodating spatial and temporal variations within the irrigation system. This flexibility allows for the exploration of irrigation-based societies in Southern Mesopotamia on larger spatial and temporal scales, providing a broader understanding of the dynamics at play.

The main RQ: how can we use agent-based model to mimic the evolution processes of irrigation systems (landscape) in Southern Mesopotamia?

The main research question was effectively addressed through the studies of IRABM, AIRABM, and IRABM^3. These models were carefully designed with a combination of human agents (farmers, water managers) and non-human agents (river, water, gates, canals, farmlands, and barley) to investigate their interactions within their environment. The short-term yields patterns in the farmland, farmland dynamics of individual farmers, and system dynamics generated from varied scenarios show connections to the longer-term emergence of irrigation systems in Southern Mesopotamia. The findings of this project highlight the significant influence of water availability (river discharge, gate capacity), farmers' location, and decision-making by agents at different levels on barley yield patterns, farmland dynamics, and system dynamics. It is evident that the consequences and benefits of decision-making are complex and multifaceted. This research also demonstrates the trade-off of ensuring individuals' profits versus collective advantages during periods of water scarcity within the irrigation system. This dilemma holds significant importance in the effective management of water resources and the long-term sustainability of irrigation systems.

The IRABMs presented in this series demonstrate the potential and trustworthiness of utilizing ABM to simulate the operation of irrigation systems. By analysing the integration of ABM with the Gini coefficient, valuable perspectives on the developmental path of the irrigation system (landscape) in Southern Mesopotamia can be obtained. These findings highlight the feasibility and dependability of ABM as a tool for studying the dynamics of irrigation systems from a short-term perspective to a long-term perspective.

6.2. ADVANTAGES AND LIMITATIONS

Our project offers several notable advantages. Through this project, I delved into experimental models that incorporate intricate details of individual farmers and irrigation systems. By considering the actions and reactions among farmers and irrigation systems in various water scenarios, these models closely resemble realistic irrigation systems. Additionally, I conducted sensitivity analyses to explore the uncertainties in yields resulting from different water scenarios. This enhanced the performance and policy relevance of the models while showcasing their robustness. Furthermore, I designed these model frameworks with flexibility in hydrological variables, crop variables, and strategies. As a result, the models can be easily applied to diverse irrigation systems worldwide, regardless of their age or development stage. Notably, all these models were developed using the NetLogo environment, which facilitates accessibility for stakeholders, including non-technical individuals. NetLogo provides a user-friendly interface that allows stakeholders to observe the simulated irrigation environment and interact with adjustable variables through buttons and sliders, enabling them to explore different scenarios.

Obviously, I still faced challenges in this project. One challenge of this research is the scarcity of data. The lack of comprehensive historical data may restrict the extent to which the model accurately represents real-world conditions. Another challenge is related to the coupling of hydrological and crop models with the ABM. While this coupling enhances the model's complexity and potential for capturing intricate interactions, the incorporation of additional hydrological data, land use data, and crop growth data can further refine the model's level of detail. However, such an expansion requires access to diverse datasets, which may not be readily available or easily integrated. Incorporating direct communication and interaction among farmers is another challenge: the models' current representation of farmers' activities and interactions may have certain limitations. Although the model captures individual and systemic patterns in irrigation systems, it may overlook certain individual and localized dynamics that arise from direct communication and interactions among farmers. Integrating these aspects into the model could provide a deeper understanding of how individual decisions and social interactions shape irrigation practices.

6.3. RESEARCH CONTRIBUTION

This research aims to develop a series of ABMs focusing on irrigation systems. These models enable the interaction, adaptation, and decision-making of agents in response to changing parameters such as river discharge, gate capacity, various water allocation strategies, and learning behaviours. The contributions of this research are as follows:

IRABM

I conclude that IRABM provides a new perspective on modelling the human-water system, as non-human model agents can replicate the dynamics observed in realistic irrigation systems. Moreover, this type of modelling approach has a large potential to be theoretically and empirically used to explore the interactions between irrigation-related agents and understand how these interactions shape water and yield patterns. Furthermore, the user interface developed for this model allows non-technical stakeholders to actively participate and contribute to the modelling process. I built the model with the flexibility to accommodate different crops and their water demands, allowing the modelling framework to be modified for any irrigation system worldwide.

