GROUNDWATER APPROPRIATION GAME: A DYNAMIC SIMULATION APPROACH

by

Elif Bal

B.Sc. in Environmental Engineering, Middle East Technical University, 2015

Submitted to the Institute of Environmental Sciences

in partial fulfillment of the requirements for the degree of

Master of Science

in

Environmental Technology

Boğaziçi University

2020

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Prof. Dr. Ali Kerem Saysel for supervising this research and providing me the opportunity to become a part of the Environmental Systems Laboratory. He gave me the opportunity to make research in the field I was interested in and provided me such a great working environment. It was such an honor to be his student.

I would like express my sincere appreciation to the examining committee members Prof. Dr. Nadim Copty and Prof. Dr. Günay Erpul for their worthful suggestions and contributions.

I am grateful to my hardworking girls Cansu Demir, Ezgi Çınar, Miray Mazlumoğlu and Ulaş Can for always setting the bar high. Their encouragements from the beginning of our undergraduate years made this research possible. It was great to feel them by myside regardless of where they live.

I would like to thank my former colleagues from Royal HaskoningDHV for their support and guidance. It was a pleasure to work with them.

I would like to thank my fellow lab mates Buse Yetişti, Mehmet Can Tunca and our part time lab member Öykü Sefiloğlu for all the inspiring discussions and brain storming sessions we had. I am also grateful to the volunteer participants for their time and consideration. Their contribution to this research is invaluable.

I would like to thank to my beloved roomie; Öykü Akman for her moral and -nutritious- support. Her rose tinted glasses and endless love provided me a peaceful working environment in our home during the days of Covid-19 outbreak.

My biggest gratitude is for my beloved family; my parents Zeliha Bal and Erdal Bal and my brother Emre Bal. I could not be more grateful to his patience during the most stressful moments. None of this would be happened without them.

Last and the most, I would like to express my special thanks to Deniz Özdaş for his unconditional love and support.

ABSTRACT

GROUNDWATER APPROPRIATION GAME: A DYNAMIC SIMULATION APPROACH

This research explores the common pool resource (CPR) characteristics of groundwater resources by dynamic simulation modeling and computer gaming. As the largest source of freshwater in the world, groundwater is deemed one of the most valuable resources. Due to the difficulty of excluding potential users and high subtractability of the benefits consumed by one user from those available to others, groundwater resource is conceptualized as a CPR. As a CPR, groundwater is prone to both provision and appropriation problems including but not limited to drying up of wells, increased pumping costs and deterioration of water quality due to the intrusion of salt water. In this research, allocation of flow (the extracted groundwater) from the resource stock (extractable water at the aquifer bed) during a single irrigation season is investigated. When groundwater users act independently to increase their water extraction, the resulting drawdown of the water table may lead to an increase in energy costs and reduce overall, as well as individual benefits. This represents a CPR dilemma among the irrigators, where the actors have to cooperate for the quantity and coordinate for the timing of their irrigation activity to increase overall benefits. To facilitate learning in and about the dynamic complexity of this dilemma, a network based dynamic simulation game is developed. The game is grounded on a dynamic simulation model. The model represents the groundwater dynamics (i.e. groundwater flows within the aquifer and recharge mechanism) and dynamic relationship between water extraction and crop yield. The model also calculates biweekly and end-of-the-season statistics for the individual farms on finances and water use efficiencies. Namely the *Groundwater Irrigation Game* is a multiplayer, dynamic game in which participants seek to maximize their farm profits while they are faced with the renewable resource limits. This game allows participants to explore consequences of different strategies and gain insights about the complex dynamics of the commons. Accordingly, the initial observations obtained from the pilot gaming indicate that the game instructions are sufficient for participants to develop a strategy and achieve their goals.

ÖZET

YERALTI SUYU PAYLAŞIMI OYUNU: DİNAMİK BENZETİM YAKLAŞIMI

Bu araştırma, dinamik benzetim modellemesi ve bilgisayar oyunu yardımı ile yeraltı suyunun müşterek kaynak özelliklerini araştırmaktadır. Dünya'daki en büyük tatlı su kaynağı olan yeraltı suyu, en değerli yenilenebilir kaynaklardan biri olarak kabul edilmektedir. Potansiyel kullanıcıları hariç tutma zorluğu ve bir kullanıcı tarafından tüketilen faydaların diğer kullanıcılara sunulan faydayı düşürmesi nedeniyle, yeraltı suyu bir müşterek kaynak olarak kavramsallaştırılmaktadır. Bir müşterek kaynak olarak yeraltı suyu, kuyuların kuruması, su çekme maliyetlerinin artması ve tuzlu su girişiyle su kalitesinin bozulması gibi tahsis ve paylaşım sorunlarına maruz kalmaktadır. Bu araştırmada, tek bir sulama mevsimi boyunca kaynak stokundan (akiferden) çekilen yeraltı suyu paylaşımı araştırılmıştır. Yeraltı suyu kullanıcıları, kendi çektikleri su miktarını artırmak için bağımsız olarak hareket ettiklerinde, su tablası düşmeye ve enerji maliyetleri artmaya başlar. Bu durum hem bireysel hem de kullanıcıların genelinin kaynaktan elde edecekleri faydanın azalmasına yol açar. Kaynaktan elde edilecek genel faydayı artırmak için kullanıcılar sulama faaliyetlerinin zamanlaması ve miktarı için iş birliği yapmak durumundadır. Bu, yeraltı suyu kullanıcıları arasında bir müşterek kaynaklar ikilemini temsil eder. Bu ikilemin dinamik karmaşıklığı hakkında öğrenmeyi kolaylaştırmak için, ağ tabanlı bir dinamik benzetim oyunu geliştirilmiştir. Oyunun temeli, dinamik bir benzetim modeline dayanmaktadır. Model, yeraltı suyu dinamiklerini (yeraltı suyu akışları, beslenme mekanizması gibi) ve yeraltı su çekimi ile mahsul verimi arasındaki dinamik ilişkiyi temsil etmektedir. Model ayrıca, çiftliklerin finansalları (mahsulden elde edilecek gelir, elektrik giderleri, net kazanç gibi) ve su kullanım verimleri hakkında çiftçi bazında hesaplamalar da yapmaktadır. *Yeraltı Suyu Paylaşım Oyunu* katılımcıların yenilenebilir kaynak limitleriyle karşı karşıya kalırken net kazançlarını en üst düzeye çıkartmayı hedefledikleri çok oyunculu, dinamik bir oyundur. Bu oyun, katılımcıların farklı stratejilerin sonuçlarını keşfetmelerini ve müşterek kaynakların karmaşık dinamikleri hakkında fikir edinmelerini amaçlamaktadır. Buna göre, deneme oyunundan elde edilen ilk gözlemler, oyun talimatlarının katılımcıların bir strateji geliştirmesi ve hedeflerine ulaşması için yeterli olduğunu göstermektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
CPR	Common Pool Resource
DSI	General Directorate of State Hydraulic Works
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization of United Nations
INIT	Initial value
MoAF	Tukey Ministry of Agriculture and Forestry
UNECA	United Nations Economic Commission for Africa
USDA	United States Department of Agriculture
USGS	United States Geological Survey

1. INTRODUCTION

Groundwater is deemed one of the most valuable renewable resources throughout the world since it is the largest source of usable and freshwater. United States (US) is one of the major countries relying on groundwater resource where groundwater supplies drinking water for half of the total US population and for more than 90% of the rural population. According to United States Geological Survey (USGS) 2015 data, groundwater is the source of approximately one-third of the freshwater supplied to households and businesses in the US. Besides, groundwater also supplies nearly 190-million m^3 water per day for agricultural use (USGS, 2016). Groundwater is also deemed as a crucial resource of drinking water, livestock water and irrigation in Africa, particularly in the arid and semi-arid countries in the southern and northern parts. In these parts of the country, the only source of water is often groundwater (UNECA, 2013).

According to U.S. Environmental Protection Agency (EPA), groundwater is such an important resource since large portion of the world's fresh water locates underground within the cracks and pores. Approximately 97% of the Earth's water is held by the oceans and 2% is locked up in glaciers or poles. Almost all of the remaining 1% (approximately 96% of the remaining freshwater) is found as groundwater (USGS, n.d.). In the areas where surface water resources and/or precipitation are limited or demand is high, people mostly rely on groundwater. Besides, certain ecological systems such as wetlands or surface waters fed by springs and seeps rely on groundwater as well. However, there are serious concerns related to the available amount of groundwater including aquifer depletion. Potential reasons behind the aquifer depletion include withdrawal of groundwater for drinking, irrigation and other uses; changes in precipitation patterns; and impervious paved surfaces that prevent aquifer recharge. Recovery of the deep aquifers may take thousands of years. Aquifer depletion may lead to several consequences including lowering lake levels and drying up of perennial streams that can threat the life of aquatic or riparian plants and animals; land subsidence and formation of sinkholes that can permanently damage the structures; and salt water intrusion due to the changes in groundwater flow and migration of saline water. (EPA, 2018)

Similarly, in Turkey, groundwater is a major resource for agricultural needs and drinking purposes particularly in rural areas. According to the statistics published by the State Hydraulic Works (DSI in Turkish acronym), groundwater extraction in Turkey has been following an increasing trend between 1995 and 2017 together with the population growth and rapid urbanization (Figure 1.1).

Considerable part of this increase in the recent years can be explained by the increasing extraction for irrigation purposes (DSI, 2018).

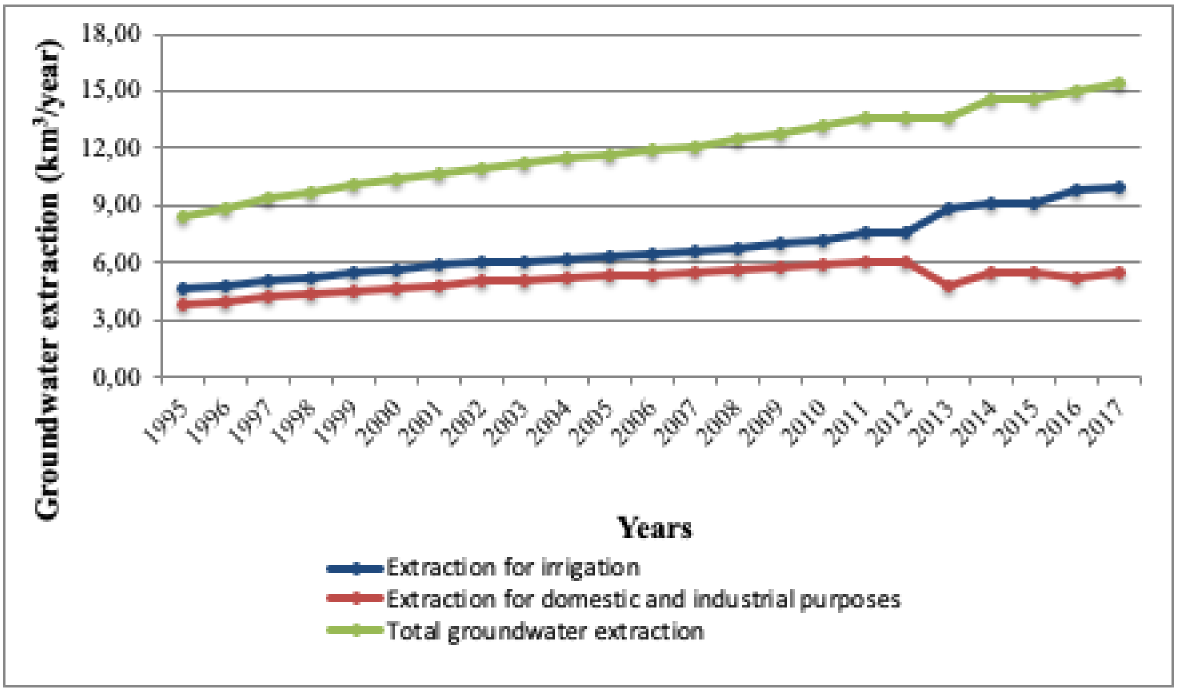

Figure 1.1. Groundwater extraction statistics (DSI, 2018).

Increase in agricultural water withdrawal between 2013 and 2017 can be explained with the increase in the area of irrigated land and number of groundwater wells. In Figure 1.2, changes in the number of registered groundwater wells and area of irrigated land between 2013 and 2017 are presented. According to the graph, both number of wells and area of irrigated land data show an increase over time. In addition to the registered groundwater wells, it is known that there is considerable number of unregistered groundwater wells. Taking these unregistered wells into account, groundwater extraction rates are estimated as much higher than the official statistics.

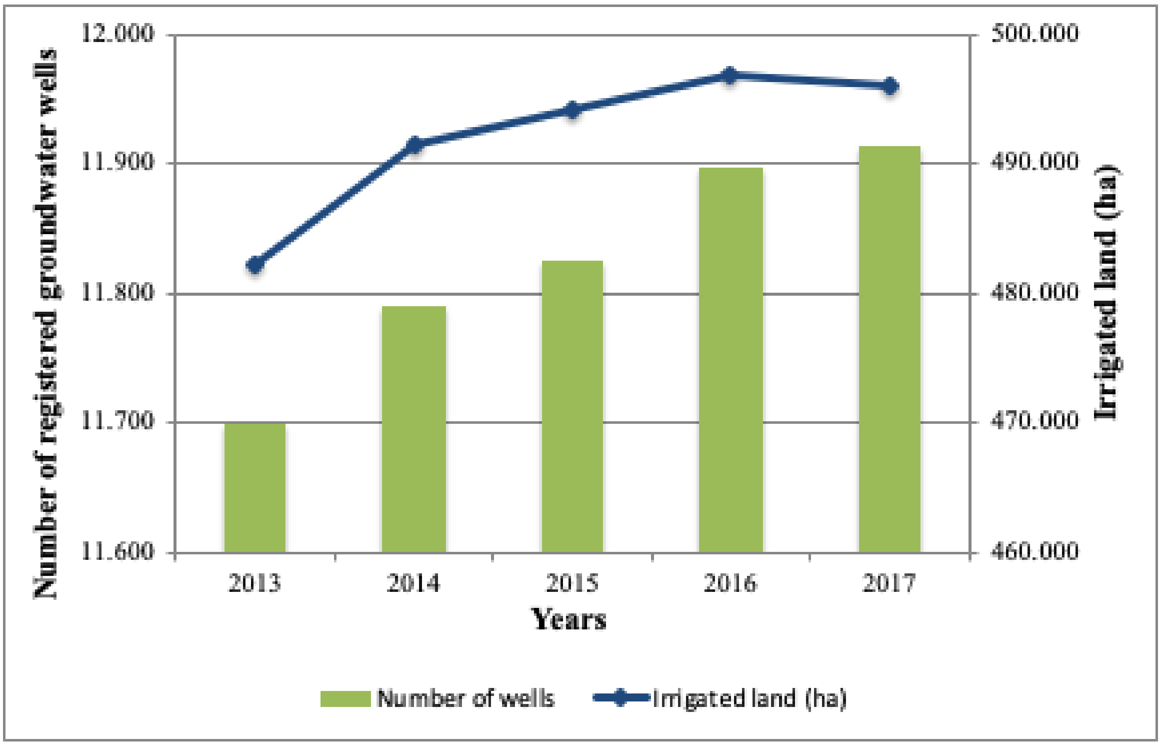

Figure 1.2. Number of registered groundwater wells and area of irrigated land data, 2013-2017 (DSI, 2018).

Maize also known as corn is a cereal grain that is among the important food crops throughout the world. Corn has hundreds of uses including but not limited to the livestock feed, food and industrial products. The United States is the world's largest corn producer. Corn is the primary feed grain in the United States, accounting for more than 95% of total production and use (USDA, 2020). In the US, approximately one third of the production is used for feeding animals (cattle, hogs and poultry). One third is used for ethanol production which is a renewable fuel additive to gasoline. The rest is processed for human consumption, beverages and other industrial purposes (USDA, 2019). In Turkey, corn is the third most cultivated food crop after wheat and barley. Similar to the US, corn is used as animal feed and industrial purposes in Turkey (MoAF, n.d.).

According to Ostrom et. al. (1994), the goods that individuals value differ in terms of their degree of excludability and subtractability. Exclusion can be assessed by evaluating how easy or costly it is to exclude or limit potential beneficiaries from using the resource once it is provided by nature. On the other hand, subtractability is related to how much of the good is left for other potential beneficiaries after consumption. These explanations provide a general classification of goods in four classes as shown in Table 1.1. Due to the difficulty of excluding potential users and high subtractability of the benefits consumed by one user from those available to others, in most settings, groundwater resource can be conceptualized as a common pool resource (CPR). (Ostrom, Gardner, & Walker, 1994).

Table 1.1. General classification of goods (Ostrom, Gardner, & Walker, 1994).

		Subtractability	
		Low	High
Exclusion	Difficult	Public goods	**Common-pool resources**
	Easy	Toll goods	Private goods

As one of the most challenging CPR, groundwater is prone to both provision and appropriation problems including but not limited to drying up of wells, increased pumping costs and deterioration of water quality due to the inclusion of salt water (USGS, 2016). While provision problems are concerned with the maintenance of resource stocks at sufficient quantity and quality, appropriation problems are concerned with the allocation of flows that are extracted from available stocks (Cardenas & Ostrom, 2004).

Appropriation problems focus on the allocation of flow from the resource stock with respect to (i) quantity of resource units to be appropriated or the problem of determining the efficient level and mixture of input resources necessary to obtain the flow, (ii) timing and venue of appropriation, and (iii) appropriation technologies adopted (Gardner, Ostrom, & Walker, 1990).

Provision problem analysis starts at the level of optimum size and productive nature of the resource and focuses on behavioral incentives for appropriators to either (i) make contribution to resources for the maintenance of the resource, which is known as supply-side provisions, or (ii) adjust appropriation activities within the system to change withdrawal patterns from the resource to avoid the resource depletion, demand-size provision (Gardner, Ostrom, & Walker, 1990).

As the changes in resource stock could affect the potential appropriation and appropriation could affect the provision, these two problems are linked to each other (Baur, Liechti, & Binder, 2014). In this research, primary focus is the groundwater appropriation problem that occurs during an irrigation season. As one of the most challenging CPR, groundwater is prone to over-extraction due to the independent behavior of users. Groundwater user's independent behavior to increase their own extraction may lead to a decrease in water table level. As the water table level decreases, pumps either need to work longer durations or increase their power to extract same amount of water. Either way, this results in an increase in extraction costs and reduced overall as well as individual benefits of CPR users and that creates a cooperation dilemma among the users. With this research, it is aimed to gain insights into the groundwater appropriation problem in the commons' environment. For this purpose, a dynamic simulation model and a web-based dynamic simulation game are developed and the outcomes of the study are presented in this thesis.

This thesis is structured as follows. In Chapter 2, detailed problem description and research objectives are given. Relevant literature on CPR gaming and expected contribution of this research to the existing literature are provided in Chapter 3. In Chapter 4, the methodology followed during the research is explained. Dynamic simulation model including model description, model validation tests and model reference behavior is explained in detail in Chapter 5. Dynamic simulation game is presented in Chapter 6. In Chapter 7, results and possible discussion topics are provided. Lastly, the study is concluded in Chapter 8.

2. PROBLEM DESCRIPTION AND RESEARCH OBJECTIVES

Groundwater is deemed one of the most valuable resources throughout the world since it constitutes approximately 96% of the Earth's freshwater (USGS, n.d.). Overuse of groundwater; in other words, extracting water with a rate faster than it renews itself results in severe economic and environmental consequences as mentioned before (USGS, 2016; EPA, 2018). The aim of this research is to assess the effects of groundwater appropriation problem in a single irrigation season by using system dynamics approach.

As a CPR, groundwater user's independent behavior with the aim of benefiting more from the resource may result in over extraction. When groundwater users act independently to increase their own water extraction, the resulting drawdown of the water table may result in an increase in energy costs since pumping duration needs to be extended or higher pump power is required to obtain same amount of water. This reduces overall, as well as individual benefits of CPR users. This represents a cooperation dilemma among the irrigators, where the actors have to cooperate for the quantity and coordinate for the timing of their irrigation activity to increase their benefits. However, in real life, it may not be possible to experience the dilemma directly and determine the optimum case for everyone.

According to Sterman (2014), in many environmental systems, the time delays between decisions and perceived consequences are longer than the time available for learning and experiencing about those systems. It is not possible to conduct direct experiments on the important natural systems. To illustrate, it is simply impossible to run experiment to assess the impacts of alternative pathways for greenhouse gas emissions since the time delays between emissions and climate impacts are long and we only have one planet. However, simulations can shorten the duration, shrink the space and eliminate many confounding variables in the real systems to allow practitioners to simulate decades on simplified models in a few seconds.

In case experimentation is not possible due to long durations, high costs or ethical impediments, simulation is the primary tool to understand how complex systems work (Sterman, J., 2014). In groundwater appropriation problem that we focus on, it is not possible to design a real experiment with the real farmers since the outcomes of the decisions can only be observed at the end of the season. In order to find improved solutions for everyone, the experiment needs to be repeated many times that makes it impractical. However, with the help of simulation, the actual duration can be compressed, which allows us to experience different results under different circumstances and determine better solutions for everyone.

The objective of this research is twofold. The first step of this research is to build a dynamic simulation model to gain insights into the underlying mechanism of the commons problem. The simulation model shows the groundwater dynamics (i.e. groundwater flows within the aquifer and recharge mechanism) and dynamic relationship between water extraction and profit to be obtained from crop yield. Second step of this research is to develop a web-based dynamic, multiplayer simulation game, which enables players to experience different results under different groundwater extraction and irrigation schedule decisions. The game helps us to identify potential reasons behind the groundwater overuse problem and emerging problems that take place depending on the players' decisions and interaction. Besides, through this simulation game, players are able to explore the outcomes of different strategies and they can learn about the complex dynamics of commons. To this end, this research aims to have a learning aspect.

3. LITERATURE REVIEW

In this section, first, available literature on fundamental theory and research practices in CPR management and role of dynamic simulation gaming in learning about dynamic complex problems are provided. Then, expected contribution of this research to the existing literature is summarized at the end of the section.

3.1. The Economic Theory of Commons

The resources for which exclusion of potential beneficiaries (exclusion) is difficult and utilization of the resource by one of the users decrease the amount left for other beneficiaries (subtractability) are characterized as CPRs (Ostrom, Gardner, & Walker, 1994). Fisheries, groundwater basin, irrigation systems, forests and pastures are the well-known CPR examples. CPRs are prone to both appropriation and provision problems. In a nutshell, appropriation problems focus on the allocation of flows from the resource stocks whereas provision problems focus on the maintenance of resource stocks at sufficient quality and quantity (Cardenas & Ostrom, 2004). In natural settings, appropriation and provision problems are generally combined. Moreover, how well a provision problem is solved affect the nature of appropriation problems (Ostrom, Gardner, & Walker, 1994).

In case an individually rational behavior leads to a counterproductive outcome, the resulting situation is called as CPR dilemma. It is noteworthy to mention that CPR situations do not necessarily mean CPR dilemmas. For example, in some cases, the amount demanded from the resource stock is not large enough to create resource scarcity which reduces individual benefits. These kinds of situations are not deemed as problematic. However, in cases where resource limits are more stringent, the amount demanded from the resource stock can be large enough to create scarcity for the others and in a longer term. That leads to an outcome, which is not rational from the group’s perspective. In case a CPR dilemma exists, proposed solution requires a change in appropriation and/or provision rules. (Ostrom, Gardner, & Walker, 1994).

The previous researches, although some of them have been developed for different resources, in general, might be applicable to other cases where natural resources are used under a common pool resource regime but exploited due to the individualistic behavior. The first formal CPR model was developed by Gordon (1954) who has investigated the common-property nature of the fishing industry. The primary aim of the study was to demonstrate the economic theory of the natural resource utilization (*i.e.* overfishing in his study). Gordon has defined common property natural resources as free goods for individuals and scarce goods for the society. According to his study, in case of unregulated private exploitation, the resource can yield no economic rent. Uncontrolled competitive fishing might even result in depletion of the resource (Gordon, 1991).

In 1968, Garrett Hardin has published a foundational paper that describes the "tragedy of the commons" (Hardin, 1968). Hardin has presented his theory on the commons by giving an example of pasture open to public. In the pasture, there are herdsmen who are seeking to maximize their individual benefit. They can increase their herd size, which makes a positive effect on their gain; however, when they increase the number of animals, it may lead to overgrazing problem. Since the negative effect of overgrazing is shared by all of the herdsmen, while the positive effect is individually subsumed, a herdsman is tempted to expand his herd until his marginal revenue is equal to zero. However, this temptation can create an overpopulation of the herds on the pasture, which yields suboptimal profits from the individual and community perspectives. According to Hardin, this individualistic behavior in the commons environment forms the basis of the tragedy of commons.

3.2. Elinor Ostrom and Governing the Commons

In many settings, management of common pool resources necessitates either government-imposed management (i.e. external regulations) or division of the resource into private property (i.e. privatization) (Ostrom E. , 2006). Over the last few decades, studies in CPR management have revealed that tragedy of the commons (Hardin, 1968) is not inevitable if people can effectively cooperate (Ostrom, Gardner, & Walker, 1994). To support this claim, CPR games and experimental researches have been conducted.

Meinzen-Dick, et.al. (2018) have developed a collective action game and conducted a set of field experiments in India to measure the desire for cooperation and to improve local understanding of groundwater interrelationships. The effect of crop choice on groundwater levels is simulated in the game. The field experiments were conducted in two consecutive years, 2013 and 2014 with 17 communities. A group of 5 men and 5 women from households attended each session. In accordance with the game instructions, all the players extract groundwater from a common resource and in each round, players decide on the type of crop that will be planted in the upcoming year. Each round represents a year and the game lasts for 10 rounds at most. There are two types of crops, namely, Crop A and Crop B. Crop A requires less irrigation and provides less income, whereas Crop B requires much more irrigation and provides more income to the players. The field studies conducted in the second year and likelihood of reaching sustainable extraction levels has increased with the communication during the game. In accordance with the Meinzen-Dick and colleagues, the games played a year before had a measurable effect on the understanding of resource dynamics by the community not solely by the players of the game. It can be deduced that the games leave a "footprint" in the communities. After the games were played, it was observed that rules for governing groundwater resources were adopted by a remarkably higher part of the communities. Since there are many other factors affecting groundwater resources, the game cannot solely end the groundwater depletion problem but can motivate behavior change towards a more sustainable resource utilization (Meinzen-Dick, et.al., 2018)

Another study focusing on the appropriation problem in irrigation systems in Colombia and Thailand has been conducted by Janssen et.al. (2012). Janssen et.al. (2012) have conducted a set of field experiments with the villagers in rural environment and students in the respective capital cities. Experiments were conducted in total of six villages in Thailand and Colombia (three villages in each country). In each country, each village has a different dominant resource of fishery, forestry and irrigation system. In 2007, the experiments were held with 4 groups (each composed of 5 people) from each of the six villages. In 2008, same experimental protocol was replicated with 20 students from the universities in Bogota and Bangkok. In the study, two fundamental problems of irrigation systems are highlighted which are (i) the provision of required infrastructure to utilize water and (ii) irrigation dilemma where sequential access to the resource is generated due to the positions of the users (i.e. "head-enders" and "tail-enders"). Earlier experimental works have mostly focused on the extraction phase of the commons dilemmas and revealed that users accessing the resource first are prone to take more from the resource. In contrast, Janssen and colleagues have also focused on the provision problem in their research. The pen and paper-based gaming experiment is composed of 20 rounds in total. First, participants are asked to make investment to the maintenance of irrigation system and the information on the amount of water available to the whole group is announced. Then, participants are asked to decide on the amount of water to be extracted from the water available, in sequential turns. Contribution to the system is crucial for the maintenance of water availability. Besides, the contribution of downstream users is required by the upstream users to maintain the resource. On the other hand, downstream users can only benefit from the resource if upstream participants leave some water for them. Therefore, in the initial contribution phase, participants face a provision dilemma, and then they experience an appropriation dilemma when they decide on the extraction. After the first 10 rounds, three different allocation rules were introduced which are equal quota, random and rotating access to the resource. The results indicate that the decisions made in the first round rely on the trust between the participants of the community. However, in the following rounds, investment and extraction decisions are mainly affected from the position of the participants. It was observed that upstream participants have a significant effect on the resource allocation. In addition, it was also resulted that participants adjust their cooperative behavior when they observe unequal results such as extracting more from the resource by one participant (Janssen, Bousquet, Cardenas, Castillo, & Worrapimphong, 2012).

Raquel, S. and colleagues (2007) have conducted a theoretical study for Alto Rio Lerna Irrigation District in Mexico. They have applied game theory to find an optimal solution between the two conflicting objectives, economic benefits from agricultural production and associated negative environmental impacts. In the study area, limited amount of precipitation combined with the high groundwater extraction rates resulted in severe aquifer overdraft. Moreover, it was observed that application of high loads of fertilizers and pesticides resulted in contamination in the groundwater. The two primary players in the game, also called as stakeholders, represent the farmers and the community. The economic benefit to be obtained through the crop yield is the payoff for the farmers, whereas reduced potential environmental risks are the payoff for the community. Groundwater extraction in terms of volume of water is the decision variable. Based on 10-year historical data of groundwater extraction in the study area, 12 different groundwater extraction scenarios are proposed. For each scenario, environmental and economic consequences have been assessed and optimum groundwater extraction rate has been identified.

3.3. Dynamic Simulation Models and Games of Commons

Hereinafter selected dynamic simulation games categorized as CPR are explained. The primary aim of these games is to reveal the management problems and enable participants to learn about important concepts of management, strategy and sustainability (Sterman, 2014).

Fishbanks is the well-known simulation game that face players with the dynamics of open-access renewable resources and challenges them to sustainable resource management. The original version of the game designed by Dennis Meadows, is a role-playing board game where participants manage their own fishing companies and compete with neighboring teams to maximize the economic value of their companies. The game has been played around the world many times by the players from different backgrounds and different disciplines. The classic game has been updated and web-based version has been created by MIT Sloan School of Management. The updated version of the *Fishbanks* is a dynamic, multi-player game where players seek to maximize their benefit in an open-access fishery. Information on the current market and fishery conditions is provided to the players through the simulation interface. The game can be played up to 10 teams representing fishing companies in an ocean. At each round, players decide on (i) the size of their fleet (i.e. buying, selling or ordering new ships to their fleet); and (ii) how to manage their fleet (i.e. keeping their ships in the harbor, performing deep-sea fishery or coastal fishery). *Fishbanks* game creates an opportunity for participants to learn about the sustainable management of renewable resources. According to Sterman (2014), participants can learn the fundamental lessons including resource dynamics, “the tragedy of the commons”, misperception of feedback and successful governance of the commons.

Moxnes (1998) has argued that open-access renewable resources depletion might take place even if there is no commons problem. Misperception of feedback could also be the problem that leads participants to overuse the resource. For this reason, a laboratory experiment has been designed where commons problem did not exist but overexploitation of the resource has already been a fact. The experiment was grounded on a simulation model developed for reindeer and lichen. Time horizon of the experiment corresponds to 12-year period and the task is to decide on the reindeer quota for the next year. The aim of the participants was to maximize their incomes. All subjects were informed about the maximum amount of animals that can be sustained and carrying capacity of lichen stock. If the lichen stock exceeds its carrying capacity, participants lose their incomes that force them to take action quickly. At the end of each simulation year, results for last year (yearly income, lichen percentage, number of reindeer, meat weight calves, calf and loss percentages) are provided to the subjects. To understand the nature of any possible misperception, two different information treatments were applied in the experiment. The aim of the information treatment was to reveal whether subjects have needed help to develop better mental models and improve their strategies. As the first information treatment (“*stock*”), stock nature of lichen was explained to the subjects (In brief, lichen stock increases by annual growth and decreases by annual eating by reindeer. To obtain a stable stock annual growth needs to be equal annual eating.). As the second information treatment (“*growth*”), lichen growth graph was demonstrated to the subjects and particular information on the lichen growth dynamics was provided. A significant direct effect of second treatment was observed. Although the treatment was deemed effective, subjects were still below the ‘optimal’ value. At the end of the experiment, it was observed that none of the participants have combined dynamic mental models with proper analysis. For most of the participants, it was observed that both lichen and reindeer herds were almost depleted. It was also deduced that effect of information treatment was limited. Identifying effective information policies is emphasized as a challenge for future research. With this experimental research, Moxnes has underlined the importance of information policies in the management of common property resources (Moxnes, 1998).

In system dynamics literature, there are a number of modeling studies and games developed for CPRs. Moreover, gaming experiments have been conducted to understand the behavior of CPR users. However, games focusing on groundwater as a CPR are rare and most of them do not consider the groundwater dynamics. This study is grounded on a dynamic simulation model that represents the dynamics of groundwater resources. Besides, in most of the game designs, decision intervals are expressed as years and time horizon is expressed as decades. Long-term impacts of the overuse problem in respect to the resource are studied. This research aims to make a contribution to the existing system dynamics literature by focusing on the short-term variations in the commons problem.

4. METHODOLOGY

‘Modeling’ is a scientific method used for exploring problems and solutions. Models represent selected aspects of actual systems responsible for creation of particular problem(s). Therefore, a problem is the main motivation of building models (Barlas, 2002).

The methodology of this research is based on system dynamics, a scientific modeling approach which was developed to enhance understanding of the complex dynamic systems (Turner, et.al. 2016). Due to the dynamic complex nature of groundwater, irrigation and crop yield interactions, we argue that system dynamics is an appropriate methodology to explore the groundwater overuse problem. Primary purpose of system dynamics methodology is to assess the causes of undesired dynamics and define new policies to eliminate them. Managerial understanding, action and control form the basis of this method. Dynamic problems of systemic, feedback nature are the primary focus of system dynamics methodology (Barlas, 2002).

Models can be categorized in several types. System dynamics models are classified as dynamic and descriptive models of real-life systems. Depending on the action and decision sequences of real systems, system dynamics models can be designed in discrete, continuous or hybrid simulation time units (Barlas, 2002).

A typical system dynamics modeling study follows these five main steps; (i) problem identification; (ii) development of the dynamic hypothesis and model conceptualization; (iii) formal model construction; (iv) model credibility (validity) testing; and (v) analysis of the model (Barlas, 2002).

The first step, meaningful dynamic feedback problem selection, is the crucial step for a successful project. The problem needs to be dynamic and feedback nature. Sub-steps of problem identification are (i) examining the dynamic behavior, (ii) deciding on the time unit and time horizon of the problem, (iii) assessing the reference dynamic behavior, and (iv) writing down the purpose statement that will guide the following steps. The second step, dynamic hypothesis, is for developing a hypothesis that can explain the causes of undesired dynamics. This step consists of examining the problem, listing relevant model variables, identifying causal relationships and developing initial causal loop diagrams and identifying primary stock and flow variables. In the third step, formal simulation model is developed which includes construction of stock flow diagrams, writing down the mathematical equations and determining numerical values and initial stock values, and verifying model consistency against dynamic hypothesis. Forth step, validity testing, is to assess whether the model is an adequate representation of the real problem or not. Validation step has two aspects, namely structural and behavioral. In structural tests, model structure is analyzed to understand whether it is a meaningful description of the real relations. On the other hand, in behavioral tests, the dynamic patterns that model generated is compared with the real dynamic patterns. The last step is the analysis of the model that aims to understand the important dynamics of the model. Properties of the model are tried to be understood with a series of logically related simulation runs that are also called as sensitivity tests. The primary aim of these runs is to determine the effects of changes in selected parameters, inputs and initial conditions on the output behavior (Barlas, 2002).

