SYSTEMS APPROACH AND MODELING FOR SUSTAINABLE GROUNDWATER IRRIGATION: A CASE STUDY IN MARDIN KIZILTEPE PLAIN

by
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to my mother,

Edla mala Xano

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ABSTRACT

SYSTEMS APPROACH AND MODELING FOR SUSTAINABLE GROUNDWATER IRRIGATION: A CASE STUDY IN MARDIN KIZILTEPE PLAIN

The use of water for agriculture has become one of the most important environmental issues since water resources are depleting very fast. Groundwater irrigation, therefore, is mostly the only alternative to sustain agricultural activities in arid and semi-arid places. The hydrology of groundwater resources and the impact of human activities that cause groundwater exploitation are complex, and this complexity causes strategic management problems. This study examines the impact of different groundwater management options for the long-term sustainable agriculture in the Kızıltepe Plain located in south-east of Turkey where groundwater is used with insufficient coordination and regulation. There has been a tremendous increase in number of wells and amount of irrigated land in Kızıltepe Plain particularly in the past ten years. This increase ultimately causes irreversible damage to groundwater resources and also triggers ecological destruction, which may occur in the future. System dynamics provides us tools to explore the relationship between nature and humans in a holistic way. Therefore, in this research, a dynamic simulation model is developed to understand the groundwater problem in a holistic way and also to seek sustainable groundwater irrigation management in Kızıltepe Plain. The dynamic model consists of four sectors representing groundwater resources, water extraction, land use change and crop profitability. The model is validated first structurally with different extreme condition tests and parameter sensitivity tests. Then, behavioral validation is performed by available data between 2005 and 2015. It is argued that although overexploitation of groundwater beyond its replenishment rates may be profitable for the farmers in the short term, it may cause irreversible economic and ecological damage in the long term. Scenario analyses performed reveal that state incentives for irrigated land and increases in irrigated crop price may cause an enormous increase in irrigated land. This increase may lead to excessive use of groundwater which may result in significant water scarcity for future generations. However, changing irrigation type from flood irrigation to drip irrigation may reduce the use of groundwater and help to achieve long term sustainable groundwater use in Kızıltepe Plain.

ÖZET

SÜRDÜRÜLEBİLİR YERALTI SUYU İLE SULAMA İÇİN SİSTEM YAKLAŞIMI VE MODELLEMESİ: MARDİN KIZILTEPE OVASI ÖRNEĞİ

Su kaynakları çok hızlı bir şekilde tükendiğinden dolayı tarım için kullanılan su en önemli çevresel olaylardan biri olmuştur. Bu yüzden, kurak ve yarı kurak yerlerde tarımsal aktivitelerin devamı için çoğunlukla yeraltı suyu ile sulama tek alternatiftir. Yeraltı suyu hidrolojisi ve insan faaliyetlerinin yeraltı suyu kullanımına etkisi kompleks bir yapıdadır ve bu kompleks yapı stratejik yönetim problemlerine neden olur. Bu çalışma Türkiye'nin güneydoğusunda yer alan ve yeraltı suyu kullanımının koordinasyonun ve kontrolünün yeterli olmadığı Kızıltepe Ovası'nda, farklı yeraltı suyu yönetim seçeneklerinin etkilerini incelemektedir. Kızıltepe Ovası'nda kuyu sayılarında ve sulanan alan miktarında özellikle son on yılda muazzam bir artış olmuştur. Bu artış en nihayetinde yeraltı suyu kaynaklarına geri dönüşü olmayan bir zarar vermektedir ve gelecekte olması muhtemel bir ekolojik yıkımı tetiklemektedir. Sistem dinamiği insan doğa ilişkisini bütüncül bir şekilde ele almamızı sağlayan araçlar sunar. Bu sebeple, Kızıltepe Ovası'ndaki yeraltı suyu problemini bütüncül bir şekilde anlamak ve sürdürülebilir yeraltı suyu sulama yönetimleri aramak için dinamik bir simülasyon modeli geliştirilmiştir. Dinamik model yeraltı suyu kaynakları, su çıkarımı, arazi kullanımı ve ürün kârlılığı olmak üzere dört sektörü temsil etmektedir. Model öncelikle yapısal olarak aşırı durum testleri ve parametre duyarlılık analizleri ile kalibre edilmiştir. Sonra da 2005 ve 2015 yılları arasında var olan veri kullanılarak davranışsal kalibrasyonu yapılmıştır. Yeraltı suyunun kendi beslenmesinden daha fazla kullanılması kısa vadede çiftçiler için kârlı olduğu iddia edilse de, uzun vadede geri dönüşü olmayan ekolojik ve ekonomik yıkımları olabilir. Model ile yapılan senaryo analizlerinde devletin sulu tarım için verdiği teşvik ve sulanarak elde edilen ürünün fiyatındaki artış sulanan alan miktarında muazzam bir artışa neden olabilir. Bu artış yeraltı suyu kullanımını aşırı derecede artırabilir ve bu durum gelecek nesillerin önemli bir su kıtlığı çekmesine neden olabilir. Diğer bir yandan vahşi sulama yerine damlama sulamaya geçilmesi yeraltı suyu kullanımını azaltabilir ve Kızıltepe Ovası'nda uzun süreli sürdürülebilir bir yeraltı suyu kullanımına ulaşmada yardımcı olabilir.

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LIST OF SYMBOLS/ABBREVIATIONS

Abbreviation	**Explanation**	**Unit**
FAO	Food and Agriculture Organization Of the United Nations	
IPPCC	Intergovernmental Panel on Climate Change	
CPR	Common Pool Resource	
DSİ	State Hydraulic Works	
TAGEM	General Directorate of Agricultural Research and Policies	
GAP	Southern Anatolia Project	
TEYAP	Tarımsal Eğitim ve Yayım Projesi	
DİKA	Tigris Development Agency	
w	Energy	joule
kW	Power	watt
g	Gravitational constant	meter/sec^2
h	Height	meter
ha	Hectare	
kg	Kilogram	
mm	Millimeter	
tl	Turkish Lira	

1. INTRODUCTION

Water is one of the most important element among natural resources since it is vital for the survival of all living organisms. It also played a crucial role in development of human civilizations throughout history. Starting from the earliest agricultural communities to urban settlements of the 21st century, human civilization has also always depended on water. The impacts of water influence all facets of life including the social, economic and ecological spheres (Briggs, 2010).

About 2.5 % of the total global water resources are fresh water which includes groundwater, lakes and rivers, polar ice and glaciers and this fresh water is used for varying purposes (Perlman, 2016). According to FAO (2016), the global groundwater withdrawal ratios are 70 % for agricultural purpose, 19% for industrial purpose and 11 % for municipal purpose. as shown in Figure 1.1.

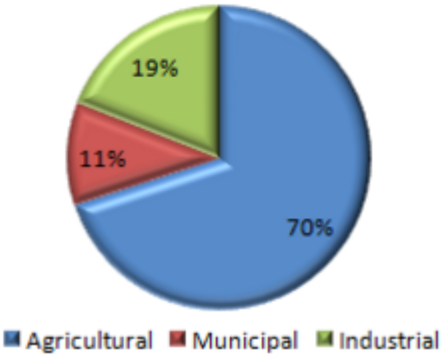

Figure 1.1. Global use of all water withdrawals [FAO,2016].

As population increases, the demand on consumption of freshwater also increases. However, this increase in demand is not direct in proportional to the increase in population. For example, although the population of the world is doubled in the last century but the consumption of water has increased six times which leads to huge water deficits for future generations in some regions of the world if adequate precautions are not taken (World Resources Institute, 2015).

The distribution of freshwater among continents and related population is also not equal. Some parts of the world are more sensitive to water stress than others. According to the Intergovernmental Panel on Climate Change, severe water deficit is expected to occur in the eastern Mediterranean Basin due to climate change (IPCC,2014).

In many agricultural areas, groundwater is the primary source since surface water sources are not present or have been depleted. For such communities, exploitation of groundwater resources may cause severe problems. Groundwater is a renewable natural resource and it should be used very carefully in order to let it replenish itself. As there has been a huge progress in technology in recent decades, the amount of water extracted from ground has also increased in great quantities, and this enormous amount of groundwater has played a very crucial role in agricultural production. The total area used globally for irrigation purposes is about 301 million ha and 38 % of which is irrigated with groundwater (Siebert, et al., 2010). Moreover, groundwater is not only used for agricultural areas but it is also used for domestic purposes. Globally, at least two billion people rely on groundwater for domestic purposes and they do not have any other water sources except groundwater (Sampat,2000).

The situation in Turkey is very similar to rest of the world and there is a growing need for the use of groundwater in Turkey’s agricultural basins. It is also predicted that the demand to exploit groundwater resources will increase further in the coming years. Groundwater resources should therefore be used wisely, and sustainable management practices should be considered both locally and globally.

2. PROBLEM DESCRIPTION AND RESEARCH OBJECTIVES

Groundwater is a major source of irrigation in Turkey’s agricultural basins, especially in arid and semi-arid regions. Kızıltepe Plain is just one example where all irrigation depends on groundwater resources.

Kızıltepe Plain, being an important area of Mesopotamia and located in the south-east of Turkey consists of four districts of Mardin. These districts are Kızıltepe, Artuklu, Nusaybin and Derik. The geographical boundaries of Kızıltepe Plain are shown in Figure 2.1.

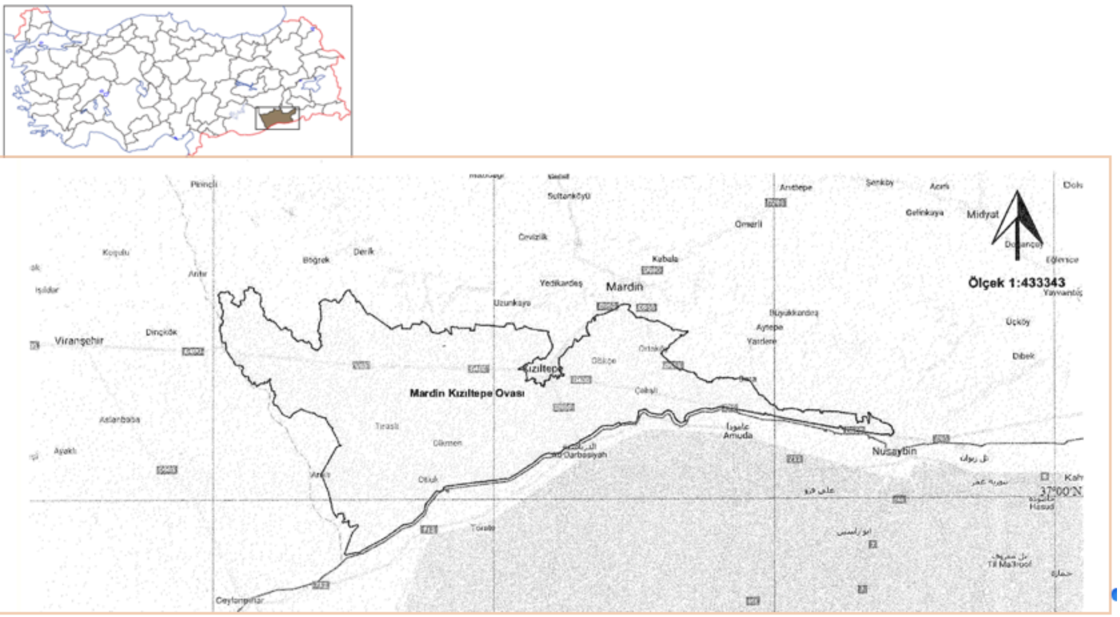

Figure 2.1. Geographical borders of Kızıltepe Plain [Ministry of Food, Agriculture and Livestock, 2017].

Field researches were conducted in order to identify firsthand issues related to groundwater use in the plain. During field researches, farmers and officials from State Hydraulic Works (DSİ), Ministry of Food, Agriculture and Livestock, Mardin Metropolitan Municipality and Tigris Development Agency (DİKA) were interviewed. These field researches were very helpful to collecting data about irrigated land, static water table level and well numbers.

The plain is one of the example where the problem of groundwater overexploitation has been occurring for more than 10 years. According to the report published by Ministry of Environment and Urbanization branch in Mardin (2015), all the water needs for agriculture are provided by groundwater resources with 93 % of Mardin's fresh water is used for agricultural purposes. The irrigated-farming activity has been increasing in the past 10 years and there is a great shift from rainfed land to irrigated land. Figure 2.2. shows the rapid change in irrigated land in Kızıltepe Plain based on data from Turkish Statistical Institute. Over the past 10 years, irrigated land increased almost three folds from 27,560 hectares in 2005 to about 76,836 hectares by 2015.

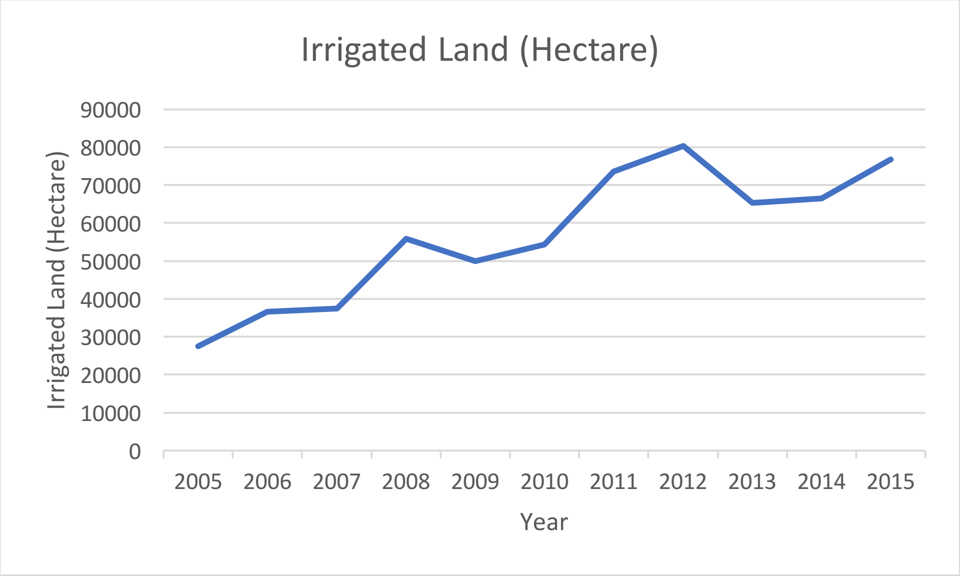

Figure 2.2. Irrigated land in Kızıltepe Plain (Turkish Statistical Institute).

Hydrological and land use studies about Kızıltepe Plain are rare. Researchers have studied individual districts, but not the entirety of Kızıltepe Plain. Figure 2.3. depicts that, 13 % of the lands in Kızıltepe district were irrigated in 2000 (Sonmez, 2012).