AIRABM

The AIRABM emphasizes farmers' decision-making processes and the uncertainty they face due to water availability and harvest outcomes, which can be used to study communication and cooperation among farmers and management in the context of shared resources. My findings provide meaningful suggestions to study and promote farmers' and management communication and (conditional) cooperation when facing common pool resources to improve the performance of irrigation systems. This research also provides the foundation for exploring how short-term activities contribute to long-term development.

IRABM^3

IRABM^3 serves as a foundation for future studies, by incorporating additional agents into the irrigation system and expanding the spatial-temporal scales of the irrigated landscapes, to reach a more comprehensive understanding of the evolutionary dynamics of irrigation systems in Southern Mesopotamia. Through my computational approach, including the analysis of the Gini coefficient, I contribute to discussions regarding the development of ancient societies in Southern Mesopotamia. By thoroughly examining the interactions among humans, water, crops, and hydraulic infrastructures, and employing decision-making from different levels, we can gain a deeper understanding of the long-term functioning and development of irrigation systems, both historical and contemporary.

The development and application of these ABMs in this research can contribute to the following advancements:

- Enhanced water management: the models can provide insights and support for water managers in achieving more equitable water distribution in irrigation management. By simulating different water allocation strategies and studying the interactions among agents, these models can offer valuable guidance for improving water distribution practices.

- Informed decision-making for farmers: the models can aid farmers in making better decisions regarding crop selection and irrigation scheduling. By considering factors such as water availability and harvest outcomes, the models help optimize decision-making processes, leading to improved agricultural practices.

- Advancement of knowledge: the development and application of these models contribute to our overall understanding of irrigation systems. By simulating the dynamics and interactions within these systems, we gain insights into their complexities and implications for both historical and contemporary contexts. This knowledge aids in improving irrigation practices, informing policy decisions, and addressing sustainability challenges associated with irrigation systems.

- Customized tuning for targeted requisites: the models were intricately fashioned to possess adaptability in manipulating a majority of variables and expanding spatial and temporal dimensions. This adaptability empowers the modelling framework to be flexibly modified to accommodate diverse irrigation systems across the globe, irrespective of their historical or contemporary, small or large-scale nature.
- Insights for archaeologists: the ABMs in this project can shed light on the emergence and development of irrigation-based societies. Archaeologists can utilize these models to gain a deeper understanding of historical agricultural practices and their societal implications, thus offering valuable perspectives on the evolution of these societies and their transformative effect on the natural environment throughout time.
- Comprehending environmental and human influences: the models delve into the complex connections between small-scale actions and processes, revealing their potential to drive substantial advancements in irrigation-based societal growth. These models illuminate the synergistic interplay between environmental dynamics and human activities. In doing so, they enhance our comprehensive comprehension of the evolutionary path taken by irrigation-based communities within this region and shed light on the intricate influence between these communities and their natural surroundings.

7

RECOMMENDATION FOR FUTURE WORK

7.1. CASE STUDIES WITH AN ACTUAL APPLICATION

The existing agent-based model frameworks for irrigation have showcased their applicability across various irrigation systems, providing realistic patterns of irrigation management. However, their implementation necessitates a historical context specific to the Southern Mesopotamia irrigation system, as well as a consideration of direct communication and interactions among farmers and irrigation water managers. By incorporating these factors, the models can offer valuable insights into decision-making mechanisms and agent interactions. Obtaining more extensive and reliable historical data for a specific case study would enable a more robust validation of the models' performance. This step is crucial in assessing the models' accuracy and reliability in capturing the dynamics of a specific irrigation system, and it would contribute to the overall advancement of irrigation research. Therefore, conducting research using a real case study becomes imperative to advance the field.

7.2. APPLICATION OF ABM IN IRRIGATION MANAGEMENT

This project demonstrates the utility of ABM in developing water allocation strategies for irrigation management, particularly in situations where water resources are limited within an irrigation community. The model outcomes shed light on the motivations of upstream farmers to adopt cooperative strategies that benefit both downstream farmers and the entire irrigation system in terms of profitability. Considering the dynamics of land use, climate, and population, it becomes important to extend the scope of cooperation beyond just upstream farmers (Okura et al., 2022). Exploring the motivations of all farmers within the same irrigation community towards cooperation provides researchers with insights into the underlying values that drive cooperative behaviours. To gain a comprehensive understanding of a specific case study, it is necessary to incorporate various human agents, including not only farmers but also entities such as the local government and the labour market. By incorporating these additional actors, researchers can gain a more holistic understanding of the complexities and interactions within the irrigation system, facilitating the development of more effective water allocation strategies.