In accordance with the major steps of system dynamics described above, the problem of increasing extraction cost depending on the decrease in groundwater level within a season is studied. Fundamental elements of our conceptual model are water resources, groundwater extraction for agricultural purposes and its impact on the crop growth and end-of-the-season impacts on the farm profits. This conceptual model is explained in detail in the next section. Formal simulation model together with the stock flow diagrams and mathematical equations, and model validation tests are also demonstrated in the next section. For the last step, a simulation game is created and model analysis is enhanced with the help of the game.

In line with the purpose of this research, a web-based dynamic simulation game is developed to study the groundwater appropriation problem (the appropriation externalities) that occurs among the irrigators who share a common aquifer during an irrigation season. The game crates a platform for the players to learn about the resource dynamics, cooperation dilemma and sustainable management of the CPRs. According to Ostrom et.al. (1994), a formal game is composed of seven elements which are (i) a set of players, (ii) a set of positions, (iii) sets of actions assigned to positions, (iv) a decision function that maps decisions into intermediate or final outcomes, (v) a set of outcomes, (vi) the kind of information available, and (vii) payoff function based on benefits and costs of actions and outcomes (Ostrom, Gardner, & Walker, 1994).

Simplest possible game having the aforementioned components is described in Figure 4.1 (Ostrom, Gardner, & Walker, 1994).

		Player 2	
		Strategy 1	Strategy 2
Player 1	Strategy 1	a a	b c
	Strategy 2	c b	d d

Figure 4.1. Game with two players and two strategies (Ostrom, Gardner, & Walker, 1994).

The first element, a set of players (i) is the two players, called Player 1 and Player 2. In our game, there are five players representing maize farmers.

A set of positions (ii) can be defined as the placeholders that links participants with the actions, such as first movers, employees, bosses and citizens and so on. In most of the games, number of positions is generally less than the number of participants. In the game design shown above, players make simultaneous and independent decisions from each other. Therefore, there is a single position held by the two players. Likewise, in our dynamic simulation game there is only one position available for players, which is the role of farmers.

Participants in particular positions can take a set of actions (iii) such as decisions to extract groundwater or not. In the matrix above, both two players can select either Strategy 1 or Strategy 2. Player 1 chooses over the two rows of the matrix, whereas Player 2 selects from the two columns of the matrix. Therefore, there are two actions (i.e. Strategy 1 and Strategy 2) available for each of the player. In our game, players can take actions on the timing and duration of the groundwater extraction and irrigation.

Forth element is the decision function (iv) that maps participants at decision nodes to the outcomes. In most of the cases, it is not possible to fully understand the complex decision function. For example, fishery experts do not fully understand the combination of factors affecting the linkage between fishing effort and fish stocks in the next year. The entire function is presented in the four cells of matrix structure. If both Player 1 and Player 2 decide on the Strategy 1, then the outcome corresponds to the upper left cell of the matrix. Since our game is grounded on a scientifically developed dynamic simulation model, the model that integrates groundwater extraction, crop yield and farm profits, creates the decision function

The fifth element is the set of outcomes (v) that players can potentially affect through their actions. The amount of groundwater extracted, physical condition of an irrigation system or degradation of regenerative capacity of a resource are examples of potential outcomes. The contents in the four cells of the matrix correspond to the outcomes. Each cell represents a different outcome and each outcome is two-folded, one in the upper left corner (for Player 1) and one in the lower right corner (for Player 2) of the cell. If Player 1 selects Strategy 2 and Player 2 selects Strategy 1, then the outcome is *c* for Player 1 and *b* for Player 2. Therefore, the four possible outcomes portrayed in the four cells of the matrix are the set of outcomes. At the end of our dynamic simulation game, outcomes of the game including crop yields, total water and electricity consumption, profits of the farms and irrigation efficiency becomes available for the players.

Information (vi) available to the players in a position is the sixth element of a formal game. In case of a simple decision function, complete information about the actions, outcomes and their relationship can be available. However, in many cases it is not possible to generate complete information. In the game shown above, the matrix itself generates the information available. A set of information is available for the players in our game interface that includes both quantitative information (i.e. crop water requirement) and descriptive information (i.e. coordination dilemma and factors affecting farm profit).

Seventh and last element is the payoff function (vii) that assigns benefits and costs to actions and outcomes. Examples of payoff include taxes paid on several activities, price of a crop offered to the farmers to bring crops to the market, or cost of traveling to a fishing spot. The letters shown in the cells of the matrix, *a*, *b*, *c* and *d* corresponds to the payoffs (amount of cash or any other valued thing) to be given to the players at the end of the game. The cash payoffs describe the payoff function. Our dynamic simulation game does not include a material payoff such as cash or any other valued thing. The outcomes of the game described in element (v) describe the payoff function.

Based on the dynamic simulation model, the simulation game called *Groundwater Irrigation Game* is created. Dynamic simulation model is described in Chapter 5 and the game is presented in detail in Chapter 6.

5. MODEL DESCRIPTION

In this section, the dynamic simulation model is explained. Overview of the model, main assumptions and limitations, model sectors, validation and reference behavior of the model are described, respectively. Stock flow diagrams, causal loop diagrams and model formulations are provided where relevant.

5.1. Overview of the Model

Diagram of the physical model is shown in Figure 5.1 below. As shown in the Figure, soil layer is divided into two parts, namely, root zone and deep zone. Root zone corresponds to the first 50 cm of the soil layer whereas deep zone locates below the root zone and extends until 80^{th} meters. There are five separate farming fields that share the same groundwater aquifer. All of the farming fields have equal surface area and equal access to the groundwater from their own well located in their fields. Groundwater is extracted from the wells and used for irrigation. Therefore, the amount of irrigation directly depends on the extraction. On the other hand, each farming field receives same amount of precipitation. Precipitation and irrigation water is used by the crops (i.e. plant transpiration) and evaporates from the soil surface (i.e. evaporation). The combination of these two processes is called as evapotranspiration. Depending on the percentage of soil moisture, water can move downward as percolation or discharge as surface runoff. Groundwater is extracted from the aquifer located in soil deep zone. Generic and representative groundwater aquifer is created and it is assumed that the aquifer can recover itself in 2688 hours (112 days) completely within the season studied. Water in the pores of soil deep zone can move upward as capillary rise. The formulations are grounded on the available soil hydrology literature and references are provided with the equations given in the following part of this section.

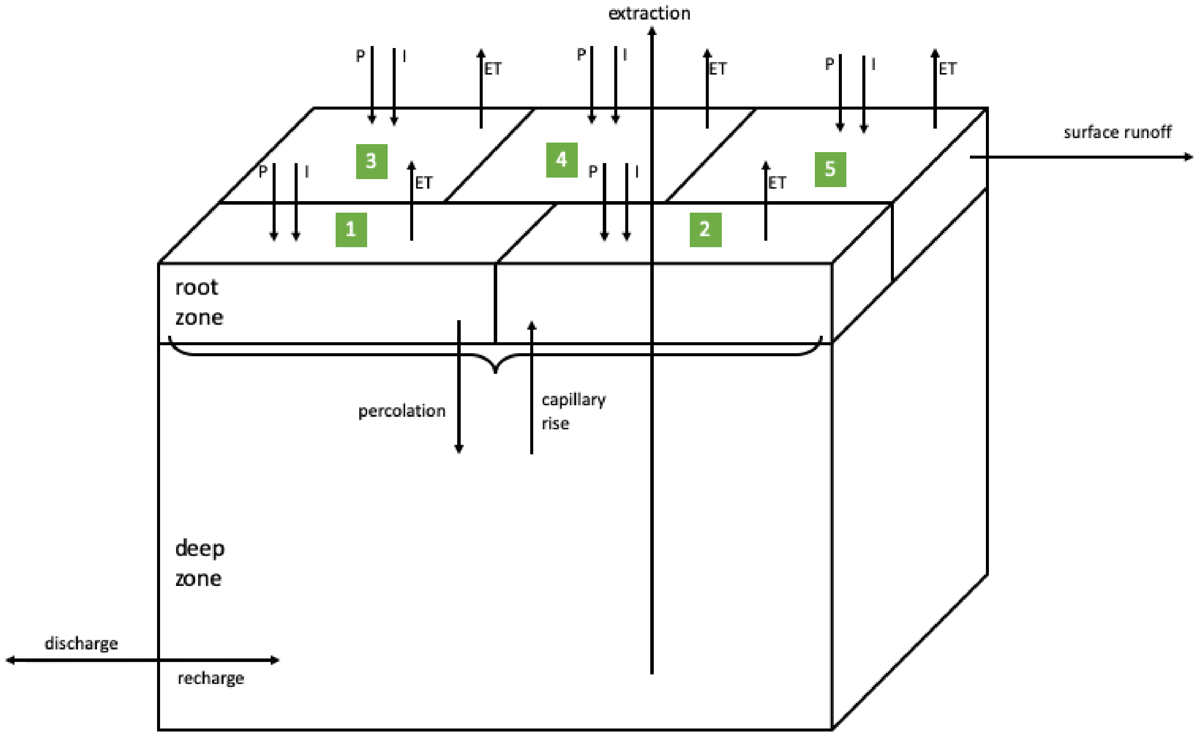

Figure 5.1. Physical model of soil water balance (P: Precipitation, I: Irrigation, ET: Evapotranspiration).

Based on the physical model described above, a dynamic simulation model is developed on *Stella Architect* and the full set of equations are presented in Appendix A. Time unit of the model is hours. Length of simulation (i.e. time horizon) is 16 weeks, which corresponds to 2688 hours. Computational step is taken as 0.125. Integration method is based on Euler's Method.

The model consists of two main sectors, namely, (i) *water resources* presenting both vertical and horizontal flows of groundwater (i.e. percolation, capillary rise, evapotranspiration, surface runoff, lateral recharge and discharge); and (ii) *crop growth* showing crop response to water and financial figures (i.e. cost due to the electricity spent, revenue to be obtained from crop yield and profit).

In water resources sector, water stored in the soil root zone and deep zone are the resource stocks whereas water movements (i.e. precipitation, percolation, capillary rise, evapotranspiration, surface runoff, irrigation, lateral recharge and discharge and extraction) are the flows.

The second sector in the model, crop growth provides the biomass growth and yield obtained at the end of irrigation season. This sector also provides the financial calculations based on the crop yield obtained and electricity cost spent for pumping.

5.2. Assumptions and Limitations

Main assumptions of the model, which also forms the basis of the simulation game:

- Each farming land is 5 hectare-sized (50,000 m^2) and has its own well used for irrigation.
- Five farms share the same groundwater aquifer and groundwater level is same for all wells.
- Groundwater table level corresponds to the distance from the ground surface to the upper boundary of reservoir. It is assumed that decrease in groundwater level occurs linearly.
- Single irrigation season for maize consists of 4 months from the beginning of May (May 1st) to the end of August (August 21st) and one month is taken as 4 weeks (672 hours).
- The model solely considers the quantity, not the quality aspects of groundwater use.
- Farms profits in the model are solely affected by energy costs and crop yields, where energy costs depend on the water extraction and crop yields depend on the irrigation throughout the season.
- Crop and energy prices are assumed as constant and it is not affected from the inflation in a single irrigation season.

5.3. Description of the Model Sectors

The dynamic simulation model is composed of 2 main model sectors called water resources, and crop growth. The relationship between the model sectors and game player's input is depicted in Figure 5.2.

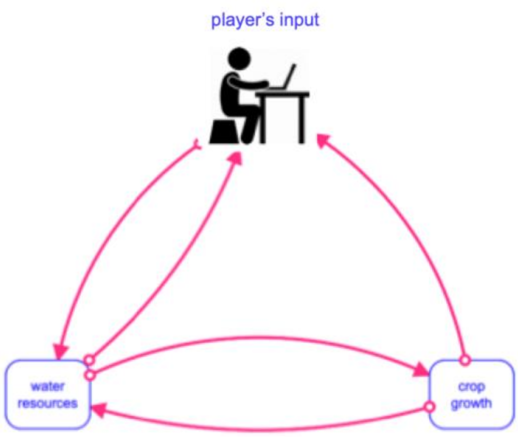

Figure 5.2. Model sector interactions.

In the Figure, the arrows from the model sectors to the “player’s input” represent the information flow from model sectors to the players. In the game interface, which will be explained and demonstrated in the following chapter, couple of information including groundwater extraction rate, relative soil moisture of the soil root zone (from the water resources sector) and crop biomass and electricity cost (from the crop growth sector) are available to the players. The arrow from player’s input to the water resources sector represents the player’s decision. In the game, players decide on their irrigation schedule which is a variable in the water resources sector. Arrows between water resources and crop growth sectors show the interaction between these two sectors. Crop growth relies on the irrigation and soil moisture content that are derived from the water resources sector. On the other hand, as crop grows, water demand of the crops changes and that provides information to the water resources sector.

Interaction between the model sectors, structure of the model sectors, equations and model variables together with the stock-flow and causal loop diagrams are presented in the following subsections.

5.3.1. Water resources sector

Water resources sector of the model is mainly composed of 2 stock and 8 flow variables. Water in root zone, water in deep zone and irrigation water in terms of m^3 are the stock variables whereas capillary rise, extraction, evapotranspiration, irrigation, percolation, precipitation, lateral recharge/discharge and surface runoff in terms of m^3/hour are the flow variables. These variables together with their units are presented in Table 5.1 below.

Table 5.1. Main stock and flow variables of water resources sector.

Stock variables	**Unit**
Water in deep zone	m^3
Water in root zone	m^3
Flow variables	**Unit**
Capillary rise	m^3/hour
Evapotranspiration	m^3/hour
Extraction	m^3/hour
Irrigation	m^3/hour
Percolation	m^3/hour

Flow variables	Unit
Precipitation	m^3/hour
Lateral Recharge & Discharge	m^3/hour
Surface runoff	m^3/hour

Causal loop diagram and stock flow diagram of water resources sector are presented in Figure 5.3 and Figure 5.4, respectively.

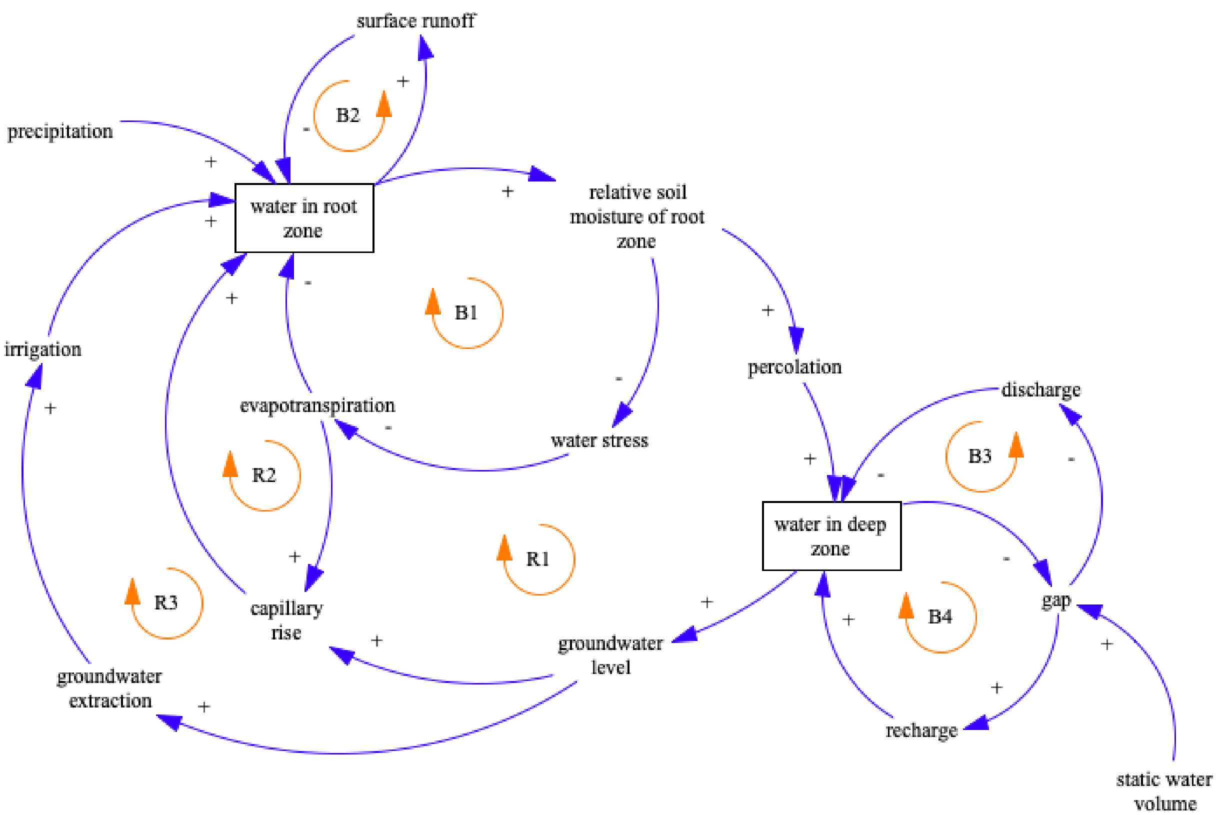

Figure 5.3. Causal loop diagram of water resources sector.

In water resources sector of the model, there are 4 balancing and 3 reinforcing feedback loops. The first loop, B1 shows the relationship between the root zone moisture content and evapotranspiration. As water in root zone increases, relative soil moisture of root zone increases and water stress on crops decreases. Decrease in water stress leads to an increase in evapotranspiration. However, as evapotranspiration increases, plants extract more water from the soil root zone and water in root zone decreases.

B2 loop shows that as surface runoff increases water in root zone decreases and as the water in root zone decreases surface runoff decreases as well.

In B3 and B4 balancing loops, effect of changes in water in deep zone on the lateral recharge and discharge mechanisms is depicted. When water in deep zone decreases, gap between static and dynamic water volumes increases. As the gap increases, lateral recharge increases. In contrast, when water in deep zone increases, gap decreases and lateral discharge increases. Increase in recharge leads to an increase in water in deep zone whereas increase in discharge leads to a decrease in water in deep zone stock.

Besides above balancing loops, the two reinforcing loops (i.e. R1 and R2) show the response of water in root zone. In the first loop (R1), interaction between the water in root zone and deep zone stocks is depicted. As water in root zone increases, relative soil moisture of root zone and therefore percolation to the deep zone increases. Increase in percolation leads to an increase in water in deep zone and groundwater level. When groundwater level increases, capillary rise to the root zone increases and water in root zone increases as well. In the second loop (R2), increase in water in root zone and relative soil moisture of root zone decreases the water stress on crops. As water stress decreases, evapotranspiration increases and capillary rise increases. When capillary rise to the root zone increases, water in root zone also increases.

R3 loop forms the basis for the coordination dilemma that the players will face in the game later on. When groundwater extraction (in terms of hours) increases, irrigation and water in root zone increases. As water in root zone increases, relative soil moisture of root zone increases as well. Increase in relative soil moisture leads to an increase in percolation to the deep zone and an increase in water in deep zone stock. When water in deep zone increases, groundwater level and groundwater extraction increases. Increase in extraction leads to an increase in irrigation, and therefore; in water in root zone stock.

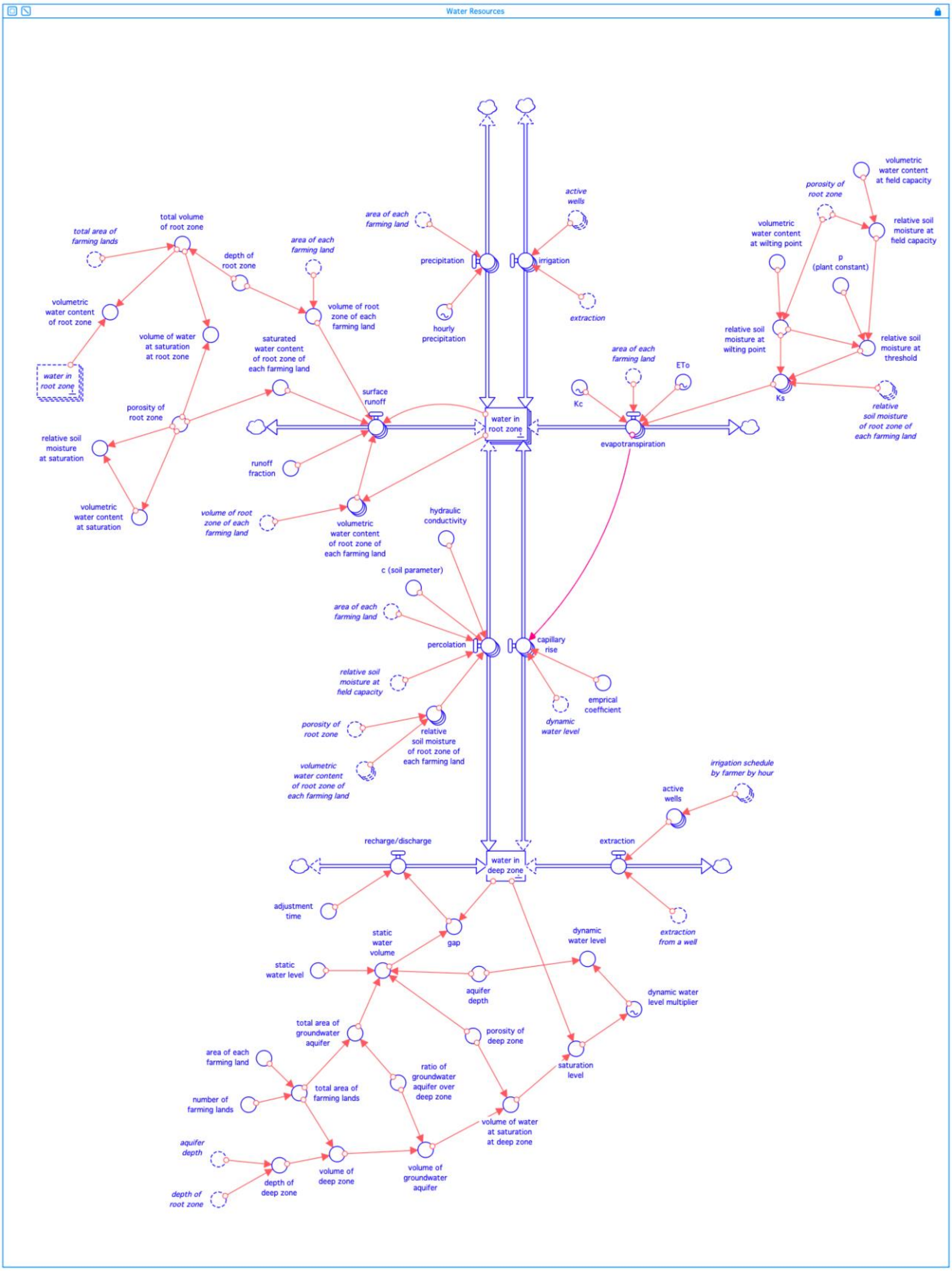

Figure 5.4. Stock flow diagram of water resources sector.

Soil root zone is composed of 5 equal-sized farming fields as shown in the physical model (Figure 5.1). The total of 5 wells are connected to the same aquifer at soil deep zone. Therefore, deep zone is taken as a single stock in the model.

In order to model each farming land separately, there is a need to replicate model structure for each farmer. To avoid visual complexity, array builtin is used. Water in root zone stock and its associated flows (i.e. capillary rise, irrigation, precipitation, evapotranspiration, percolation and surface runoff) are defined as an arrayed variable in the model. Array dimension is “Farmer” and it is created as a Label dimension. The elements are named as Farmer 1, Farmer 2, Farmer 3, Farmer 4 and Farmer 5.

In general, stock and flow equation can be written as presented below:

$$Stock\ (t + \Delta t) = Stock\ (t) + [inflow - outflow] * \Delta t \qquad 5.1$$

$$\frac{Stock\ (t + \Delta t) - Stock\ (t)}{\Delta t} = inflow - outflow \qquad 5.2$$

For soil root zone, S represents the volume of water stored in the soil root zone in m^3. Inflows are capillary rise, irrigation and precipitation whereas outflows are evapotranspiration, percolation to soil deep zone and surface runoff in m^3/hour.

Therefore, the equation for root zone can be written as below:

$$\begin{aligned} Water\ in\ root\ zone\ (t) \\ &= Water\ in\ root\ zone\ (t - dt) \\ &+ (CR + I + R - ET - P - SR) * dt \end{aligned} \qquad 5.3$$

Where CR is the capillary rise from soil deep zone (m^3/hour); I is irrigation applied (m^3/hour); R is the amount of hourly precipitation (m^3/hour); ET is evapotranspiration (m^3/hour); P is percolation to the soil deep zone (m^3/hour); and SR is surface runoff (m^3/hour).

Formulations for flow variables associated with the water in root zone stock are provided in an alphabetical order hereinafter.

Capillary Rise

According to Khan, et.al. (2007), capillary rise (CR) is estimated by using empirical formulas that include depth of groundwater level and parameters related to soil type. In accordance with the formula, CR is strongly affected from the actual crop evapotranspiration. In the model, CR is calculated by using the following relationship (Khan, Yufeng, & Ahmad, 2009).

$$CR = ET_c * e^{-h*\beta} \qquad 5.4$$

Where ET_c is the crop evapotranspiration (m^3/hour);

h is the groundwater depth (m); and

β is an empirical value related with the capacity of the soil to transmit capillary fluxes, 2 for sandy loam (m^{-1}).

Evapotranspiration

Evapotranspiration (ET) refers to the combination of two separate processes which are evaporation from the soil surface and transpiration by the crop. Evaporation; in other words, vaporization is the process of turning from liquid water into the water vapor from a variety of evaporating surfaces including soil, pavements and surface water bodies such as rivers and lakes. Required energy to vaporize water is provided by the ambient air temperature and direct solar radiation. The difference between water vapor pressure at the evaporating surface and the atmosphere acts as a driving force to remove water vapor from the evaporating surface. As evaporation proceeds the surrounding air reaches saturation gradually which will result in slowing evapotranspiration. Therefore, climatological parameters including air temperature, solar radiation, humidity and wind speed are the parameters affecting evapotranspiration process. On the other hand, in case the soil surface is an evaporating surface, evaporation process is affected from some other factors including but not limited to the amount of water available and shading of the crop canopy. As long as soil can provide required water that meets the evaporation demand, evaporation proceeds based solely on the meteorological conditions (FAO, 1998).

Therefore, evapotranspiration can be calculated by using the formula below (FAO, 1998):

$$ET_c = K_c * ET_o \qquad 5.5$$

Where ET_o is the reference crop evapotranspiration, mm; and

K_c is single crop coefficient, dimensionless.

In the model, both ET_o and K_c data are inserted as table functions. It is not possible to find hourly ET_o data in the literature, since measurement periods are generally much longer. In order to insert it in the model as hourly data, data belong to the field measurements conducted with 10 days intervals are used. First the graph of the data is plotted, and then a 4th order parabolic trendline is added. By using the equation of the trendline, hourly ET_o data is generated. ET_o data used in the model is based on the measurements conducted in the same region where precipitation measurements are performed (Figure 5.5).

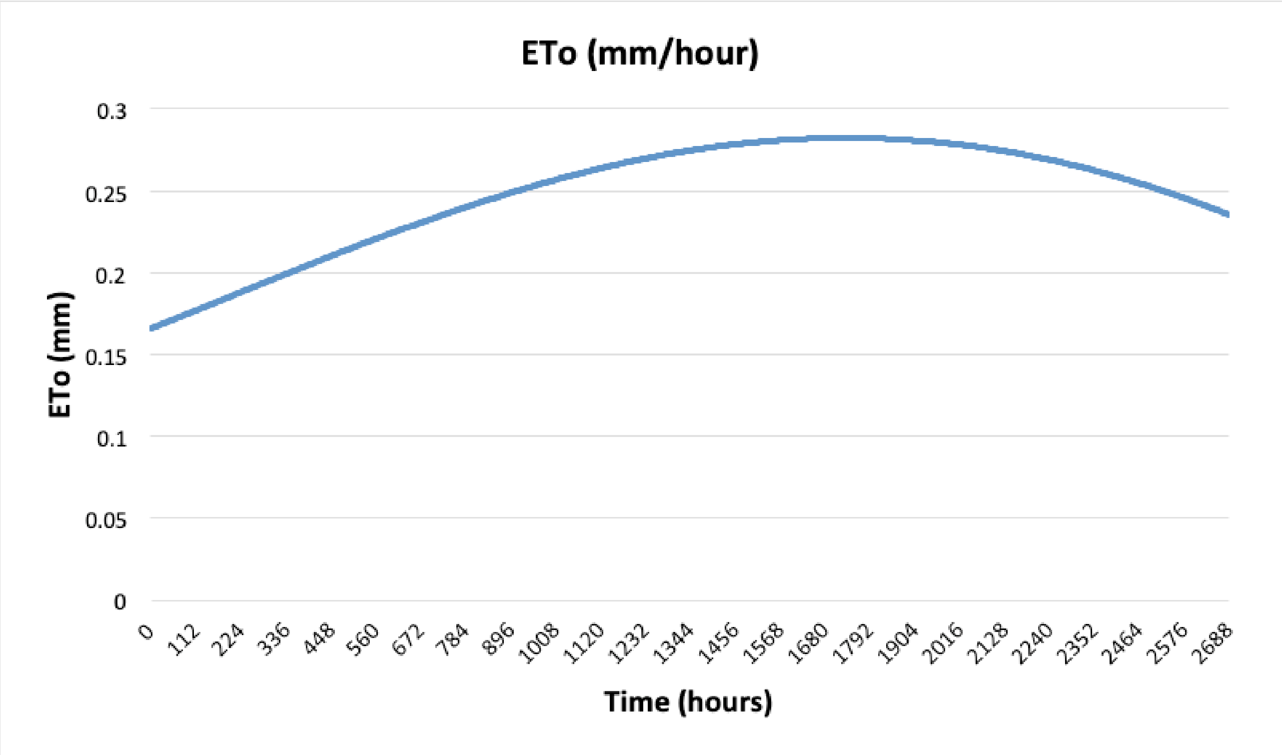

Figure 5.5. Hourly ETo data (DSI, 2017).

Kc is crop coefficient and it takes different constant values for different development stages. With the aim of inserting Kc data as an hourly time series into the model, same approach explained previously is followed. Kc data is shown in Figure 5.6 below.

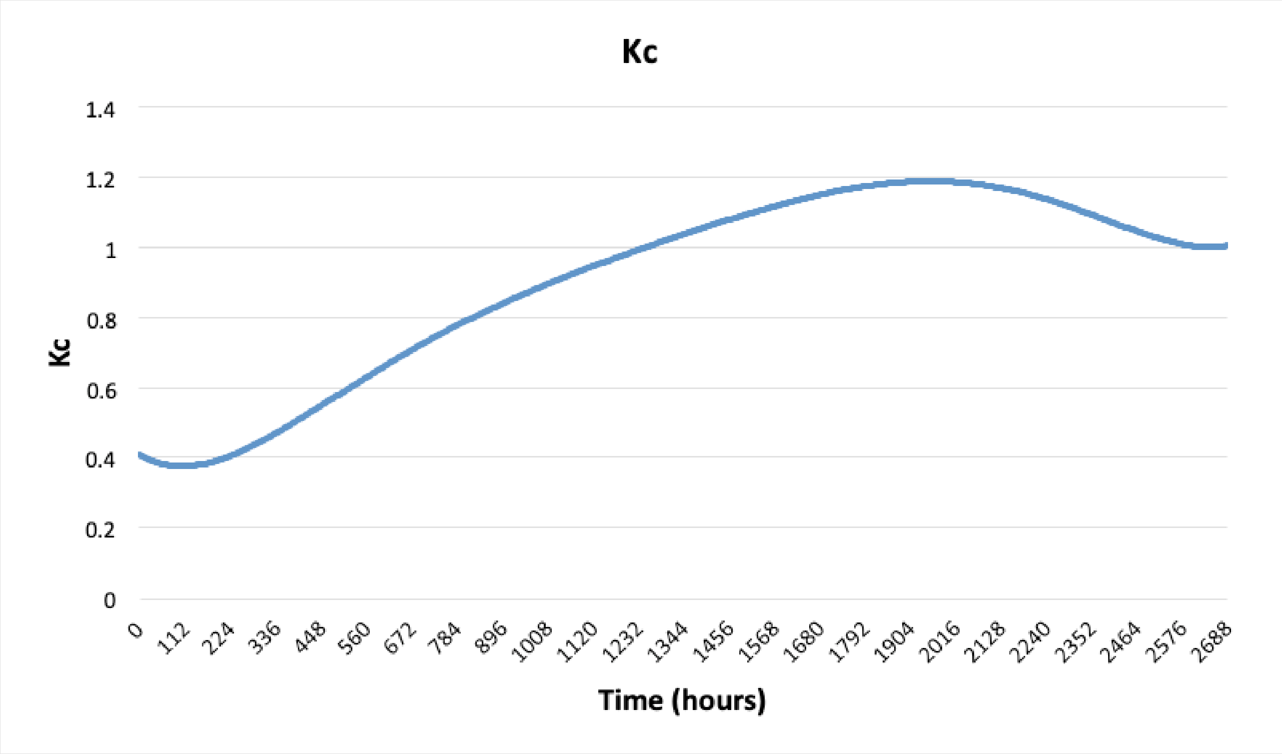

Figure 5.6. Hourly Kc data (DSI, 2017).

However, in case of limited water availability, evaporation from soil surface is restricted. Forces acting on the soil water reduce its potential energy and the amount of water available for plant root extraction becomes less. When the soil is dry, the water has low potential energy and cannot be taken up by the plants easily. On the other hand, in wet soils, water with high potential energy can be easily taken up by the plants. Water stress is occurred when the soil water potential energy falls below a certain level which will be called threshold value later on. The effect of water stress on the evapotranspiration is considered by integrating the water stress coefficient, K_S to the evapotranspiration formula given above. Accordingly, evapotranspiration calculation can be adjusted as shown below (Khan, Yufeng, & Ahmad, 2009):

$$ET_c = K_s * K_c * ET_o \tag{5.6}$$

K_s equals to 1 when there is no soil water stress; however, in case of soil water limiting conditions, K_s is less than 1. K_s is calculated by using the following conditional expression (Khan, Yufeng, & Ahmad, 2009):

$$K_s = \begin{cases} 1, & \theta_{threshold} \leq \theta \\ \dfrac{\theta - \theta_{wp}}{\theta_{threshold} - \theta_{wp}}, & \theta_{wp} \leq \theta < \theta_{threshold} \end{cases} \tag{5.7}$$

Where θ is the volumetric water content at soil root zone which is defined as the ratio of water volume to soil volume ($\theta = V_w/V_s$), m^3/m^3;

θ_{wp} is the volumetric water content at wilting point, m^3/m^3; and

$\theta_{threshold}$ is the threshold water content at soil root zone, m^3/m^3.

$\theta_{threshold}$ is determined as shown below (Khan, Yufeng, & Ahmad, 2009):

$$\theta_{threshold} = (1 - p) * \theta_{fc} + p * \theta_{wp} \qquad 5.8$$

Where θ_{fc} is the volumetric water content at field capacity, m^3/m^3; and

p is the ratio of readily available water to the total available water.

Total available water (TAW) is defined as the amount of water that plants can extract from their root zone. Theoretically, TAW is defined as the amount of water between wilting point and field capacity. Field capacity refers to the amount of water that can be retained against gravitational forces. When the soil water content exceeds its field capacity, it cannot be held against gravitational forces and moves downward. On the other hand, as the soil water content decreases below the wilting point, plants can no longer extract the water and they will permanently wilt (FAO, 1998).

TAW is calculated by using the formula given below (FAO, 1998):

$$TAW = 1000(\theta_{fc} - \theta_{wp}) * Z_r \qquad 5.9$$

Where TAW the total available water in the soil root zone, mm,

Z_r the rooting depth, m.