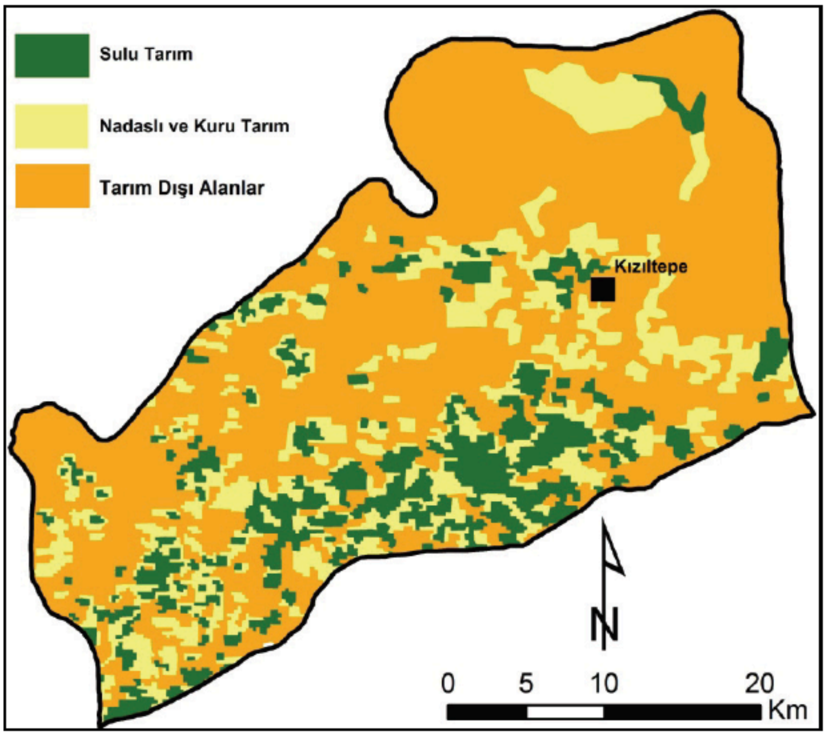

Figure 2.3. Land use in Kızıltepe district in 2000 (Sonmez, 2012).

However, as farmers had more access to groundwater, the amount of irrigated land increased dramatically as shown below Figure 2.4. In 2010, the amount of irrigated land has reached 44% of total land in Kzıltepe (Sonmez, 2012) and it is still increasing.

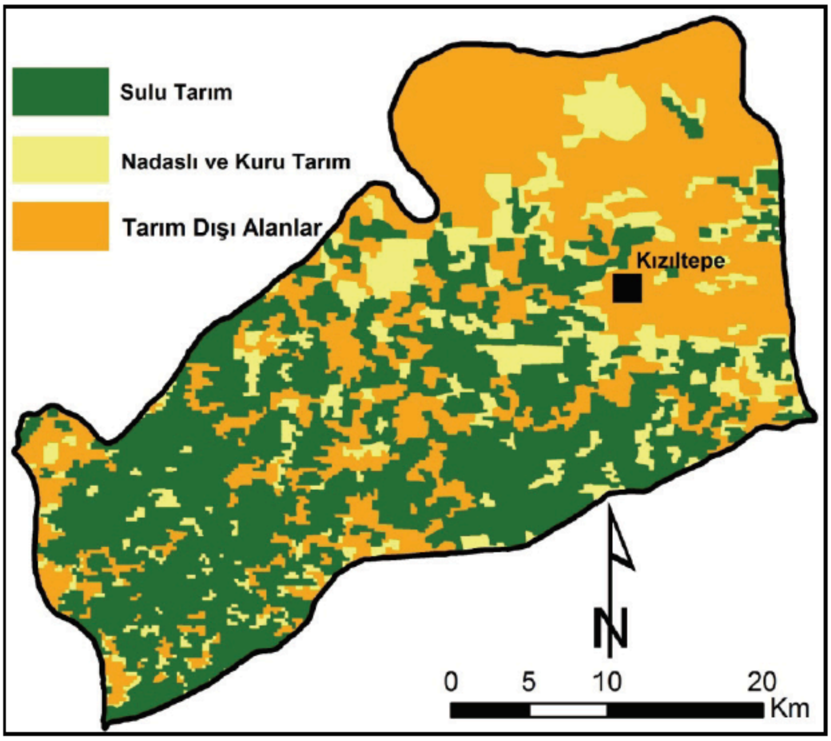

Figure 2.4. Land use in Kızıltepe district in 2010 (Sonmez, 2012).

The change in irrigated land was accompanied with a large increase in number of wells, which means that water extraction has also increased. Figure 2.5. shows the increases in the number of wells in Kızıltepe Plain between 2005 and 2016. However, interviews in field researches with officials from State Hydraulic Works (DSİ) and Ministry of Food, Agriculture and Livestock suggest that the actual number of wells in the distrcit may be two times more than officially recorded amounts. According to State Hydraulic Works records, there are 1,976 recorded wells in Kızıltepe Plain. However, the report published by Ministry of Environment and Urbanization branch in Mardin states that the number of wells in Kızıltepe plain are approximately 3,000. Also, according to Mardin Metropolitian Municipality report, there are more than 7,000 wells in Mardin.

Farmers extract water from deep wells without any effective regulation or limits and they keep on deepening their wells when they face water deficits.

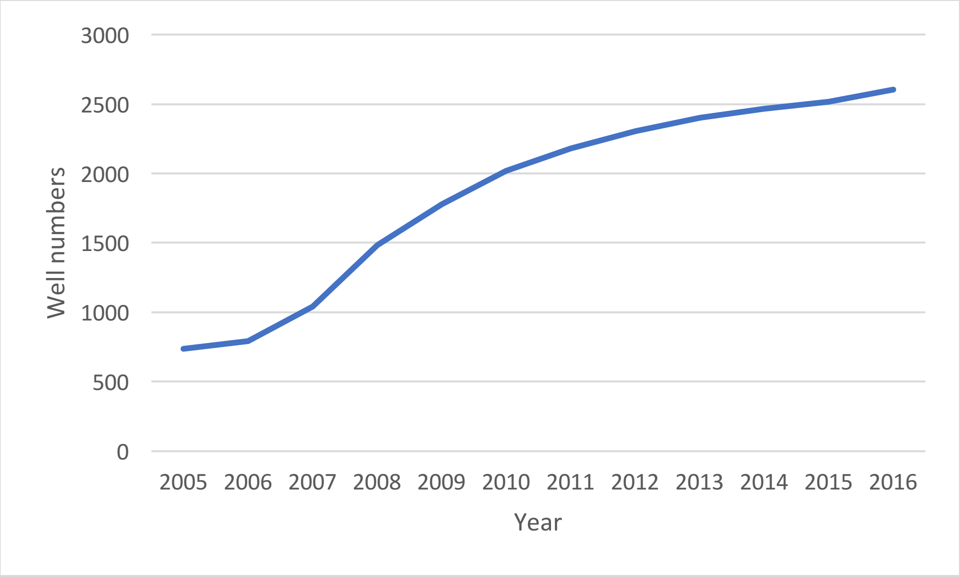

Figure 2.5. Number of wells in Kızıltepe Plain (State Hydraulic Works).

The increase in number of wells and unregulated groundwater extraction has lead to a significant change in static level of groundwater resources in Kızıltepe Plain. Below figure shows this change based on data from State Hydraulic Works.

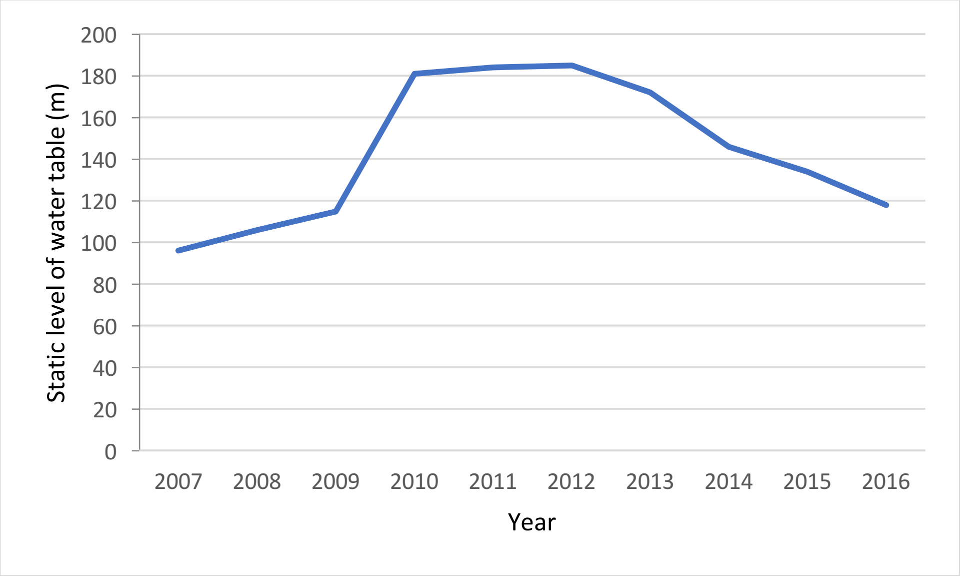

Figure 2.6. Static level of water table (State Hydraulic Works).

According to Figure 2.6., there is a decrease in static level, suggesting that the average groundwater table level in the plain has increased after 2013. The reason of this decline is not clear. There are some possible explanations, which can explain this decline: One reason can be the crop choice since there is a huge shift from very high water consumptive cotton cultivation to corn cultivation between 2005 and 2015. Figures 2.7 and 2.8 show this change.

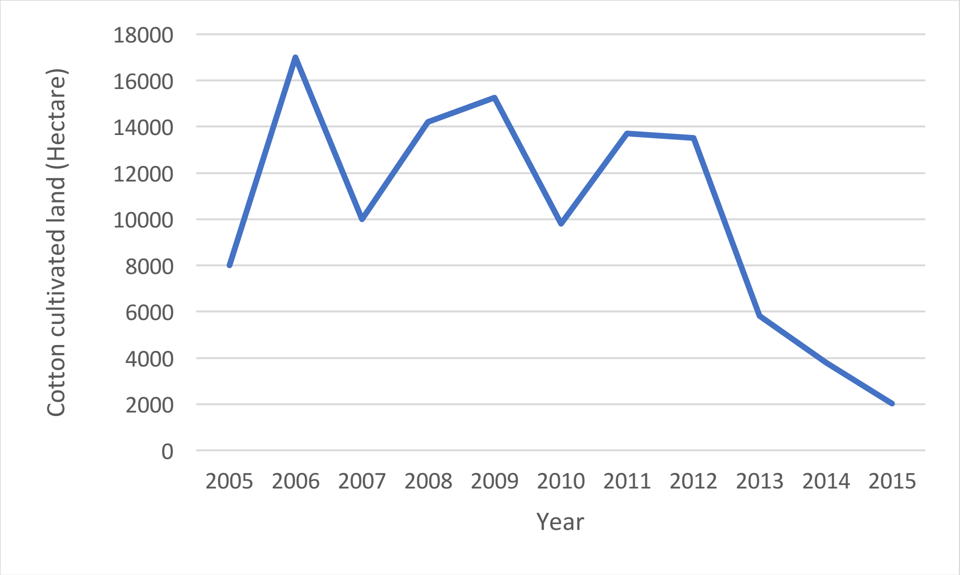

Figure 2.7. Cotton cultivated land (Hectare).

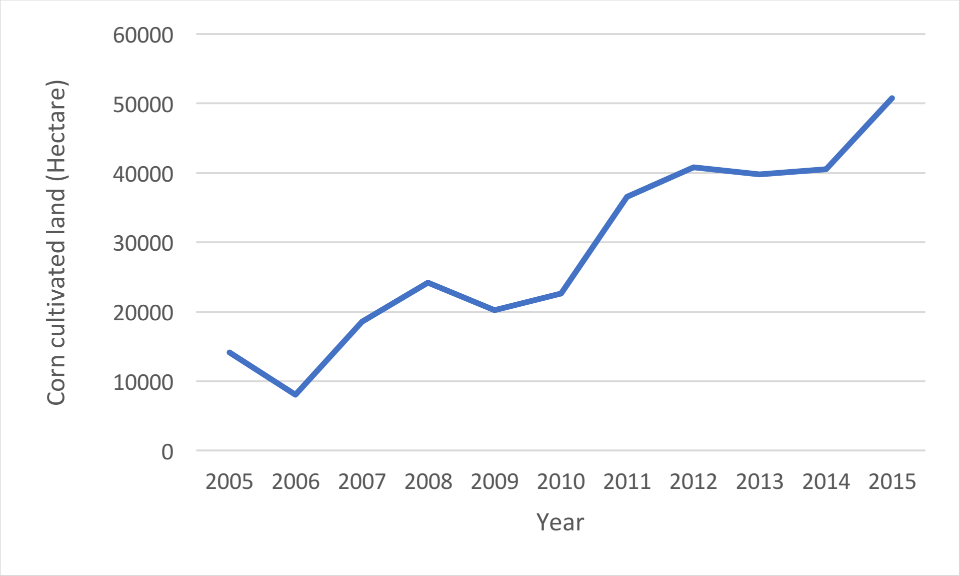

Figure 2.8. Corn cultivated land (Hectare).

Moreover, there is a tendency to plant less rainfed crops (such as barley) by farmers as they have the chance to access groundwater since irrigated crops are much more profitable compared with rainfed crops. The figure below illustrates the change in barley cultivation between 2005 and 2015.

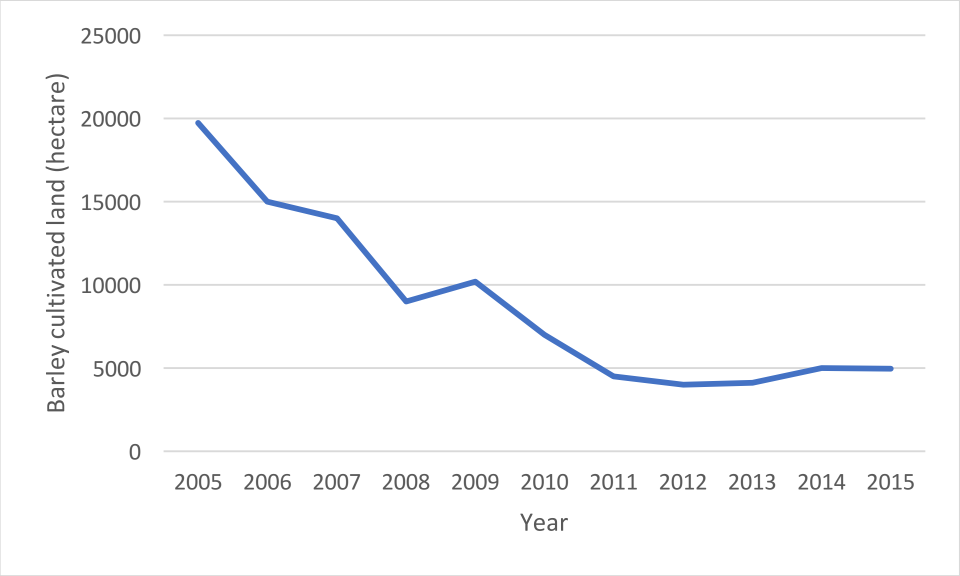

Figure 2.9. Barley cultivated land (Hectare).