In recent discussions, researchers have explored the potential and capacity of ABM and Complex Social Systems prediction or forecasting problems (Elsenbroich and Polhill, 2023; Chattoe-Brown, 2023; Edmonds, 2023; Anzola and Garcıa-Dıaz, 2023; Dignum, 2023; Elsenbroich and Badham, 2023; Carpentras and Quayle, 2023). Irrigation system as an example of complex social systems should not only consider the decision-making processes for the current situation but also involve the prediction for future scenarios. Building upon the incorporation of farmers' actions in the current project, I propose that irrigation-related agent-based models should further integrate farmers' risk perception of water scarcity, their willingness to learn from past harvest and water situations, and predictions of future water availability. By integrating farmers' and water managers' cognitive and decision-making processes into ABMs, researchers can bridge the gap between irrigation management and social science research. This integration can lead to a deeper understanding of the factors influencing farmers' activities, ultimately improving the interpretation of their dynamics and fostering more efficient irrigation management practices.

Due to resource limitations and practical constraints, the NetLogo platform does not support hydrodynamic calculations. As a result, the models implemented in this platform utilize artificial water units and simplified hydrological and hydraulic processes instead of comprehensive calculations to depict flow and runoff processes. Hydraulic and hydrological models are extensively employed for simulating hydrology processes and land management practices. For instance, the Soil and Water Assessment Tool (SWAT) is a valuable tool for assessing irrigation and yield in watersheds (Hussainzada and Lee, 2022; Samimi et al., 2020), while SOBEK can model the hydraulic properties of irrigation canals and scenarios for distributing irrigation water (Seyed Hoshiyar et al., 2021; Zheng et al., 2019). Crop models such as the water-drive AquaCrop model, Water-Heat Driven Crop model (WHCrop), CropSyst Model, and Decision Support System for Agrotechnology Transfer (DSSAT) are widely used to determine crop growth response to water at different scales (Davarpanah and Ahmadi, 2021; Dhouib et al., 2022; He et al., 2023; Mandeewal et al., 2020; Zhou et al., 2022). However, these models do not account for human activities that can affect agricultural irrigation management. Therefore, future research should explore the potential of coupling ABMs with hydrology and crop models to enhance agricultural irrigation management. This integration has the capacity to bring significant benefits to water resource management and food security.

7.3. MODELLING EMERGENCE OF IRRIGATION-BASED SOCIETIES IN SOUTHERN MESOPOTAMIA

The early civilization in Southern Mesopotamia thrived due to a mode of production centered around the surplus yields of irrigation agriculture (Wampler, 1978). Adams (1981) argues that human activities had a profound impact on shaping the landscape of this region. The emergence and growth of society in Southern Mesopotamia were heavily dependent on the critical development of irrigation systems within the landscape. This co-evolutionary relationship endured over an extensive period of millenia, significantly shaping the region's history. My current set of models demonstrates the potential for modelling irrigation systems on larger scales, both temporally and spatially. In collaboration with the eScienceCenter in the Netherlands, our ongoing project "*Modelling Emerging Irrigation-Based Societal Systems in Mesopotamia*" aims to extend the temporal scale of irrigation systems' evolution to millennia – it will trace the timeline of irrigation management all the way back to 6000 B.C. In terms of the spatial scale, we will seek to uncover the fascinating journey of how irrigated landscapes originated from simple crevasses and gradually transformed into intricate hydraulic landscapes through remarkable construction efforts driven by human ingenuity and adaptation. This endeavour will enable a deeper understanding of the societal development rooted in irrigation practices.

Both farmers and managers are key players in effective irrigation management strategies. Rost (2015) suggests that irrigation management in Southern Mesopotamia was highly centralised at a certain stage. However, the irrigation canals would have originated from dispersed crevasses along the rivers, and the initial farmers did not necessarily already form a community. The coming together of farmers marked a significant milestone in forming a cohesive group, a community, and ultimately, a society. Therefore, it is important to also examine the dynamics of settlements. It is crucial to study how individual actions or behaviours developed into centralized or hierarchical actions, shedding light on the emergence of society. Exploring the dynamics of irrigation farmland requires considering factors such as direct communication among farmers, family cereal consumption, and adaptive measures taken by farmers. To understand the dynamics of the irrigation systems and landscapes, it is important to incorporate factors like population, immigration, political and religious influences, and economic power. Additionally, the construction and maintenance of canals necessitate considering labour dynamics. Lastly, including hydrology data and meteorological data is essential for comprehending the reciprocal interactions between water and human activities in Southern Mesopotamia, spanning the past, present, and future.