Theoretically, water is available to plants until wilting point; however, water uptake of the plants is reduced before the wilting point is reached. As the soil water content decreases, it becomes more difficult to extract the water. When soil water content falls below the threshold value, water stress conditions emerge and plants can no longer extract water fast enough to meet their transpiration demand. The fraction of TAW that plants can extract without suffering water stress is defined as readily available soil water and can be calculated as shown below:

$$RAW = TAW * p \tag{5.10}$$

Where RAW is the readily available water in soil root zone, mm;

p is the average fraction of TAW before the moisture stress occurs, 0.5 for maize.

Irrigation

It is assumed that all of the extracted groundwater is applied as irrigation water without any conveyance loss. Accordingly:

$$I_j = Extraction \tag{5.11}$$

Percolation

When soil water content exceeds its field capacity, water moves below the root zone and percolation occurs. Percolation is affected from the soil texture and soil moisture content (FAO, 1985). Percolation calculation in the model is based on the following formula (Rodriguez-Iturbe & Porporato, 2004):

$$P = K_s * s^c \tag{5.12}$$

Where K_s is saturated hydraulic conductivity, 0.033 m/hour;

c is an empirical constant depending on the soil properties, 12.8 for sandy loam soil; and

s is relative soil moisture which represents the fraction of pore volume including water, m^3/m^3.

Relative soil moisture content can be calculated by using the expression below (Rodriguez-Iturbe & Porporato, 2004):

$$s = \frac{V_w}{V_w + V_a} = \frac{\theta}{porosity} \tag{5.13}$$

Where V_w is the volume of water, m^3; and

V_a is the volume of air, m^3.

Porosity can be defined as the volume of void, which is either filled with water or air over the total volume. Therefore, porosity can be calculated as below (Rodriguez-Iturbe & Porporato, 2004):

$$Porosity = \frac{V_w + V_a}{V_s} \qquad 5.14$$

Where V_s is the volume of soil, m^3.

Precipitation

In the model, precipitation data is inserted as a table function. Since precipitation measurements are generally conducted on daily or monthly basis, it is not possible to find hourly precipitation data. Data belong to the field measurements conducted with 10 days intervals are used for creating hourly time series. Graph of precipitation data is plotted and parabolic 4th order trendline is added to the graph. By using the equation of the trendline, hourly precipitation data is generated. The hourly data used in the model is based on meteorological measurements conducted in a semi-arid region. It is assumed that each farming land receives same amount of precipitation. Precipitation data is presented in Figure 5.7 below.

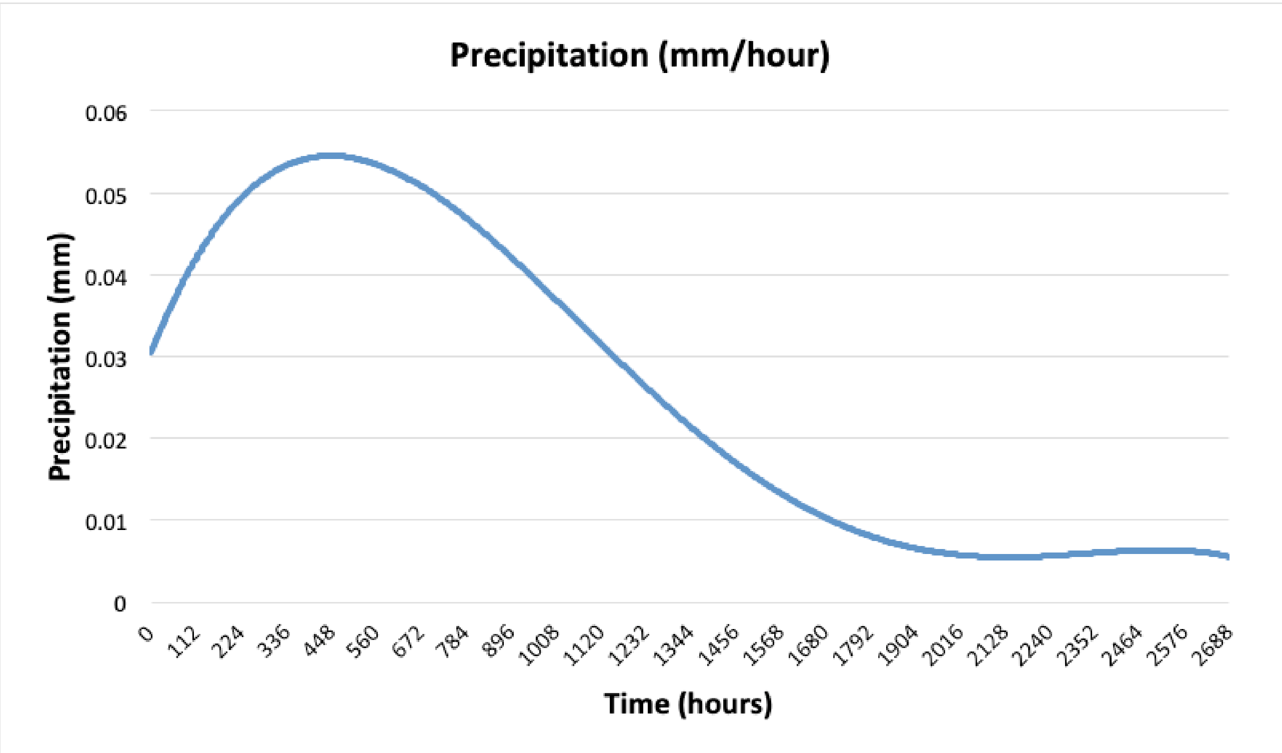

Figure 5.7. Hourly precipitation data (DSI, 2017).

Surface Runoff

Surface runoff (SR) takes place as soil water content exceeds saturation level. In other words, when volumetric water content of root zone exceeds saturated water content, excess amount of water is discharged as surface runoff. SR is estimated by using following expression (Khan, Yufeng, & Ahmad, 2009):

$$SR = \begin{cases} 0, & \theta \leq \theta_s \\ S_j - \theta_s * D_r, & \theta_s \leq \theta \end{cases} \qquad 5.15$$

Where θ_s is the saturated water content, m^3/m^3;

D_r is the depth of root zone, m.

For soil deep zone, S represents the volume of water stored in the soil deep zone in m^3 in equation 5.2. Inflow is percolation whereas outflows are capillary rise and extraction in m^3/hour. Lateral recharge & discharge can either behave as an inflow or outflow depending on the gap between dynamic and static water levels that will be explained later on.

Therefore, the equation for deep zone can be written as below:

$$\begin{aligned} &Water\ in\ deep\ zone\ (t) \\ &\quad = Water\ in\ deep\ zone\ (t - dt) + (P - CR - E \pm RD) * dt \end{aligned} \qquad 5.16$$

Where P is percolation from root zone (m^3/hour); CR is capillary rise to root zone (m^3/hour); E is the groundwater extraction (m^3/hour); and RD is the lateral recharge & discharge from/to the surrounding aquifers (m^3/hour).

Formulations for percolation and capillary rise are explained in equation 5.12 and 5.4, respectively. Other flow variables associated with the water in deep zone stock are provided below.

Extraction

Groundwater extraction is not interrupted as long as the pump stays in the water. The pump is initially located in the water; however, depending on the artificial extraction rates, groundwater level may drop below the pump level. In such a case, the pump can no longer extract water and groundwater extraction rate will be zero. Accordingly:

$$Extraction\ from\ a\ well = \begin{cases} 0, & pump\ height < groundwater\ level \\ Q, & pump\ height \geq groundwater\ level \end{cases}$$

Where Q corresponds to the potential flow rate in the model and calculated by using the formula below:

$$Q = \frac{P * Pump\ efficiency}{H * g * \rho} \qquad 5.17$$

Where Q is the flow through the well, m^3/s;

P is the pump power, watts;

H is the pump head, m;

g is the acceleration due to gravity, m/s^2; and

ρ is the density of the fluid, kg/m^3.

Pump head is the summation of dynamic water level and head loss through the well due to friction, which corresponds to 10% of the dynamic water level. Accordingly, pump head calculation can be formulized as follows:

$$Pump\ head\ (H) = Dynamic\ water\ level + Head\ loss \qquad 5.18$$

$$Head\ loss = Dynamic\ water\ level * 0.1 \qquad 5.19$$

Lateral Recharge & Discharge

Recharge/discharge is the lateral movement of groundwater depending on the changes in dynamic water level and volumetric water content of deep zone. Initial water table level of 50 m and initial volume of water in deep zone (named as *static water volume* in the model) of 150,000 m^3 are given as model constants. As groundwater extraction proceeds and groundwater level declines, there will be a gap between the initial static groundwater volume and dynamic groundwater volume in deep zone (i.e. stock variable of *water in deep zone*). In that case, groundwater flows horizontally from the surrounding aquifers to adjust the gap.

Similarly, as the groundwater level rises up, the gap between static and dynamic water volumes will be negative and water starts flowing to the surrounding aquifers to adjust the level. Accordingly, lateral recharge/discharge flow is calculated based on the following expression:

$$Lateral\ Recharge/Discharge = \frac{Gap}{Adjustment\ time} \quad 5.20$$

5.3.2. Crop growth sector

In the crop growth sector of the model, biomass growth from seeding to harvesting depending on the irrigation is simulated. Costs generated due to the electricity spent by the pumps and revenue to be obtained from the crop yield are also calculated. In order to model the growth, crop biomass is considered as the stock and growth and decay are considered as the flow variables. In line with the literature, crop growth is divided into stages. At each stage, certain amount of biomass is decayed which is represented by decay flow in the model. Decay fraction is a constant and same at all of the stages. On the other hand, growth fraction changes depending on the development stage since maize growth is not same throughout the season. At each stage, crop grows to reach the maximum attainable biomass, which is determined in line with the available literature. Besides, crop growth flow is formulized as to consider the effect of potential water limiting conditions. This approach is detailed together with the model equations in the following subsection.

In this sector of the model, there are 5 stock variables and 14 flow variables, in total. 4 of the stock variables represent crop biomass at different development stages and the remaining one represents the cost accumulated throughout the simulation. Stock and flow variables together with their units are provided in Table 5.2 below.

Table 5.2. Stock and flow variables of crop growth sector.

Stock variables	**Unit**
Biomass at stage A	Tons
Biomass at stage B	Tons
Biomass at stage C	Tons
Biomass at stage D	Tons
Total cost	TL

Flow variables	**Unit**
Cost accumulation	TL/hour
Decay A	Tons/hour
Decay B	Tons/hour
Decay C	Tons/hour
Decay D	Tons/hour
Growth A	Tons/hour
Growth B	Tons/hour
Growth C	Tons/hour
Growth D	Tons/hour
Harvesting	Tons/hour
Seeding	Tons/hour
Switch (A to B)	Tons/hour
Switch (B to C)	Tons/hour
Switch (C to D)	Tons/hour

Causal loop diagram and stock flow diagram of crop growth sector are presented in Figure 5.8 and Figure 5.9, respectively.

As shown in Figure 5.8, in crop growth sector of the model, there are 8 balancing and 7 reinforcing feedback loops. Balancing loops, B5, B7, B9 and B11 illustrate the direct relationship between crop biomass at each development stage and decay function. In each loop, as crop biomass increases, decay increases. On the other hand, as decay increases, crop biomass decreases.

B6, B8, B10 and B12 are the balancing loops that control the crop growth. In these loops, as the crop biomass increases, relative crop biomass (actual biomass/maximum crop biomass) increases as well. When relative crop biomass increases, growth decreases and that leads to a decrease in crop biomass.

In contrast to the abovementioned balancing loops, there are 4 reinforcing loops (i.e. R4, R5, R6 and R7) that depict the direct relationship between the crop biomass and growth. As shown in the Figure, as the crop biomass increases, growth increases and as growth increases, biomass increases as well.

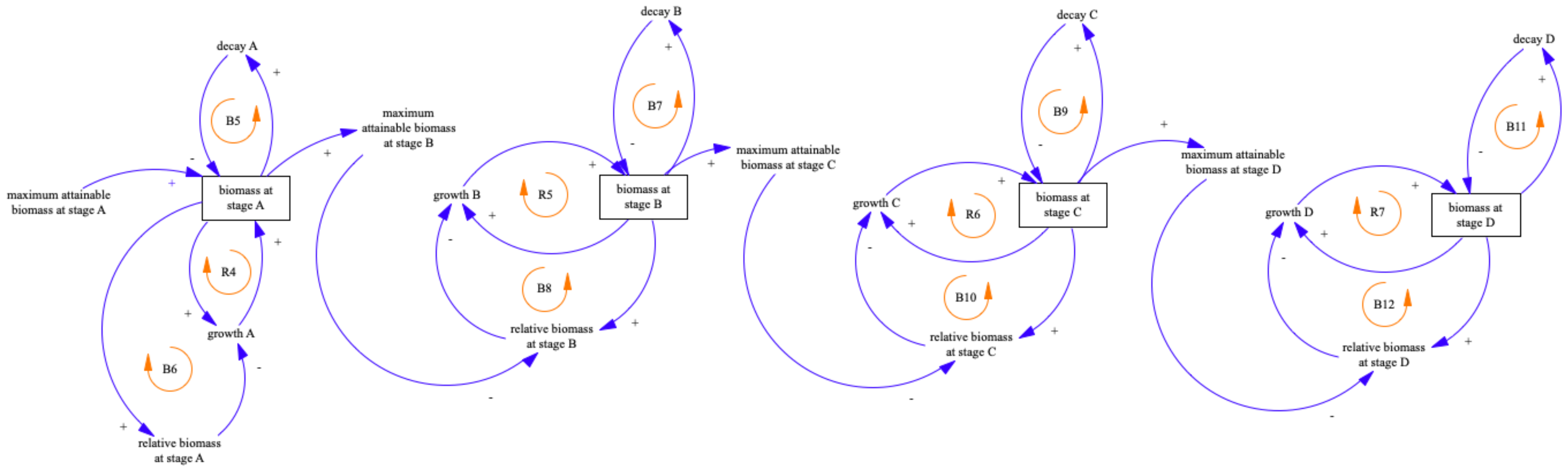

Figure 5.8. Causal loop diagram of crop growth sector.

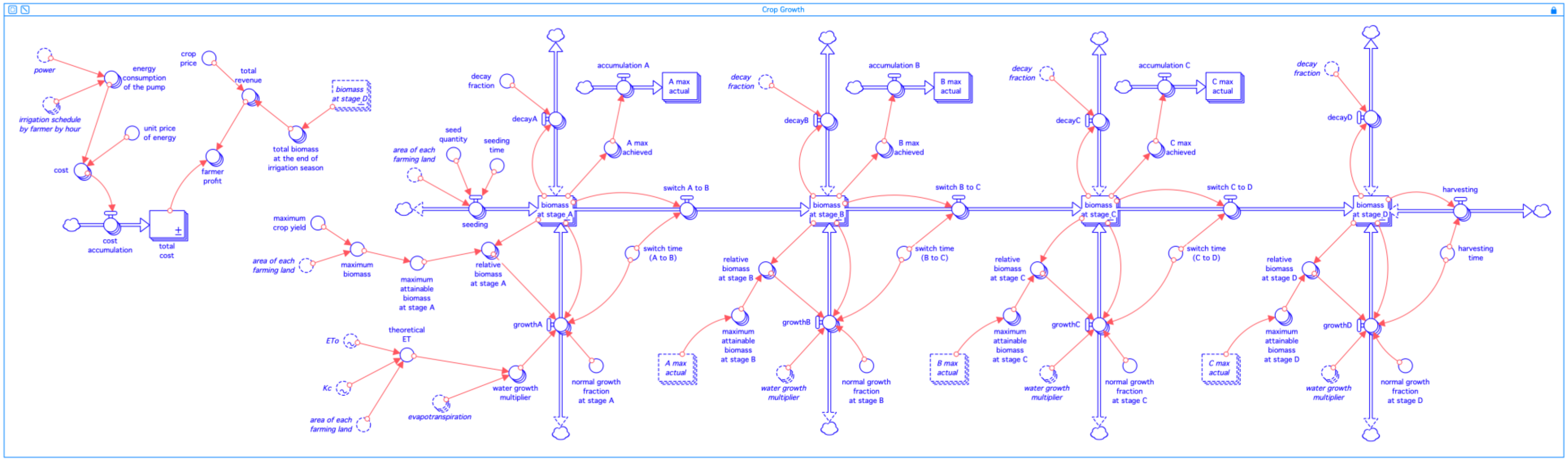

Figure 5.9. Stock flow diagram of crop growth sector.

5.3.2.1. Crop growth calculations: Crop growth period of maize is divided into 4-development stages (i) initial (15-30 days), (i) crop development (30-45 days), (iii) mid-season (30-45 days) and (iv) late-season (10-30 days) (FAO, 2020). Considering total simulation duration of 112 days (i.e. 2688 hours), the lengths of the stages are assumed as presented in Table 5.3 below (FAO, 2020).

Table 5.3. Length of development stages for maize (FAO, 2020).

	Stages of Development			
	Initial (Stage A)	**Crop development (Stage B)**	**Mid-season (Stage C)**	**Late-season (Stage D)**
Stage length (days)	20 days	32 days	32 days	28 days

In accordance with the development stages, crop growth model is composed of 4 stock variables representing the biomasses of these four stages in terms of tons. Associated flow variables represent growth and decay of the biomass and switch between the stages, in terms of tons per hour. In addition, seeding and harvesting are also flow variables in terms of tons per hour.

Seeding is applied at the beginning of the simulation (i.e. at time=0) and harvesting takes place at the end of the simulation (i.e. at time=2688). Development stage lengths are integrated as switching times. As the simulation clock equals to the switching time, biomass accumulated at that stage is transferred to the next stage. Initial values for the stock variables (i.e. biomasses) are taken as zero.

Accordingly, for biomass at stage A stock and associated flow equations are presented below.

$$\begin{aligned} Biomass\ at\ stage\ A\ (t) &= Biomass\ at\ stage\ A\ (t-dt) \\ &+ (Seeding + Growth\ A - Decay\ A - Switch\ from\ A\ to\ B) \\ &* dt \end{aligned} \tag{5.21}$$

$$INIT\ (Biomass\ at\ stage\ A) = 0 \tag{5.22}$$

$$Seeding = PULSE((Seed\ quantity * Area\ of\ each\ farming\ land * DT);\ Seeding\ time;\ 0) \tag{5.23}$$

Where seed quantity is 0,000004 tons/m^2;

Area of each farming land is 50,000 m^2; and
Seeding time is 0.

$$Growth\ A = Biomass\ at\ stage\ A * Normal\ growth\ fraction\ of\ A * (1 - Relative\ biomass\ at\ stage\ A) * Water\ growth\ multiplier \quad 5.24$$

Where normal growth fraction of A is a model constant, dimensionless.

$$Relative\ biomass\ at\ stage\ A = \frac{Biomass\ at\ stage\ A}{Maximum\ attainable\ biomass\ at\ stage\ A} \quad 5.25$$

Where maximum attainable biomass at stage A corresponds to the 10% of total maximum attainable biomass. Total maximum attainable biomass for each farming land is calculated as follows:

$$Total\ maximum\ attainable\ biomass = Maximum\ crop\ yield * Area\ of\ each\ farming\ land \quad 5.26$$

Where maximum crop yield is 0,007 tons/m^2 (PDoAF, 2015); and
Area of each farming land is 50,000 m^2.

Therefore, for each farming land, total maximum attainable biomass is 350 tons and for stage A is 35 tons.

In order to consider the effect of water stress, growth formula is multiplied with the water growth multiplier. Water growth multiplier is estimated by the ratio of actual evapotranspiration the to theoretical evapotranspiration. Accordingly:

$$Water\ growth\ multiplier = \frac{Evapotranspiration}{Theoretical\ evapotranspiration} \quad 5.27$$

Water growth multiplier is same for all the stages.

At each development stage, certain fraction of biomass is decayed. Decay fraction is assumed same for all stages. Accordingly decay equation is shown below:

$$Decay\ (A) = Biomass\ at\ stage\ A * Decay\ fraction \qquad 5.28$$

Where decay fraction is assumed as 0,0002 $hour^{-1}$.

When simulation clock ≥ switching time (A to B), accumulated biomass at *biomass at stage A* stock is transferred to the *biomass at stage B* stock in a single dt. This switch is formulated as presented below:

$$Switch\ (A\ to\ B) = \frac{Biomass\ at\ stage\ A}{DT} \qquad 5.29$$

For biomass at stage B stock and associated flow equations are presented hereinafter.

$$\begin{aligned} Biomass\ at\ stage\ B\ (t) &\\ &= Biomass\ at\ stage\ B\ (t-dt) \\ &+ (Growth\ B + Switch\ from\ A\ to\ B - Decay\ B \\ &- Switch\ from\ B\ to\ C) * dt \end{aligned} \qquad 5.30$$

$$INIT\ (Biomass\ at\ stage\ B) = 0 \qquad 5.31$$

$$\begin{aligned} Growth\ B = {} & Biomass\ at\ stage\ B * Normal\ growth\ fraction\ of\ B * (1 \\ & - Relative\ biomass\ at\ stage\ B) \\ & * Water\ growth\ multiplier \end{aligned} \qquad 5.32$$

Where normal growth fraction of B is a model constant, dimensionless.

$$\begin{aligned} Relative\ biomass\ at\ stage\ B &\\ &= \frac{Biomass\ at\ stage\ B}{Maximum\ \ attainable\ biomass\ at\ stage\ B} \end{aligned} \qquad 5.33$$

When there is no water stress, maximum attainable biomass at stage B corresponds to the 50% of total maximum attainable biomass (i.e. 350 tons for each 50,000 m^2 farming land; therefore, 175 tons for stage B). However, water stress at the previous development stage can affect the maximum attainable biomass of the next stages. Therefore, maximum attainable biomass calculation for stage B, C and D relies on the total biomass obtained at the previous stages. Accordingly:

$$Maximum\ \ attainable\ biomass\ at\ stage\ B = Total\ biomass\ obtained\ at\ stage\ A * 5 \qquad 5.34$$

When simulation clock ≥ switching time (B to C), accumulated biomass at *biomass at stage B* stock is transferred to the *biomass at stage C* stock in a single dt. Switch flow from stage B to C is formulated as presented below:

$$Switch\ (B\ to\ C) = \frac{Biomass\ at\ stage\ B}{DT} \qquad 5.35$$

$$Decay\ (B) = Biomass\ at\ stage\ B * Decay\ fraction \qquad 5.36$$

For biomass at stage C stock and associated flow equations are presented hereinafter.

$$Biomass\ at\ stage\ C\ (t) = Biomass\ at\ stage\ C\ (t - dt) + (Growth\ C + Switch\ from\ B\ to\ C - Decay\ C - Switch\ from\ C\ to\ D) * dt \qquad 5.37$$

$$INIT\ (Biomass\ at\ stage\ C) = 0 \qquad 5.38$$

$$Growth\ C = \ Biomass\ at\ stage\ C * Normal\ growth\ fraction\ of\ C * (1 - Relative\ biomass\ at\ stage\ C) * \ Water\ growth\ multiplier \qquad 5.39$$

Where normal growth fraction of C is a model constant, dimensionless.

$$Relative\ biomass\ at\ stage\ C = \frac{Biomass\ at\ stage\ C}{Maximum\ \ attainable\ biomass\ at\ stage\ C} \qquad 5.40$$

When there is no water stress, maximum attainable biomass at stage C corresponds to the 80% of total maximum attainable biomass (i.e. 350 tons for each 50,000 m^2 farming land; therefore, 280 tons for stage C). Due to the aforementioned explanation, maximum attainable biomass at stage C calculation is as follows:

$$\begin{aligned}&Maximum\ \ attainable\ biomass\ at\ stage\ C\\&\qquad = Total\ biomass\ obtained\ at\ stage\ B * 1.6\end{aligned} \tag{5.41}$$

When simulation clock ≥ switching time (C to D), accumulated biomass at *biomass at stage C* stock is transferred to the *biomass at stage D* stock in a single dt. Switch flow from stage C to D is formulated as presented below:

$$Switch\ (C\ to\ D) = \frac{Biomass\ at\ stage\ C}{DT} \tag{5.42}$$

$$Decay\ (C) = Biomass\ at\ stage\ C * Decay\ fraction \tag{5.43}$$

For biomass at stage D stock and associated flow equations are presented hereinafter.

$$\begin{aligned}&Biomass\ at\ stage\ D\ (t)\\&\qquad = Biomass\ at\ stage\ D\ (t - dt)\\&\qquad + (Growth\ D + Switch\ from\ C\ to\ D - Decay\ D\\&\qquad - Harvesting) * dt\end{aligned} \tag{5.44}$$

$$INIT\ (Biomass\ at\ stage\ D) = 0 \tag{5.45}$$

$$\begin{aligned}Growth\ D = &\ Biomass\ at\ stage\ D * Normal\ growth\ fraction\ of\ D * (1\\&- Relative\ biomass\ at\ stage\ D)\\&* \ Water\ growth\ multiplier\end{aligned} \tag{5.46}$$

Where normal growth fraction of D is a model constant, dimensionless.

$$\begin{aligned}&Relative\ biomass\ at\ stage\ D\\&\qquad = \frac{Biomass\ at\ stage\ D}{Maximum\ \ attainable\ biomass\ at\ stage\ D}\end{aligned} \tag{5.47}$$

When there is no water stress, maximum attainable biomass at stage D corresponds to the total maximum attainable biomass (i.e. 350 tons for each 50,000 m^2 farming land). Maximum attainable biomass at stage D calculation is as follows:

$$Maximum\ \ attainable\ biomass\ at\ stage\ D \\ = Total\ biomass\ obtained\ at\ stage\ C * 1.25 \tag{5.48}$$

$$Decay\ (D) = Biomass\ at\ stage\ D * Decay\ fraction \tag{5.49}$$

At the end of the simulation; in other words, when simulation clock equals to the hour of 2688, whole biomass accumulated at *biomass at stage D* stock is harvested to calculate the at the end crop yield. Harvesting flow is formulated as below:

$$Harvesting = \ PULSE((Biomass\ at\ stage\ D * DT);\ Harvesting\ time;\ 0) \tag{5.50}$$

Where harvesting time is 2688.

<u>5.3.2.2. Farm profit calculations:</u> Cost and revenue calculation part is composed of 1 stock and 1 flow variable, which are total cost and cost accumulation, respectively. Total cost is in terms of Turkish liras (TL) whereas cost accumulation is in terms of Turkish liras per hour (TL/hour).

In order to calculate the at the end profit, total cost which is accumulated over time as the groundwater pumping continues and revenue are calculated. These values are calculated separately for each farmer. Therefore, they are created as an arrayed variable with a single dimension of *Farmer*.

Total cost calculation is as follows:

$$Total\ cost\ (t) = Total\ cost\ (t - dt) + Cost\ accumulation * dt \tag{5.51}$$

$$INIT\ (Total\ cost) = 0 \tag{5.52}$$

Where

$$Cost\ accumulation = Cost \qquad 5.53$$

$$Cost = Unit\ price\ of\ energy * Energy\ consumption\ of\ the\ pump \qquad 5.54$$

Unit price of energy is a constant value in terms of TL/kWh; on the other hand, energy consumption of the pump is a variable that changes according to the working schedule of the pump (i.e. irrigation schedule by the players of the game).

$$Energy\ consumption\ of\ the\ pump = Power * Irrigation\ schedule\ by\ farmer\ by\ hour \qquad 5.55$$

Power of the pumps is a model constant and assumed as 20 kW. Irrigation schedule by farmer by hour represents the duration of pumping in terms of hours and this value is generated from the player inputs. Energy consumption is calculated in terms of kWh.

Since there are no other costs of farming operations considered in the model, total cost is calculated solely from the electricity spent. To calculate the at the end profit, revenue needs to be estimated which is based on the crop yield obtained at the end. Accordingly:

$$Revenue = Crop\ price * Total\ biomass\ at\ the\ end\ of\ the\ irrigation\ season \qquad 5.56$$

Where crop price is a model constant in terms of TL/tons and total biomass at the end of the irrigation season is a model variable in terms of tons. Revenue is calculated in terms of TL.

Total biomass at the end of the irrigation season is the biomass obtained at the end of the simulation. Estimation of total crop biomass is explained in detail in the following part of this section.

5.4. Model Validation

Model validation is a crucial step in any model-based methodology since validity of the outputs heavily relies on the validity of the model. Particularly, model validation is an important and controversial aspect of system dynamics methodology. In practice, validation exists in every stage of the modeling; however, in formal validation methodology validation tests take place at the end of initial model formulation (Barlas, 1996).

In this part, structural validation of the dynamic simulation model is demonstrated. The dynamic simulation model is grounded on the available scientific literature. Model constants and equations are taken from the literature. During the course of modeling process, units of the model constants and variables are assigned carefully and unit consistency is ensured. Units of the variables are provided with the model equations in the previous section and shown in detailed model equations presented in Appendix A.

In formal validation methodology, structural validation of the model is tested first. There are two types of structural validation tests, namely *direct structure tests* and *structure-oriented behavior tests*. Direct structure tests assess validity of the model by direct comparison with the real system structure and do not involve any simulation. These tests are categorized as empirical and theoretical tests. On the other hand, structure-oriented behavior tests validate the structure of the model indirectly that involve simulation. These are extreme-condition, behavior sensitivity and phase relationship tests. These tests can either be applied to the entire model or isolated sub-models. Once structure of the model is assessed adequate, then behavioral validation tests can be performed. Behavioral validation is simply defined as measuring how accurately model can represent the real systems (Barlas, 1996). Since this dynamic simulation model is hypothetic that does not represent a real case, behavior validation tests are not applied.

Validation of the model structure is the ultimate objective of system dynamics model validation (Barlas, 1996). As structure-oriented behavior tests, extreme condition (indirect) test is applied to the model. Throughout the modeling process, certain model variables are tested at extremes. In this section, selected extreme conditions tests applied to the isolated runs of the model sectors and the whole model are demonstrated.

5.4.1. Extreme condition test - No precipitation & No irrigation

In this test, precipitation and irrigation is taken as zero and both water resources and crop growth sectors of the model are run. It is expected that relative soil moisture of root zone decreases and approaches to the wilting point since crops can use the initial soil water. As the relative soil moisture drops below the wilting point, crops can no longer take up water. Therefore, it is not expected to observe a decrease below the wilting point. In Figure 5.10 below, it is observed that relative soil moisture decreases over time and approaches to the wilting point as expected.

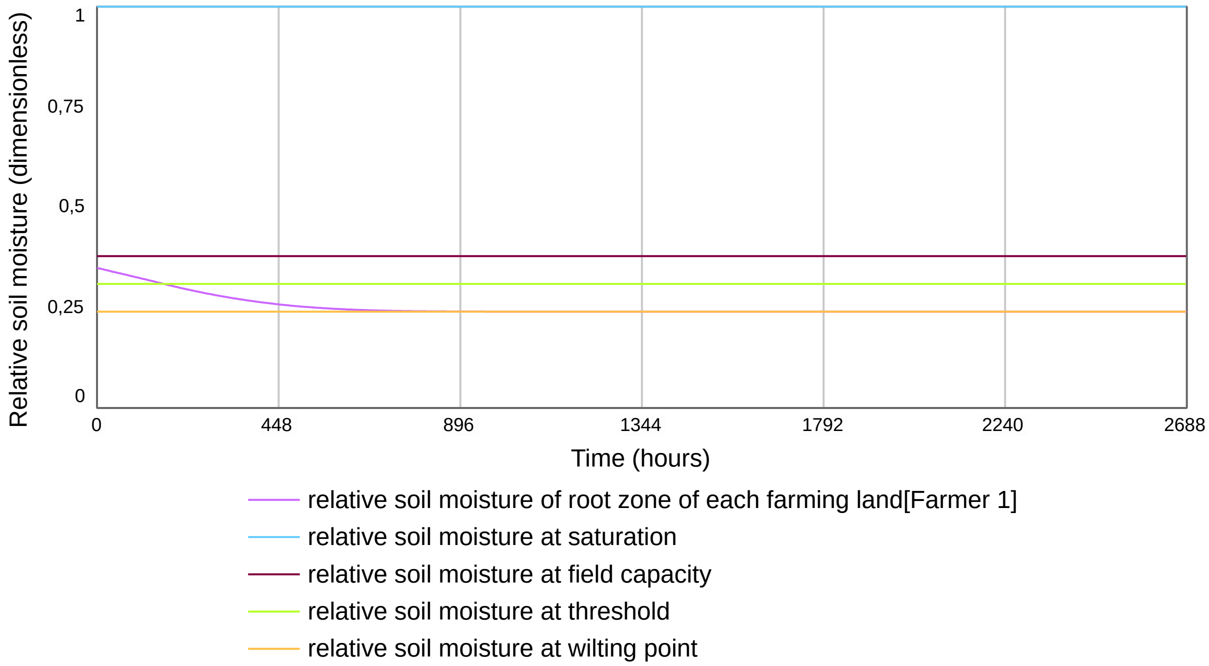

Figure 5.10. Extreme condition test result for relative soil moisture of root zone (no precipitation & no irrigation).

In Figure 5.11, root zone flows (precipitation, evapotranspiration, percolation, capillary rise and surface runoff) are demonstrated. In the Figure, it is seen that there is no precipitation, percolation and surface runoff. Since crops can transpire the initially presented soil water until wilting point, evapotranspiration is expected to take place. Moreover, it is anticipated that evapotranspiration equals to the theoretical evapotranspiration until threshold. As relative soil moisture drops below the threshold, water limiting conditions emerge and evapotranspiration starts decreasing. Since evapotranspiration takes place, capillary rise is also expected to occur at very low rates. As it can be deduced from the Figure, test results comply with the expected behavior.

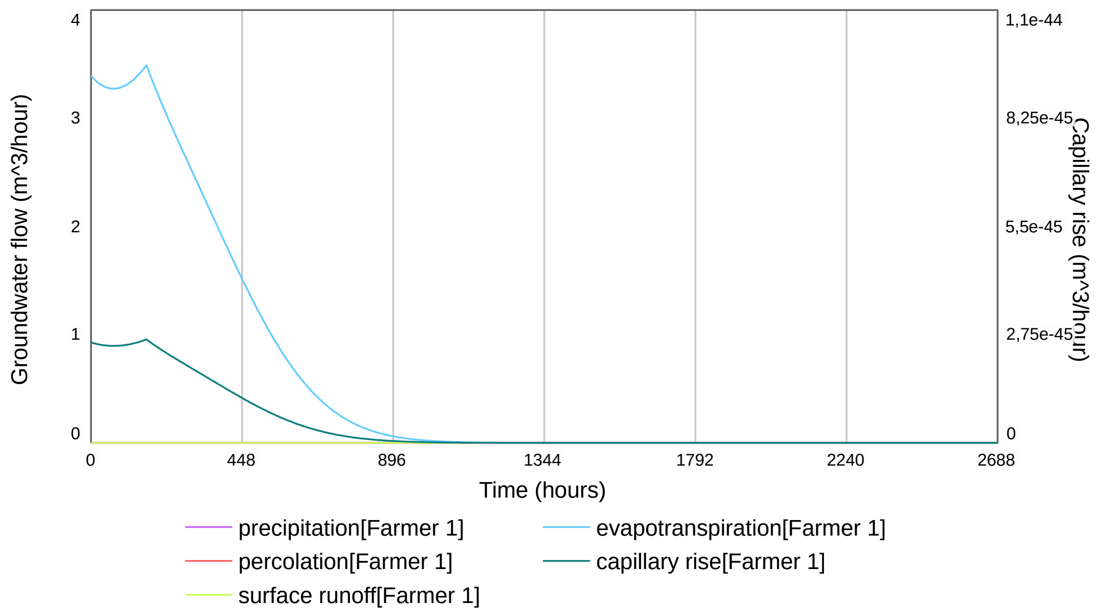

Figure 5.11. Extreme condition test result for root zone flows (no precipitation & no irrigation).