It is clear that there is a strategic water management problem because of the complexity of the hydrology of groundwater resources and the impact of human activities on groundwater exploitation in Kızıltepe Plain.

The main objective of this research is to build a dynamic simulation model based on system dynamics methodology which will help us find effective strategies to achieve long term sustainability in Kızıltepe Plain. This model will be a socio-ecological model which comprises the interactions between human and nature.

3. LITERATURE REVIEW

Groundwater is categorized as a common pool resource (CPR) in environmental and natural resources economics. Elinor Ostrom (1994) uses the following two criteria to describe CPR's: (1) whether it is easy or difficult to "exclude" potential users of CPR's, (2) whether the resource is degraded and/or subtracted as it is used, in other words, whether using the resource causing a competition between users or not. Resources which are degraded and difficult to "exclude" users are considered as common pool resources.

If groundwater commons are used under open access regime, meaning that there isn't any control over groundwater use, farmers do not jointly plan how to use groundwater and they do not communicate with each other, then each farmer may try to extract maximum water in order to maximize his/her profit. However, if all farmers try to extract maximum water, groundwater resources will be used beyond their replenishment rates. Although this fact may be profitable for the farmers in the short term, it may cause irreversible economic and ecological damage in the long term. This problem archetype can be an example of tragedy of commons (Hardin, 1968). Additionally, if farmers continue using water without any rules and coordination, there will be a competition between farmers, and this will ultimately prevent use of groundwater commons in the long term and will also affect peace and welfare of region negatively (Lowi, 1995).

Groundwater, like other renewable resources, is a dynamic resource. The amount of water stored in an aquifer increases by recharge and infiltration which is mainly caused by precipitation and irrigation and it decreases by extraction, discharge and evapotranspiration. From the concept of conversation of mass, the amount of water accumulated in the aquifer is equal to the difference between inflow and outflow rates. (Domenico & Schwartz, 1998; Rushton, 2004). Overconsumption of groundwater causes a considerable decrease in water table level and this decrease may change the recharge regime and capacity of aquifer irreversibly. Once tipping points (Walker & Salt, 2006) are exceeded, there is a permanent change in dynamics of resource. Therefore, safe limits of groundwater regime (Eamus et al., 2006). are very important for sustainable use of groundwater.

System dynamics provides useful approaches, methods and tools to represent dynamic and non-linear properties of renewable resources and these properties are vital for sustainable management of these resources. The Fishbanks game and the simulation model (Meadows, et al.,

1993) which address tragedy of commons are one of the most well-known application of system dynamics approach to common pool resources. Fishbanks web game (Sterman et al., 2011), which is based on Fishbanks model, is played by many players every year and provides the opportunity for students to learn about challenges of how to manage resources sustainably. Additionally, the natural resources management online-course (Moxnes, 2015) taught in Bergen University, Norway includes models about management of fishing zones and pastures. One of the objectives of this online course is to explore factors that cause tragedy of commons in fishery industry.

Access to common pool resources and the factors that can lead to the tragedy of commons are shown below Figure 3.1. R loops show consumption of water activities while B loops show decrease in water table level.

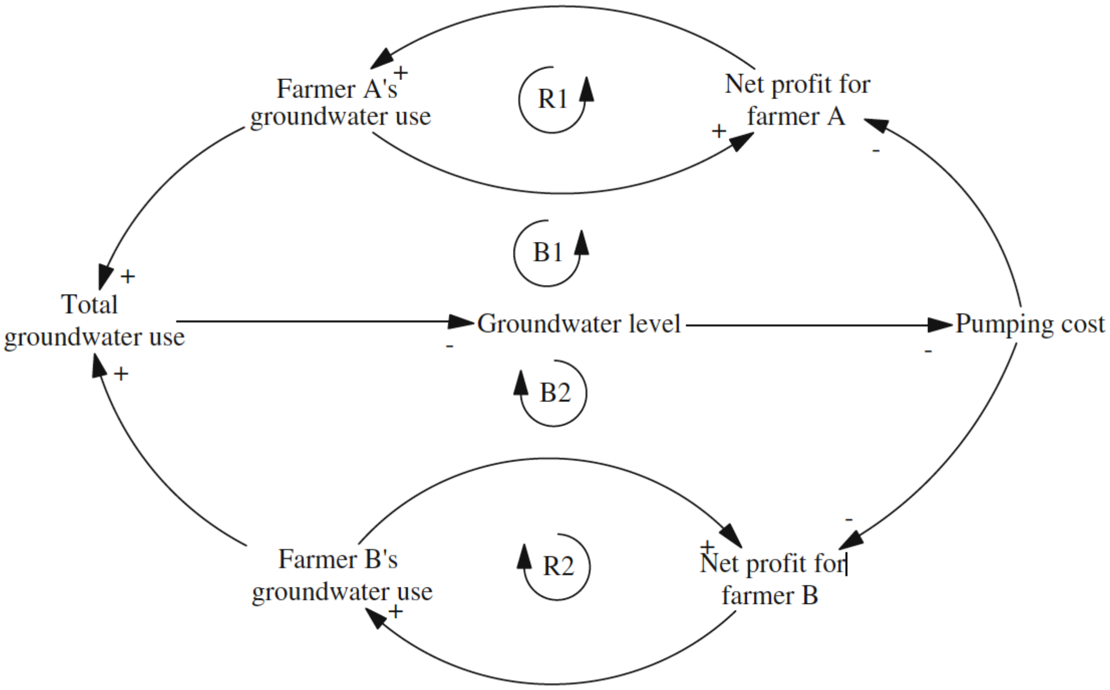

Figure 3.1. Tragedy of commons causal loop diagram (Mirchi et al., 2012).

Groundwater modelling studies using system dynamics approach and studies dealing with groundwater management as a common pool resource are limited. Bagheri et al. (2015) discusses sinkhole problem caused by overconsumption of groundwater by using system dynamics and simulation modelling methodology. The field research area is Abarkuh region in Iran and their model consists of population, agricultural production and demand for irrigation water. Mirchi et al. (2012) examines groundwater management problem as a system and commons problem by using conceptual models. Mirchi et al. (2012) also discusses the potential of dynamic feedback models in water management, however, there isn’t any simulation based analysis in this study.

Fernandez & Selma (2004) and Saysel et al. (2002) show how policies promoting the use of agricultural water causes water shortage, economic loss and environmental damage in the long run by using simulation models which consisting of many feedback loops. Bueno N.P. (2014) discusses commons problem in agricultural water use by using a dynamic system model and explains how irreversible effect may occur because of overuse of water.

Winz & Brierley (2007) summarizes studies about water resources and irrigation by using system dynamics methodology. Van den Belt (2004) and Stave (2003) use participatory modelling methods and suggest some practices to implement solution proposals, which emerge during modelling, simulation and analysis.

4. METHODOLOGY

The hydrology of groundwater resources and the impact of human activities on groundwater exploitation are complex and this complexity causes strategic management problems. System dynamics, which is the methodology selected for this research, provides us methods and tools to explore the relationships among nature and human in a holistic way. System dynamics is a powerful methodology to understand and analyze complex systems, to create and test hypothesis on the causes of dynamic problems and also to design policies. It is often difficult to understand a dynamic problem without help of modeling since our brain capacity is limited and may not be able to anticipate the consequences of multiple simultaneous influences. Groundwater irrigation system is such a dynamic feedback problem. It contains various positive and negative feedback loops and as well as interactions of various sub-systems. Therefore, the interaction of groundwater and human systems is a very proper example in order to be analyzed by the principles of system dynamics modeling and simulation.

According to Barlas (2002), the main steps of analyzing a complex problem by using system dynamics methodology are:

-Problem identification and definition (purpose)
-Dynamic hypothesis and model conceptualization
-Formal model construction
-Model credibility (validity) testing
-Analysis of the model
-Design improvement
-Implementation

This study has been designed according to the above steps which are discussed below:

1. **Literature research and field work:** National and regional legislations about groundwater use were analyzed. Additionally, national and international academic researches about groundwater fed irrigation were examined. Stakeholders who are responsible for using and protecting groundwater were identified. Interviews were conducted with the stakeholders during fieldwork about how they perceive the current situation and what their expectations for the future are. Also, agricultural production, monthly water consumption and groundwater reservoir data were obtained during fieldwork.

2. **Definition of dynamic problem:** Based on literature research and field work, the change in water table level and irrigated land, amount of extracted water and crop profitability were determined.

3. **Dynamic hypothesis:** In order to analyze the causes behind the dynamic problem, related variables and their cause-effect relations were determined and causal loop diagrams were formed based on these relationships.

4. **Simulation model construction:** At this stage, mathematical formulations that describe cause-effect relations of each variable were defined and the stock-flow diagram was built.

5. **Validation of simulation model:** Model validation has two aspects. The first aspect is structural validity. This was done in order to see if the structure of model is meaningful when it is compared to real system. The second aspect is behavioral validity. This was done in order to assess if behaviors generated by model are close enough to the real dynamic behaviors.

6. **Model analysis:** The behaviors of the model according to different irrigation scenarios were examined.

7. **Implementation:** The model and its results are going to be shared with all stakeholders whom we have interview during fieldwork and their feedbacks about model and its usefulness are going to be evaluated in future studies.

The feedback structure is the main characteristic property of system dynamics methodology. The main target of the system dynamics approach is to focus on circular causality rather than direct causality between the system variables. For instance, groundwater extraction and its effect on water table level can be identified by the help of change in water in saturated zone. The direct causality of the problem is shown in below Figure 3.1. The arrows represent the direction between the variables whereas the signs represent the polarity between the variables.

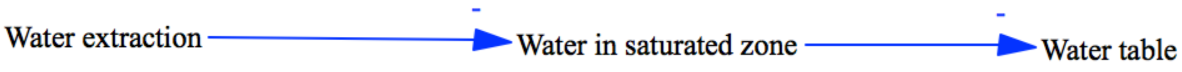

Figure 4.1. Direct causal representation of the relationships between the factors affecting water table.

Other things being equal, if water extraction increases water in saturated zone decreases. The polarity is therefore negative. Also, Other things being equal, if water in saturated zone decreases, water table increases (vectorally, a decline in water table is coded as an increase). So, the polarity is again negative.

However, there is an effect of water table on water extraction and other things being equal, as water table increases (i.e. water table declines), water extraction decreases. This feedback causality is shown in Figure 4.2. The polarity of the whole loop is negative since an initial increase in water extraction results in a decrease as the feedback loop operates over time.

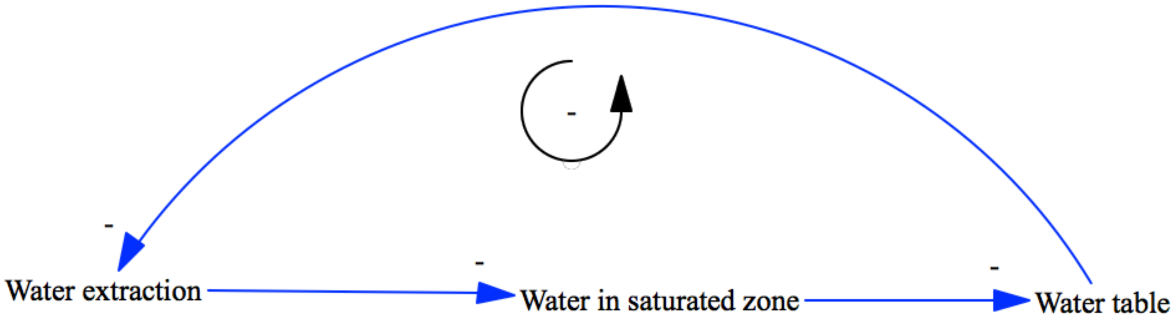

Figure 4.2. The feedback causality between water table and water extraction

The system dynamics model consist of stocks, flows and converters. Stocks represent entities that accumulate or deplete over time whereas flows represent the rate of change of stocks. Converters are used to define the relationship between the elements of the model. For example, the below stock-flow structure represents the relationship of water extraction and water in saturated zone.

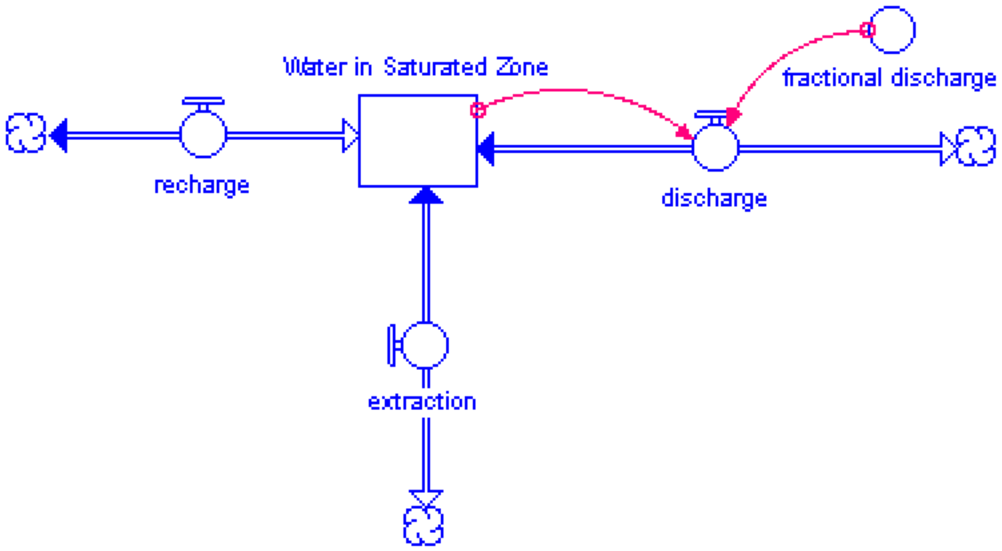

Figure 4.3. Stock-flow structure of water extraction.

Stock equations are integral equations and can be represented as:

$S(t+dt)=S(t)+[\Sigma flows(t)]*dt$ (4.1.)

Flows are represented as functions of stocks, flows and converters, i.e.,

$Flow(t)=f(stock, flow, converter, t)$ (4.2.)

The methodology of system dynamics is summarized in Forrester (1997), Ford (1999), Sterman (2000) and Barlas (2007). These research and text books can be considered as the main sources for detailed information on system dynamics methodology.

5. MODEL DESCRIPTION

A system dynamics model investigating the use of groundwater for irrigation purpose in Kızıltepe Plain is constructed. The model is a socio-ecological model of human and nature interactions. It has four sectors representing groundwater resources, water extraction, land use change and crop profitability.

The aim of the model is to explore management options to achieve long term sustainability in Kızıltepe Plain. The time horizon of the model is set to 20 years, from 2005 to 2025. While the period between 2005-2015 serves for model calibration purposes, 2015-2025 period serves for generating foresights to the future of this irrigation system. Model time unit is in months, i.e. in the reference run and scenario analyses, the model is simulated for 240 time units.