While studying the short-term and long-term impacts of irrigation practices, agriculture landscape features, and watercourse patterns of both the natural environment and human settlements, we can build further understanding of the role of natural resources (water and land) in human society and how human activities can shape the natural environment over time and space. Collectively, these forthcoming studies have the potential to address a core question in archaeology: the extent to which human activities impact and shape natural systems and vice versa. These efforts are also aligned with ongoing discussions about human-induced environmental changes and the need to enhance sustainability and resilience in the face of climate and environmental shifts. Future work will entail in-depth research and analysis to tackle the aforementioned concerns, contributing to an enhanced comprehension of the interplay between humans and the environment across historical contexts. ABM is here to stay, as it is a key methodology to assist our thinking on these complicated matters.

A

SUPPLEMENTARY MATERIAL TO CHAPTER 4

A.1. EXPANSION PATTERN OF THE FARMLANDS

Table A.1 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 modelling 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, farmland2 becoming in use in the fifth year and farmland3 in the thirteenth year. In contrast, F2 has two farmlands, with these farmland 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 A.1: 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

A.2. GOOD HARVEST SITUATIONS

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

- Figures A.1a and A.1b 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.

- Figures A.1c-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.

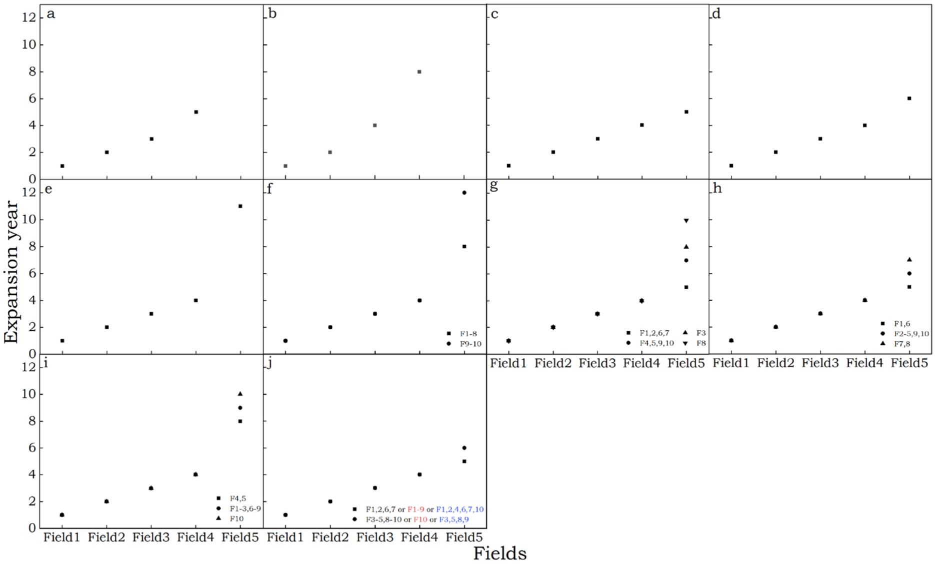


Figure A.1: Expansion year of farmlands when farmers have good harvest situation.

A.3. RD = 30 WU/TICK, IGC = 10, 20, 30 WU/TICK

Figure A.2 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 202605, 215573, and 224948 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 (Figure A.2a and A.2b). 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 (Figure A.2b). 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 (Figure A.2c). 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.

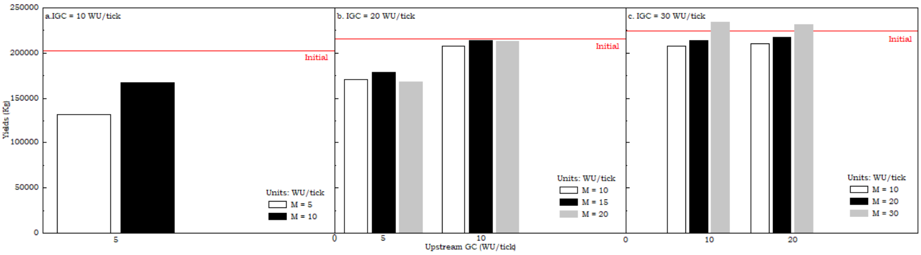


Figure A.2: The comparison of total system yields before and after GC adjustment when RD = 30 WU/tick (red line shows the initial total system yields).