Since there is no groundwater extraction and no downward movement, water in deep zone is not anticipated to change. Therefore, dynamic water level is not expected to change either. Capillary rise occurs at very low rates; however, its effect on the water in deep zone can be negligible. Since, water in deep zone remains same, there is no gap between the static and dynamic water volumes. Lateral recharge or discharge is not expected to take place. Test results are demonstrated in Figure 5.12 and Figure 5.13 for water in deep zone and dynamics water level, and lateral recharge & discharge flows, respectively.

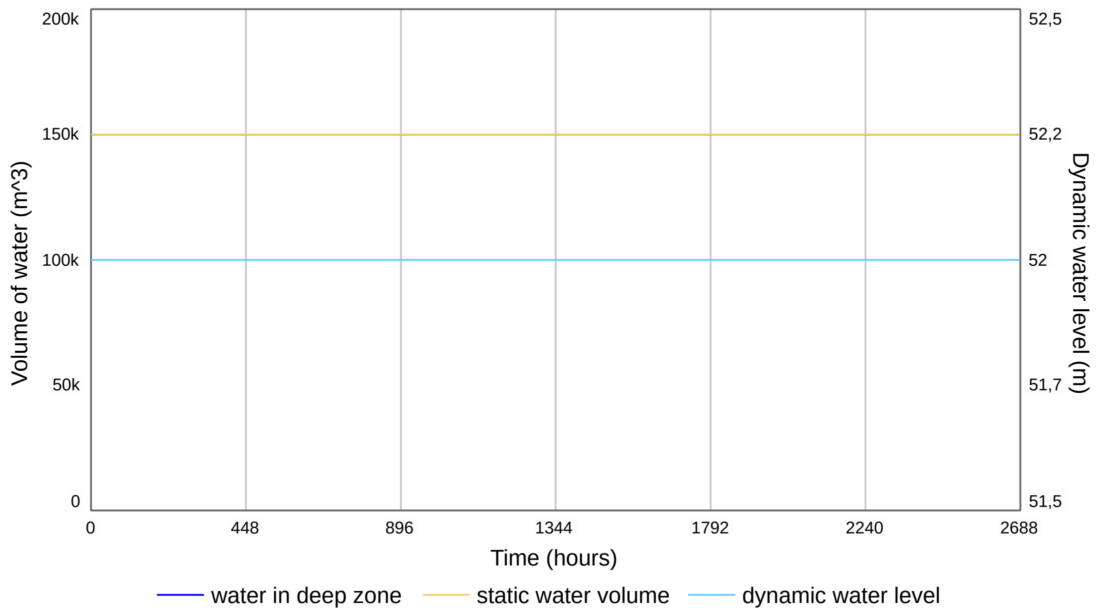

Figure 5.12. Extreme condition test result for water in deep zone and dynamic water level (no precipitation & no irrigation).

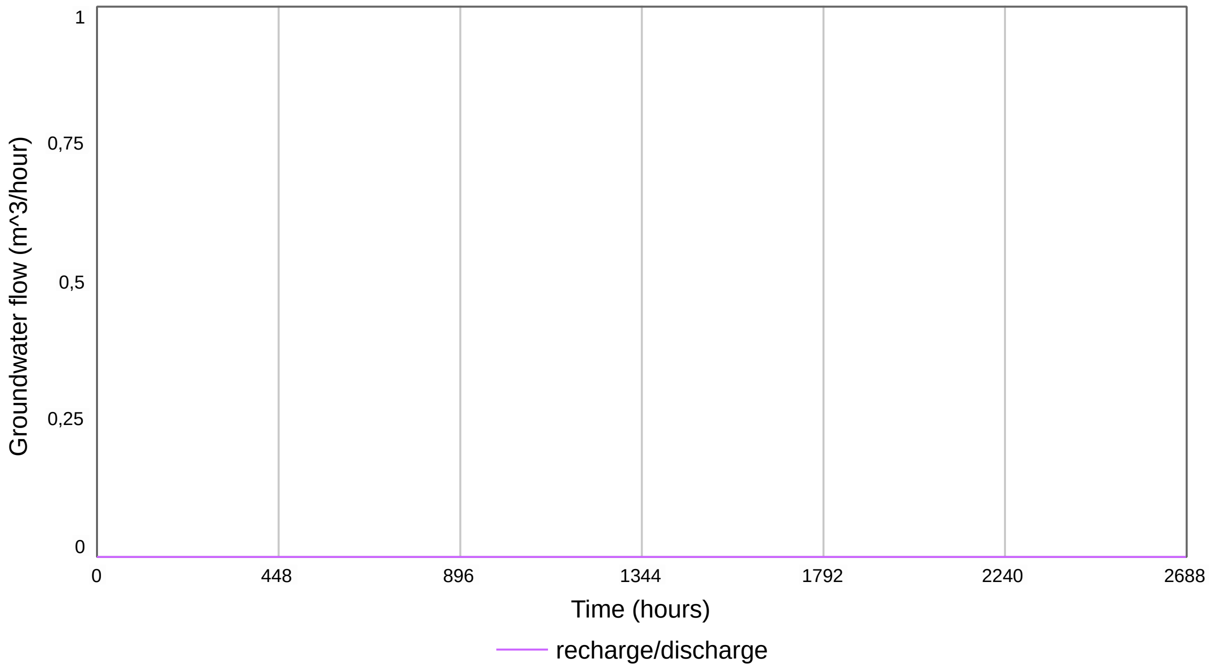

Figure 5.13. Extreme condition test result for deep zone flows (no precipitation & no irrigation).

Due to the water limiting conditions, it is anticipated that crop biomass is significantly lower than the maximum attainable biomass. Behavior of crop biomass at different development stages in such an extreme condition with respect to the maximum attainable biomass is presented in Figure 5.14. It is seen that the test result is in line with the expectations.

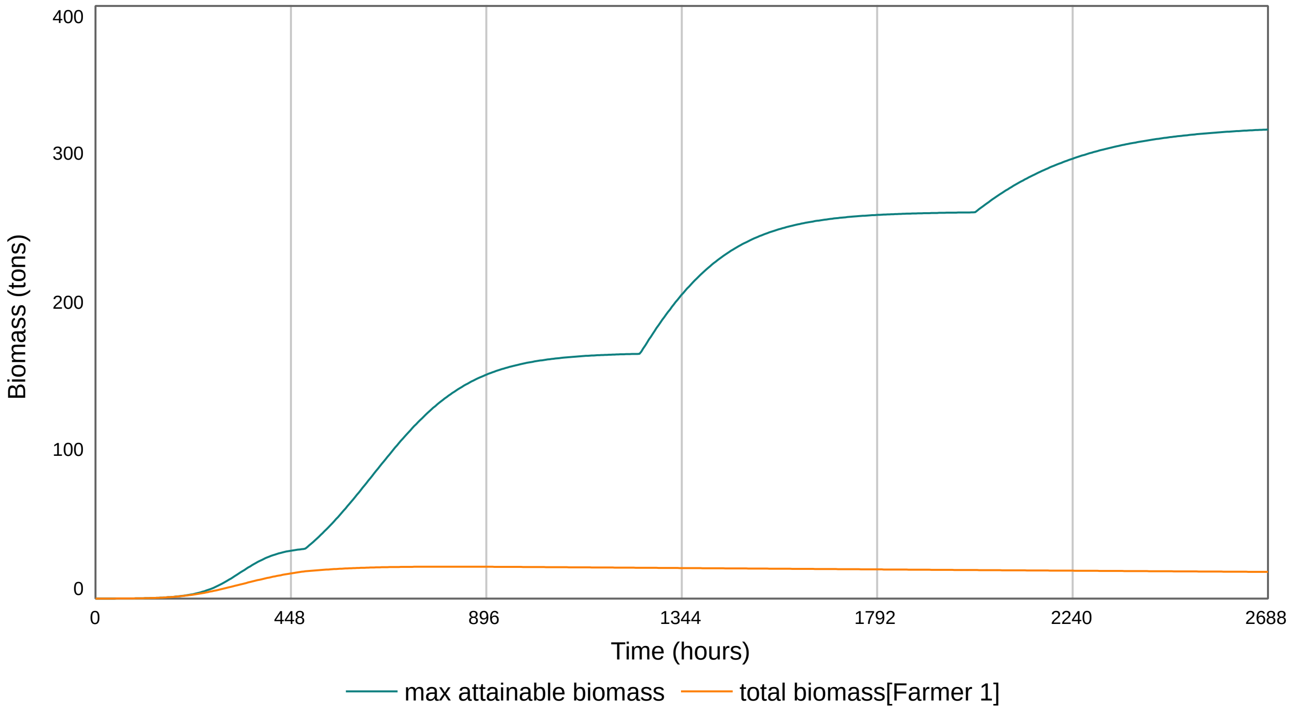

Figure 5.14. Extreme condition test result for biomass (no precipitation & no irrigation).

5.4.2. Extreme condition test - Extreme irrigation

In this test, precipitation is included and extreme irrigation is applied. In order to create such an environment, pumps operate and extract groundwater continuously. Extracted groundwater is applied as irrigation water. It is anticipated that relative soil moisture of root zone increases with the extreme irrigation. Change in relative soil moisture of root zone with respect to the saturation, field capacity, threshold and wilting point is demonstrated in Figure 5.15 and it can be deduced that the results comply with the expected behavior in such an extreme condition.

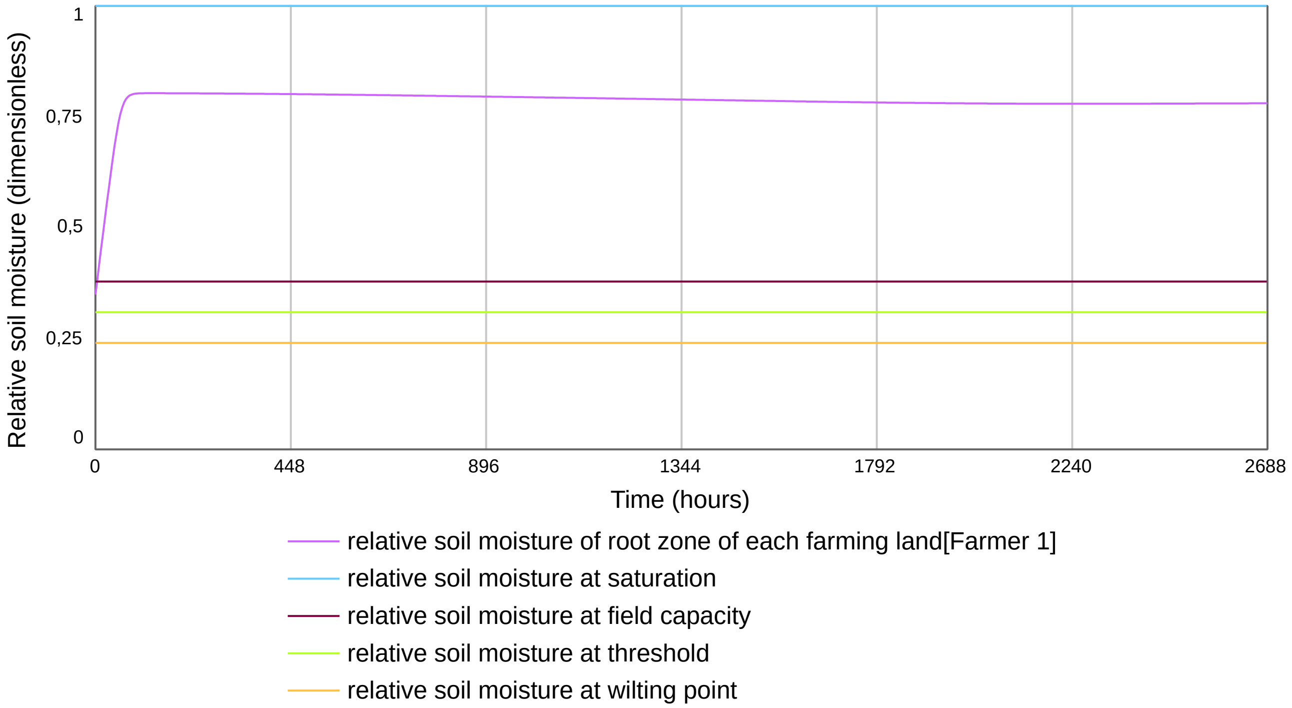

Figure 5.15. Extreme condition test result for relative soil moisture of root zone (extreme irrigation).

As the water content of root zone exceeds field capacity, excess amount of water is expected to be moved downward as percolation. Since there is no water stress on the crops, evapotranspiration is anticipated to follow the theoretical evapotranspiration. Test results for root zone flows are illustrated in Figure 5.16 and it is observed that the obtained results comply with the expected behavior.

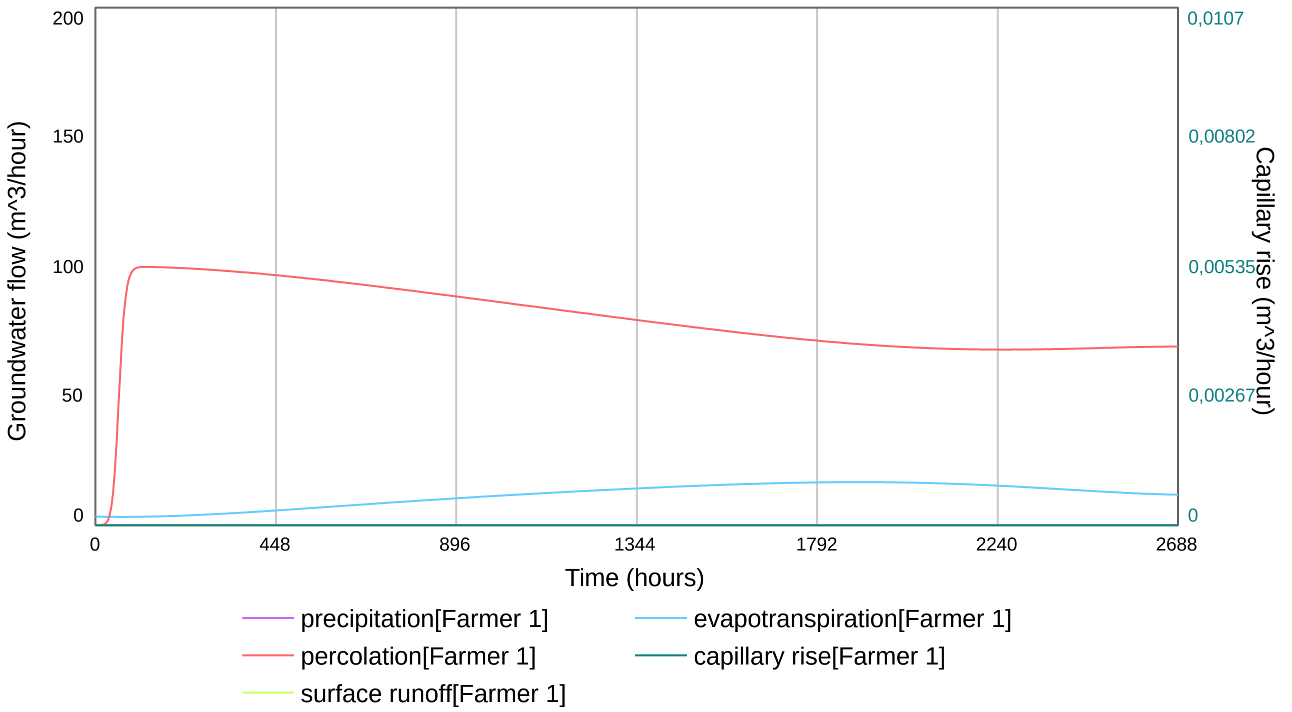

Figure 5.16. Extreme condition test result for root zone flows (extreme irrigation).

In case of extreme extraction and irrigation, it can be expected to observe a decrease in water in deep zone and dynamic water table level. The results correspond to the expected behavior and illustrated in Figure 5.17.

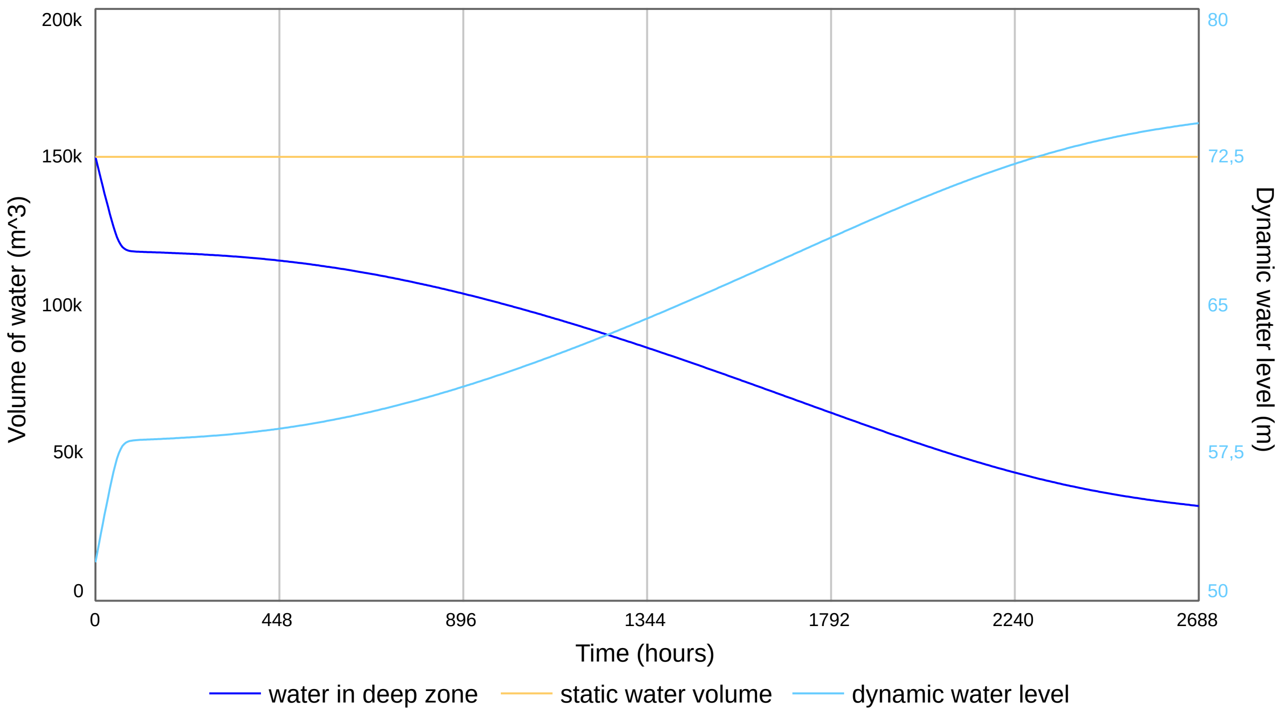

Figure 5.17. Extreme condition test result for water in deep zone and dynamic water level (extreme irrigation).

In line with the decrease in water in deep zone, gap between static and dynamic water volumes leads to the lateral recharge. Figure 5.18 demonstrates the expected behavior of lateral recharge flow.

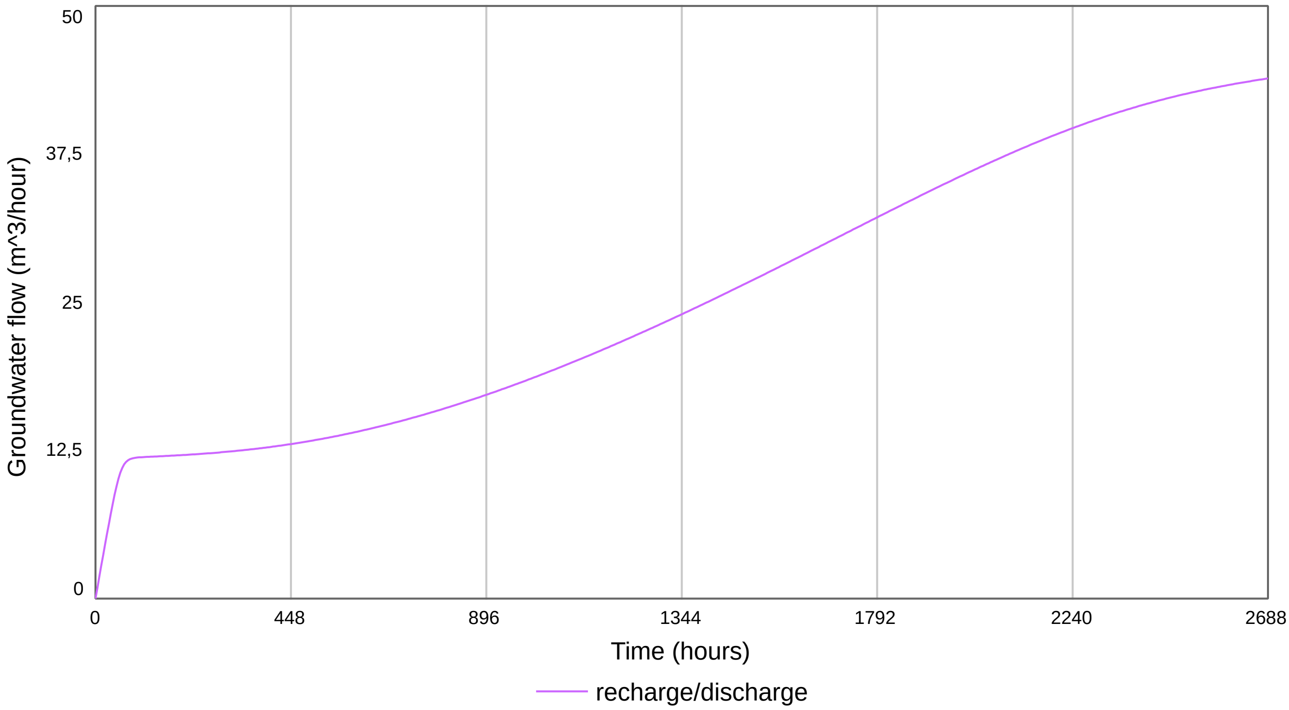

Figure 5.18. Extreme condition test result for deep zone flows (extreme irrigation).

Crop growth sector of the model is also tested for extreme irrigation. Since relative soil moisture does not drop below threshold, actual evapotranspiration equals to the theoretical evapotranspiration throughout the simulation. Therefore, crop biomass is expected to be equal the maximum attainable biomass. Behavior of biomass in case of extreme irrigation is presented Figure 5.19. It can be deduced that the behavior is as expected.

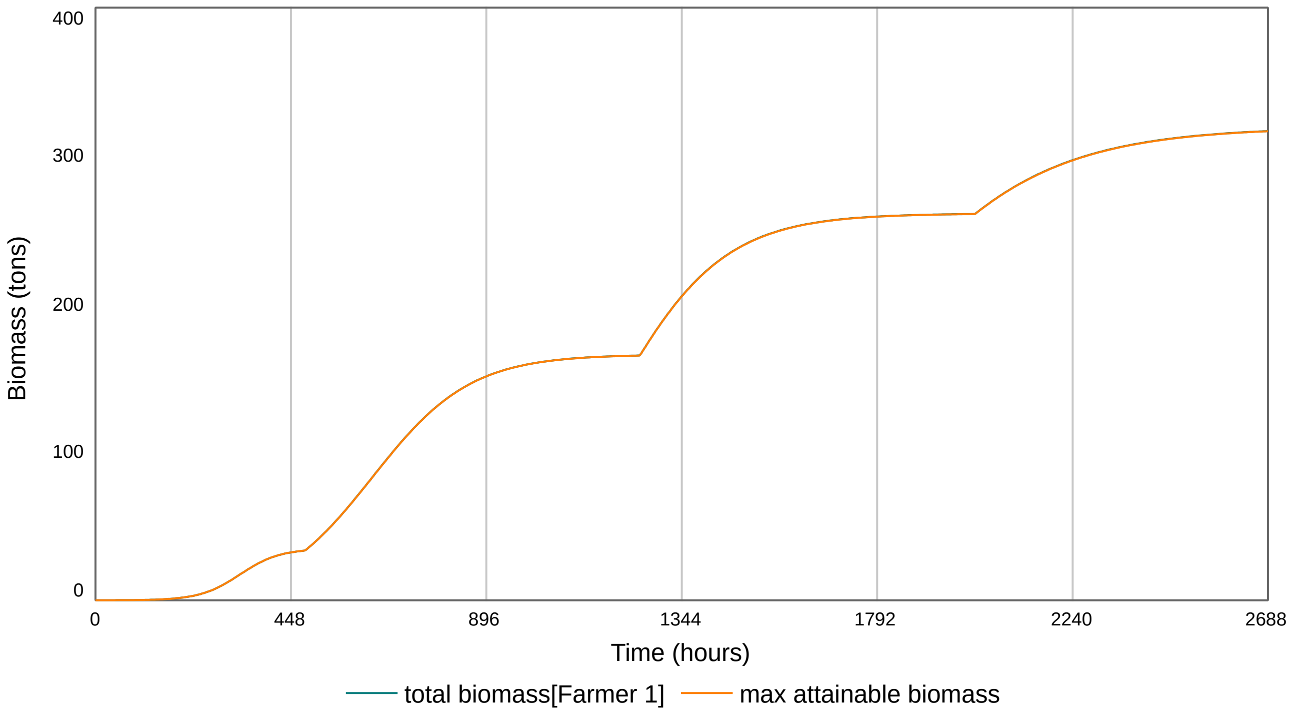

Figure 5.19. Extreme condition test result for biomass (extreme irrigation).

5.4.3. Extreme lateral recharge & discharge adjustment time

In this test, both precipitation and irrigation is applied and water resources sector of the model is tested for extreme adjustment times for lateral recharge & discharge. Groundwater extraction and irrigation rate is adjusted as to meet the crop water demand. Graphical outputs of this test are illustrated for water in deep zone stock together with the dynamic water level.

First, extremely low value (i.e. 1 hour) is assigned to adjustment time variable. That means the water in deep zone stock can fully recover itself in 1 hour. It is expected that there will be no gap between the static and dynamic water content of the deep zone since the stock recovers itself quickly. Accordingly, no significant change in dynamic water level is anticipated. It can be deduced that test results comply with the expected behavior (Figure 5.20).

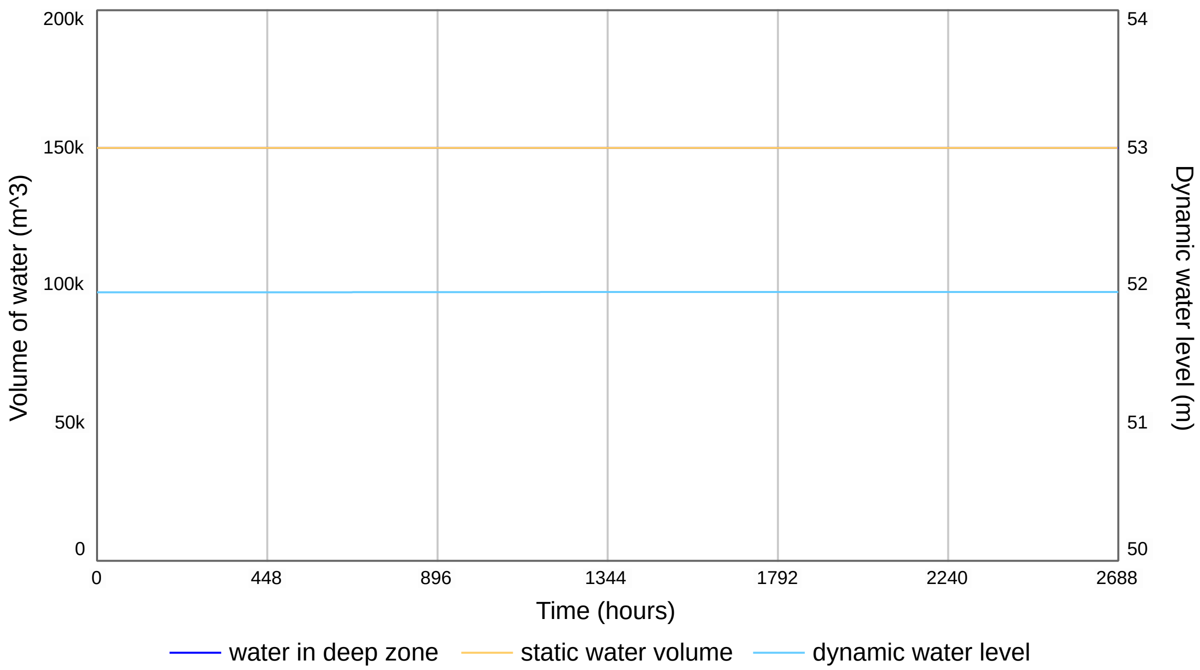

Figure 5.20. Extreme condition test result for water in deep zone and dynamic water level (extremely low adjustment time).

Second, extreme high value (i.e. 10 years) is assigned to the adjustment time variable. Accordingly, it is estimated that the water in deep zone stock can fully recover the gap in 10 years. Since lateral recharge to the stock occurs slowly, groundwater recharge is mostly based on the percolation from root zone. It is anticipated that the water in deep zone stock and groundwater level decreases due to the slow recharge of the aquifer. Test result is as expected and demonstrated in Figure 5.21.

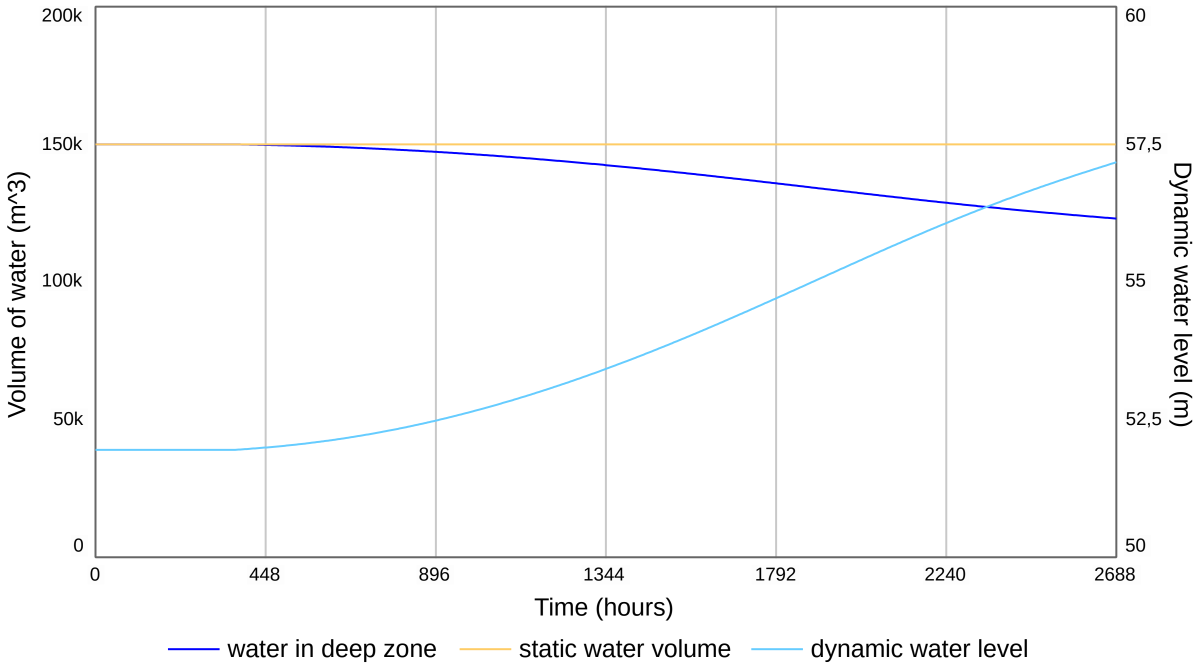

Figure 5.21. Extreme condition test result for water in deep zone and dynamic water level (extremely high adjustment time).

5.4.4. Extreme condition test - Irrigation at a single stage

In this test, irrigation is applied at a single crop development stage and only crop growth sector is run. In order to observe how changes in any development stage affect others, required amount of irrigation is supplied at the first development stage (i.e. stage A) and the structural validity of the sector is tested.

After the first stage (i.e. stage A), it is expected to observe water limiting conditions since irrigation is not applied at the next three stages (i.e. stages B, C and D). At the first stage, it is anticipated that biomass can reach the maximum attainable biomass; however, at the next stages biomass is expected to be lower than the maximum attainable biomass. In Figure 5.22 below, behavior of biomass with respect to the maximum attainable biomass is presented. It is observed that the test result complies with the expected behavior.

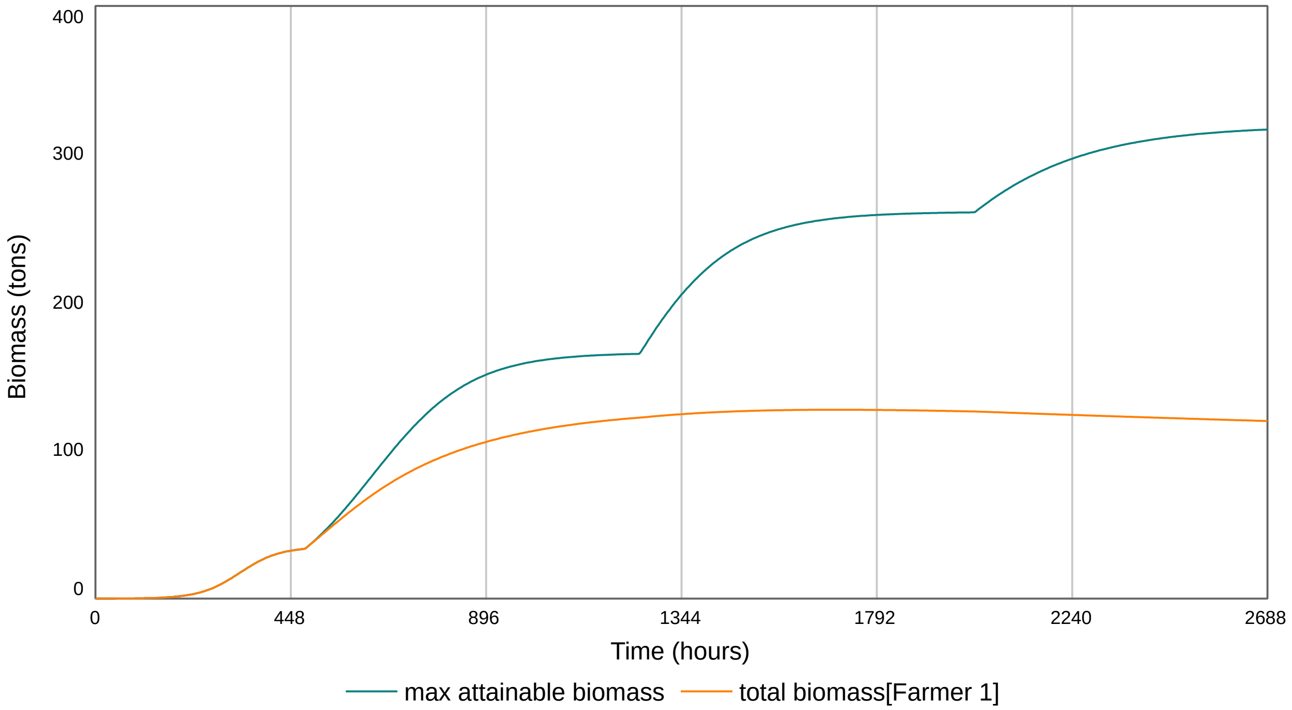

Figure 5.22. Extreme condition test result for biomass (irrigation at single stage).

5.5. Reference Model Behavior

In this section, reference model behavior under two different circumstances is analyzed and results are demonstrated with graphical outputs. These are (i) without extraction and (iii) with extraction of required amount of water.