The model is built and simulated on Stella dynamic simulation platform. It is numerically solved by Euler's method with a computational step of dt=0.125.

5.1. Overview of the Model

5.1.1. Feedback View of the Model

A simplified causal loop diagram of the model is depicted in Figure 5.1. There are mainly four feedback loops in Figure 5.1.

In the irrigated land loop, as extraction increases, there is more irrigation which results in more evapotranspiration. As evapotranspiration increases, there is more crop yield for irrigated crops and increase in crop yield results in more irrigated land. Desired extraction increases since more water is required if there is an increase in irrigated land and extraction increases as desired extraction increases. The polarity of the loop is positive and it is found by the algebraic product of the signs of all individual causalities around the loop (Richardson, 1986). There are two small lines on the row between irrigated crop yield and irrigated land variables which means there is a delay between these two variables.

In the more power loop, the desired extraction leads to more desired energy and more desired energy requires more pump power. More energy is achieved by using more power and more power results in more extraction. As extraction increases, irrigation increases and as explained above, increase in irrigation results in increase in desired extraction. The polarity of this loop is also positive since the algebraic product of all individual causalities around the loop is positive.

In more operation time loop, as desired extraction increases, desired energy increases. Increase in desired energy leads to an increase in monthly operation time which results in more energy. As energy increases, there is more extraction and as there is more extraction, there is also more irrigation which results in more desired extraction.

In the water depletion loop, as extraction increases, water in saturated zone decreases and decrease in water in saturated zone causes an increase in water table level (i.e. water table declines). As water table level increases, it is difficult to extract water and water extraction decreases. The polarity of this loop is negative.

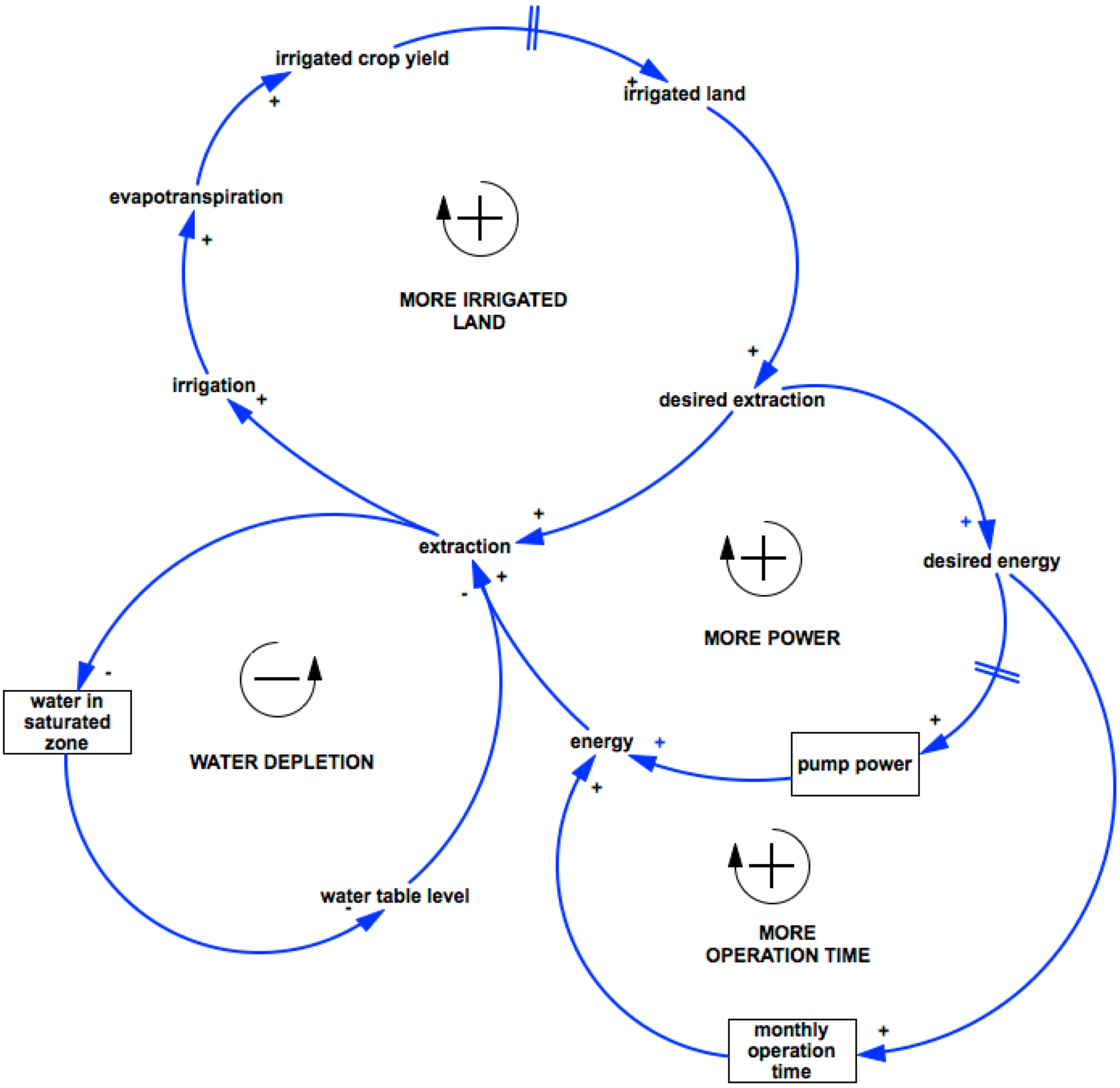

Figure 5.1. Simplified feedback view of the model

5.1.2. Sector View of the Model

The sectors and basic interactions of the model are represented in Figure 5.2. Each box on the figure represents a sector whereas the arrows between box objects are used to show the flows between each sector.

The groundwater resources sector informs the water extraction sector about desired extraction. The water extraction sector supplies water extraction according to desired extraction information and sends water extraction information to groundwater resources sector. Then, groundwater resources sector compares water extraction information with irrigation requirement and starts to irrigate crop for whole irrigation season that is between April and September. After that, irrigated crop yield information sent by groundwater resources sector is received by crop profitability sector and this information is compared with rainfed crop yield. Land use sector receives the ratio of irrigated crop yield to rainfed crop yield. Land use sector uses this ratio to decide how much land is going to be irrigated and then sends irrigated land information to groundwater resources and water extraction sectors.

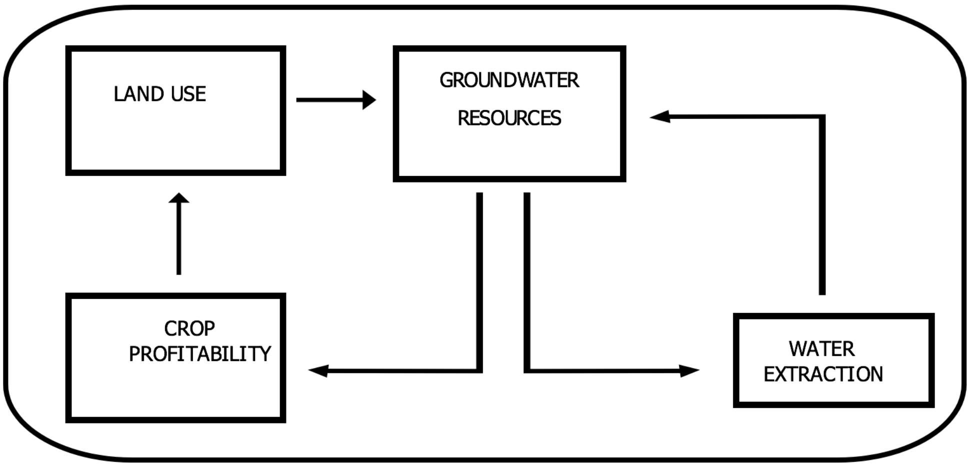

Figure 5.2. Model sector overview.

5.1.3. Main Assumptions of the Model

The model assumes that all arable land in Kızıltepe Plain is used either as rainfed land or as irrigated land. Moreover, irrigated crop is chosen as corn while rainfed crop is chosen as winter wheat. The model also assumes that water in saturated zone is replenished by the whole arable land and.

5.2. Description of the Sectors

Each sector is explained in detail in this section. The dynamic model has four sectors representing groundwater resources, water extraction, land use and crop profitability. Also, main equations and table functions are presented for each sector.

5.2.1. Groundwater Sector

Groundwater resources sector is central to this model since it gives information about how much water is needed and how much water is given to crops. There are mainly two stocks in groundwater resources sector named as water in root zone and water in saturated zone. The details of this sector with flows and stocks is depicted in Figure 5.3.

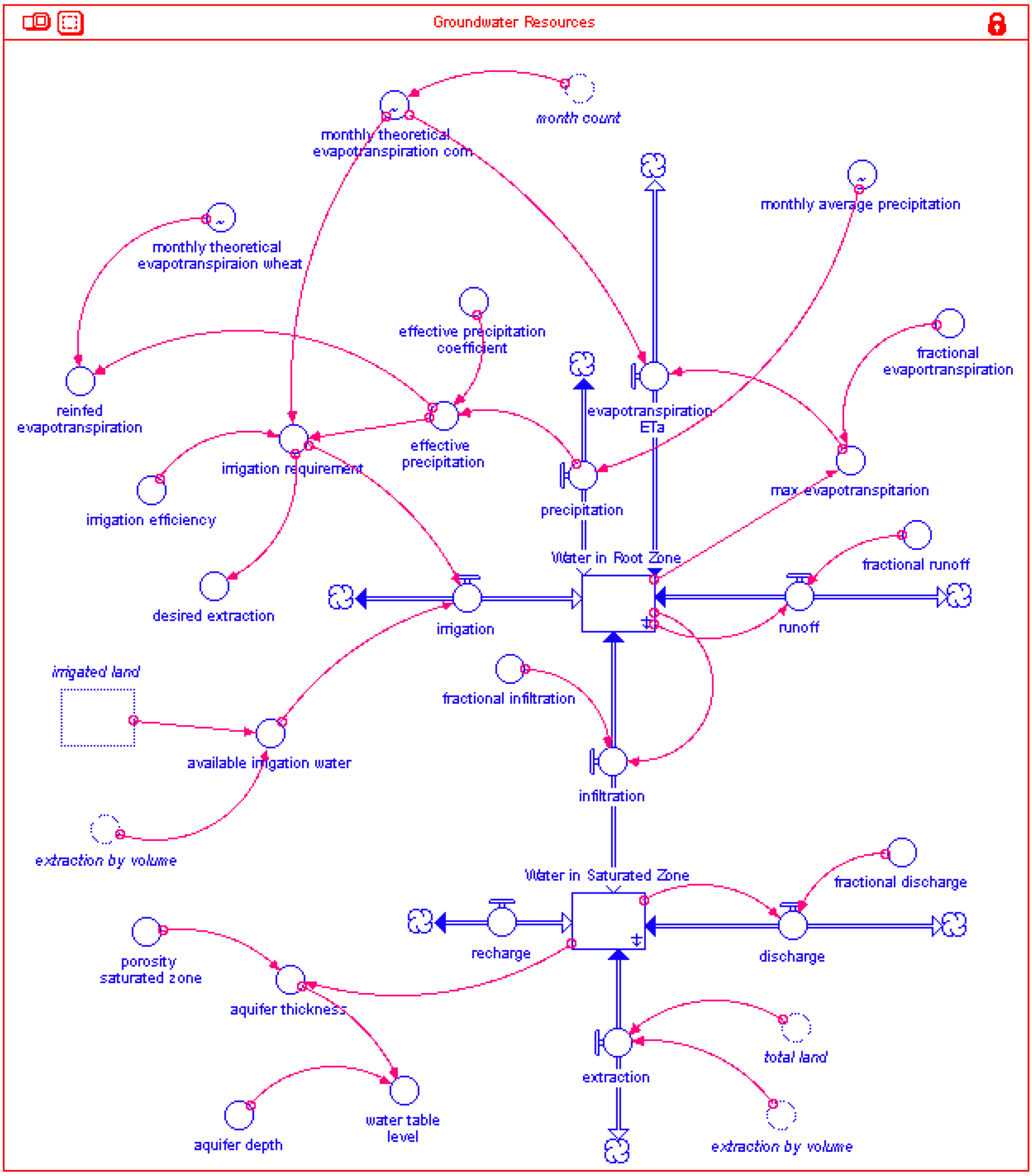

Figure 5.3. Stock-flow diagram of groundwater resources sector.

Water in root zone stands for water available at root zone in mm. The value of water in root zone increases by irrigation and precipitation whereas it decreases by runoff, evapotranspiration and infiltration.

Kızıltepe Plain is a semi-arid place and there is a huge seasonal difference in precipitation. Therefore, monthly average precipitation values for Mardin which have been published by general directorate of meteorology between 1981 and 2010 are used (Mardin, 2017). The seasonal change can be seen in from Figure 5.4.

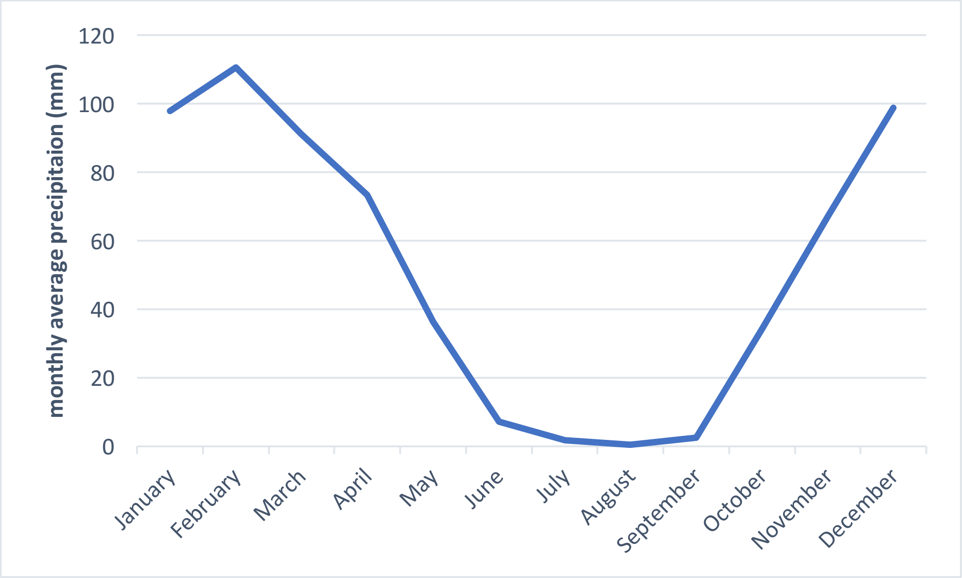

Figure 5.4. Monthly average precipitation.