A.4. RD = 160 WU/TICK, WITH IGC = 80, 130, 160 WU/TICK

Figure A.3 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 (Figure A.3a). 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 (Figure A.3b). 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 (Figure A.3c). 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.

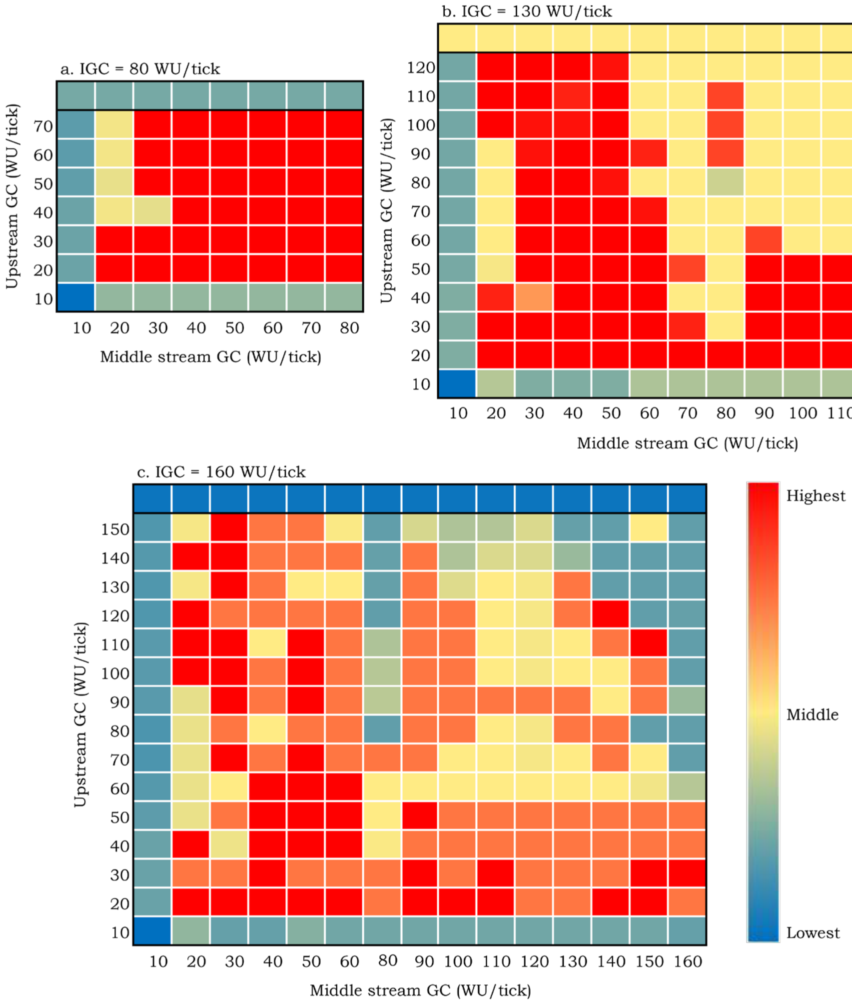


Figure A.3: Total system harvest with varied up and middle stream GC (RD = 160 WU/tick) (the initial total system yields shown in the black frame on the top for reference). Figures A.3a, A.3b, and A.3c share the same legend but the color scale means different values. We use the heatmap to show the yield 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. Figure A.4 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.

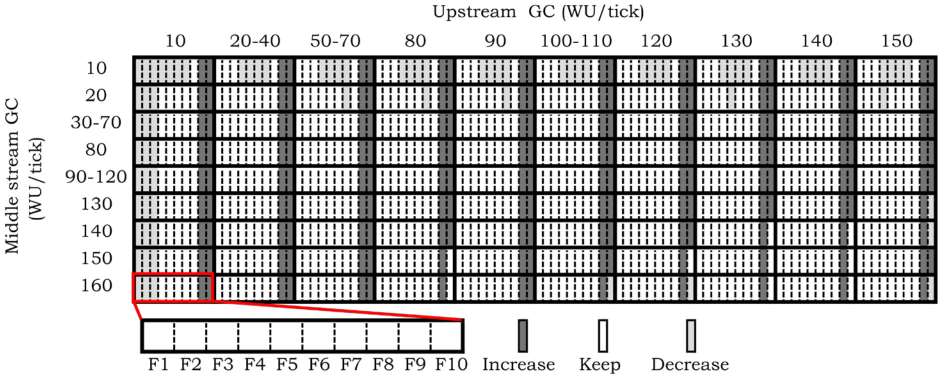


Figure A.4: Harvest situation of individual farmer after GC adjustment (RD = 160 WU/tick, IGC = 160 WU/tick).