5.5.1. Reference Model Behavior – No Extraction

Model behavior in case of zero extraction is demonstrated with respect to relative soil moisture of root zone (dimensionless), root zone flows (m^3/hour), water at deep zone (m^3), dynamic water level (m), biomass (tons) and crop growth (tons/hour) in this part. When extraction sets to zero, irrigation becomes zero as well. Therefore, there is no difference between the farming fields. For arrayed variables (i.e. relative soil moisture of root zone, precipitation, percolation, evapotranspiration, capillary rise, surface runoff, biomass and growth), only *Farmer 1* is shown in the following graphs.

In Figure 5.23, change in relative soil moisture of root zone with respect to the relative soil moisture at saturation, field capacity, threshold and wilting point is illustrated. In this Figure, it is observed that the relative soil moisture of root zone that is between threshold and field capacity initially, decreases over time and approaches to the wilting point.

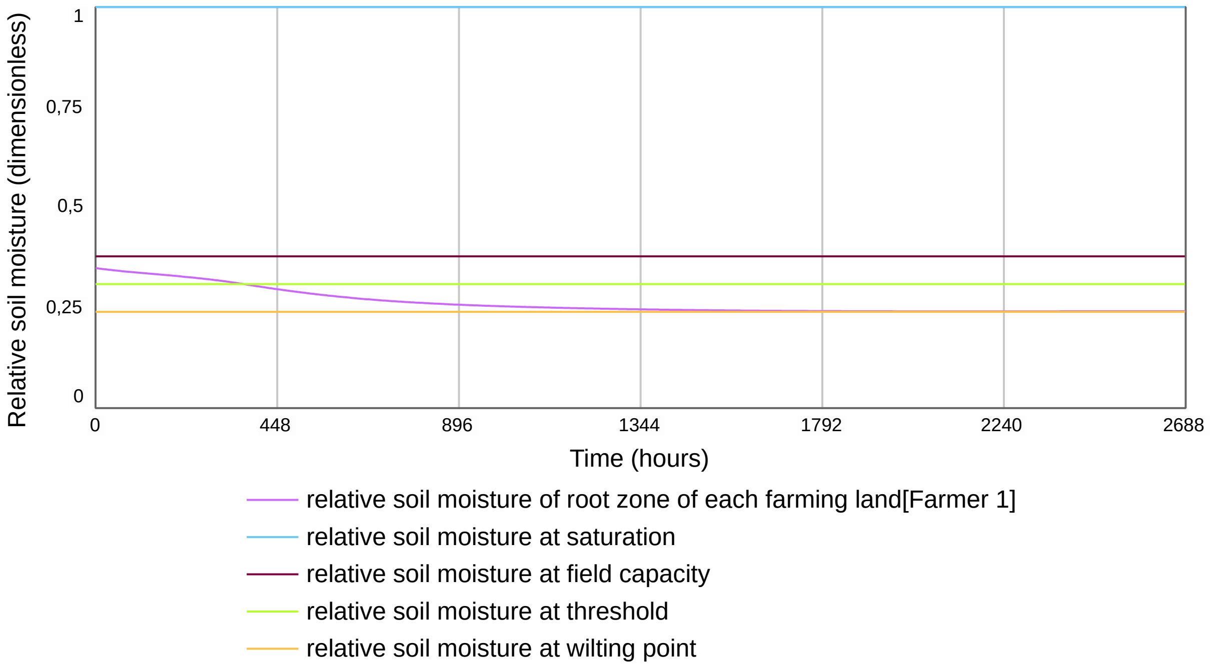

Figure 5.23. Reference behavior of relative soil moisture of root zone (no extraction).

Behavior of precipitation, percolation, evapotranspiration, capillary rise and surface runoff is demonstrated in Figure 5.24. Precipitation is one of the model constant and its behavior is not affected from the changes. Since relative soil moisture does not exceed the field capacity and saturation, percolation and surface runoff do not take place. Until relative soil moisture drops below the threshold value (i.e. at time=370), evapotranspiration curve follows the theoretical evapotranspiration. However, when relative soil moisture drops below threshold, water limiting conditions emerge and evapotranspiration starts decreasing. Capillary rise curve is similar to the evapotranspiration, as expected since it is estimated by an empirical formula that includes actual crop evapotranspiration as a multiplier. Capillary rise values can be read from the right y-axis.

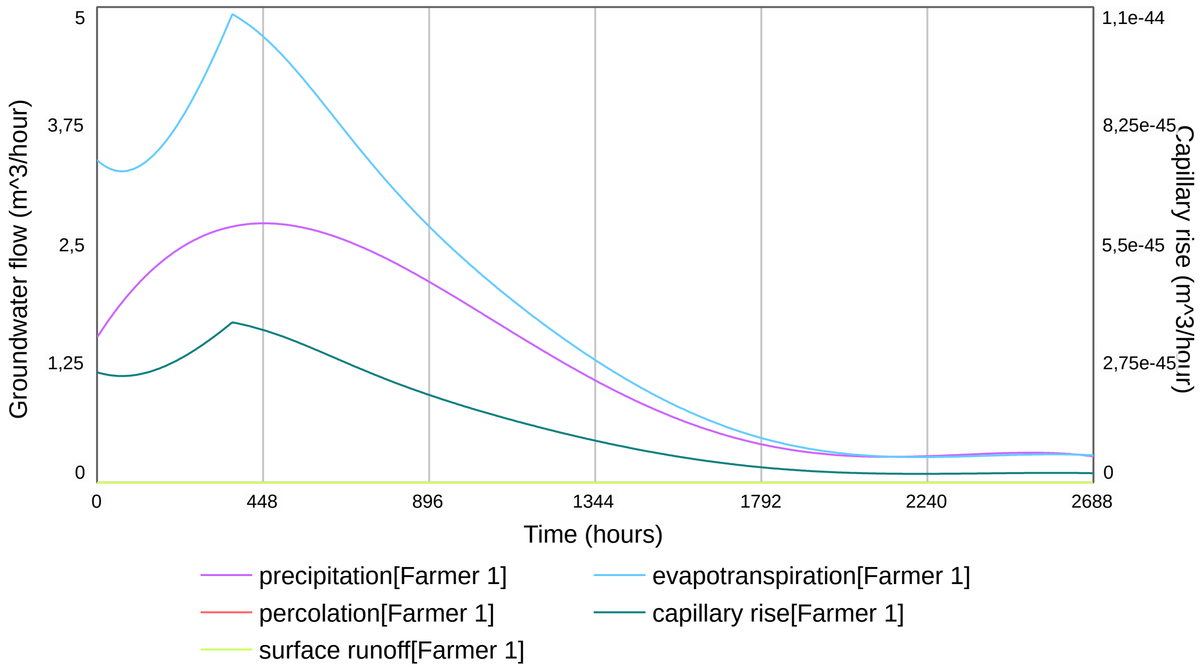

Figure 5.24. Reference behavior of precipitation, evapotranspiration, percolation and capillary rise (without extraction).

In Figure 5.24, behavior of water in deep zone stock with respect to the static water volume at deep zone and dynamic water table level is illustrated. It is seen that in case of no extraction, there is no change in water in deep zone and dynamic water level.

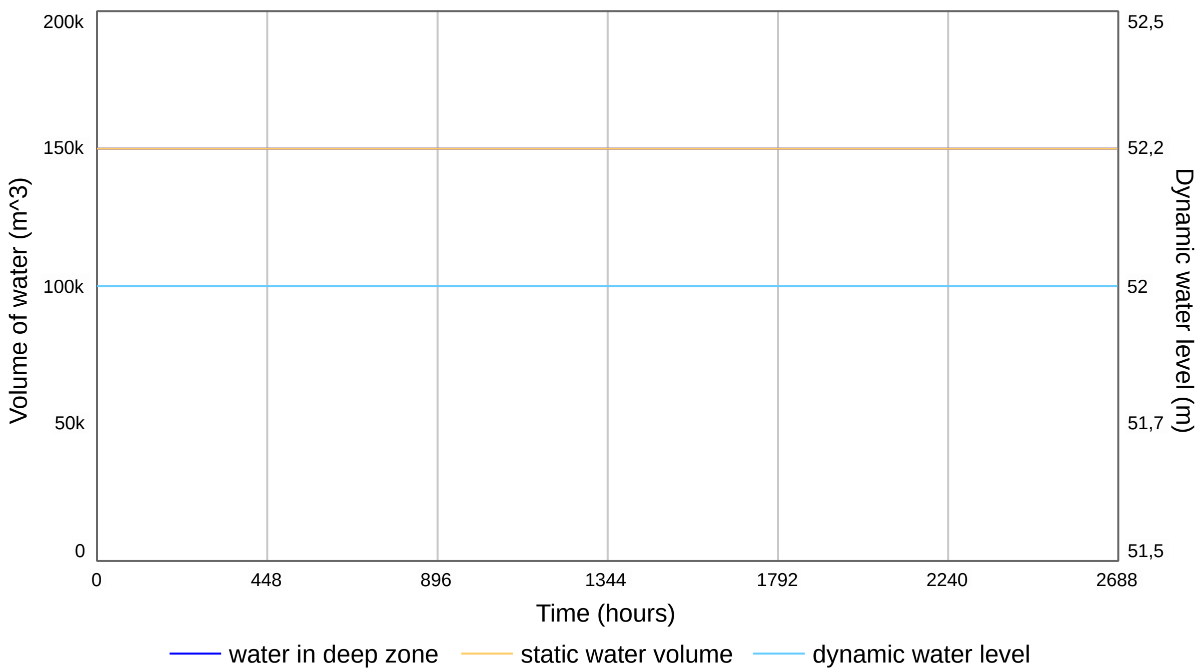

Figure 5.25. Reference behavior of soil moisture at deep zone and dynamic water level (without extraction).

Figure 5.26 demonstrates lateral recharge & discharge and extraction flows. Since water in deep zone remains same, there is no gap created between the static water volume and water in deep zone stock. Therefore, no lateral groundwater movement (i.e. recharge or discharge) is observed.

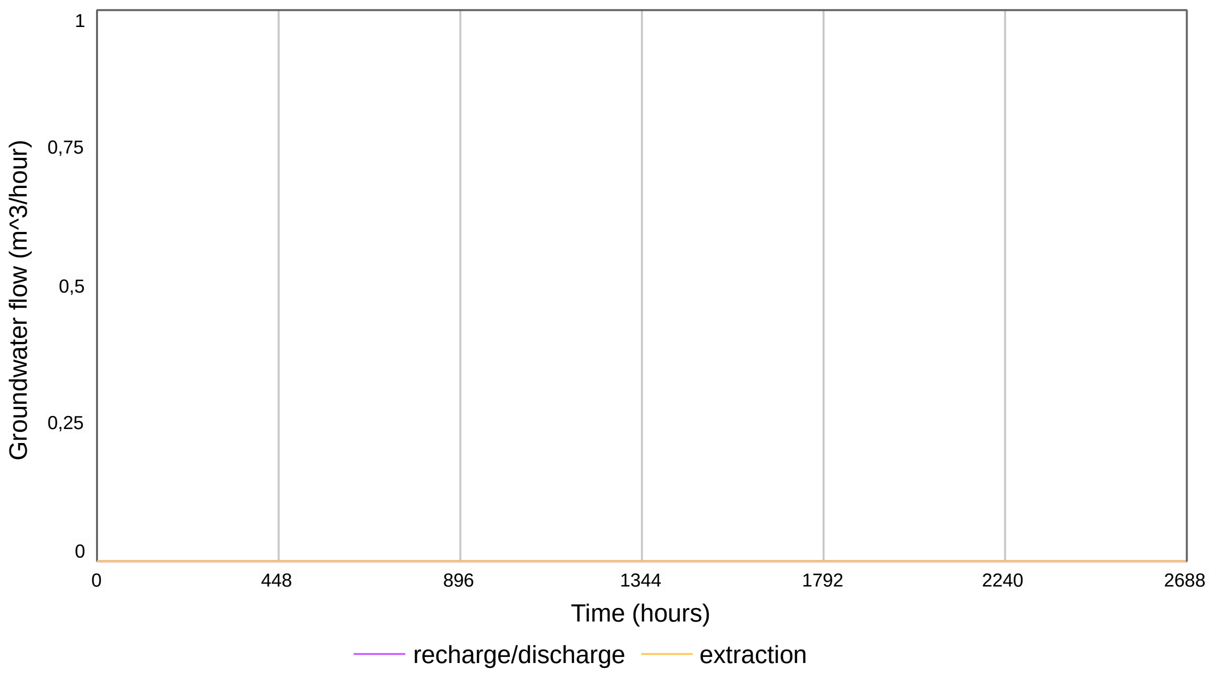

Figure 5.26. Reference behavior of lateral recharge/discharge and extraction (without extraction).

Reference behavior of crop biomass at different development stages is shown in Figure 5.27. In case of zero extraction and irrigation, water limiting conditions emerge and attainable crop yield is decreased significantly. In the Figure, at the end of stage D, it is seen that total biomass is approximately 109 tons whereas total maximum attainable biomass is approximately 317 tons under standard conditions.

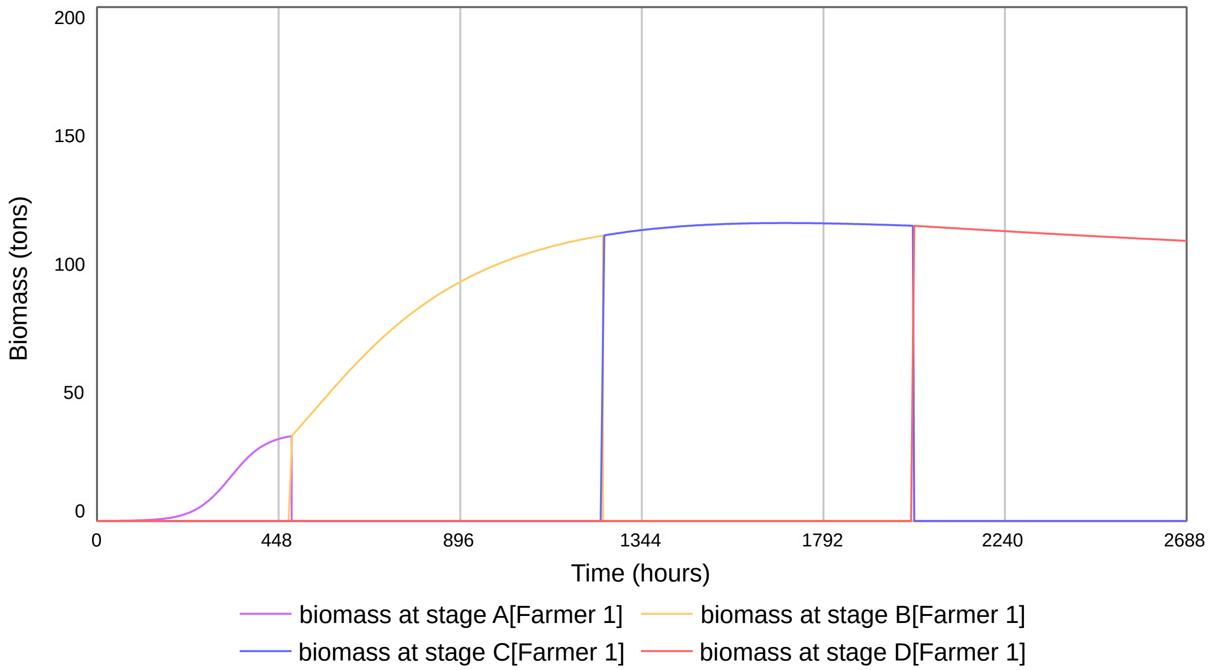

Figure 5.27. Reference behavior of crop biomass at different development stages (without extraction).

Some of the important model variables are calculated at the end of the simulation. In Table 5.4 below, irrigation efficiency, irrigation/cost ratio, total revenue obtained, total electricity cost spent and profit obtained is shown together with their units. Since irrigation is not applied throughout the simulation, irrigation efficiency and irrigation/cost ratio become zero. Similarly, since extraction is not performed pumps do not work and total electricity cost becomes zero. On the other hand, obtained crop yield creates a revenue and profit.

Table 5.4. Certain model variables at the end of the simulation (in case of zero extraction).

Model variable	**Unit**	**Value**
Irrigation efficiency	Dimensionless	0
Irrigation cost	m^3/TL	0
Revenue	TL	43,618
Total electricity cost	TL	0
Profit	TL	43,618

5.5.2. Reference Model Behavior – With Extraction

In this part, reference model behavior in case of extraction is analyzed and the results are demonstrated with graphical outputs. Changes in relative soil moisture of root zone (dimensionless), root zone flows (m^3/hour), water at deep zone (m^3), dynamic water level (m), deep zone flows (m^3/hour), biomass (tons) and crop growth (tons/hour) variables are presented. In this case, pumps extract groundwater as to meet the irrigation demand of the crops and operate continuously. In order to adjust the groundwater extraction rate to the irrigation demand, pumps adjust their power. Since all of the pumps work simultaneously, there is no difference between the farming fields. Therefore, for arrayed variables, only *Farmer 1* is shown in the graphs.

In this case, our primary objective is to maximize the irrigation efficiency. Irrigation efficiency can be simply defined as the ratio of irrigation demand over irrigation water applied as formulated below:

$$Irrigation\ efficiency = \frac{Irrigation\ demand\ of\ the\ crop}{Applied\ water\ irrigation} \tag{5.57}$$

In other words, efficiency represents how much of the irrigation water is available for plant. Irrigation efficiency is maximized when volumetric water content of root zone is exactly at threshold. In that case, there is no water loss due to percolation or surface runoff since water content does not exceed the field capacity. Also, there is no water stress on the crops since water content does not drop below the threshold. With this purpose, water content of root zone (i.e. water in root zone stock) is aimed to be kept at threshold that is called desired water content in terms of m^3. Accordingly:

$$Desired\ water\ content\ of\ root\ zone = \ Water\ content\ at\ threshold \tag{5.58}$$

$$Gap = \ MAX(0; (Desired\ water\ content - Water\ in\ root\ zone) \tag{5.59}$$

$$Irrigation\ requirement = \frac{Gap}{Adjustment\ time} \tag{5.60}$$

Where adjustment time is taken as 1 hour.

$$Extraction = \ Irrigation\ requirement \tag{5.61}$$

In order to extract the required amount of water, pump power is adjusted at each hour.

Results obtained at the end of the simulation are presented below.

In Figure 5.28, change in relative soil moisture of root zone with respect to the relative soil moisture at saturation, field capacity, threshold and wilting point is demonstrated. Initial value of relative soil moisture is between field capacity and threshold. In the Figure, it is observed that relative soil moisture decreases until time=364 and remains constant at threshold after then that. Since relative soil moisture remains below the field capacity, there is no downward water movement expected. On the other hand, since relative soil moisture does not fall below the threshold, it is not expected to observe water stress on the crops as explained before.

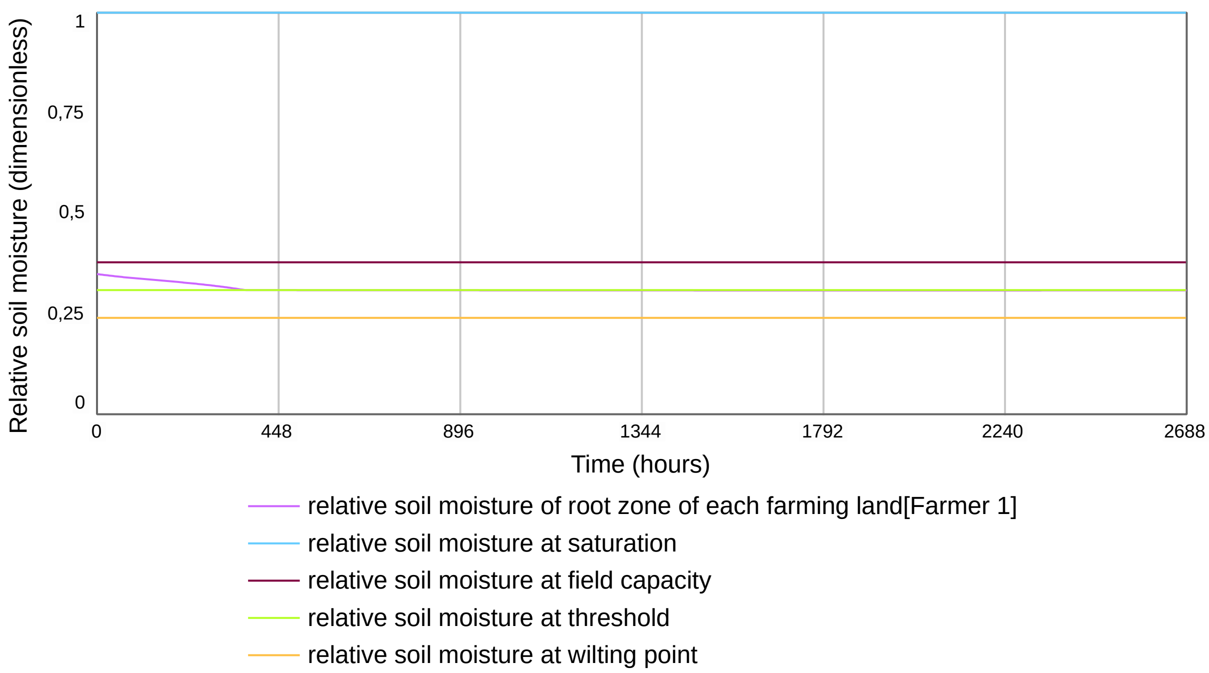

Figure 5.28. Reference behavior of relative soil moisture of root zone (with extraction).

In Figure 5.29, behaviors of groundwater flows associated with the water in root zone stock (precipitation, evapotranspiration, percolation, capillary rise and surface runoff) are shown. Precipitation is one of the model constant and it is not affected from the changes in the model. In the Figure, it is seen that evapotranspiration curve follows the theoretical evapotranspiration since there is no water stress on crop. Capillary rise shows as increase in the first two intervals; however, after time=366, it starts decreasing and approaches to zero. In addition to the evapotranspiration, capillary rise is also strongly affected from the dynamic water level. In this reference behavior, capillary rise is significantly affected from the changes in dynamic water level that is shown and explained in the following part. Percolation and surface runoff do not take place since relative soil moisture does not exceed field capacity and saturation.

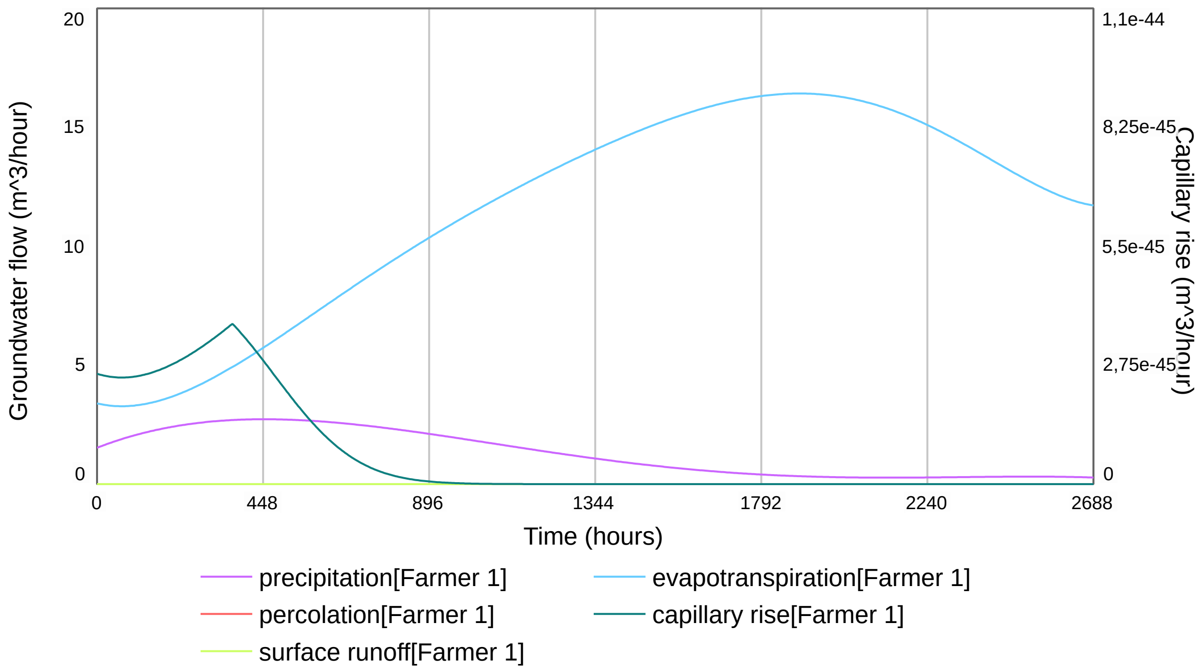

Figure 5.29. Reference behavior of precipitation, evapotranspiration, percolation and capillary rise (with extraction).

In Figure 5.30, behavior of dynamic water level and water in deep zone stock with respect to the static water volume at deep zone is demonstrated. It is observed that water in deep zone decreases depending on the continuous groundwater extraction. On the contrary, groundwater level is seen as increasing. As it is explained before, groundwater level is the distance from ground surface to the upper boundary of reservoir. Therefore, the increase in its numerical value means decrease in the groundwater level. The initial groundwater level is 52 meters whereas final level is 70.1 meters.

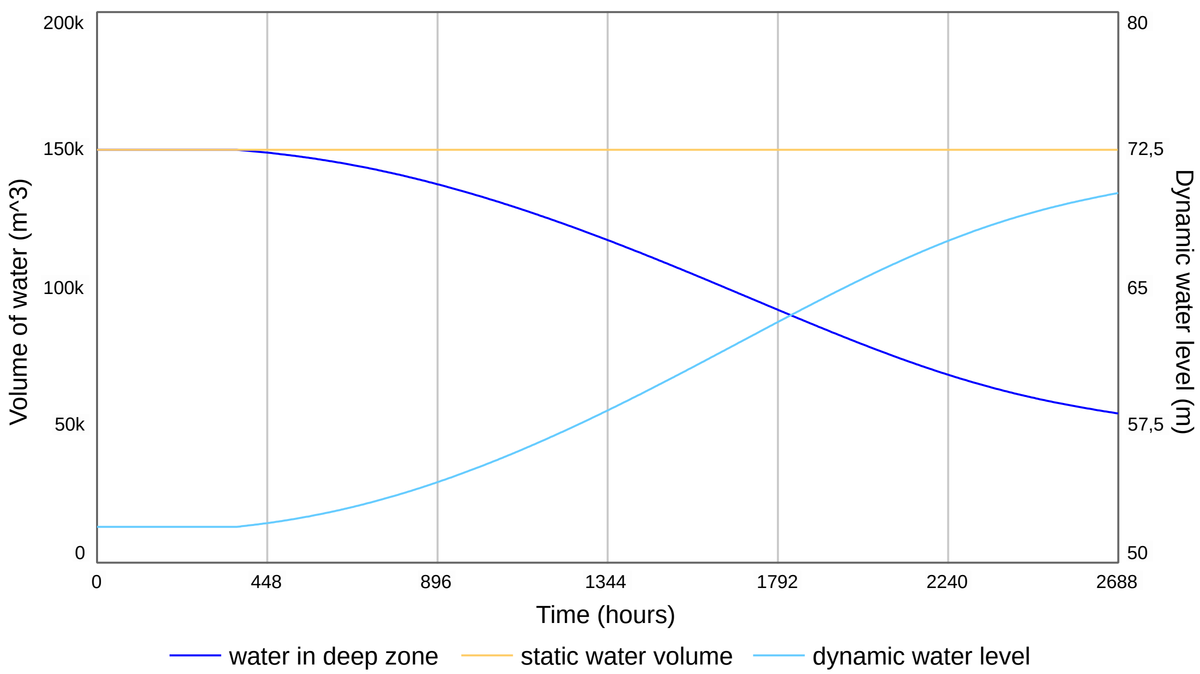

Figure 5.30. Reference behavior of soil moisture at deep zone and dynamic water level (with extraction).

In Figure 5.31, behavior of lateral recharge & discharge flow is illustrated. Since water in deep zone decreases over time, gap between the static and dynamic water volumes increases as shown in the previous Figure. To adjust the gap between static and dynamic levels, lateral recharge takes place. In the Figure, it is seen that lateral recharge increases with the increasing gap.

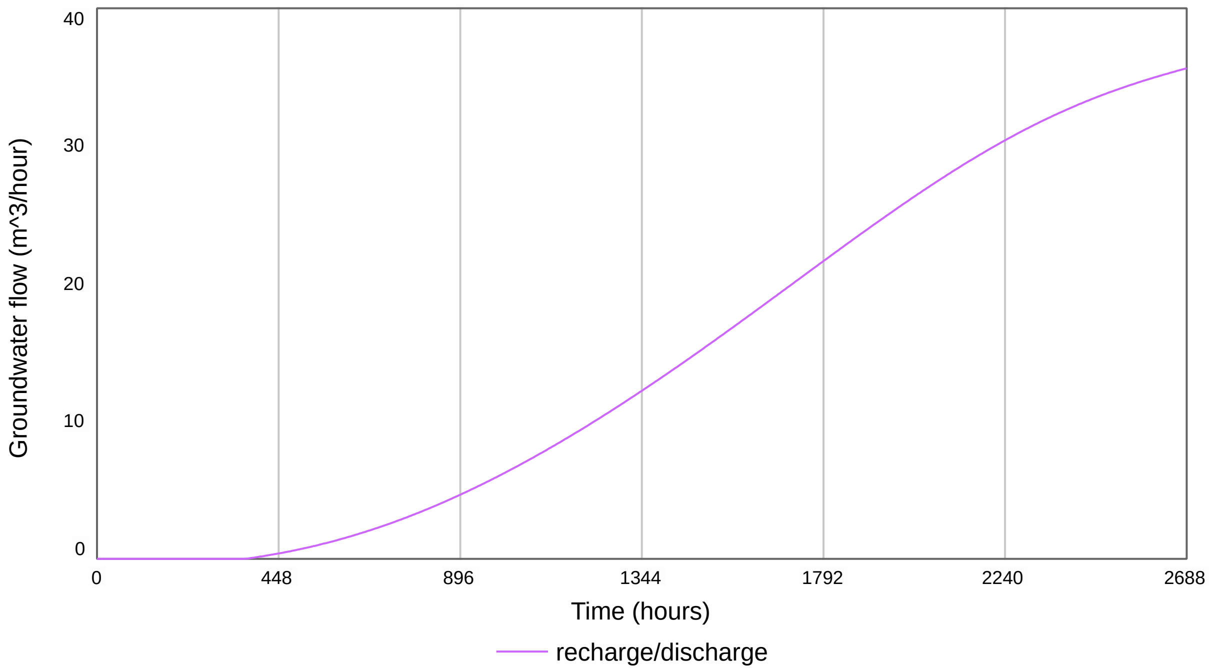

Figure 5.31. Reference behavior of lateral recharge/discharge (with extraction).

Figure 5.32 demonstrates reference behavior of crop biomass at different development stages. Since irrigation meets the water demand of the crop, crop biomass increases over time and approaches to the maximum attainable biomass of 317 tons.

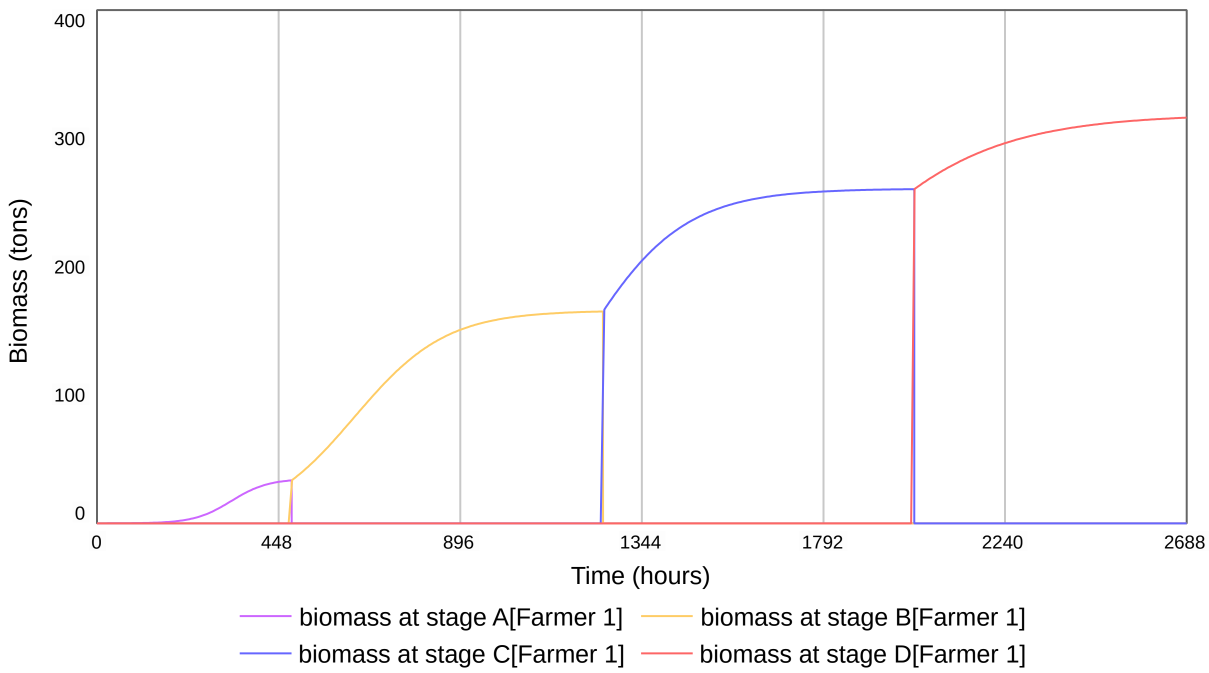

Figure 5.32. Reference behavior of crop biomass at different development stages (with extraction).

In addition to the graphical outputs, some of the major model variables that are calculated at the end of the simulation are presented in Table 5.5 below. Since the required amount of water is provided to the plant without any loss, irrigation efficiency is calculated as 100%. Money spent for each m^3 of water extraction (i.e. irrigation/cost ratio) is calculated as 0.0219 TL. Total money spent to the electricity is 598 TL. Revenue obtained from the crop yield and profit at the end of the simulation are calculated as 126,649 TL and 126,051 TL, respectively.

Table 5.5. Certain model variables at the end of the simulation (in case of extraction).

Model variable	**Unit**	**Value**
Irrigation efficiency	Dimensionless	100%
Irrigation cost	m^3/TL	0.0219
Revenue	TL	126,649
Total electricity cost	TL	598
Profit	TL	126,051

6. DYNAMIC SIMULATION GAME

The *groundwater appropriation game* is a dynamic, multiplayer game in which players aim to obtain maximum possible farm profit at the end of the game. Profit of each player is calculated as below:

$$Profit = Revenue - Total\ cost \qquad 6.1$$

Revenue corresponds to the crop yield obtained at the end of the game, whereas cost represents the accumulated electricity cost over the rounds of the game. As it was mentioned in 5.2. Assumptions and Limitations section, other costs in farm operations including use of fertilizer and pesticides, working force or machinery are not included.

The game is parameterized considering the environmental conditions of a semiarid region where supplemental irrigation is essential to keep the moisture content of the soil in a certain range for crop growth. Irrigation water is supplied through groundwater pumping. Maize, as a sensitive crop to water shortages, is cultivated across all the farming fields. The game can be played with 5 individuals representing maize farmers.

Simulation runs in hours and the time horizon of the simulation covers a single irrigation season from sowing to harvesting. The duration is taken as 16 weeks from the 1st of May to the 21st of August. Players make their decisions on a biweekly basis and the game is composed of 8 rounds in total. At each round, players decide on their irrigation schedule in terms of the total duration of irrigation and its distribution over the 2-weeks period. As the game proceeds, players are informed on their irrigation performance including average extraction rate (m^3/hour) during the previous period, the difference between the actual and ideal crop biomass growth (tons), electricity cost (TL) accumulated over time and average soil moisture (dimensionless) with respect to the threshold and wilting point. The information provided between the rounds of the game is private to each player. Other players cannot see any information about the performance of their neighboring farmers.