The irrigation equation consists of two variables named irrigation requirement and available irrigation water. The equation is:

$$\text{irrigation} = MIN(\text{irrigation\_requirement}, \text{available\_irrigation\_water}) \quad (5.1)$$

The equation takes the minimum values of irrigation requirement and available irrigation water. Irrigation requirement equation is:

$$\text{Irrigation requirement} = MAX(0,(\text{monthly\_theoretical\_evapotranspiration\_corn} - \text{effective\_precipitation})/\text{irrigation\_efficiency}) \quad (5.2)$$

Monthly theoretical evapotranspiration corn is the value at which corn reaches its maximum evapotranspiration if there is enough water supply. It is determined according to real data that is calculated by the Ministry of Food, Agriculture and Livestock and State Hydraulic Works. The closest research station to Kızıltepe Plain is Ceylanpinar research station. Therefore, the monthly average theoretical evapotranspiration results of Ceylanpinar station for corn were taken from the report prepared by the Ministry of Food, Agriculture and Livestock and State Hydraulic Works. (TAGEM, 2016). The monthly theoretical evapotranspiration for corn in mm is shown below in Figure 5.5.

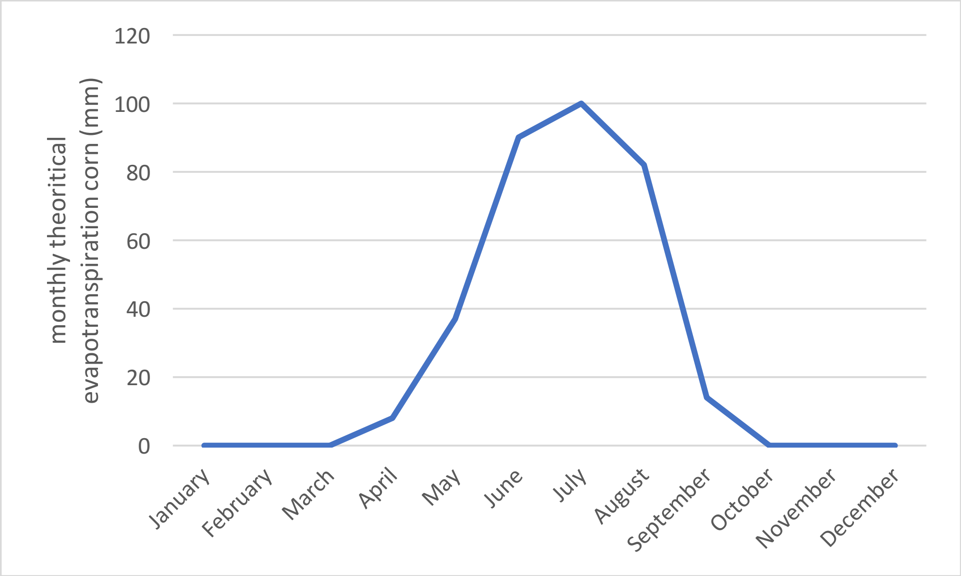

Figure 5.5. Monthly theoretical evapotranspiration for corn.

The effective precipitation is defined as the amount water that is taken by plant and the effective precipitation is usually less than actual precipitation. According to research conducted in south-east of Turkey, the effective precipitation is 0.8 percent of actual precipitation (GAP TEYAP, 2015).

Irrigation efficiency is also an important parameter and can be varied according to irrigation techniques. During fieldworks, different farmers and officials who are responsible for water use for agricultural purposes were interviewed According to farmers and officials that we interviewed, only about 2% of farmers use efficient irrigation techniques such as sprinkler or drip irrigation. The rest of the farmers still irrigate their land in a traditional way which is known as flood irrigation. According to Sharmasarkar et al. (2001), irrigation efficiency for flood irrigation is 0.65. This value is therefore applied in the model since approximately 98% of the farmers in Kızıltepe Plain are practicing flood irrigation.

Available irrigation water equation can be shown as,

$$\textit{available irrigation water} = \textit{extraction\_by\_volume}/\textit{Irrigated\_Land}/10 \qquad (5.3)$$

where extraction by volume will be explained in water extraction sector and irrigated land is the amount of land irrigated in hectares. The parameter value 10 stands for the conversion from meter cubes of extraction per year to millimeters of irrigation water available, given that the area to be irrigated is measured in hectares.

Rainfed evapotranspiration equation can be explained as,

$$Rainfedevapotranspiration=MIN(effective\_\_precipitation,\ monthly\_theoretical\_evapotranspiraion\_wheat) \qquad (5.4)$$

where both effective precipitation and theoretical evapotranspiration wheat are in mm/month. The average monthly theoretical evapotranspiration for wheat is taken from research that is held at Ceylanpınar research station (TAGEM,2016) and the average monthly values are shown in Figure 5.6.

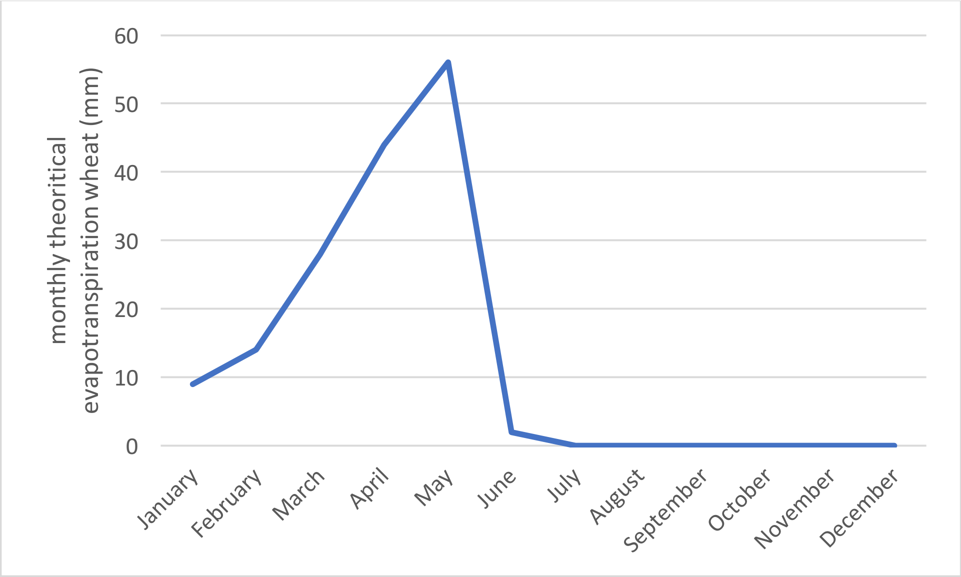

Figure 5.6. Monthly theoretical evapotranspiration for wheat.

There is runoff parameter in the model since some water is lost by runoff. The runoff equation is:

$$Runoff=Water\_in\_Root\_Zone*fractional\_runoff \qquad (5.5)$$

where water in root zone is in mm and fractional runoff is per month.

The infiltration inflow equation which is in mm/month is also similar to runoff equation and can be shown as,

$$infiltration= Water\_in\_Root\_Zone*fractional\_infiltration \qquad (5.6)$$

Water in saturated stock is one of the most important stocks, since all water is taken from this stock. The value of this stock increases with flows of infiltration and recharge whereas it decreases by discharge and extraction.

The type of soil in Kızıltepe Plain is limestone which allows a little water infiltration to the saturated zone. Therefore, saturated zone is mainly recharged by water coming from the north part of Kızıltepe Plain shown in Figure 5.7. with the blue bordered area. The hydrogeological map of Kızıltepe Plain included in Appendix B.

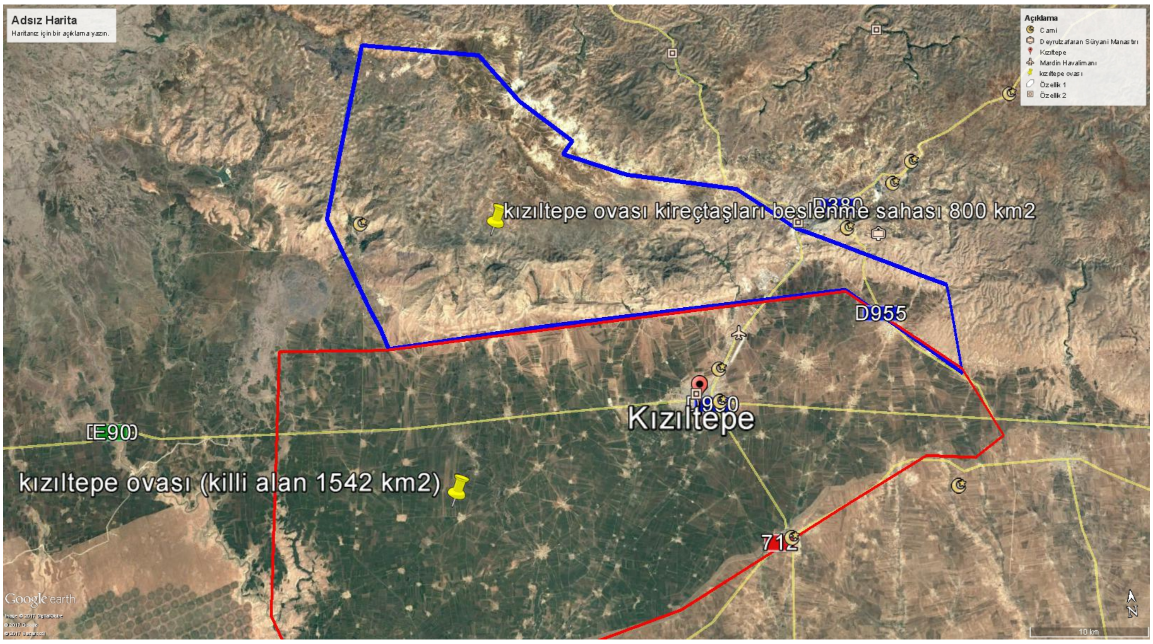

Figure 5.7. Recharge area of Kızıltepe Plain.

The value of recharge is calibrated by the model and taken as 14500 mm/month.

There is a discharge from Turkey to Syria, therefore a discharge flow is required and the equation of discharge is shown as:

$$discharge = Water\_in\_Saturated\_Zone * fractional\_discharge \tag{5.7}$$

Also, water in satured zone decreases by extraction as explained in water extraction sector and the equation for extraction is:

$$extraction = extraction\_by\_volume / total\_land / 10 \tag{5.8}$$

where extraction is in mm/month and total land is in hectares and 10 is the unit conversion parameter.

5.2.2. Water Extraction Sector

Water extraction sector gives information about the amount of water that is extracted and the amount of water that is desired. This sector consists of stock-flow equations that calculate pump power, monthly operation time, desired energy, energy per well, desired extraction and extraction by volume per well. All results are presented per month. The diagram of water extraction sector is shown in Figure 5.8.

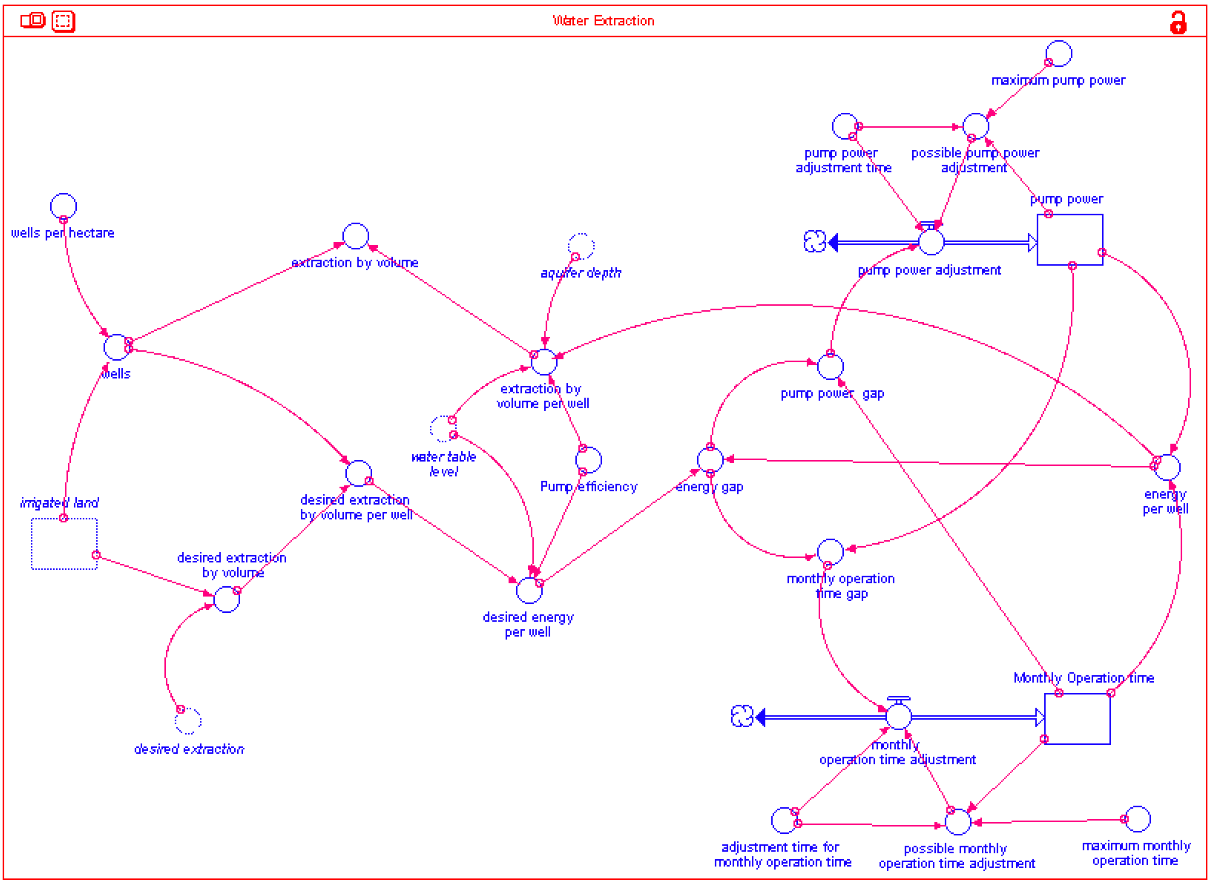

Figure 5.8. Stock-flow diagram of water extraction sector.

One of the governing equation of this sector is the equation of desired energy per well. In order to calculate desired energy per well, a theoretical relationship assuming ideal conditions which determines the energy required to lift a mass is used and it is shown as:

$$w=m*g*h \tag{5.9.}$$

Where,
w= energy in joules
m= mass in kilogram
g= gravitational constant, which is equal to about 9.8 meters/sec^2
h= height in meters

Height is multiplied by 0.001 in order to convert water table level in mm and mass is multiplied by 1000 in order to convert meter in cubic meter. Also, equation (5.9.) is divided by $3.6*10^6$ *since 1 kWhour is equal to* $3.6*10^6$*. After conversions, equation becomes:*

$$\begin{aligned}&desired\ energy\ per\ well\\&=(0.001*water\_table\_level)*9.8*(1000*desired\_extraction\_by\_volume\_per\_well)\\&/(3.6*10^6)/Pump\_efficiency\end{aligned} \tag{5.10.}$$

Water table level, desired extraction by volume per well and pump efficiency should be defined for equation (5.10.). Desired extraction by volume per well is:

$$\begin{aligned}&desired\ extraction\ by\ volume\ per\ well=\\&desired\_extraction\_\_by\_volume/Wells\end{aligned} \tag{5.11.}$$

In order to calculate desired extraction by volume per well, number of wells and desired extraction by volume also need to be defined. The number of wells is:

$$wells=Irrigated\_Land*wells\_per\_hectare \tag{5.12.}$$

wells per hectare is chosen as 1/15 since 1 well is enough for irrigation of 15 hectares according to farmers experiences in Kızıltepe Plain. This data is obtained during fieldwork interviews with farmers.