B

SUPPLEMENTARY MATERIAL TO CHAPTER 5

B.1. NEW FARMS EXPANSION YEAR

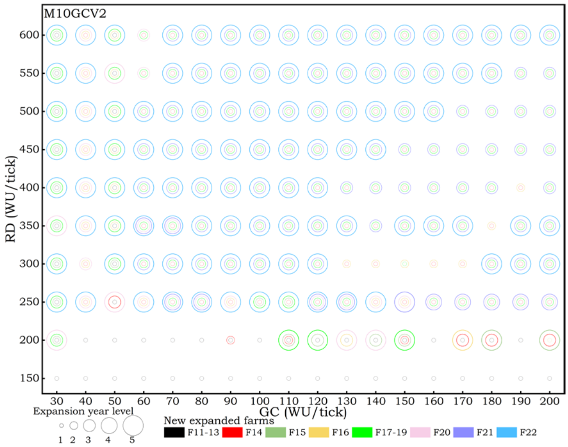


Figure B.1: The expansion year of new farms when M = 10 years, GCV = 2 year.

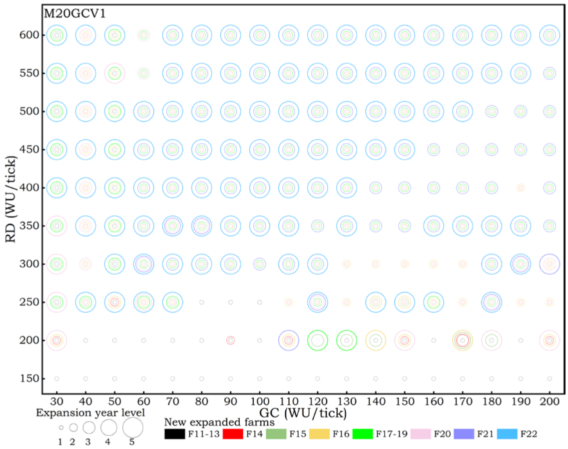


Figure B.2: The expansion year of new farms when M = 20 years, GCV = 1 year.