At the end of the game, all of the players can see each other's performance together with the average of the group. The information includes crop yield (tons), total water consumption (m^3), total electricity consumption (kW), profit (TL) and irrigation efficiency (dimensionless).

At the beginning of the game, the start page of the game interface is shown to the players (Figure 6.1). Players can start the game by clicking on the “Start” button.

Figure 6.1. Dynamic simulation game interface – Start page.

After the start page, primary goal of the players together with their roles is provided in the *Introduction* page (Figure 6.2). Players can move to the next page by simply clicking on the *“Next”* button or clicking on the tab bar available at the upper right of the page.

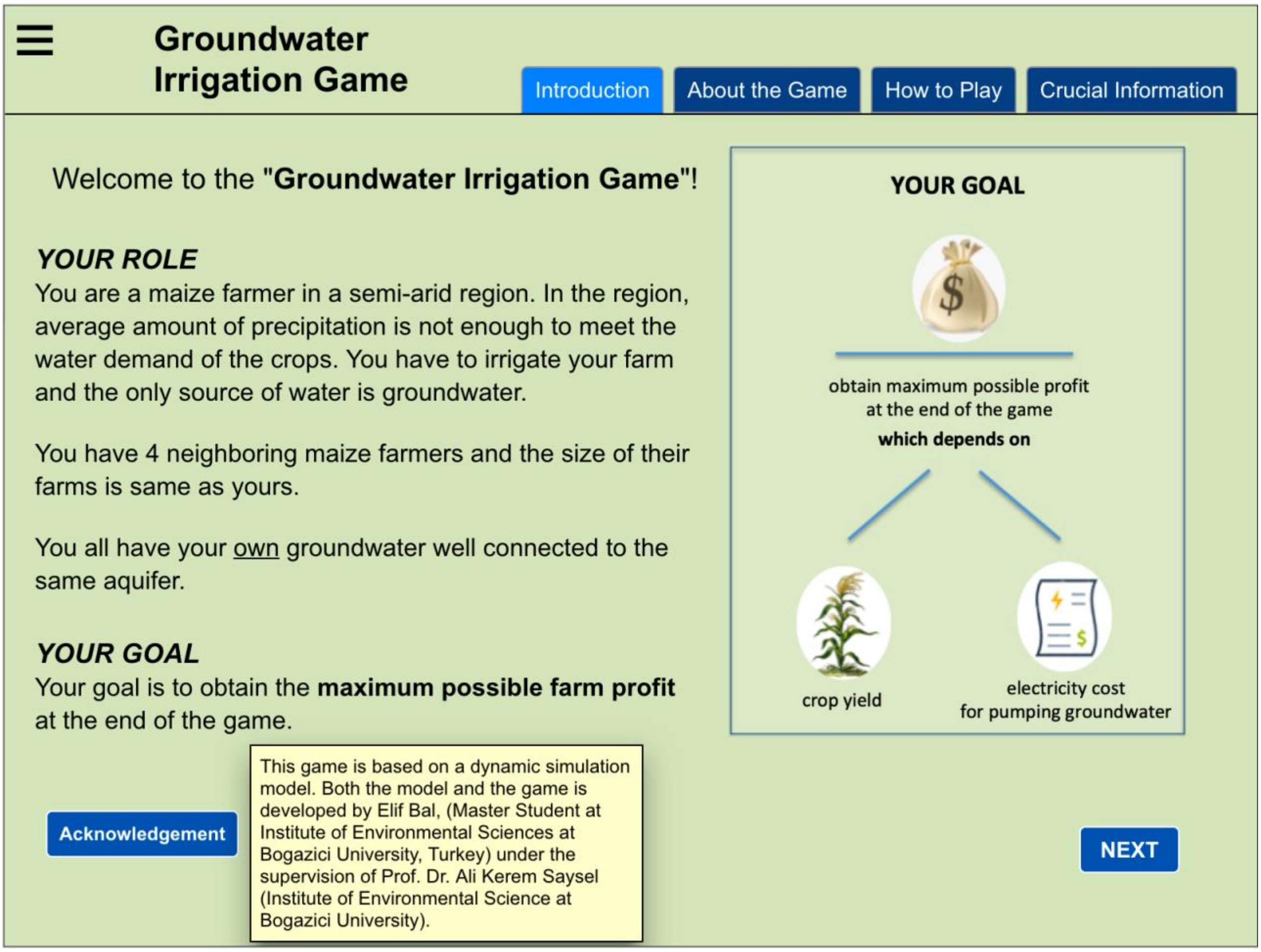

Figure 6.2. Dynamic simulation game interface - *Introduction* page.

Introduction page is followed by *"About the Game"* page where a brief outline about the game design is provided. In that page, players can obtain information on the size of their farms, sowing and harvesting days of the crops. Irrigation requirement of the crops per round and maximum attainable biomass to be obtained in case of meeting the irrigation demand are also given in that page. A scheme illustrating the factors affecting the end of the season farm profit is also provided to the players (Figure 6.3).

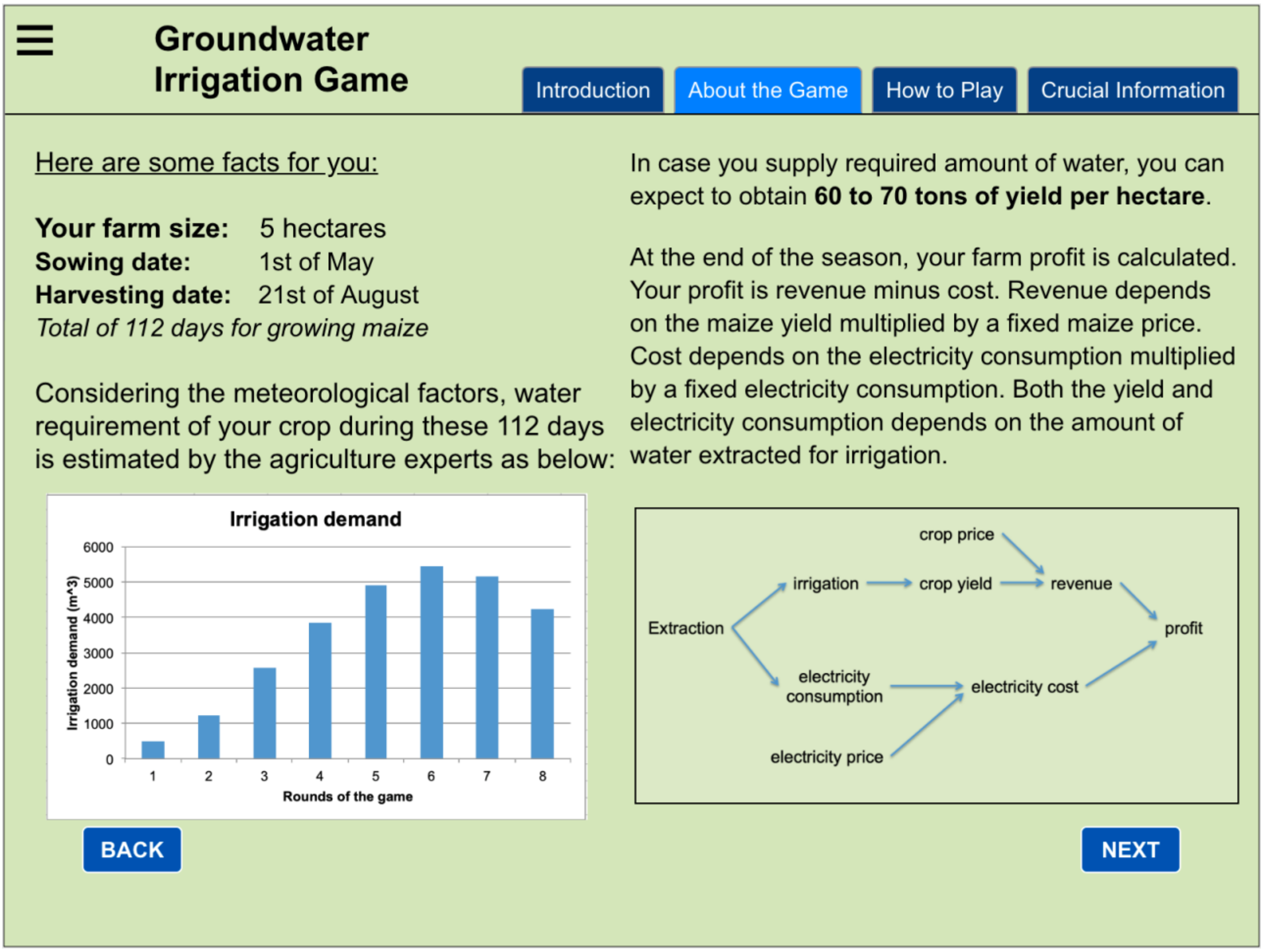

Figure 6.3. Dynamic simulation game interface – *About the Game* page.

In the next page, namely *"How to Play"*, players can obtain information on the duration of the game, decision variable, how to submit their decisions and what kind of feedbacks they receive at the end of each round (Figure 6.4).

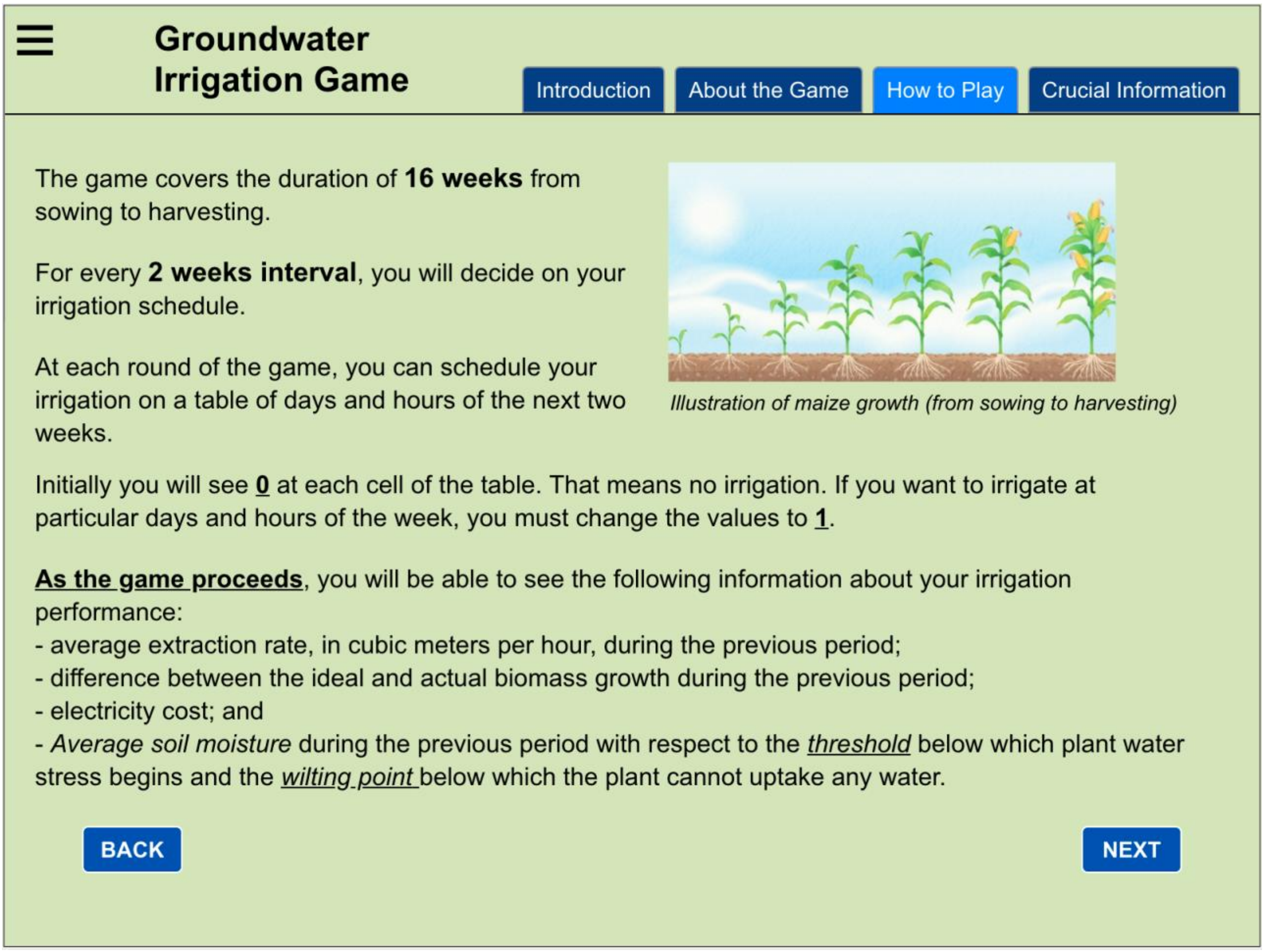

Figure 6.4. Dynamic simulation game interface – *How to Play* page.

In line with the purpose of this research, the concept of coordination dilemma is introduced to the players on the next page, namely *"Crucial Information"*. Considering that the game can be played by anyone with any education level, the dilemma is explained clearly and concisely to the extent possible (Figure 6.5).

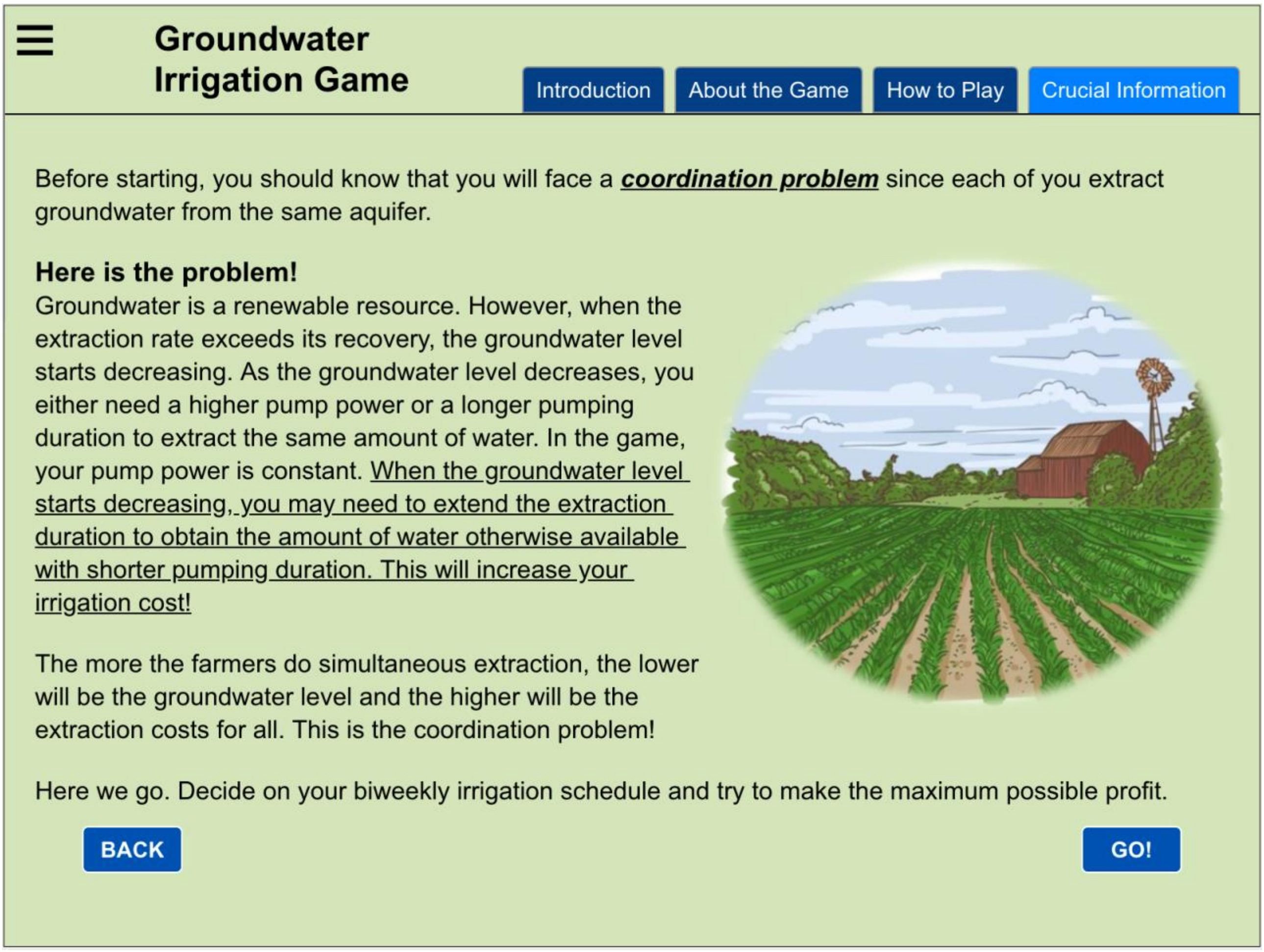

Figure 6.5. Dynamic simulation game interface – *Crucial Information* page.

Essential information to play the game is given in these four pages (i.e. Introduction, About the Game, How to Play and Crucial Information). Before starting the game, players are able to visit the previous pages and read the instructions as many times as they want. When a player is ready to start the game, s/he is supposed to click on "GO!" button and move to the *"Decision"* page. The game is initiated when all the players click on "GO!" button.

On the *"Decision"* page (Figure 6.6), a blank hourly schedule for the next 14 days is given at the top of the page. Rows represent the days of the next two weeks whereas columns represent the hours of the day. Players can either input "0" or "1" as their decisions into the schedule. "0" means that irrigation is not applied and "1" represents that irrigation is applied at that time slot. After completing the data entry, players need to click on "Ready" button to advance the game. The game proceeds after all the players submit their decisions. Until all the players advance the game, players are directed to the waiting room (Figure 6.7). On that page, until the last player makes her/his decision, players have time to go back and make changes in their decisions by clicking on the "*Cancel*" button. This directs the players to the Decision page again.

At the end of each round, information about the irrigation performance of players is provided which are (i) average extraction rate (m^3/hour) during the previous period; (ii) difference between the actual and ideal crop biomass growth (tons); (iii) electricity cost (TL) accumulated over time; and (iv) relative soil moisture (dimensionless) with respect to the threshold and wilting point. These are private information for each player and players are not allowed to see each other's performance until the game is finished.

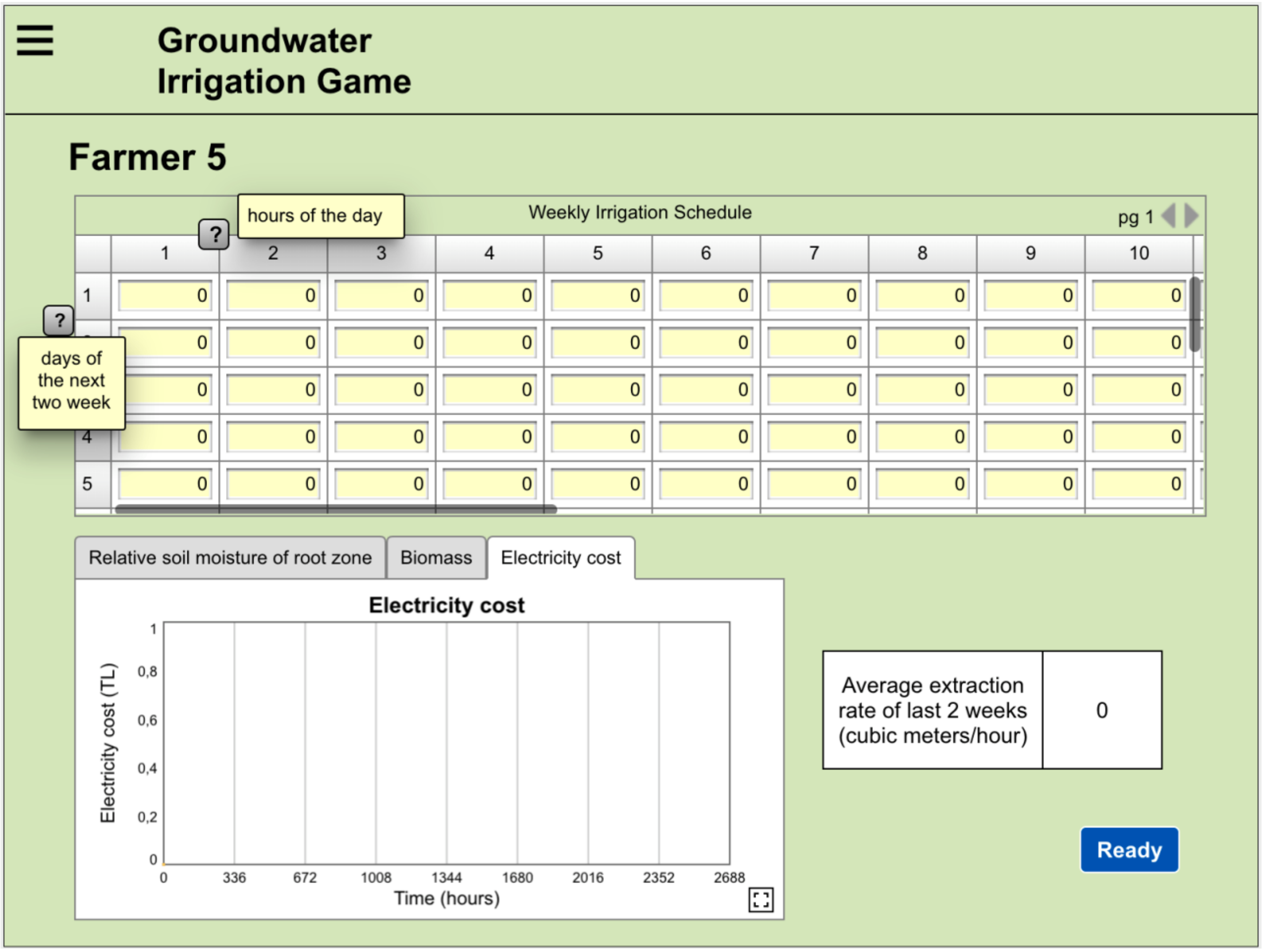

Figure 6.6. Dynamic simulation game interface - *Decision* page.

Figure 6.7. Dynamic simulation game interface – Waiting room.

At the end of the game, the player who has obtained the highest farm profit is announced as the winner and following information is available to everyone in the game. The information is provided for each farmer and average of the group (total of 5 farmers).

- Yield (tons)
- Total water consumption (m^3)
- Total electricity consumption (kW)
- Profit (TL)
- Irrigation efficiency (dimensionless)

After each player examines the results, they are invited to a second round where communication between the players is allowed. Same gaming procedure is replicated in the second round and the effect of communication on the results is aimed to be observed.

7. RESULTS AND DISCUSSION

The main findings of our study are demonstrated in this chapter. A pilot game is played by the graduate students from Boğaziçi University Institute of Environmental Sciences. None of the participants had any experience with maize farming.

After participants have read the game instructions and before starting the game, they were asked to answer couple of questions which are listed below:

- Do you think the explanation of the game and the player instructions are easy to understand? If not please explain.
- Could you please state your expected amount of yield by the end of the game?
- To achieve your stated goal above, would you seek more information from the game leader or from any of your fellow farmers? If you do, what are they?

In accordance with the answers collected from the participants, they all agree that the explanations are clear and game instructions are easy to understand. Regarding the second question, participants have stated their expected yields ranging from 10 to 50 tons per hectare whilst the maximum attainable yield was given them as 60 to 70 tons per hectare. To achieve their stated goal, most of the participants did not ask for more information from the game leader. On the other hand, one participant has expressed that it would be preferred to communicate before and during the game with the fellow farmers for potential collaboration. Besides, one participant has asked for some more tips and strategies to achieve the stated goal.

After the game, participants were asked to answer following questions:

- Please explain if the game was sufficiently represented the real-life issue of irrigation and crop production. In other words, was the game realistic enough? If not please explain your criticism.
- Were you able meet your expected yield? If not, why you think that you were not?

According to the answers collected from the participants, the game was found realistic in general. Besides, it was stated that the game has represented real-life phenomena and helped them to understand the irrigation system dynamics. On the other hand, there were two main criticism received. First one has criticized the lack of difference between day time and night time irrigation since they thought the evaporation from soil surface is expected to be higher when compared with the night time. Second one has criticized the lack of impact of overirrigation on the crops. Regarding the second question, four of the participants have expressed that they achieved their goal. The remaining one participant has realized and stated that his/her total water extraction was above the required amount and s/he would achieve more profit.

The game was played 2 rounds in total. In the first round, communication was not allowed and participants were asked to develop their own strategies. At the end of the first round, the results shown in Table 7.1 and Figure 7.1 were obtained.

Table 7.1. Game results - Round 1.

	Revenue	**Cost**	**Profit**
Farmer 1	120k	3,69k	117k
Farmer 2	119k	4,28k	115k
Farmer 3	119k	3,2k	116k
Farmer 4	119k	3,26k	116k
Farmer 5	120k	3,37k	117k

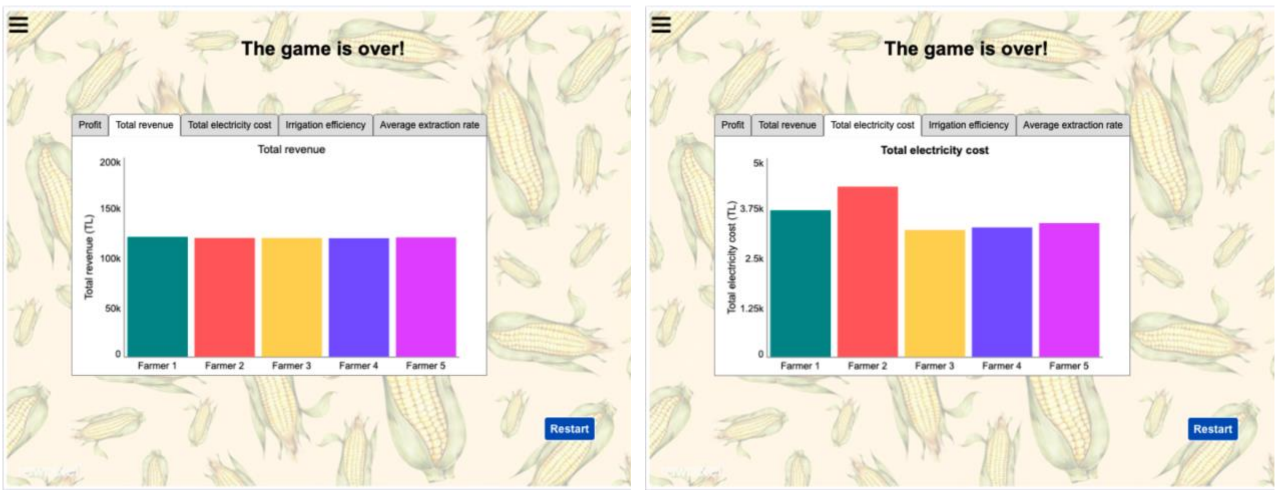

Figure 7.1. Game results - Round 1.

After the first round results were collected, it was realized that the results did not show the full precision of the figures. Therefore, it was not possible to analyze results in detail. It can be deduced that all of the participants have achieved similar results in terms of revenue and profit. However, the results differ in terms of electricity costs. It reveals the participants who extract more groundwater than the others. For example, Farmer 2 has spent the highest amount of money to the electricity. In contrast, Farmer 2 achieves the maximum attainable yield similar to the other farmers. Therefore, it is clear that the extracted amount of water is more than the required. In fact, it decreases the farmer profit. It can be inferred that extracting groundwater more than the requirement of the crops does not lead to a better outcome in terms of yield and profit.

After the first round was completed, participants were asked for a second round. In this round, chat box within the game interface was activated and players were encouraged to communicate among themselves to develop a cooperative strategy. The results obtained at the end of this round is demonstrated in Table 7.2 and Figure 7.2.

Table 7.2. Game results - Round 2.

	Revenue	**Cost**	**Profit**
Farmer 1	120,417.6	3,544.6	116,873
Farmer 2	120,406.8	3,543.8	116,863
Farmer 3	120,417.6	5,014.6	115,403
Farmer 4	120,196	3,544	116,652
Farmer 5	119,986.4	3,553.4	116,433

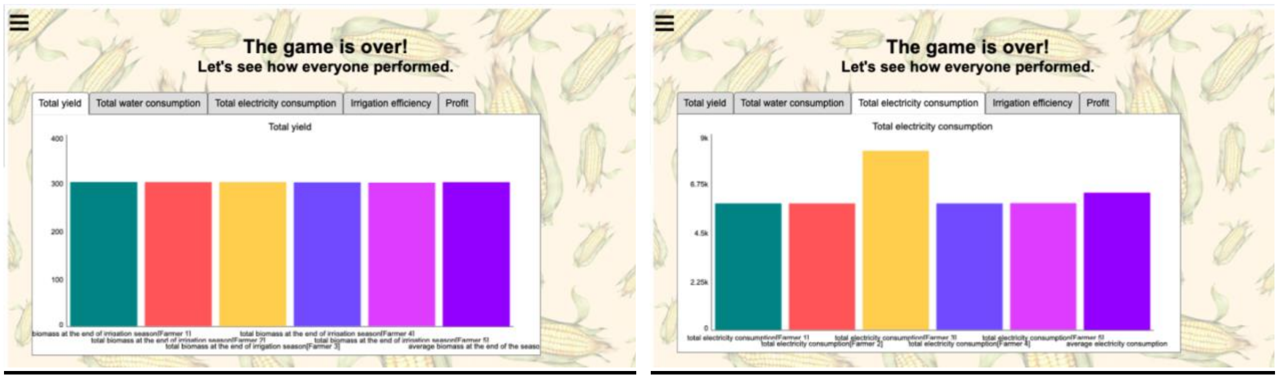

Figure 7.2. Game results - Round 2 (x axis - from left to right: Farmer 1, Farmer 2, Farmer 3, Farmer 4, Farmer 5 and average of the group).

In order to analyze results better, the display settings were changed as to show full precision of the figures. Graphs were also changed as to demonstrate group average values. Before the game has started, players were decided to cooperate on the timing of extraction. According to their strategy, Farmer 1 extracts first, then Farmer 2, then Farmer 3 and so forth. With this strategy, participants have aimed to minimize the schedule overlapping.

According to the results obtained at the end of second round, it can be seen that most of the participants have followed the cooperative strategy. However, Farmer 3 did not follow the strategy and extracted more water than everyone. It is known that as groundwater extraction continues, extraction rate decreases over time since water level decreases. In the light of this information, it is expected to observe the highest yield in the farmer who extracts first (Farmer 1 in this case) and lowest yield in the farmer who extracts last (Farmer 5). The game results comply with the expectation. Although the differences are too small, Farmer 1 has obtained the highest yield.

When game results obtained from both two rounds are analyzed, it can be inferred that all of the participants understood the dynamic structure of the game. While making their decisions, they were aware that groundwater extraction rate decreases over time; therefore, they needed to extend their pumping duration to achieve their goal. Accordingly, in both two rounds, almost all participants have achieved maximum attainable biomass at the end of the season. On the other hand, electricity cost is relatively cheap when compared with the revenue obtained from the crop yield. Therefore, we cannot observe a remarkable difference in the farm profits between these two rounds.

8. CONCLUSION

In this research, dynamic complex nature of groundwater appropriation problem is studied. Groundwater is deemed one of the most valuable renewable resources and conceptualized as a common pool resource (CPR). In case individual rational decisions of groundwater users do not lead to an outcome which is rational for the group, the resulting situation is defined as CPR dilemma. To benefit more from the resource, groundwater users act with self-interest and increase their own extraction that may result in decrease in water level and even depletion of the resource. As water table level decreases, groundwater extraction rate decreases and pumps need to work longer durations or increase their power. Either way, total energy consumption and extraction costs increase. This reduces overall as well as individual benefits of CPR users and creates a cooperation dilemma among them. The dilemma requires actors to cooperate with each other for the quantity and timing of their irrigation activity to increase their benefits. However, in real systems it is not possible to directly experience the dilemma and find the desirable solutions.

In order to understand the dynamic feedback nature of the problem, a dynamic simulation model based on the system dynamics methodology is developed. The model shortens the actual duration and allows us to simulate an irrigation season (i.e. approximately 4 months) in few seconds. The model is grounded on the available scientific literature. The confidence of the model structure is ensured through the validation tests in line with the system dynamics methodology. Isolated subsectors and whole model are structurally validated by applying structural validation tests. After the model is structurally validated, reference behavior of the model under two different circumstances (i.e. (i) without groundwater extraction and (ii) with groundwater extraction of highest irrigation efficiency is analyzed.

In the first case of no extraction, water in deep zone and groundwater level does not change. Soil moisture in the root zone decreases and approaches to the wilting point. It does not drop below the wilting point since plant roots cannot take any water below wilting point. Accordingly, due to the water limiting conditions, crop yield obtained at the end of the season is approximately one third of the maximum attainable yield. In the second case where groundwater is extracted as to meet the irrigation demand of the crops with highest possible efficiency, the reference behavior shows that the water in deep zone decreases depending on the extraction and groundwater level decreases. With the decreasing groundwater level, extraction rate decreases that leads to an increase in extraction costs.

Based on the model, a dynamic multiplayer simulation game, namely *Groundwater Irrigation Game*, is created. With the help of the game, implementation of the model, which is the last step of system dynamics methodology, is enhanced. The game allows players to explore the resource dynamics and successful management of commons. A group of people who do not have a professional experience in maize farming play the game for 2 times in total. In the first round, communication between the participants is not allowed and in the second round, communication is not only allowed but also promoted. The results indicate that the participants understand the dynamic structure of the game and play accordingly. In both two rounds, almost all of the participants achieve maximum attainable biomass and revenue. Although their irrigation schedules are different and some of them prefer irrigating their lands for longer durations, it is observed that electricity cost does not have a significant impact on the farm profits since it constitutes relatively small amount.

The model is built based on theoretical knowledge and mostly with empirical model constants taken from the field measurements. As for future research, collecting field data regarding the groundwater level, aquifer properties and aquifer lateral recharge mechanism can further develop the model and make the game more realistic. The crop development model can be further improved with a stronger reference to the available literature. In this way, the game can be used in laboratory or in field-lab conditions and make stronger contribution to farmers' knowledge on CPR dilemma. In addition, the variations of the game in line with the real life phenomena can be created. Thus, the game can represent the real life problems more adequately that allows both authorities and individuals to better understand dynamic complexity of the groundwater systems to promote their sustainable use.

REFERENCES

Barlas, Y., 2002. System Dynamics: Systemic Feedback Modeling for Policy Analysis.

Barlas, Y., 1996. Formal Aspects of Model Validity and Validation in System Dynamics. System Dynamics Review, 12, 183-210.

Cardenas, J.C., Ostrom, E., 2004. What do people bring into the game? Experiments in the field about cooperation in the commons. Agricultural Systems, 82, 307-326.

Food and Agriculture Organization of United Nations (FAO), 2020. Land & Water - Maize. http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/. Date accessed May 2020.

Food and Agriculture Organization of United Nations (FAO), 1998. Chapter 8 - ETc under soil water stress conditions. http://www.fao.org/3/x0490e/x0490e0e.htm. Date accessed May 2020.

Food and Agriculture Organization of United Nations (FAO), 1985. Chapter 2 - Soil and Water. http://www.fao.org/3/r4082e/r4082e03.htm. Date accessed May 2020.

Gardner, R., Ostrom, E., Walker, J. M., 1990. The Nature of Common-Pool Resource Problems. Rationality and Society, 2, 335-358.

Gordon, S. H, 1954. The Economic Theory of a Common-Property Resource: The Fishery. The Journal of Political Economy, 62, 124-142.