Furthermore, desired extraction by volume is:

$$desired\ extraction\ by\ volume = Irrigated\_Land*desired\_extraction*10 \tag{5.13.}$$

Desired extraction shown in equation 5.13. is equal to irrigation requirement and its calculation detail is discussed in the groundwater resources sector. Also, irrigated land should be found for a complete calculation of desired extraction by volume. Moreover, water table level data is vital for equation 5.9., and its calculation is shown in groundwater resources sector. Finally, pump efficiency data is required. According to farmers' experiences in Kızıltepe Plain, 0.85 is chosen as pump efficiency.

After explaining how to calculate desired energy per well, the next calculation is for energy per well. The ultimate aim is to compare how much energy is desired and how much energy is produced. For this reason, energy per well is:

$$\mathit{energy\ per\ well}=\mathit{pump\_power}*\mathit{monthly\_Operation\_time} \tag{5.14.}$$

Pump power and monthly operation time are required in order to calculate energy per well and the value of pump power is changed with its flow named pump power adjustment. The unit of pump power is kW and the equation of pump power adjustment is:

$$\mathit{pump\ power\ adjustment}=\mathit{MIN}(\mathit{pump\_power\_\_gap}/\mathit{pump\_power\_\_adjustment\_time},\ \mathit{possible\_pump\_power\_adjustment}) \tag{5.15.}$$

where pump power adjustment time is chosen as 36 months according to farmers' experiences. Also, possible pump power adjustment is:

$$\mathit{possible\ pump\ power\ adjustment}=(\mathit{maximum\_pump\_power}-\mathit{monthly\_pump\_power})/\mathit{pump\_power\_\_adjustment\_time} \tag{5.16.}$$

In order to calculate equation 5.16., maximum pump power value is chosen as 220 kW since it is the maximum pump power that was recorded during fieldwork. Farmers also agree that it is maximum power that they can use.

The other stock is monthly operation time and its unit is chosen as hours. The value of monthly operation time is changed with its flow named monthly operation adjustment time. The equation of monthly operation adjustment time is:

monthly operation adjustment time= MIN(monthly_operation__time_gap/adjustment_time_for_monthly_operation_time,possible_monthly_operation_time_adjustment) (5.17.)

where monthly operation adjustment time is chosen as 1 month according to farmers' experiences. Also, possible monthly operation time adjustment is:

possible monthly operation time adjustment= (maximum_monthly_operation_time-Monthly_Operation_time)/adjustment_time_for_monthly_operation_time (5.18.)

In order to calculate equation 5.18., maximum monthly operation time is needed and it is chosen as 720 hours which is equal to 1 month.

5.2.3. Land Use Sector

The land use sector gives information about conversion between irrigated land and rainfed land. The details of this sector are shown in Figure 5.9.

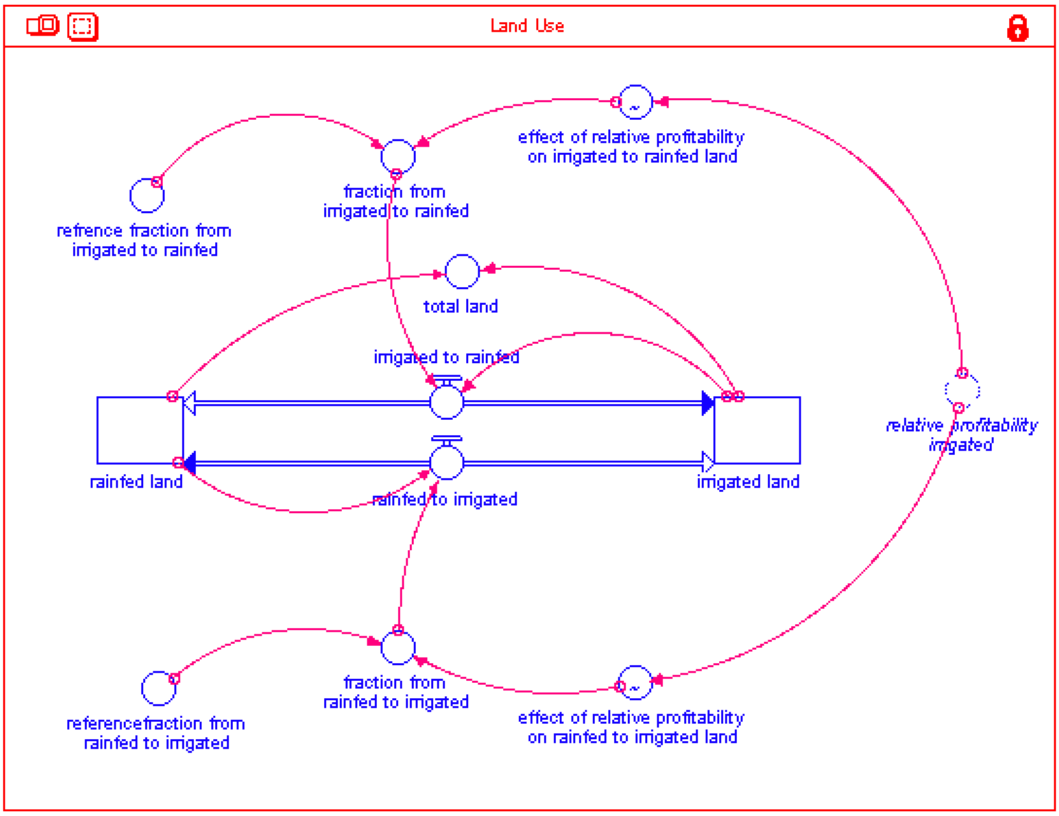

Figure 5.9. Stock-flow diagram of land use sector.

One of the most important parameters is “relative profitability irrigated” in this sector. Because, farmers’ crop choice decision is mostly depend on this parameter. If irrigated crop is more profitable, they will tend to choose irrigated crop. Otherwise, they will choose rainfed crop since it is less tedious and has less crop cost. The equation of relative profitability irrigated is:

Relative profitability irrigated=irrigated_crop_profit/(rainfed_crop_profit) (5.19)

The equation (5.19) shows the ratio of irrigated crop profit over rainfed crop profit In our base case, the ratio is 2.5 which means planting irrigated crop is 2.5 times more profitable than planting rainfed crop.

There are mainly two stocks in land use sector named as irrigated land and rainfed land.

The inflow equation from rainfed land to irrigated land is:,

*rainfed to irrigated=rainfed_land*fraction_from_rainfed_to_irrigated* (5.20)

Where fraction from rainfed to irrigated is equal to,

*fraction from rainfed to irrigated= effect_of_relative_profitability_on_rainfed_to_irrigated_land*referencefraction_from_rainfed_to_irrigated* (5.21)

There is an important effect of relative profitability irrigated parameter on change in rainfed land to irrigated land and this effect can be shown in Figure 5.10.

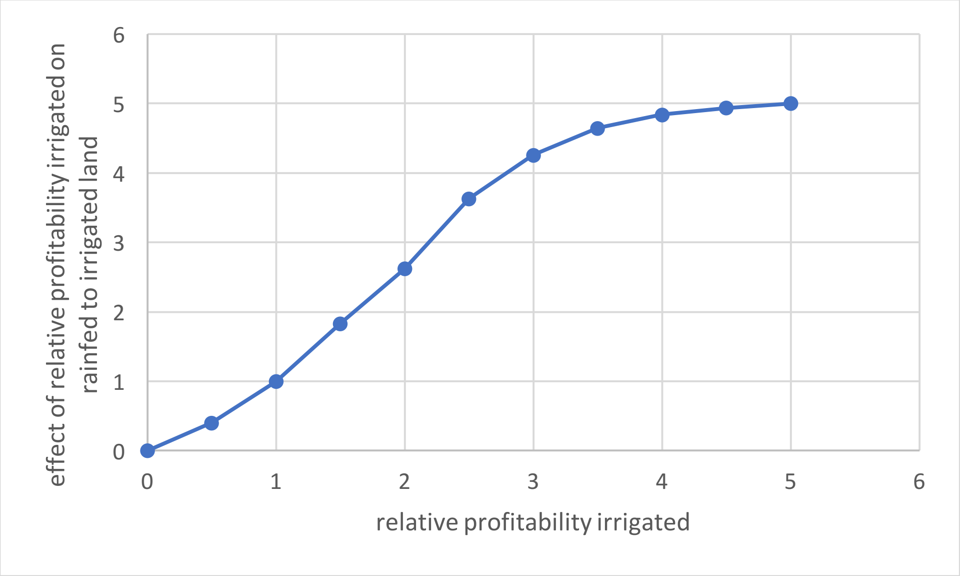

Figure 5.10. Effect of relative profitability on rainfed to irrigated land.

According to above Figure 5.9, as relative profitability irrigated parameter increases, conversion of rainfed land to irrigated land increases.

The outflow equation from irrigated land to reinfed is:

*Irrigated to reinfed= Irrigated_Land*fraction_from_irrigated_to_rainfed* (5.22)

Where fraction from irrigated to reinfed is:

*fraction from irrigated to reinfed= effect_of_relative_profitability_on_irrigated_to_rainfed_land*refrence_fraction_from_irrigated_to_rainfed* (5.23)

The effect of relative profitability parameter on change in irrigated land to rainfed land can be shown in Figure 5.11.

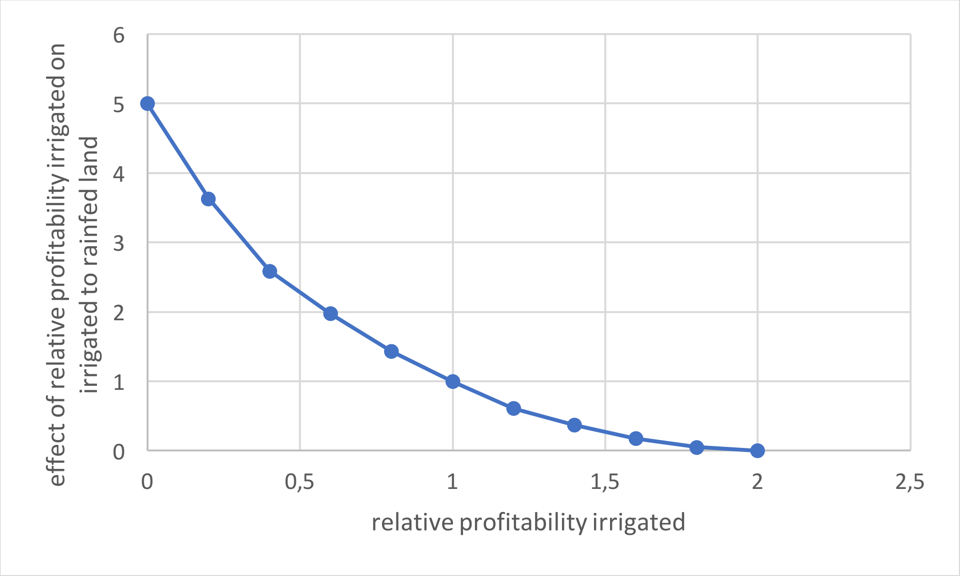

Figure 5.11. Effect of relative profitability on irrigated land to rainfed.

According to Figure 5.11, as relative profitability irrigated increases, conversion from rainfed land to irrigated land occurs.

5.2.4. Crop Profit Sector

Crop profit sector describes about the profitability of irrigated and rainfed crops. In this model, irrigated crop represents corn whereas rainfed crop represents wheat. The diagram of crop profit sector can be seen in Figure 5.12.

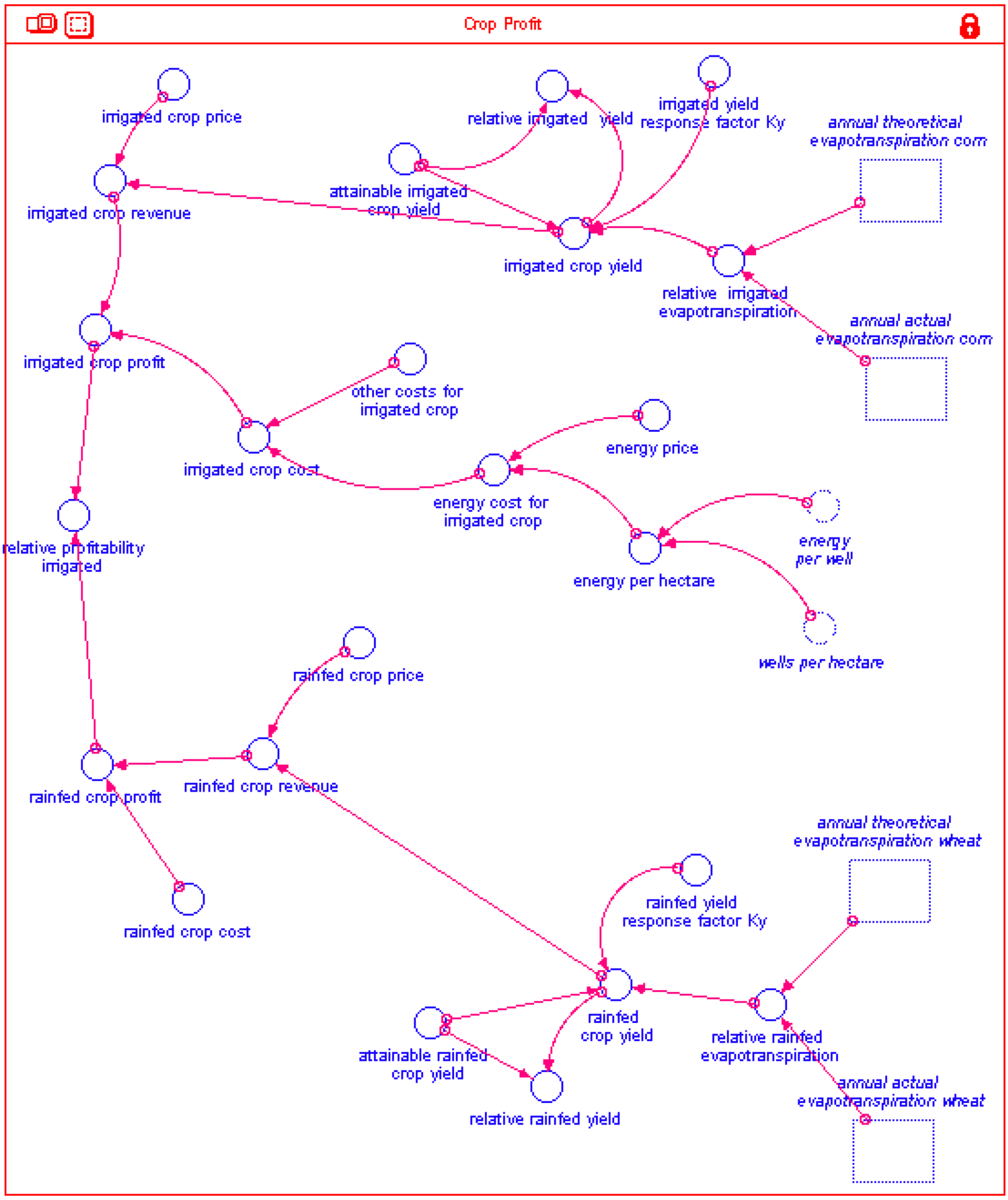

Figure 5.12. The diagram of crop profit sector.