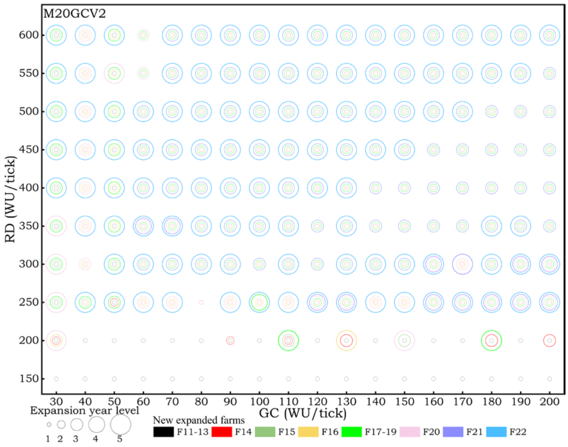
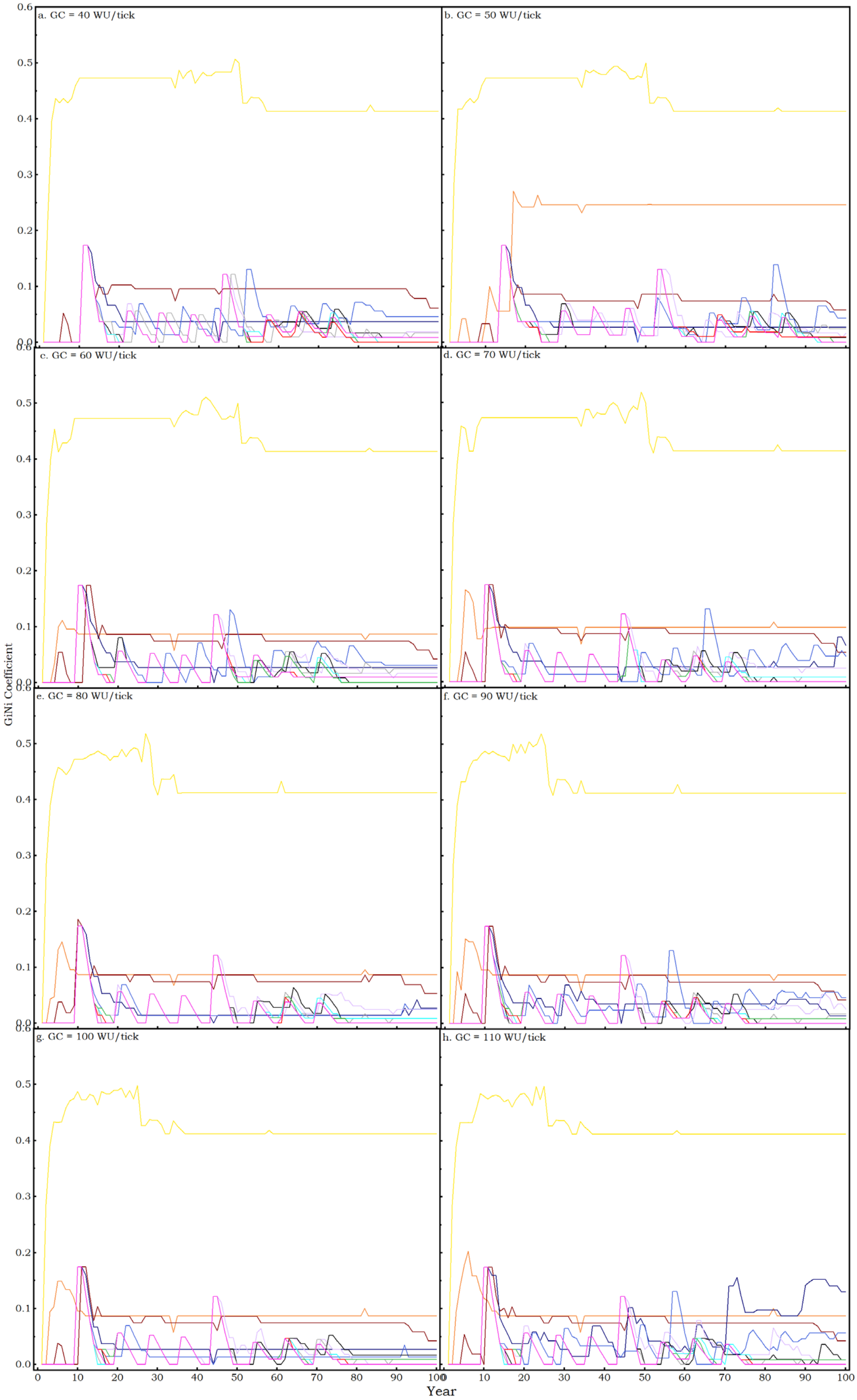


Figure B.3: The expansion year of new farms when M = 20 years, GCV = 2 year.

B.2. BARLEY YIELDS GINI COEFFICIENT WITH OTHER GCS IN 100 YEARS



Barley yields Gini coefficient with other GCs in 100 years (Continued on next page).