Gordon, S. H, 1991. The Economic Theory of a Common-Property Resource: The Fishery. Bulletin of Mathematical Biology, 53, 231-252.

Hardin, G., 1968. The Tragedy of Commons. Science, 162, 1243-1248.

Janssen, M. A., Bousquet, F., Cardenas, C., Castillo, D., Worrapimphong, K., 2012, Field experiments on irrigation dilemmas. Agricultural Systems, 109, 65-75.

Khan, S., Yufeng, L., Ahmad, A., 2009. Analysing complex behaviour of hydrological systems through a system dynamics approach. Environmental Modeling & Software, 24, 1363-1372.

Luo, Y., Khan, S., 2009. Application of system dynamics approach for time varying water balance in aerobic paddy fields. Paddy and Water Environment, 7, 1-9.

Meinzen-Dick, R., Janssen, M. A., Kandikuppa, S., Chaturvedi, R., Rao, K., Theis, S., 2018. Playing games to save water: Collective action games for groundwater management in Andhra Pradesh, India. World Development, 107, 40-53.

Meinzen-Dick, R., Chaturvedi, R., Domènech, L., Ghate, R., Janssen, M., Rollins, N., Sandeep, K, 2016. Games for groundwater governance: field experiments in Andhra Pradesh, India. Ecology and Society, 21(3): 38.

Ministry of Agriculture and Forestry General Directorate of Agricultural Research and Policy (TAGEM), State Hydraulic Works (DSI), 2017. Türkiye'de Sulanan Bitkilerin Bitki Su Tüketimleri. Ankara.

Ministry of Agriculture and Forestry (MoAF) Institute of Agricultural Research Thrace Region. Corn Production. https://arastirma.tarimorman.gov.tr/ttae/Sayfalar/Detay.aspx?SayfaId=89. Date accessed July 2020.

Moxnes, E., 1998. Overexploitation of renewable resources: The role of misperceptions. Economic Behavior & Organization, 37, 107-127.

Ostrom, E., Gardner, R., Walker, J., 1994. Rules, Games and Common-Pool Resources. The University of Michigan Press, U.S.A.

Ostrom, E., 2006. The value-added of laboratory experiments for the study of institutions and common-pool resources. Journal of Economic Behavior & Organization, 61, 149-163.

Raquel, A., Ferenc, S., Emery, C., Abraham, R., 2007. Application of game theory for a groundwater conflict in Mexico. Environmental Management, 84, 560-571.

Rodriguez-Iturbe, I., Porporato, A., 2004. Ecohydrology of Water-Controlled Ecosystems Soil Moisture and Plant Dynamics Soil Moisture and Plant Dynamics. Cambridge University Press, UK.

State Hydraulic Works (DSI), 2018. DSI Official Water Resources Statistics for 2017. http://www.dsi.gov.tr/dsi-resmi-istatistikler/resmi-i-statistikler-2017/2017-yılı-verileri. Date accessed May 2020.

Sterman, J., 2014. Interactive web-based simulations for strategy and sustainability: The MIT Sloan LearningEdge management flight simulators, Part I. System Dynamics Review, 30, 89-121.

Sterman, J., 2014. Interactive web-based simulations for strategy and sustainability: The MIT Sloan LearningEdge management flight simulators, Part II. System Dynamics Review, 30, 206-231.

United Nations Economic Commission for Africa (UNECA), 2013. Management of Groundwater in Africa: Implications for Meeting MDGs, Livelihood Goals and Adaptation to Climate Change. https://www.uneca.org/sites/default/files/PublicationFiles/policy_brief_5_management_of_groundwater_in_africa_implications_for_meeting_mdgs_livelihood_goals.pdf. Date accessed May 2020.

United States Department of Agriculture (USDA) Economic Research Service, 2020. Feedgrains Sector at a Glance. https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/. Date accessed July 2020.

United States Department of Agriculture (USDA), 2019. Corn is America's Largest Crop in 2019. https://www.usda.gov/media/blog/2019/07/29/corn-americas-largest-crop-2019. Date accessed July 2020.

United States Environmental Protection Agency (EPA), 2018. Groundwater. https://www.epa.gov/report-environment/ground-water. Date accessed May 2020.

United States Geological Surveys (USGS), 2016. Groundwater Decline and Depletion. https://water.usgs.gov/edu/gwdepletion.html. Date accessed May 2020.

United States Geological Survey (USGS). Where is Earth's Water? https://www.usgs.gov/special-topic/water-science school/science/where-earths-water?qt-science_center_objects=0#qt-science_center_objects. Date accessed May 2020.

APPENDIX A: MODEL EQUATIONS

Top-Level Model:

A_max_actual[Farmer](t) = A_max_actual[Farmer](t - dt) + (accumulation_A[Farmer]) * dt {NON-NEGATIVE}

INIT A_max_actual[Farmer] = 0

UNITS: Tons

INFLOWS:

accumulation_A[Farmer] = A_max_achieved[Farmer]/DT {UNIFLOW}

UNITS: Tons/Hours

B_max_actual[Farmer](t) = B_max_actual[Farmer](t - dt) + (accumulation_B[Farmer]) * dt {NON-NEGATIVE}

INIT B_max_actual[Farmer] = 0

UNITS: Tons

INFLOWS:

accumulation_B[Farmer] = B_max_achieved[Farmer]/DT {UNIFLOW}

UNITS: Tons/Hours

biomass_at_stage_A[Farmer](t) = biomass_at_stage_A[Farmer](t - dt) + (seeding[Farmer] + growthA[Farmer] - decayA[Farmer] - switch_A_to_B[Farmer]) * dt

INIT biomass_at_stage_A[Farmer] = 0

UNITS: Tons

INFLOWS:

seeding[Farmer] = PULSE((seed_quantity*area_of_each_farming_land*DT);seeding_time;0)

UNITS: Tons/Hours

growthA[Farmer] = IF TIME<"switch_time_(A_to_B)" THEN (biomass_at_stage_A[Farmer]*normal_growth_fraction_at_stage_A*(1-relative_biomass_at_stage_A[Farmer])*water_growth_multiplier[Farmer]) ELSE 0

UNITS: Tons/Hours

OUTFLOWS:

decayA[Farmer] = biomass_at_stage_A[Farmer]*decay_fraction

UNITS: Tons/Hours

switch_A_to_B[Farmer] = IF TIME>="switch_time_(A_to_B)" THEN biomass_at_stage_A[Farmer]/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

biomass_at_stage_B[Farmer](t) = biomass_at_stage_B[Farmer](t - dt) + (growthB[Farmer] + switch_A_to_B[Farmer] - decayB[Farmer] - switch_B_to_C[Farmer]) * dt

INIT biomass_at_stage_B[Farmer] = 0

UNITS: Tons

INFLOWS:

growthB[Farmer] = IF TIME<"switch_time_(B_to_C)" THEN (biomass_at_stage_B[Farmer]*normal_growth_fraction_at_stage_B*(1-relative_biomass_at_stage_B[Farmer])*water_growth_multiplier[Farmer]) ELSE 0

UNITS: Tons/Hours

switch_A_to_B[Farmer] = IF TIME>="switch_time_(A_to_B)" THEN biomass_at_stage_A[Farmer]/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

OUTFLOWS:

decayB[Farmer] = biomass_at_stage_B[Farmer]*decay_fraction

UNITS: Tons/Hours

switch_B_to_C[Farmer] = IF TIME>="switch_time_(B_to_C)" THEN biomass_at_stage_B[Farmer]/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

biomass_at_stage_C[Farmer](t) = biomass_at_stage_C[Farmer](t - dt) + (growthC[Farmer] + switch_B_to_C[Farmer] - decayC[Farmer] - switch_C_to_D[Farmer]) * dt

INIT biomass_at_stage_C[Farmer] = 0

UNITS: Tons

INFLOWS:

growthC[Farmer] = IF TIME<"switch_time_(C_to_D)" THEN (biomass_at_stage_C[Farmer]*normal_growth_fraction_at_stage_C*(1-relative_biomass_at_stage_C[Farmer])*water_growth_multiplier[Farmer]) ELSE 0

UNITS: Tons/Hours

switch_B_to_C[Farmer] = IF TIME>="switch_time_(B_to_C)" THEN biomass_at_stage_B[Farmer]/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

OUTFLOWS:

decayC[Farmer] = biomass_at_stage_C[Farmer]*decay_fraction

UNITS: Tons/Hours

switch_C_to_D[Farmer] = IF TIME>="switch_time_(C_to_D)" THEN biomass_at_stage_C/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

biomass_at_stage_D[Farmer](t) = biomass_at_stage_D[Farmer](t - dt) + (switch_C_to_D[Farmer] + growthD[Farmer] - harvesting[Farmer] - decayD[Farmer]) * dt

INIT biomass_at_stage_D[Farmer] = 0

UNITS: Tons

INFLOWS:

switch_C_to_D[Farmer] = IF TIME>="switch_time_(C_to_D)" THEN biomass_at_stage_C/DT ELSE 0 {UNIFLOW}

UNITS: Tons/Hours

growthD[Farmer] = IF TIME<harvesting_time THEN (biomass_at_stage_D[Farmer]*normal_growth_fraction_at_stage_D*(1-relative_biomass_at_stage_D[Farmer])*water_growth_multiplier[Farmer]) ELSE 0

UNITS: Tons/Hours

OUTFLOWS:

harvesting[Farmer] = PULSE(biomass_at_stage_D[Farmer];harvesting_time;0)

UNITS: Tons/Hours

decayD[Farmer] = biomass_at_stage_D[Farmer]*decay_fraction

UNITS: Tons/Hours

C_max_actual[Farmer](t) = C_max_actual[Farmer](t - dt) + (accumulation_C[Farmer]) * dt {NON-NEGATIVE}

INIT C_max_actual[Farmer] = 0

UNITS: Tons

INFLOWS:

accumulation_C[Farmer] = C_max_achieved[Farmer]/DT {UNIFLOW}

UNITS: Tons/Hours

cum_CR[Farmer](t) = cum_CR[Farmer](t - dt) + (CR_accumulation[Farmer]) * dt {NON-NEGATIVE}

INIT cum_CR[Farmer] = 0

INFLOWS:

CR_accumulation[Farmer] = capillary_rise[Farmer] {UNIFLOW}

cum_ET[Farmer](t) = cum_ET[Farmer](t - dt) + (ET_acc[Farmer]) * dt {NON-NEGATIVE}

INIT cum_ET[Farmer] = 0

INFLOWS:

ET_acc[Farmer] = evapotranspiration[Farmer] {UNIFLOW}

cumulative_extraction_duration[Farmer](t) = cumulative_extraction_duration[Farmer](t - dt) + (well_number_accumulation[Farmer] - zero_duration[Farmer]) * dt {NON-NEGATIVE}

INIT cumulative_extraction_duration[Farmer] = 0

UNITS: Hours

INFLOWS:

well_number_accumulation[Farmer] = active_wells {UNIFLOW}

UNITS: Dimensionless

OUTFLOWS:

zero_duration[Farmer] = PULSE (cumulative_extraction_duration; 336; 336) {UNIFLOW}

UNITS: Dimensionless

day_of_the_week(t) = day_of_the_week(t - dt) + (day_counter - day_resetter) * dt

INIT day_of_the_week = 0

UNITS: Days

INFLOWS:

day_counter = IF TIME MOD 24=24-DT THEN PULSE(1; TIME; 0) ELSE 0

UNITS: Days/Hours

OUTFLOWS:

day_resetter = IF TIME MOD 168=168-DT THEN day_of_the_week/DT ELSE 0

UNITS: Days/Hours

electricity_consumption[Farmer](t) = electricity_consumption[Farmer](t - dt) + (electricity_consumption_accumulation[Farmer]) * dt {NON-NEGATIVE}

INIT electricity_consumption[Farmer] = 0

UNITS: kW

INFLOWS:

electricity_consumption_accumulation[Farmer] = energy_consumption_of_the_pump {UNIFLOW}

UNITS: kW/Hours

irrigation_water_accumulated[Farmer](t) = irrigation_water_accumulated[Farmer](t - dt) + (irrigation_accumulation[Farmer] - zero_water[Farmer]) * dt {NON-NEGATIVE}

INIT irrigation_water_accumulated[Farmer] = 0

UNITS: Cubic Meters

INFLOWS:

irrigation_accumulation[Farmer] = irrigation {UNIFLOW}

UNITS: m^3/hour

OUTFLOWS:

zero_water[Farmer] = PULSE (irrigation_water_accumulated; 336; 336) {UNIFLOW}

UNITS: m^3/hour

irrigation_water_accumulated_1[Farmer](t) = irrigation_water_accumulated_1[Farmer](t - dt) + (irrigation_accumulation_1[Farmer]) * dt {NON-NEGATIVE}

INIT irrigation_water_accumulated_1[Farmer] = 0

UNITS: Cubic Meters

INFLOWS:

irrigation_accumulation_1[Farmer] = irrigation {UNIFLOW}

UNITS: m^3/hour

month(t) = month(t - dt) + (month_counter) * dt

INIT month = 0

UNITS: Weeks

INFLOWS:

month_counter = IF TIME MOD 672=672-DT THEN PULSE(1; TIME; 0) ELSE 0

UNITS: Weeks/Hours

total_cost[Farmer](t) = total_cost[Farmer](t - dt) + (cost_accumulation[Farmer]) * dt

INIT total_cost[Farmer] = 0

UNITS: TL

INFLOWS:

cost_accumulation[Farmer] = cost[Farmer] {UNIFLOW}

UNITS: TL

total_irrigation_applied[Farmer](t) = total_irrigation_applied[Farmer](t - dt) + (irrigation_water_accumulation[Farmer]) * dt {NON-NEGATIVE}

INIT total_irrigation_applied[Farmer] = 0

UNITS: m^3

INFLOWS:

irrigation_water_accumulation[Farmer] = irrigation[Farmer] {UNIFLOW}

UNITS: m^3/hour

total_precipitation[Farmer](t) = total_precipitation[Farmer](t - dt) + (precipitation_accumulation[Farmer]) * dt {NON-NEGATIVE}

INIT total_precipitation[Farmer] = 0

UNITS: m^3

INFLOWS:

precipitation_accumulation[Farmer] = precipitation[Farmer] {UNIFLOW}

UNITS: m^3/hour

total_theoretical_ET(t) = total_theoretical_ET(t - dt) + (ET_accumulation) * dt {NON-NEGATIVE}

INIT total_theoretical_ET = 0

UNITS: m^3

INFLOWS:

ET_accumulation = theoretical_ET {UNIFLOW}

UNITS: m^3/hour

water_in_deep_zone(t) = water_in_deep_zone(t - dt) + ("recharge/discharge" + percolation[Farmer_1] + percolation[Farmer_2] + percolation[Farmer_3] + percolation[Farmer_4] + percolation[Farmer_5] - extraction - capillary_rise[Farmer_1] - capillary_rise[Farmer_2] - capillary_rise[Farmer_3] - capillary_rise[Farmer_4] - capillary_rise[Farmer_5]) * dt

INIT water_in_deep_zone = 150000

UNITS: m^3

INFLOWS:

"recharge/discharge" = (gap/adjustment_time)

UNITS: m^3/hr

percolation[Farmer_1] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

percolation[Farmer_2] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

percolation[Farmer_3] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

percolation[Farmer_4] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

percolation[Farmer_5] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

OUTFLOWS:

extraction = extraction_from_a_well*SUM(active_wells)

UNITS: m^3/hr

capillary_rise[Farmer_1] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

capillary_rise[Farmer_2] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

capillary_rise[Farmer_3] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

capillary_rise[Farmer_4] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

capillary_rise[Farmer_5] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

water_in_root_zone[Farmer](t) = water_in_root_zone[Farmer](t - dt) + (irrigation[Farmer] + precipitation[Farmer] + capillary_rise[Farmer] - evapotranspiration[Farmer] - surface_runoff[Farmer] - percolation[Farmer]) * dt

INIT water_in_root_zone[Farmer] = 4800

UNITS: m^3

INFLOWS:

irrigation[Farmer] = IF active_wells[Farmer]=1 THEN extraction/(SUM(active_wells)) ELSE 0

UNITS: m^3/hour

precipitation[Farmer] = (hourly_precipitation/1000)*area_of_each_farming_land

UNITS: m^3/hr

capillary_rise[Farmer] = evapotranspiration[Farmer]*EXP(-dynamic_water_level*emprical_coefficient)

UNITS: m^3/hr

OUTFLOWS:

evapotranspiration[Farmer] = (ETo/1000)*Kc*Ks[Farmer]*area_of_each_farming_land

UNITS: m^3/hr

surface_runoff[Farmer] = IF volumetric_water_content_of_root_zone_of_each_farming_land[Farmer]>saturated_water_content_of_root_zone_of_each_farming_land THEN (water_in_root_zone[Farmer]-(saturated_water_content_of_root_zone_of_each_farming_land*volume_of_root_zone_of_each_farming_land))*runoff_fraction ELSE 0

UNITS: m^3/hr

percolation[Farmer] = IF relative_soil_moisture_of_root_zone_of_each_farming_land>relative_soil_moisture_at_field_capacity THEN (area_of_each_farming_land*hydraulic_conductivity*(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]^"c_(soil_parameter)")) ELSE 0

UNITS: m^3/hr

week(t) = week(t - dt) + (week_counter) * dt

INIT week = 0

UNITS: Weeks

INFLOWS:

week_counter = IF TIME MOD 168=168-DT THEN PULSE(1; TIME; 0) ELSE 0

UNITS: Weeks/Hours

A_max_achieved[Farmer] = IF TIME=480 THEN biomass_at_stage_A[Farmer] ELSE 0

UNITS: Tons

active_wells[Farmer] = IF irrigation_schedule_by_farmer_by_hour[Farmer]=1 THEN 1 ELSE 0

UNITS: Dimensionless

actual_total_biomass[Farmer] = biomass_at_stage_A+biomass_at_stage_B+biomass_at_stage_C+biomass_at_stage_D

UNITS: Tons

adjustment_time = 2688

UNITS: hours

aquifer_depth = 80

UNITS: meters

area_of_each_farming_land = 50000

UNITS: Square Meters

average_electricity_consumption = SUM(electricity_consumption)/5

average_extraction_rate_at_the_end[Farmer] = IF TIME=2688 THEN irrigation_water_accumulated_1[Farmer]/2688 ELSE 0

UNITS: m^3/hour

average_extraction_rate_of_last_2_weeks[Farmer] = IF cumulative_extraction_duration>0 THEN irrigation_water_accumulated/cumulative_extraction_duration ELSE 0

UNITS: m^3/hour

average_irrigation_efficiency = SUM(irrigation_efficiency)/5

UNITS: Dimensionless

average_profit = SUM(profit)/5

UNITS: TL

average_water_consumption = SUM(total_irrigation_applied)/5

UNITS: Cubic Meters

average_yield = SUM(total_yield)/5

UNITS: Tons

B_max_achieved[Farmer] = IF TIME=1248 THEN biomass_at_stage_B[Farmer] ELSE 0

UNITS: Tons

"c_(soil_parameter)" = 12,8

UNITS: Dimensionless

C_max_achieved[Farmer] = IF TIME=2016 THEN biomass_at_stage_C[Farmer] ELSE 0

UNITS: Tons

cost[Farmer] = unit_price_of_energy*energy_consumption_of_the_pump[Farmer]

UNITS: TL

crop_price = 400

UNITS: TL/ton

daily_clock = INT (TIME MOD 24)

UNITS: Hours

decay_fraction = 0,0002

UNITS: Per Hour

density_of_the_fluid = 1000

UNITS: kg/m^3

depth_of_deep_zone = aquifer_depth-depth_of_root_zone

UNITS: Meters

depth_of_root_zone = 0,5

UNITS: meters

dynamic_water_level = (aquifer_depth-(aquifer_depth*dynamic_water_level_multiplier))

UNITS: meters

dynamic_water_level_multiplier = GRAPH(saturation_level)

UNITS: Dimensionless

emprical_coefficient = 2 {for loam}

UNITS: Dimensionless

energy_consumption_of_the_pump[Farmer] = power*irrigation_schedule_by_farmer_by_hour[Farmer]

UNITS: Kwh

ETo = GRAPH(TIME)

UNITS: mm/hour

extraction_from_a_well = IF pump_height>dynamic_water_level THEN (potential_extraction) ELSE 0

UNITS: m^3/hour

g = 9,81

UNITS: meters per second squared

game_advanced = IF (TIME MOD 336=1) THEN 1 ELSE 0

UNITS: Dimensionless

game_over = IF (STOPTIME-TIME<DT) THEN 1 ELSE 0

UNITS: Dimensionless

gap = static_water_volume-water_in_deep_zone

UNITS: cubic meters

harvesting_time = 2688

UNITS: Hours

head_loss = dynamic_water_level*head_loss_fraction

UNITS: Meters

head_loss_fraction = 0,10

UNITS: Dimensionless

hourly_precipitation = GRAPH(TIME)

UNITS: millimeters per hour

hydraulic_conductivity = 0,033

UNITS: meters per hour

ideal_electricity_consumption = GRAPH(TIME)

UNITS: kW

ideal_profit = GRAPH(TIME)

UNITS: TL

ideal_total_yield = GRAPH(TIME)

UNITS: Tons

ideal_water_consumption = GRAPH(TIME)

UNITS: Cubic Meters

integer_simulation_clock = INT (TIME)

UNITS: Hours

"irr/cost_ratio"[Farmer] = IF total_irrigation_applied[Farmer]>0 THEN total_cost[Farmer]/total_irrigation_applied[Farmer] ELSE 0

UNITS: m^3/TL

irrigation_demand[Farmer] = total_theoretical_ET-total_precipitation[Farmer]

UNITS: Cubic Meters

irrigation_demand_per_round = GRAPH(TIME)

(0, 0), (336, 488,1150898), (672, 1238,370253), (1008, 2573,282699), (1344, 3857,549948), (1680, 4898,407346), (2016, 5447,012847), (2352, 5161,946928), (2688, 4246,529469)

UNITS: Cubic Meters

irrigation_efficiency[Farmer] = IF total_irrigation_applied[Farmer]>0 THEN MIN (1; (irrigation_demand[Farmer]/total_irrigation_applied[Farmer])) ELSE 0

UNITS: Dimensionless

irrigation_hours_in_a_single_schedule = integer_simulation_clock MOD 336

irrigation_schedule_by_farmer_by_hour[Farmer] = IF irrigation_hours_in_a_single_schedule=0 THEN weekly_irrigation_schedule[Farmer;1;1] ELSE IF irrigation_hours_in_a_single_schedule=1 THEN weekly_irrigation_schedule[Farmer;1;2] ELSE IF irrigation_hours_in_a_single_schedule=2 THEN weekly_irrigation_schedule[Farmer;1;3] ELSE IF irrigation_hours_in_a_single_schedule=3 THEN weekly_irrigation_schedule[Farmer;1;4] ELSE IF irrigation_hours_in_a_single_schedule=4 THEN weekly_irrigation_schedule[Farmer;1;5] ELSE IF irrigation_hours_in_a_single_schedule=5 THEN weekly_irrigation_schedule[Farmer;1;6] ELSE IF irrigation_hours_in_a_single_schedule=6 THEN weekly_irrigation_schedule[Farmer;1;7] ELSE IF irrigation_hours_in_a_single_schedule=7 THEN weekly_irrigation_schedule[Farmer;1;8] ELSE IF irrigation_hours_in_a_single_schedule=8 THEN weekly_irrigation_schedule[Farmer;1;9] ELSE IF irrigation_hours_in_a_single_schedule=9 THEN weekly_irrigation_schedule[Farmer;1;10] ELSE IF irrigation_hours_in_a_single_schedule=10 THEN weekly_irrigation_schedule[Farmer;1;11] ELSE IF irrigation_hours_in_a_single_schedule=11THEN weekly_irrigation_schedule[Farmer;1;12] ELSE IF irrigation_hours_in_a_single_schedule=12 THEN weekly_irrigation_schedule[Farmer;1;13] ELSE IF irrigation_hours_in_a_single_schedule=13 THEN weekly_irrigation_schedule[Farmer;1;14] ELSE IF irrigation_hours_in_a_single_schedule=14 THEN weekly_irrigation_schedule[Farmer;1;15] ELSE IF irrigation_hours_in_a_single_schedule=15 THEN weekly_irrigation_schedule[Farmer;1;16] ELSE IF irrigation_hours_in_a_single_schedule=16 THEN weekly_irrigation_schedule[Farmer;1;17] ELSE IF irrigation_hours_in_a_single_schedule=17 THEN weekly_irrigation_schedule[Farmer;1;18] ELSE IF irrigation_hours_in_a_single_schedule=18 THEN weekly_irrigation_schedule[Farmer;1;19] ELSE IF irrigation_hours_in_a_single_schedule=19 THEN weekly_irrigation_schedule[Farmer;1;20] ELSE IF irrigation_hours_in_a_single_schedule=20 THEN weekly_irrigation_schedule[Farmer;1;21] ELSE IF irrigation_hours_in_a_single_schedule=21 THEN weekly_irrigation_schedule[Farmer;1;22] ELSE IF irrigation_hours_in_a_single_schedule=22 THEN weekly_irrigation_schedule[Farmer;1;23] ELSE IF irrigation_hours_in_a_single_schedule=23 THEN weekly_irrigation_schedule[Farmer;1;24] ELSE IF irrigation_hours_in_a_single_schedule=24 THEN weekly_irrigation_schedule[Farmer;2;1] ELSE IF irrigation_hours_in_a_single_schedule=25 THEN weekly_irrigation_schedule[Farmer;2;2] ELSE IF irrigation_hours_in_a_single_schedule=26 THEN weekly_irrigation_schedule[Farmer;2;3] ELSE IF irrigation_hours_in_a_single_schedule=27 THEN weekly_irrigation_schedule[Farmer;2;4] ELSE IF irrigation_hours_in_a_single_schedule=28 THEN weekly_irrigation_schedule[Farmer;2;5] ELSE IF irrigation_hours_in_a_single_schedule=29 THEN weekly_irrigation_schedule[Farmer;2;6] ELSE IF irrigation_hours_in_a_single_schedule=30 THEN weekly_irrigation_schedule[Farmer;2;7] ELSE IF irrigation_hours_in_a_single_schedule=31 THEN weekly_irrigation_schedule[Farmer;2;8] ELSE IF irrigation_hours_in_a_single_schedule=32 THEN weekly_irrigation_schedule[Farmer;2;9] ELSE IF irrigation_hours_in_a_single_schedule=33 THEN weekly_irrigation_schedule[Farmer;2;10] ELSE IF irrigation_hours_in_a_single_schedule=34 THEN weekly_irrigation_schedule[Farmer;2;11] ELSE IF irrigation_hours_in_a_single_schedule=35 THEN weekly_irrigation_schedule[Farmer;2;12] ELSE IF irrigation_hours_in_a_single_schedule=36 THEN weekly_irrigation_schedule[Farmer;2;13] ELSE IF irrigation_hours_in_a_single_schedule=37 THEN weekly_irrigation_schedule[Farmer;2;14] ELSE IF irrigation_hours_in_a_single_schedule=38 THEN weekly_irrigation_schedule[Farmer;2;15] ELSE IF irrigation_hours_in_a_single_schedule=39 THEN weekly_irrigation_schedule[Farmer;2;16] ELSE IF irrigation_hours_in_a_single_schedule=40 THEN weekly_irrigation_schedule[Farmer;2;17] ELSE IF irrigation_hours_in_a_single_schedule=41 THEN weekly_irrigation_schedule[Farmer;2;18] ELSE IF irrigation_hours_in_a_single_schedule=42 THEN weekly_irrigation_schedule[Farmer;2;19] ELSE IF irrigation_hours_in_a_single_schedule=43 THEN weekly_irrigation_schedule[Farmer;2;20] ELSE IF irrigation_hours_in_a_single_schedule=44 THEN weekly_irrigation_schedule[Farmer;2;21] ELSE IF irrigation_hours_in_a_single_schedule=45 THEN weekly_irrigation_schedule[Farmer;2;22] ELSE IF irrigation_hours_in_a_single_schedule=46 THEN weekly_irrigation_schedule[Farmer;2;23] ELSE IF irrigation_hours_in_a_single_schedule=47 THEN weekly_irrigation_schedule[Farmer;2;24] ELSE IF irrigation_hours_in_a_single_schedule=48 THEN weekly_irrigation_schedule[Farmer;3;1] ELSE IF irrigation_hours_in_a_single_schedule=49 THEN weekly_irrigation_schedule[Farmer;3;2] ELSE IF irrigation_hours_in_a_single_schedule=50 THEN weekly_irrigation_schedule[Farmer;3;3] ELSE IF irrigation_hours_in_a_single_schedule=51 THEN weekly_irrigation_schedule[Farmer;3;4] ELSE IF irrigation_hours_in_a_single_schedule=52 THEN weekly_irrigation_schedule[Farmer;3;5] ELSE IF irrigation_hours_in_a_single_schedule=53 THEN weekly_irrigation_schedule[Farmer;3;6] ELSE IF irrigation_hours_in_a_single_schedule=54 THEN weekly_irrigation_schedule[Farmer;3;7] ELSE IF irrigation_hours_in_a_single_schedule=55 THEN weekly_irrigation_schedule[Farmer;3;8] ELSE IF irrigation_hours_in_a_single_schedule=56 THEN weekly_irrigation_schedule[Farmer;3;9] ELSE IF irrigation_hours_in_a_single_schedule=57 THEN weekly_irrigation_schedule[Farmer;3;10] ELSE IF irrigation_hours_in_a_single_schedule=58 THEN weekly_irrigation_schedule[Farmer;3;11] ELSE IF irrigation_hours_in_a_single_schedule=59 THEN weekly_irrigation_schedule[Farmer;3;12] ELSE IF irrigation_hours_in_a_single_schedule=60 THEN weekly_irrigation_schedule[Farmer;3;13] ELSE IF irrigation_hours_in_a_single_schedule=61 THEN weekly_irrigation_schedule[Farmer;3;14] ELSE IF irrigation_hours_in_a_single_schedule=62 THEN weekly_irrigation_schedule[Farmer;3;15] ELSE IF irrigation_hours_in_a_single_schedule=63 THEN weekly_irrigation_schedule[Farmer;3;16] ELSE IF irrigation_hours_in_a_single_schedule=64 THEN weekly_irrigation_schedule[Farmer;3;17] ELSE

IF irrigation_hours_in_a_single_schedule=65 THEN weekly_irrigation_schedule[Farmer;3;18] ELSE IF irrigation_hours_in_a_single_schedule=66 THEN weekly_irrigation_schedule[Farmer;3;19] ELSE IF irrigation_hours_in_a_single_schedule=67 THEN weekly_irrigation_schedule[Farmer;3;20] ELSE IF irrigation_hours_in_a_single_schedule=68 THEN weekly_irrigation_schedule[Farmer;3;21] ELSE IF irrigation_hours_in_a_single_schedule=69 THEN weekly_irrigation_schedule[Farmer;3;22] ELSE IF irrigation_hours_in_a_single_schedule=70 THEN weekly_irrigation_schedule[Farmer;3;23] ELSE IF irrigation_hours_in_a_single_schedule=71 THEN weekly_irrigation_schedule[Farmer;3;24] ELSE IF irrigation_hours_in_a_single_schedule=72 THEN weekly_irrigation_schedule[Farmer;4;1] ELSE IF irrigation_hours_in_a_single_schedule=73 THEN weekly_irrigation_schedule[Farmer;4;2] ELSE IF irrigation_hours_in_a_single_schedule=74 THEN weekly_irrigation_schedule[Farmer;4;3] ELSE IF irrigation_hours_in_a_single_schedule=75 THEN weekly_irrigation_schedule[Farmer;4;4] ELSE IF irrigation_hours_in_a_single_schedule=76 THEN weekly_irrigation_schedule[Farmer;4;5] ELSE IF irrigation_hours_in_a_single_schedule=77 THEN weekly_irrigation_schedule[Farmer;4;6] ELSE IF irrigation_hours_in_a_single_schedule=78 THEN weekly_irrigation_schedule[Farmer;4;7] ELSE IF irrigation_hours_in_a_single_schedule=79 THEN weekly_irrigation_schedule[Farmer;4;8] ELSE IF irrigation_hours_in_a_single_schedule=80 THEN weekly_irrigation_schedule[Farmer;4;9] ELSE IF irrigation_hours_in_a_single_schedule=81 THEN weekly_irrigation_schedule[Farmer;4;10] ELSE IF irrigation_hours_in_a_single_schedule=82 THEN weekly_irrigation_schedule[Farmer;4;11] ELSE IF irrigation_hours_in_a_single_schedule=83 THEN weekly_irrigation_schedule[Farmer;4;12] ELSE IF irrigation_hours_in_a_single_schedule=84 THEN weekly_irrigation_schedule[Farmer;4;13] ELSE IF irrigation_hours_in_a_single_schedule=85 THEN weekly_irrigation_schedule[Farmer;4;14] ELSE IF irrigation_hours_in_a_single_schedule=86 THEN weekly_irrigation_schedule[Farmer;4;15] ELSE IF irrigation_hours_in_a_single_schedule=87 THEN weekly_irrigation_schedule[Farmer;4;16] ELSE IF irrigation_hours_in_a_single_schedule=88 THEN weekly_irrigation_schedule[Farmer;4;17] ELSE IF irrigation_hours_in_a_single_schedule=89 THEN weekly_irrigation_schedule[Farmer;4;18] ELSE IF irrigation_hours_in_a_single_schedule=90 THEN weekly_irrigation_schedule[Farmer;4;19] ELSE IF irrigation_hours_in_a_single_schedule=91 THEN weekly_irrigation_schedule[Farmer;4;20] ELSE IF irrigation_hours_in_a_single_schedule=92 THEN weekly_irrigation_schedule[Farmer;4;21] ELSE IF irrigation_hours_in_a_single_schedule=93 THEN weekly_irrigation_schedule[Farmer;4;22] ELSE IF irrigation_hours_in_a_single_schedule=94 THEN weekly_irrigation_schedule[Farmer;4;23]

ELSE IF irrigation_hours_in_a_single_schedule=95 THEN weekly_irrigation_schedule[Farmer;4;24] ELSE IF irrigation_hours_in_a_single_schedule=96 THEN weekly_irrigation_schedule[Farmer;5;1] ELSE IF irrigation_hours_in_a_single_schedule=97 THEN weekly_irrigation_schedule[Farmer;5;2] ELSE IF irrigation_hours_in_a_single_schedule=98 THEN weekly_irrigation_schedule[Farmer;5;3] ELSE IF irrigation_hours_in_a_single_schedule=99 THEN weekly_irrigation_schedule[Farmer;5;4] ELSE IF irrigation_hours_in_a_single_schedule=100 THEN weekly_irrigation_schedule[Farmer;5;5] ELSE IF irrigation_hours_in_a_single_schedule=101 THEN weekly_irrigation_schedule[Farmer;5;6] ELSE IF irrigation_hours_in_a_single_schedule=102 THEN weekly_irrigation_schedule[Farmer;5;7] ELSE IF irrigation_hours_in_a_single_schedule=103 THEN weekly_irrigation_schedule[Farmer;5;8] ELSE IF irrigation_hours_in_a_single_schedule=104 THEN weekly_irrigation_schedule[Farmer;5;9] ELSE IF irrigation_hours_in_a_single_schedule=105 THEN weekly_irrigation_schedule[Farmer;5;10] ELSE IF irrigation_hours_in_a_single_schedule=106 THEN weekly_irrigation_schedule[Farmer;5;11] ELSE IF irrigation_hours_in_a_single_schedule=107 THEN weekly_irrigation_schedule[Farmer;5;12] ELSE IF irrigation_hours_in_a_single_schedule=108 THEN weekly_irrigation_schedule[Farmer;5;13] ELSE IF irrigation_hours_in_a_single_schedule=109 THEN weekly_irrigation_schedule[Farmer;5;14] ELSE IF irrigation_hours_in_a_single_schedule=110 THEN weekly_irrigation_schedule[Farmer;5;15] ELSE IF irrigation_hours_in_a_single_schedule=111 THEN weekly_irrigation_schedule[Farmer;5;16] ELSE IF irrigation_hours_in_a_single_schedule=112 THEN weekly_irrigation_schedule[Farmer;5;17] ELSE IF irrigation_hours_in_a_single_schedule=113 THEN weekly_irrigation_schedule[Farmer;5;18] ELSE IF irrigation_hours_in_a_single_schedule=114 THEN weekly_irrigation_schedule[Farmer;5;19] ELSE IF irrigation_hours_in_a_single_schedule=115 THEN weekly_irrigation_schedule[Farmer;5;20] ELSE IF irrigation_hours_in_a_single_schedule=116 THEN weekly_irrigation_schedule[Farmer;5;21] ELSE IF irrigation_hours_in_a_single_schedule=117 THEN weekly_irrigation_schedule[Farmer;5;22] ELSE IF irrigation_hours_in_a_single_schedule=118 THEN weekly_irrigation_schedule[Farmer;5;23] ELSE IF irrigation_hours_in_a_single_schedule=119 THEN weekly_irrigation_schedule[Farmer;5;24] ELSE IF irrigation_hours_in_a_single_schedule=120 THEN weekly_irrigation_schedule[Farmer;6;1] ELSE IF irrigation_hours_in_a_single_schedule=121 THEN weekly_irrigation_schedule[Farmer;6;2] ELSE IF irrigation_hours_in_a_single_schedule=122 THEN weekly_irrigation_schedule[Farmer;6;3] ELSE IF irrigation_hours_in_a_single_schedule=123