This sector can be analyzed in two parts. The first part is calculation of irrigated crop profit and while the second part is calculation of rainfed profit.

In order to calculate irrigated crop profit, irrigated crop revenue and cost should be calculated since irrigated crop profit equation is defined as,

$$\textit{Irrigated crop profit} = MAX(0, irrigated\_crop\_revenue - irrigated\_crop\_cost) \tag{5.24}$$

Irrigated crop revenue equation is:

*Irrigated crop revenue=irrigated_crop_price*irrigated_crop_yield* (5.25)

Where irrigated crop price (corn) is chosen as 0.87 tl/kg. This value is defined according to the price announced by Kızıltepe commodity exchange (KIZILTEPE, 2017).

According to Doorenbos J. and Kassam A.H. (1979), irrigated crop yield can be calculated as:

$$\left(1-\frac{\mathrm{Ya}}{\mathrm{Yx}}\right)=\mathrm{Ky}*\left(1-\frac{\mathrm{ETa}}{\mathrm{ETx}}\right) \tag{5.26}$$

where,
Ya= actual yield
Yx= maximum yield
ETa=actual evapotranspiration
ETx= maximum evapotranspiration
Ky= yield response factor

By using above equation (5.26), irrigated crop yield is:

irrigated crop yield= attainable_irrigated___crop_yield(1-irrigated_yield_response_factor_Ky+irrigated_yield_response_factor_Ky*relative__irrigated_evapotranspiration)* (5.27)

In equation (5.27), attainable irrigated crop yield is chosen as 11000 kg/hectares and irrigated response factor is defined 1.25 for corn (Steduto et al., 2012).

Relative irrigated evapotranspiration equation is:

relative irrigated evapotranspiration= evapotranspiration__ETa/(monthly_theoretical___evapotranspiration_corn) (5.28)

where the equations of annual theoretical evapotranspiration corn and annual actual evapotranspiration corn are shown in groundwater resources sector.

Irrigated crop cost is another important parameter for the calculation of irrigated crop profit. The equation of irrigated crop cost is:

$$\textit{Irrigated crop cost} = \textit{energy\_cost\_for\_\_irrigated\_crop} + \textit{other\_costs\_for\_\_irrigated\_crop} \tag{5.29}$$

As seen from above the above equation (5.29), there are two parts of irrigated crop cost. Other costs for irrigated crops consist of cost of seed, fertilizer etc. whereas energy cost for irrigated crop represents the cost of energy needed to extract water. The equation for energy cost is:

$$\textit{energy cost for irrigated crop} = \textit{energy\_per\_hectare} * \textit{energy\_price} \tag{5.30}$$

This cost is calculated as tl/hectare. Energy price is determined as tl/kWhours and the value is currently 0.39 tl/kWhours. However, 65% of energy used for agriculture is subsidized by the state since it is used for agriculture (DEDAŞ, 2016). Thus, the energy price becomes 0.39*0.35=0.1365 tl/kWhours.

The rainfed crop profit calculation is similar to irrigated crop profit calculation. The only difference between rainfed crop profit and irrigated crop profit is energy cost since there are no energy cost needed for rainfed crop.

6. MODEL VALIDATION

Model validation is one of the most important steps in any modeling effort, including system dynamics methodology (Forrester, 1968; Forrester et al., 1974; Senge and Forrester, 1980; Barlas, 1989a; Barlas and Carpenter, 1990).

In system dynamics modeling, validation consists of two main parts referred to as structure validation and behavior validation. Since “the structure creates the behavior”, first structure of the model should be tested sufficiently. Structure validation is done in order to check whether the relationships used in the model are close enough to real relationships. After sufficient results are obtained from structure validation, behavior validation is carried out in order to demonstrate whether the behavior of the model is close enough to the real system behavior (Barlas, 1996).

6.1. Structural Validation with Indirect Structure Tests

The structural validation with indirect structure (or structure-oriented behavior) tests can be performed by extreme condition, parameter sensitivity, phase relationship, boundary adequacy tests and others (Barlas 1996).

We apply the extreme condition and parameter sensitivity tests in this study. In extreme condition tests, extreme values are assigned to selected parameters and then behaviors generated by the model are compared to “anticipated” (or observed) behavior of the real system under the same extreme conditions (Barlas,1989b). In parameter sensitivity tests, the values of selected parameters are changed and it is inquired whether the model and the mentally anticipated real system behavior exhibit similar sensitivity to those parameters.

6.1.1. Extreme Condition Tests

All extreme condition test results are shown for the first 48 months in order to analyze monthly change in detail.

6.1.1.1. No desired extraction by volume. For this test, desired extraction by volume is set to zero and only the water extraction sector is run. Since there is not any desired extraction, extraction by volume and energy per well rapidly decrease and become zero as anticipated. (Figure 6.1.)

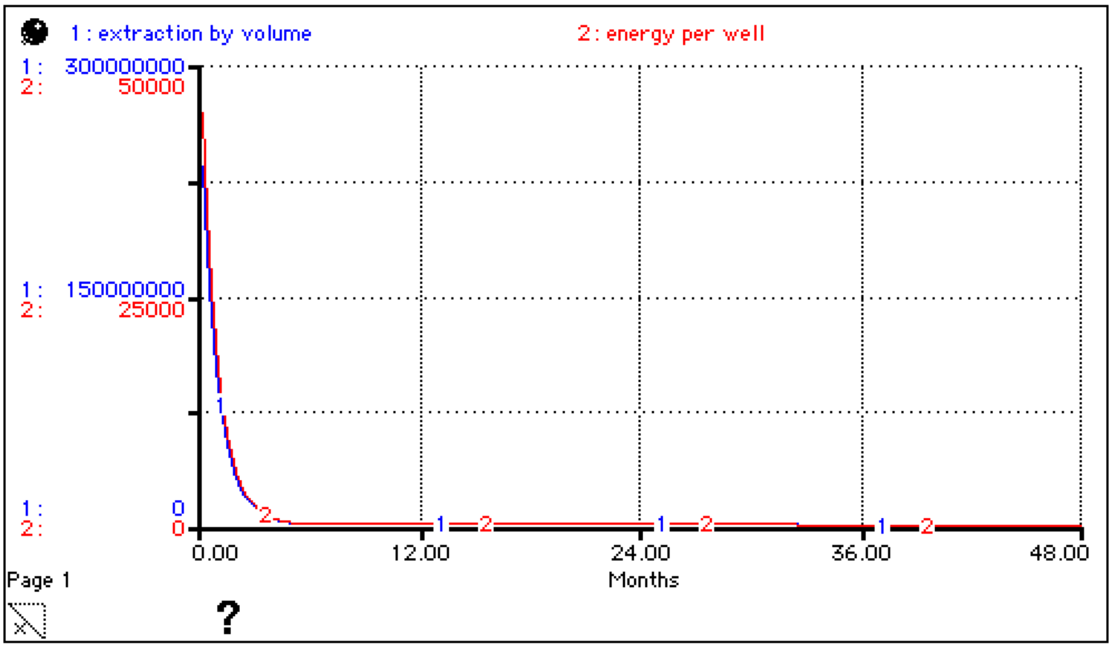

Figure 6.1. No desired extraction by volume.

6.1.1.2. Maximum desired extraction by volume. For this test, desired extraction by volume is set to its maximum value and the simulation is run. Since desired extraction by volume is maximum, both extraction by volume and energy per well reach their maximum value by the tenth month. It is meaningful to reach maximum volume and energy at tenth month since this is the month when harvesting starts and after tenth month, there is no need for irrigation until next season which starts at fourth month of the next year (Figure 6.2.).

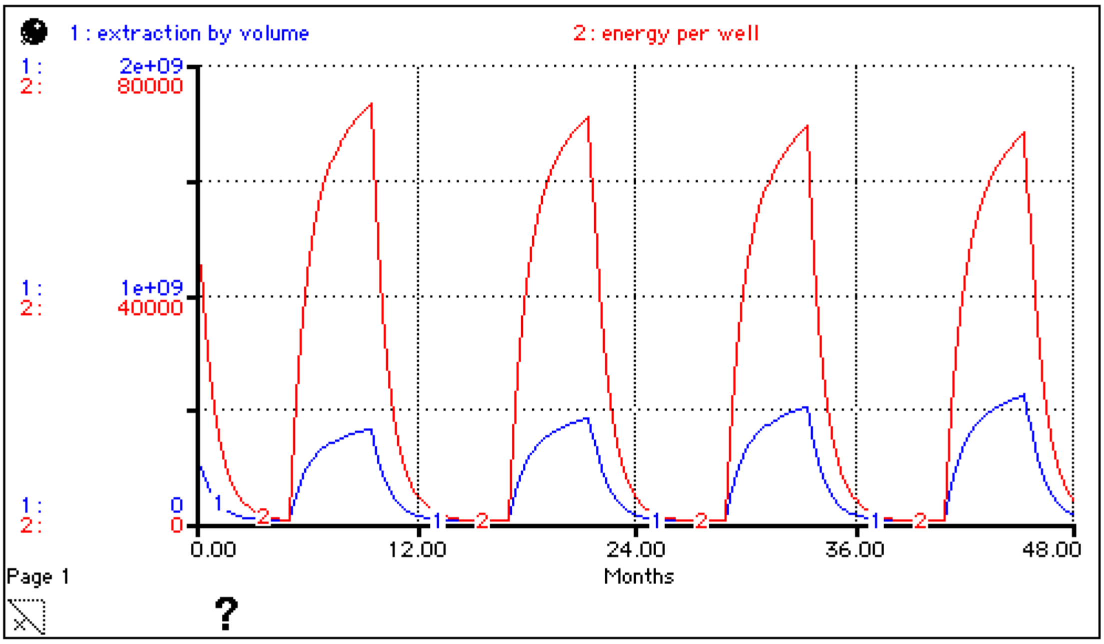

Figure 6.2. Maximum desired extraction by volume.

6.1.1.3. No extraction by volume. For this test, extraction by volume is set to zero and only the water extraction sector is run. Since there is not extraction by volume, monthly operation time and energy per well decrease and both of them become zero which is similar to real life practices (Figure 6.3.).

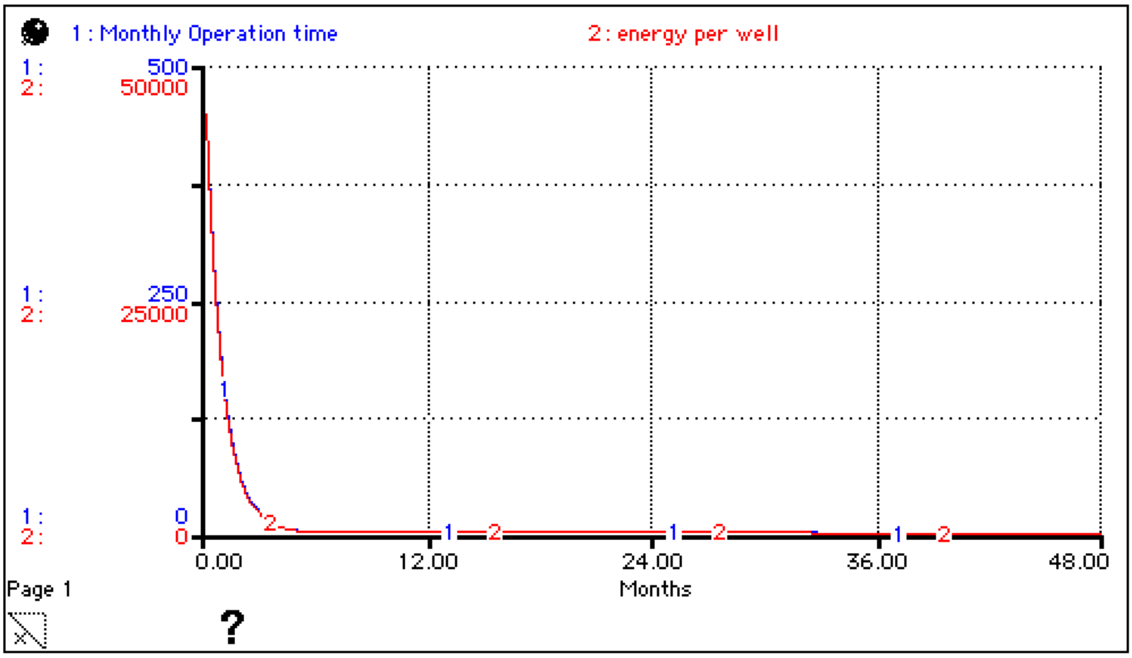

Figure 6.3. No extraction by volume.

6.1.1.4. Maximum extraction by volume. For this test, extraction by volume is set to its maximum value and simulation is run. Monthly operation time and energy per well reach their maximum values during irrigation season which is between April and September. After irrigation season finishes, both monthly operation time and energy per well values decrease and become zero until next irrigation season (Figure 6.4.).

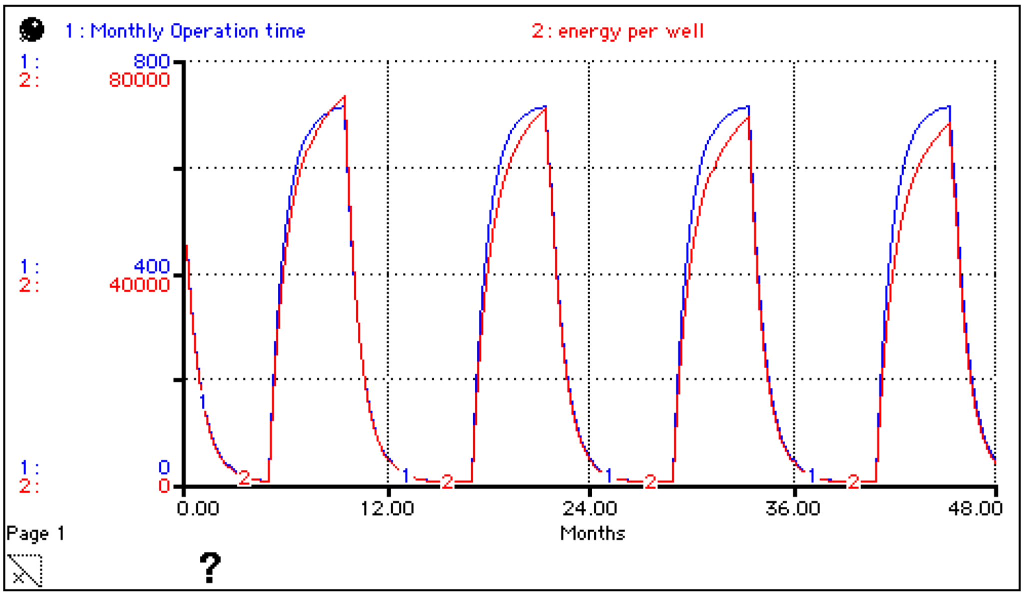

Figure 6.4. Maximum extraction by volume.