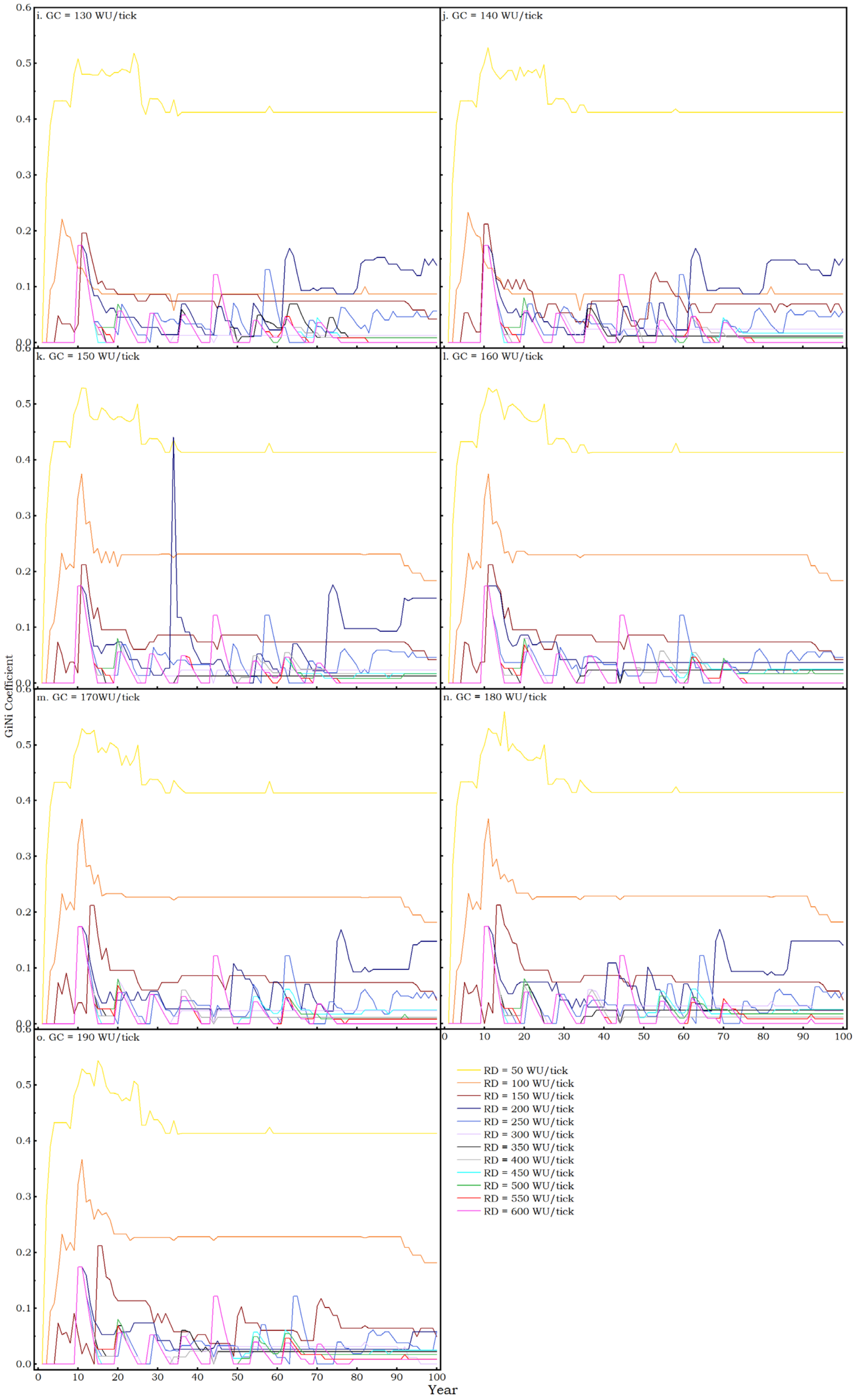


Figure B.4: Barley yields Gini coefficient with other GCs in 100 years.

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List of Terms

Agent-Based Model (ABM): an integrated approach for complex system simulation.

Irrigation-Related Agent-Based Model (IRABM): the first version of ABM in irrigation systems.

Advanced Irrigation-Related Agent-Based Model (AIRABM): the further developed ABM in irrigation systems.

Irrigation Memory (IM): refers to the interval between two irrigation actions.

Average Available Water (AAW): 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 nth year (HBY$_n$): it refers to the barley yields in a specific year.

Available Water in the nth year (AW$_n$): it refers to the received water in a specific year.

Water Units (WU): 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): the 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): this is the capacity of the main river, WU/tick.

Gate Capacity Adjustment: when there is a poor harvest situation along the canal, the collective action is to adjust the GC of upstream farms and middle-stream farms. The adjustment does not adjust once but probably many times depending on the evaluated yields.

Gate Capacity Variation (GCV): the time used to keep the new UGC and MGC after the adjustment, year. In this research, we set GCV = 1 year and 2 years, which means the model evaluates the yields every year or every two years to see if the GC adjustment is needed again or not.

Head Gate: gate structure at the head of the canal, it is a water distribution structure used to transfer water from the river to canals or from canals to the next level of canals.

Memory of Harvest Barley and Memory of Available Water (M): the memory of yields in the past years of each farm and the memory of received water in the past years of each farm, year. These two memories are always consistent. We set 10 years and 20 years in this model. These are factors used for decision-making in farmlands dynamics.

Expansion Year Level (EYL): the expansion years of new farms under all combinations of RDs and GCs are too complex for visualisation. In order to make the figures clearer to readers, we divided the simulated 100 years into five levels, the details are shown in the Note of Figure 5.8.

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游子吟

孟郊 （唐）

慈母手中线，游子身上衣。

临行密密缝，意恐迟迟归。

谁言寸草心，报得三春晖。

希望我的母亲平安喜乐，健康长寿。

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LIST OF PUBLICATIONS

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1. **Lang, D.**, Ertsen, M. W. *Irrigation landscape and the evolution of irrigation systems in south Mesopotamia.* EGU General Assembly 2019, Vienna, Austria (Poster).