THEN weekly_irrigation_schedule[Farmer;6;4] ELSE IF irrigation_hours_in_a_single_schedule=124 THEN weekly_irrigation_schedule[Farmer;6;5] ELSE IF irrigation_hours_in_a_single_schedule=125 THEN weekly_irrigation_schedule[Farmer;6;6] ELSE IF irrigation_hours_in_a_single_schedule=126 THEN weekly_irrigation_schedule[Farmer;6;7] ELSE IF irrigation_hours_in_a_single_schedule=127 THEN weekly_irrigation_schedule[Farmer;6;8] ELSE IF irrigation_hours_in_a_single_schedule=128 THEN weekly_irrigation_schedule[Farmer;6;9] ELSE IF irrigation_hours_in_a_single_schedule=129 THEN weekly_irrigation_schedule[Farmer;6;10] ELSE IF irrigation_hours_in_a_single_schedule=130 THEN weekly_irrigation_schedule[Farmer;6;11] ELSE IF irrigation_hours_in_a_single_schedule=131 THEN weekly_irrigation_schedule[Farmer;6;12] ELSE IF irrigation_hours_in_a_single_schedule=132 THEN weekly_irrigation_schedule[Farmer;6;13] ELSE IF irrigation_hours_in_a_single_schedule=133 THEN weekly_irrigation_schedule[Farmer;6;14] ELSE IF irrigation_hours_in_a_single_schedule=134 THEN weekly_irrigation_schedule[Farmer;6;15] ELSE IF irrigation_hours_in_a_single_schedule=135 THEN weekly_irrigation_schedule[Farmer;6;16] ELSE IF irrigation_hours_in_a_single_schedule=136 THEN weekly_irrigation_schedule[Farmer;6;17] ELSE IF irrigation_hours_in_a_single_schedule=137 THEN weekly_irrigation_schedule[Farmer;6;18] ELSE IF irrigation_hours_in_a_single_schedule=138 THEN weekly_irrigation_schedule[Farmer;6;19] ELSE IF irrigation_hours_in_a_single_schedule=139 THEN weekly_irrigation_schedule[Farmer;6;20] ELSE IF irrigation_hours_in_a_single_schedule=140 THEN weekly_irrigation_schedule[Farmer;6;21] ELSE IF irrigation_hours_in_a_single_schedule=141 THEN weekly_irrigation_schedule[Farmer;6;22] ELSE IF irrigation_hours_in_a_single_schedule=142 THEN weekly_irrigation_schedule[Farmer;6;23] ELSE IF irrigation_hours_in_a_single_schedule=143 THEN weekly_irrigation_schedule[Farmer;6;24] ELSE IF irrigation_hours_in_a_single_schedule=144 THEN weekly_irrigation_schedule[Farmer;7;1] ELSE IF irrigation_hours_in_a_single_schedule=145 THEN weekly_irrigation_schedule[Farmer;7;2] ELSE IF irrigation_hours_in_a_single_schedule=146 THEN weekly_irrigation_schedule[Farmer;7;3] ELSE IF irrigation_hours_in_a_single_schedule=147 THEN weekly_irrigation_schedule[Farmer;7;4] ELSE IF irrigation_hours_in_a_single_schedule=148 THEN weekly_irrigation_schedule[Farmer;7;5] ELSE IF irrigation_hours_in_a_single_schedule=149 THEN weekly_irrigation_schedule[Farmer;7;6] ELSE IF irrigation_hours_in_a_single_schedule=150 THEN weekly_irrigation_schedule[Farmer;7;7] ELSE IF irrigation_hours_in_a_single_schedule=151

THEN weekly_irrigation_schedule[Farmer;7;8] ELSE IF irrigation_hours_in_a_single_schedule=152 THEN weekly_irrigation_schedule[Farmer;7;9] ELSE IF irrigation_hours_in_a_single_schedule=153 THEN weekly_irrigation_schedule[Farmer;7;10] ELSE IF irrigation_hours_in_a_single_schedule=154 THEN weekly_irrigation_schedule[Farmer;7;11] ELSE IF irrigation_hours_in_a_single_schedule=155 THEN weekly_irrigation_schedule[Farmer;7;12] ELSE IF irrigation_hours_in_a_single_schedule=156 THEN weekly_irrigation_schedule[Farmer;7;13] ELSE IF irrigation_hours_in_a_single_schedule=157 THEN weekly_irrigation_schedule[Farmer;7;14] ELSE IF irrigation_hours_in_a_single_schedule=158 THEN weekly_irrigation_schedule[Farmer;7;15] ELSE IF irrigation_hours_in_a_single_schedule=159 THEN weekly_irrigation_schedule[Farmer;7;16] ELSE IF irrigation_hours_in_a_single_schedule=160 THEN weekly_irrigation_schedule[Farmer;7;17] ELSE IF irrigation_hours_in_a_single_schedule=161 THEN weekly_irrigation_schedule[Farmer;7;18] ELSE IF irrigation_hours_in_a_single_schedule=162 THEN weekly_irrigation_schedule[Farmer;7;19] ELSE IF irrigation_hours_in_a_single_schedule=163 THEN weekly_irrigation_schedule[Farmer;7;20] ELSE IF irrigation_hours_in_a_single_schedule=164 THEN weekly_irrigation_schedule[Farmer;7;21] ELSE IF irrigation_hours_in_a_single_schedule=165 THEN weekly_irrigation_schedule[Farmer;7;22] ELSE IF irrigation_hours_in_a_single_schedule=166 THEN weekly_irrigation_schedule[Farmer;7;23] ELSE IF irrigation_hours_in_a_single_schedule=167 THEN weekly_irrigation_schedule[Farmer;7;24] ELSE IF irrigation_hours_in_a_single_schedule=168 THEN weekly_irrigation_schedule[Farmer;8;1] ELSE IF irrigation_hours_in_a_single_schedule=169 THEN weekly_irrigation_schedule[Farmer;8;2] ELSE IF irrigation_hours_in_a_single_schedule=170 THEN weekly_irrigation_schedule[Farmer;8;3] ELSE IF irrigation_hours_in_a_single_schedule=171 THEN weekly_irrigation_schedule[Farmer;8;4] ELSE IF irrigation_hours_in_a_single_schedule=172 THEN weekly_irrigation_schedule[Farmer;8;5] ELSE IF irrigation_hours_in_a_single_schedule=173 THEN weekly_irrigation_schedule[Farmer;8;6] ELSE IF irrigation_hours_in_a_single_schedule=174 THEN weekly_irrigation_schedule[Farmer;8;7] ELSE IF irrigation_hours_in_a_single_schedule=175 THEN weekly_irrigation_schedule[Farmer;8;8] ELSE IF irrigation_hours_in_a_single_schedule=176 THEN weekly_irrigation_schedule[Farmer;8;9] ELSE IF irrigation_hours_in_a_single_schedule=177 THEN weekly_irrigation_schedule[Farmer;8;10] ELSE IF irrigation_hours_in_a_single_schedule=178 THEN weekly_irrigation_schedule[Farmer;8;11] ELSE IF irrigation_hours_in_a_single_schedule=179THEN weekly_irrigation_schedule[Farmer;8;12] ELSE IF irrigation_hours_in_a_single_schedule=180 THEN weekly_irrigation_schedule[Farmer;8;13] ELSE IF irrigation_hours_in_a_single_schedule=181 THEN weekly_irrigation_schedule[Farmer;8;14] ELSE IF irrigation_hours_in_a_single_schedule=182 THEN weekly_irrigation_schedule[Farmer;8;15] ELSE IF irrigation_hours_in_a_single_schedule=183 THEN weekly_irrigation_schedule[Farmer;8;16] ELSE IF irrigation_hours_in_a_single_schedule=184 THEN weekly_irrigation_schedule[Farmer;8;17] ELSE IF irrigation_hours_in_a_single_schedule=185 THEN weekly_irrigation_schedule[Farmer;8;18] ELSE IF irrigation_hours_in_a_single_schedule=186 THEN weekly_irrigation_schedule[Farmer;8;19] ELSE IF irrigation_hours_in_a_single_schedule=187 THEN weekly_irrigation_schedule[Farmer;8;20] ELSE IF irrigation_hours_in_a_single_schedule=188 THEN weekly_irrigation_schedule[Farmer;8;21] ELSE IF irrigation_hours_in_a_single_schedule=189 THEN weekly_irrigation_schedule[Farmer;8;22] ELSE IF irrigation_hours_in_a_single_schedule=190 THEN weekly_irrigation_schedule[Farmer;8;23] ELSE IF irrigation_hours_in_a_single_schedule=191 THEN weekly_irrigation_schedule[Farmer;8;24] ELSE IF irrigation_hours_in_a_single_schedule=192 THEN weekly_irrigation_schedule[Farmer;9;1] ELSE IF irrigation_hours_in_a_single_schedule=193 THEN weekly_irrigation_schedule[Farmer;9;2] ELSE IF irrigation_hours_in_a_single_schedule=194 THEN weekly_irrigation_schedule[Farmer;9;3] ELSE IF irrigation_hours_in_a_single_schedule=195 THEN weekly_irrigation_schedule[Farmer;9;4] ELSE IF irrigation_hours_in_a_single_schedule=196 THEN weekly_irrigation_schedule[Farmer;9;5] ELSE IF irrigation_hours_in_a_single_schedule=197 THEN weekly_irrigation_schedule[Farmer;9;6] ELSE IF irrigation_hours_in_a_single_schedule=198 THEN weekly_irrigation_schedule[Farmer;9;7] ELSE IF irrigation_hours_in_a_single_schedule=199 THEN weekly_irrigation_schedule[Farmer;9;8] ELSE IF irrigation_hours_in_a_single_schedule=200 THEN weekly_irrigation_schedule[Farmer;9;9] ELSE IF irrigation_hours_in_a_single_schedule=201 THEN weekly_irrigation_schedule[Farmer;9;10] ELSE IF irrigation_hours_in_a_single_schedule=202 THEN weekly_irrigation_schedule[Farmer;9;11] ELSE IF irrigation_hours_in_a_single_schedule=203 THEN weekly_irrigation_schedule[Farmer;9;12] ELSE IF irrigation_hours_in_a_single_schedule=204 THEN weekly_irrigation_schedule[Farmer;9;13] ELSE IF irrigation_hours_in_a_single_schedule=205 THEN weekly_irrigation_schedule[Farmer;9;14] ELSE IF irrigation_hours_in_a_single_schedule=206 THEN weekly_irrigation_schedule[Farmer;9;15] ELSE IF irrigation_hours_in_a_single_schedule=207 THEN weekly_irrigation_schedule[Farmer;9;16] ELSE IF irrigation_hours_in_a_single_schedule=208 THEN weekly_irrigation_schedule[Farmer;9;17] ELSE IF irrigation_hours_in_a_single_schedule=209 THEN weekly_irrigation_schedule[Farmer;9;18] ELSE IF irrigation_hours_in_a_single_schedule=210 THEN weekly_irrigation_schedule[Farmer;9;19] ELSE IF irrigation_hours_in_a_single_schedule=211 THEN weekly_irrigation_schedule[Farmer;9;20] ELSE IF irrigation_hours_in_a_single_schedule=212 THEN weekly_irrigation_schedule[Farmer;9;21] ELSE IF irrigation_hours_in_a_single_schedule=213 THEN weekly_irrigation_schedule[Farmer;9;22] ELSE IF irrigation_hours_in_a_single_schedule=214 THEN weekly_irrigation_schedule[Farmer;9;23] ELSE IF irrigation_hours_in_a_single_schedule=215 THEN weekly_irrigation_schedule[Farmer;9;24] ELSE IF irrigation_hours_in_a_single_schedule=216 THEN weekly_irrigation_schedule[Farmer;10;1] ELSE IF irrigation_hours_in_a_single_schedule=217 THEN weekly_irrigation_schedule[Farmer;10;2] ELSE IF irrigation_hours_in_a_single_schedule=218 THEN weekly_irrigation_schedule[Farmer;10;3] ELSE IF irrigation_hours_in_a_single_schedule=219 THEN weekly_irrigation_schedule[Farmer;10;4] ELSE IF irrigation_hours_in_a_single_schedule=220 THEN weekly_irrigation_schedule[Farmer;10;5] ELSE IF irrigation_hours_in_a_single_schedule=221 THEN weekly_irrigation_schedule[Farmer;10;6] ELSE IF irrigation_hours_in_a_single_schedule=222 THEN weekly_irrigation_schedule[Farmer;10;7] ELSE IF irrigation_hours_in_a_single_schedule=223 THEN weekly_irrigation_schedule[Farmer;10;8] ELSE IF irrigation_hours_in_a_single_schedule=224 THEN weekly_irrigation_schedule[Farmer;10;9] ELSE IF irrigation_hours_in_a_single_schedule=225 THEN weekly_irrigation_schedule[Farmer;10;10] ELSE IF irrigation_hours_in_a_single_schedule=226 THEN weekly_irrigation_schedule[Farmer;10;11] ELSE IF irrigation_hours_in_a_single_schedule=227 THEN weekly_irrigation_schedule[Farmer;10;12] ELSE IF irrigation_hours_in_a_single_schedule=228 THEN weekly_irrigation_schedule[Farmer;10;13] ELSE IF irrigation_hours_in_a_single_schedule=229 THEN weekly_irrigation_schedule[Farmer;10;14] ELSE IF irrigation_hours_in_a_single_schedule=230 THEN weekly_irrigation_schedule[Farmer;10;15] ELSE IF irrigation_hours_in_a_single_schedule=231 THEN weekly_irrigation_schedule[Farmer;10;16] ELSE IF irrigation_hours_in_a_single_schedule=232 THEN weekly_irrigation_schedule[Farmer;10;17] ELSE IF irrigation_hours_in_a_single_schedule=233 THEN weekly_irrigation_schedule[Farmer;10;18] ELSE IF irrigation_hours_in_a_single_schedule=234 THEN weekly_irrigation_schedule[Farmer;10;19] ELSE IF irrigation_hours_in_a_single_schedule=235 THEN weekly_irrigation_schedule[Farmer;10;20] ELSE IF irrigation_hours_in_a_single_schedule=236 THEN weekly_irrigation_schedule[Farmer;10;21] ELSE IF irrigation_hours_in_a_single_schedule=237 THEN weekly_irrigation_schedule[Farmer;10;22] ELSE IF irrigation_hours_in_a_single_schedule=238 THEN weekly_irrigation_schedule[Farmer;10;23] ELSE IF irrigation_hours_in_a_single_schedule=239 THEN weekly_irrigation_schedule[Farmer;10;24] ELSE IF irrigation_hours_in_a_single_schedule=240 THEN weekly_irrigation_schedule[Farmer;11;1] ELSE IF irrigation_hours_in_a_single_schedule=241 THEN weekly_irrigation_schedule[Farmer;11;2] ELSE IF irrigation_hours_in_a_single_schedule=242 THEN weekly_irrigation_schedule[Farmer;11;3] ELSE IF irrigation_hours_in_a_single_schedule=243 THEN weekly_irrigation_schedule[Farmer;11;4] ELSE IF irrigation_hours_in_a_single_schedule=244 THEN weekly_irrigation_schedule[Farmer;11;5] ELSE IF irrigation_hours_in_a_single_schedule=245 THEN weekly_irrigation_schedule[Farmer;11;6] ELSE IF irrigation_hours_in_a_single_schedule=246 THEN weekly_irrigation_schedule[Farmer;11;7] ELSE IF irrigation_hours_in_a_single_schedule=247 THEN weekly_irrigation_schedule[Farmer;11;8] ELSE IF irrigation_hours_in_a_single_schedule=248 THEN weekly_irrigation_schedule[Farmer;11;9] ELSE IF irrigation_hours_in_a_single_schedule=249 THEN weekly_irrigation_schedule[Farmer;11;10] ELSE IF irrigation_hours_in_a_single_schedule=250 THEN weekly_irrigation_schedule[Farmer;11;11] ELSE IF irrigation_hours_in_a_single_schedule=251 THEN weekly_irrigation_schedule[Farmer;11;12] ELSE IF irrigation_hours_in_a_single_schedule=252 THEN weekly_irrigation_schedule[Farmer;11;13] ELSE IF irrigation_hours_in_a_single_schedule=253 THEN weekly_irrigation_schedule[Farmer;11;14] ELSE IF irrigation_hours_in_a_single_schedule=254 THEN weekly_irrigation_schedule[Farmer;11;15] ELSE IF irrigation_hours_in_a_single_schedule=255 THEN weekly_irrigation_schedule[Farmer;11;16] ELSE IF irrigation_hours_in_a_single_schedule=256 THEN weekly_irrigation_schedule[Farmer;11;17] ELSE IF irrigation_hours_in_a_single_schedule=257 THEN weekly_irrigation_schedule[Farmer;11;18] ELSE IF irrigation_hours_in_a_single_schedule=258 THEN weekly_irrigation_schedule[Farmer;11;19] ELSE IF irrigation_hours_in_a_single_schedule=259 THEN weekly_irrigation_schedule[Farmer;11;20] ELSE IF irrigation_hours_in_a_single_schedule=260 THEN weekly_irrigation_schedule[Farmer;11;21] ELSE IF irrigation_hours_in_a_single_schedule=261

THEN weekly_irrigation_schedule[Farmer;11;22] ELSE IF irrigation_hours_in_a_single_schedule=262 THEN weekly_irrigation_schedule[Farmer;11;23] ELSE IF irrigation_hours_in_a_single_schedule=263 THEN weekly_irrigation_schedule[Farmer;11;24] ELSE IF irrigation_hours_in_a_single_schedule=264 THEN weekly_irrigation_schedule[Farmer;12;1] ELSE IF irrigation_hours_in_a_single_schedule=265 THEN weekly_irrigation_schedule[Farmer;12;2] ELSE IF irrigation_hours_in_a_single_schedule=266 THEN weekly_irrigation_schedule[Farmer;12;3] ELSE IF irrigation_hours_in_a_single_schedule=267 THEN weekly_irrigation_schedule[Farmer;12;4] ELSE IF irrigation_hours_in_a_single_schedule=268 THEN weekly_irrigation_schedule[Farmer;12;5] ELSE IF irrigation_hours_in_a_single_schedule=269 THEN weekly_irrigation_schedule[Farmer;12;6] ELSE IF irrigation_hours_in_a_single_schedule=270 THEN weekly_irrigation_schedule[Farmer;12;7] ELSE IF irrigation_hours_in_a_single_schedule=271 THEN weekly_irrigation_schedule[Farmer;12;8] ELSE IF irrigation_hours_in_a_single_schedule=272 THEN weekly_irrigation_schedule[Farmer;12;9] ELSE IF irrigation_hours_in_a_single_schedule=273 THEN weekly_irrigation_schedule[Farmer;12;10] ELSE IF irrigation_hours_in_a_single_schedule=274 THEN weekly_irrigation_schedule[Farmer;12;11] ELSE IF irrigation_hours_in_a_single_schedule=275 THEN weekly_irrigation_schedule[Farmer;12;12] ELSE IF irrigation_hours_in_a_single_schedule=276 THEN weekly_irrigation_schedule[Farmer;12;13] ELSE IF irrigation_hours_in_a_single_schedule=277 THEN weekly_irrigation_schedule[Farmer;12;14] ELSE IF irrigation_hours_in_a_single_schedule=278 THEN weekly_irrigation_schedule[Farmer;12;15] ELSE IF irrigation_hours_in_a_single_schedule=279 THEN weekly_irrigation_schedule[Farmer;12;16] ELSE IF irrigation_hours_in_a_single_schedule=280 THEN weekly_irrigation_schedule[Farmer;12;17] ELSE IF irrigation_hours_in_a_single_schedule=281 THEN weekly_irrigation_schedule[Farmer;12;18] ELSE IF irrigation_hours_in_a_single_schedule=282 THEN weekly_irrigation_schedule[Farmer;12;19] ELSE IF irrigation_hours_in_a_single_schedule=283 THEN weekly_irrigation_schedule[Farmer;12;20] ELSE IF irrigation_hours_in_a_single_schedule=284 THEN weekly_irrigation_schedule[Farmer;12;21] ELSE IF irrigation_hours_in_a_single_schedule=285 THEN weekly_irrigation_schedule[Farmer;12;22] ELSE IF irrigation_hours_in_a_single_schedule=286 THEN weekly_irrigation_schedule[Farmer;12;23] ELSE IF irrigation_hours_in_a_single_schedule=287 THEN weekly_irrigation_schedule[Farmer;12;24] ELSE IF irrigation_hours_in_a_single_schedule=288 THEN weekly_irrigation_schedule[Farmer;13;1] ELSE IF irrigation_hours_in_a_single_schedule=289 THEN weekly_irrigation_schedule[Farmer;13;2] ELSE IF irrigation_hours_in_a_single_schedule=290 THEN weekly_irrigation_schedule[Farmer;13;3] ELSE IF irrigation_hours_in_a_single_schedule=291 THEN weekly_irrigation_schedule[Farmer;13;4] ELSE IF irrigation_hours_in_a_single_schedule=292 THEN weekly_irrigation_schedule[Farmer;13;5] ELSE IF irrigation_hours_in_a_single_schedule=293 THEN weekly_irrigation_schedule[Farmer;13;6] ELSE IF irrigation_hours_in_a_single_schedule=294 THEN weekly_irrigation_schedule[Farmer;13;7] ELSE IF irrigation_hours_in_a_single_schedule=295 THEN weekly_irrigation_schedule[Farmer;13;8] ELSE IF irrigation_hours_in_a_single_schedule=296 THEN weekly_irrigation_schedule[Farmer;13;9] ELSE IF irrigation_hours_in_a_single_schedule=297 THEN weekly_irrigation_schedule[Farmer;13;10] ELSE IF irrigation_hours_in_a_single_schedule=298 THEN weekly_irrigation_schedule[Farmer;13;11] ELSE IF irrigation_hours_in_a_single_schedule=299 THEN weekly_irrigation_schedule[Farmer;13;12] ELSE IF irrigation_hours_in_a_single_schedule=300 THEN weekly_irrigation_schedule[Farmer;13;13] ELSE IF irrigation_hours_in_a_single_schedule=301 THEN weekly_irrigation_schedule[Farmer;13;14] ELSE IF irrigation_hours_in_a_single_schedule=302 THEN weekly_irrigation_schedule[Farmer;13;15] ELSE IF irrigation_hours_in_a_single_schedule=303 THEN weekly_irrigation_schedule[Farmer;13;16] ELSE IF irrigation_hours_in_a_single_schedule=304 THEN weekly_irrigation_schedule[Farmer;13;17] ELSE IF irrigation_hours_in_a_single_schedule=305 THEN weekly_irrigation_schedule[Farmer;13;18] ELSE IF irrigation_hours_in_a_single_schedule=306 THEN weekly_irrigation_schedule[Farmer;13;19] ELSE IF irrigation_hours_in_a_single_schedule=307 THEN weekly_irrigation_schedule[Farmer;13;20] ELSE IF irrigation_hours_in_a_single_schedule=308 THEN weekly_irrigation_schedule[Farmer;13;21] ELSE IF irrigation_hours_in_a_single_schedule=309 THEN weekly_irrigation_schedule[Farmer;13;22] ELSE IF irrigation_hours_in_a_single_schedule=310 THEN weekly_irrigation_schedule[Farmer;13;23] ELSE IF irrigation_hours_in_a_single_schedule=311 THEN weekly_irrigation_schedule[Farmer;13;24] ELSE IF irrigation_hours_in_a_single_schedule=312 THEN weekly_irrigation_schedule[Farmer;14;1] ELSE IF irrigation_hours_in_a_single_schedule=313 THEN weekly_irrigation_schedule[Farmer;14;2] ELSE IF irrigation_hours_in_a_single_schedule=314 THEN weekly_irrigation_schedule[Farmer;14;3] ELSE IF irrigation_hours_in_a_single_schedule=315

THEN weekly_irrigation_schedule[Farmer;14;4] ELSE IF irrigation_hours_in_a_single_schedule=316 THEN weekly_irrigation_schedule[Farmer;14;5] ELSE IF irrigation_hours_in_a_single_schedule=317 THEN weekly_irrigation_schedule[Farmer;14;6] ELSE IF irrigation_hours_in_a_single_schedule=318 THEN weekly_irrigation_schedule[Farmer;14;7] ELSE IF irrigation_hours_in_a_single_schedule=319 THEN weekly_irrigation_schedule[Farmer;14;8] ELSE IF irrigation_hours_in_a_single_schedule=320 THEN weekly_irrigation_schedule[Farmer;14;9] ELSE IF irrigation_hours_in_a_single_schedule=321 THEN weekly_irrigation_schedule[Farmer;14;10] ELSE IF irrigation_hours_in_a_single_schedule=322 THEN weekly_irrigation_schedule[Farmer;14;11] ELSE IF irrigation_hours_in_a_single_schedule=323 THEN weekly_irrigation_schedule[Farmer;14;12] ELSE IF irrigation_hours_in_a_single_schedule=324 THEN weekly_irrigation_schedule[Farmer;14;13] ELSE IF irrigation_hours_in_a_single_schedule=325 THEN weekly_irrigation_schedule[Farmer;14;14] ELSE IF irrigation_hours_in_a_single_schedule=326 THEN weekly_irrigation_schedule[Farmer;14;15] ELSE IF irrigation_hours_in_a_single_schedule=327 THEN weekly_irrigation_schedule[Farmer;14;16] ELSE IF irrigation_hours_in_a_single_schedule=328 THEN weekly_irrigation_schedule[Farmer;14;17] ELSE IF irrigation_hours_in_a_single_schedule=329 THEN weekly_irrigation_schedule[Farmer;14;18] ELSE IF irrigation_hours_in_a_single_schedule=330 THEN weekly_irrigation_schedule[Farmer;14;19] ELSE IF irrigation_hours_in_a_single_schedule=331 THEN weekly_irrigation_schedule[Farmer;14;20] ELSE IF irrigation_hours_in_a_single_schedule=332 THEN weekly_irrigation_schedule[Farmer;14;21] ELSE IF irrigation_hours_in_a_single_schedule=333 THEN weekly_irrigation_schedule[Farmer;14;22] ELSE IF irrigation_hours_in_a_single_schedule=334 THEN weekly_irrigation_schedule[Farmer;14;23] ELSE IF irrigation_hours_in_a_single_schedule=335 THEN weekly_irrigation_schedule[Farmer;14;24] ELSE 0

UNITS: Hours

is_active[Farmer] = IF Farmer=1 THEN 1 ELSE 0

UNITS: Dimensionless

Kc = GRAPH(TIME)

UNITS: Dimensionless

Ks[Farmer] = IF relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]>=relative_soil_moisture_at_threshold THEN 1 ELSE MAX(0;

(relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer]-relative_soil_moisture_at_wilting_point)/(relative_soil_moisture_at_threshold-relative_soil_moisture_at_wilting_point))

UNITS: Dimensionless

maximum_attainable_biomass = GRAPH(TIME)

UNITS: Tons

maximum_attainable_biomass_at_stage_A = maximum_biomass*0,1

UNITS: Tons

maximum_attainable_biomass_at_stage_B[Farmer] = A_max_actual[Farmer]*5

UNITS: Tons

maximum_attainable_biomass_at_stage_C[Farmer] = B_max_actual[Farmer]*1,6

UNITS: Tons

maximum_attainable_biomass_at_stage_D[Farmer] = C_max_actual[Farmer]*1,25

UNITS: Tons

maximum_biomass = maximum_crop_yield*area_of_each_farming_land

UNITS: Tons

maximum_crop_yield = 0,007

UNITS: tons per square meters

normal_growth_fraction_at_stage_A = 0,022

UNITS: Per Hour

normal_growth_fraction_at_stage_B = 0,009

UNITS: Per Hour

normal_growth_fraction_at_stage_C = 0,008

UNITS: Per Hour

normal_growth_fraction_at_stage_D = 0,005

UNITS: Per Hour

number_of_farming_lands = 5

UNITS: Dimensionless

"p_(plant_constant)" = 0,50

UNITS: Dimensionless

porosity_of_deep_zone = 0,4

UNITS: Dimensionless

porosity_of_root_zone = 0,55

UNITS: Dimensionless

potential_extraction = IF dynamic_water_level<=aquifer_depth THEN (time_conversion*(pump_efficiency*power*1000)/(pump_head*g*density_of_the_fluid)) ELSE 0

UNITS: m^3/hour

power = 15 {1 kW=1000 watts; watts=kg*m^2/sec^3}

UNITS: kW

profit[Farmer] = total_revenue[Farmer]-total_cost[Farmer]

UNITS: TL

pump_efficiency = 0,90

UNITS: Dimensionless

pump_head = dynamic_water_level+head_loss

UNITS: meters

pump_height = 80

UNITS: meters

ratio_of_groundwater_aquifer_over_deep_zone = 0,05

UNITS: Dimensionless

reference_growth = GRAPH(TIME)

UNITS: Tons/Hours

relative_biomass_at_stage_A[Farmer] = biomass_at_stage_A[Farmer]/maximum_attainable_biomass_at_stage_A

UNITS: Dimensionless

relative_biomass_at_stage_B[Farmer] = IF TIME>480 THEN (biomass_at_stage_B[Farmer]/maximum_attainable_biomass_at_stage_B[Farmer]) ELSE 0

UNITS: Dimensionless

relative_biomass_at_stage_C[Farmer] = IF TIME>1248 THEN (biomass_at_stage_C[Farmer]/maximum_attainable_biomass_at_stage_C[Farmer]) ELSE 0

UNITS: Dimensionless

relative_biomass_at_stage_D[Farmer] = IF TIME>2016 THEN (biomass_at_stage_D[Farmer]/maximum_attainable_biomass_at_stage_D[Farmer]) ELSE 0

UNITS: Dimensionless

relative_soil_moisture_at_field_capacity = volumetric_water_content_at_field_capacity/porosity_of_root_zone {m^3/m^3}

UNITS: Dimensionless

relative_soil_moisture_at_saturation = volumetric_water_content_at_saturation/porosity_of_root_zone {m^3/m^3}

UNITS: Dimensionless

relative_soil_moisture_at_threshold = (1-"p_(plant_constant)")*relative_soil_moisture_at_field_capacity+"p_(plant_constant)"*relative_soil_moisture_at_wilting_point {m^3/m^3}

UNITS: Dimensionless

relative_soil_moisture_at_wilting_point = volumetric_water_content_at_wilting_point/porosity_of_root_zone {m^3/m^3}

UNITS: Dimensionless

relative_soil_moisture_of_root_zone_of_each_farming_land[Farmer] = MIN ((volumetric_water_content_of_root_zone_of_each_farming_land[Farmer]/porosity_of_root_zone); 1) {m^3/m^3}

UNITS: Dimensionless

runoff_fraction = 1

UNITS: Per Hour

saturated_water_content_of_root_zone_of_each_farming_land = porosity_of_root_zone {m^3/m^3}

UNITS: Dimensionless

saturation_level = water_in_deep_zone/volume_of_water_at_saturation_at_deep_zone

UNITS: Dimensionless

seed_quantity = 0,000004

UNITS: tons per square meters

seeding_time = 0

UNITS: Hours

static_water_level = 50

UNITS: meters

static_water_volume = (aquifer_depth-static_water_level)*total_area_of_groundwater_aquifer*porosity_of_deep_zone

UNITS: cubic meters

"switch_time_(A_to_B)" = 480

UNITS: Hours

"switch_time_(B_to_C)" = 1248

UNITS: Hours

"switch_time_(C_to_D)" = 2016

UNITS: Hours

theoretical_ET = (ETo/1000)*Kc*area_of_each_farming_land

UNITS: m^3/hour

time_conversion = 3600

UNITS: seconds/hour

total_area_of_farming_lands = area_of_each_farming_land*number_of_farming_lands

UNITS: Square Meters

total_area_of_groundwater_aquifer = total_area_of_farming_lands*ratio_of_groundwater_aquifer_over_deep_zone

UNITS: Square Meters

total_revenue[Farmer] = crop_price*total_yield[Farmer]

UNITS: TL

total_volume_of_root_zone = total_area_of_farming_lands*depth_of_root_zone

UNITS: Cubic Meters

total_yield[Farmer] = IF TIME=2688 THEN biomass_at_stage_D[Farmer] ELSE 0

UNITS: Tons

unit_price_of_energy = 0,609

UNITS: TL/kWh

volume_of_deep_zone = total_area_of_farming_lands*depth_of_deep_zone

UNITS: Cubic Meters

volume_of_groundwater_aquifer = volume_of_deep_zone*ratio_of_groundwater_aquifer_over_deep_zone

UNITS: Cubic Meters

volume_of_root_zone_of_each_farming_land = area_of_each_farming_land*depth_of_root_zone

UNITS: Cubic Meters

volume_of_water_at_saturation_at_deep_zone = volume_of_groundwater_aquifer*porosity_of_deep_zone

UNITS: Cubic Meters

volume_of_water_at_saturation_at_root_zone = total_volume_of_root_zone*porosity_of_root_zone

UNITS: Cubic Meters

volumetric_water_content_at_field_capacity = 0,2082

UNITS: Dimensionless

volumetric_water_content_at_saturation = porosity_of_root_zone {m^3/m^3}

UNITS: Dimensionless

volumetric_water_content_at_wilting_point = 0,132

UNITS: Dimensionless

volumetric_water_content_of_root_zone = (SUM(water_in_root_zone))/total_volume_of_root_zone {m^3/m^3}

UNITS: Dimensionless

volumetric_water_content_of_root_zone_of_each_farming_land[Farmer] = water_in_root_zone[Farmer]/volume_of_root_zone_of_each_farming_land {m^3/m^3}

UNITS: Dimensionless

water_growth_multiplier[Farmer] = evapotranspiration[Farmer]/theoretical_ET

UNITS: Dimensionless

weekly_irrigation_schedule[Farmer, Day, Hour] = 0

UNITS: Hours

{ The model has 176 (2167) variables (array expansion in parens).

In root model and 0 additional modules with 8 sectors.

Stocks: 22 (90) Flows: 40 (172) Converters: 114 (1905)

Constants: 38 (1717) Equations: 116 (360) Graphicals: 11 (11)

}