6.1.1.5. No precipitation. For this test, precipitation is set to zero and only groundwater sector is run. Rainfed crop yield decreases and reaches to zero since rainfed crop yield directly depends on precipitation. If there is not any precipitation, there will be no rainfed crop yield. However, it is not the same for irrigated crop yield since there is irrigation even though there is not any precipitation. With no precipitation, there is more irrigation and irrigated crop yield reaches equilibrium at very close to its maximum level. The situation in real life is also similar to model behavior (Figure 6.5.).

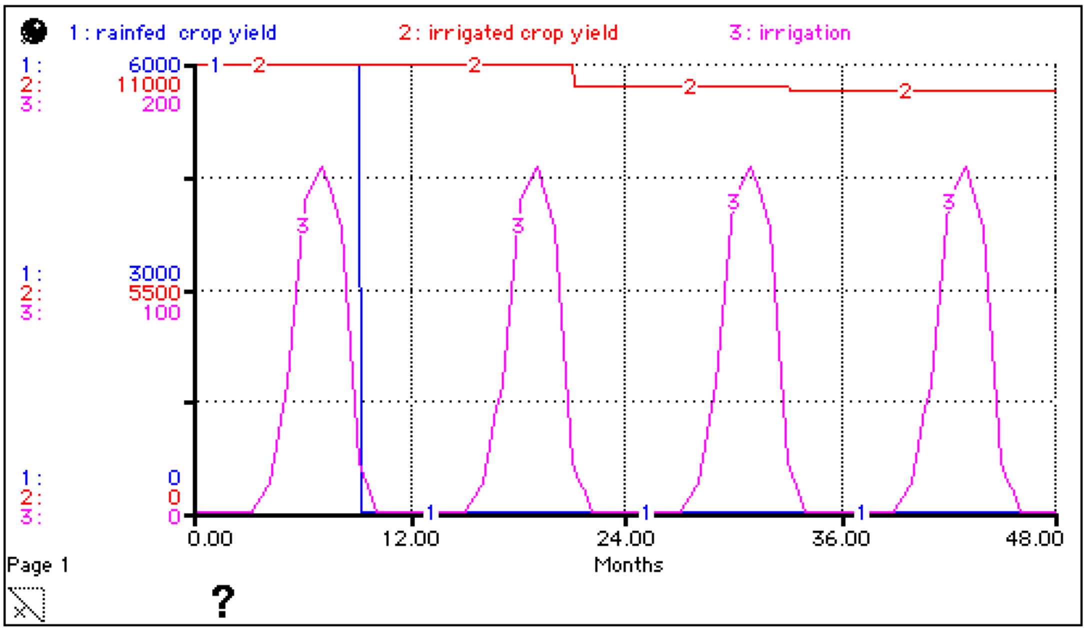

Figure 6.5. No precipitation.

<u>*6.1.1.6. Maximum precipitation*</u>. For this test, precipitation is set to its maximum value and only groundwater sector is run. Since there is excess precipitation, there is enough water for both type of crops. Therefore, irrigated crop yield and rainfeld crop yield reach their maximum values. Also, there is no need for irrigation. So, irrigation becomes zero. (Figure 6.6.).

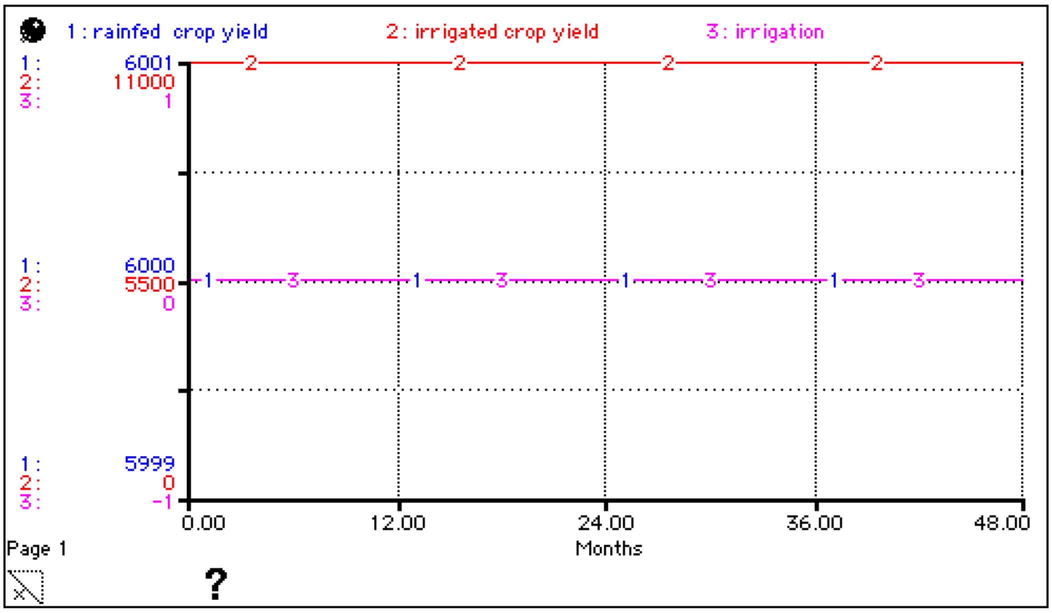

Figure 6.6. Maximum precipitation.

6.1.2. Parameter Sensitivity Tests

6.1.2.1. Sensitivity of the energy per well to pump efficiency. A sensitivity analysis is performed to assess the sensitivity of the results to pump efficiency. For this purpose, the efficiency was taken to be 0.7, 0.85 and 0.99 respectively. The results are shown in below Figure 6.7. Run 1 represents the behavior when pump efficiency is equal to 0.7, run 2 is for 0.85 and run 3 is for 0.99.

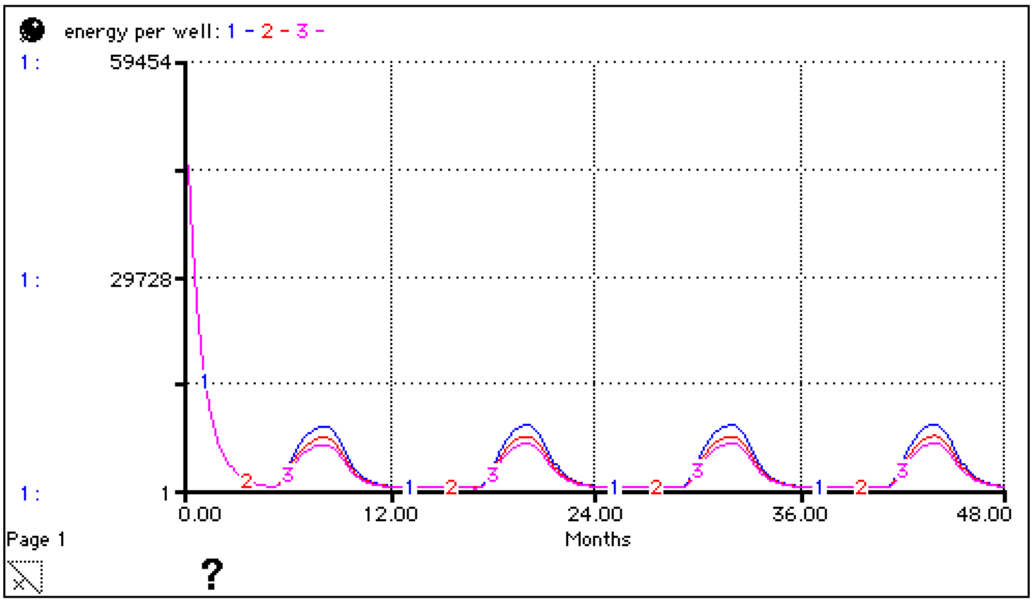

Figure 6.7. Sensitivity analysis for energy per well (change of pump efficiency).

According to above Figure 6.7., as pump efficiency increases less energy is required which can be shown to be the case using equation 5.10. This result is consistent with real life situations.

6.1.2.2. Sensitivity of irrigation requirement to irrigation efficiency. Irrigation efficiency is used in order to determine the amount of water required for irrigation. Therefore, a sensitivity analysis is performed with the values 0.5, 0.65 and 0.99 respectively. As irrigation efficiency increases, less water is required which can be proven by equation and can be seen in real life. This analysis is very important since nearly all farmers in Kızıltepe Plain are using flood irrigation as an irrigation technique. This technique has 0.65 efficiency which means it is not very effective. Therefore, as it is seen from below figure 6.8, if farmers change their irrigation techniques with sprinkler or drip irrigation, less water will be needed for irrigation.

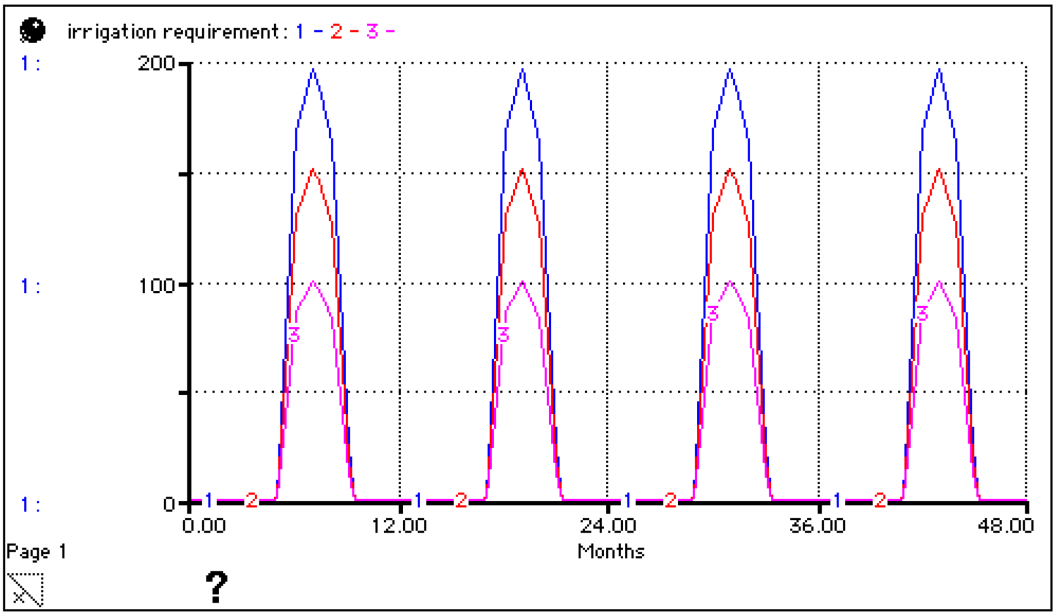

Figure 6.8. Sensitivity analysis of irrigation requirement (change of irrigation efficiency).

6.2. Behavioral Validation

Behavioral validation was conducted by comparing model results with historical data of the real system. Specifically, behavioral validation was conducted by comparing well numbers, irrigated land and water table level to their model counter parts. These tests are presented in the following sections.

6.2.1. Comparison of Model Output of Number of Wells with Historical Data

Number of wells is one of the most important parameter since it shows approximately the amount of water that is extracted from whole Kızıltepe Plain. The historical data shown in Figure 6.9 was taken from Work Hydraulic Works of Diyarbakır Branch. According to Figure 6.9., the behavior patterns of historical data and simulated data are similar to each other. However, the model consistently over-estimates the number of historical wells needed. The difference is attributed to the large number of unrecorded wells. The interviewed farmers and officials have mentioned this problem by claiming that half of the wells in Kızıltepe Plain may not be registered by State Hydraulic Works. To achieve historical crop yields, the number of wells must be larger than what is officially declared as the model results show.

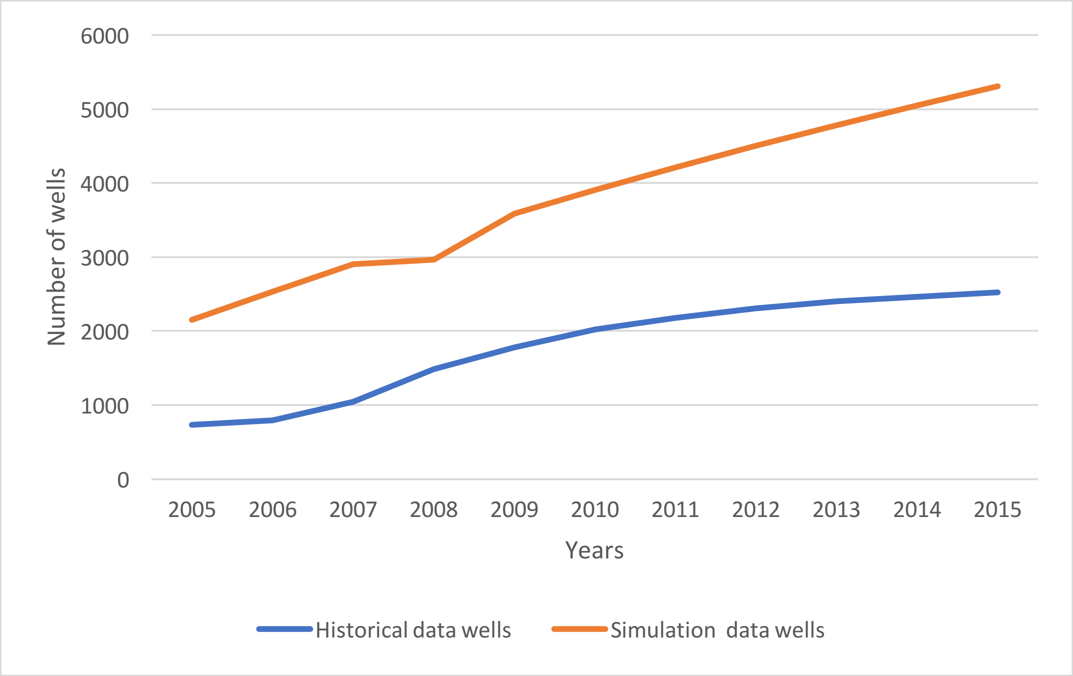

Figure 6.9. Number of wells historical vs simulation data.

6.2.2. Comparison of Model Output of Irrigated Land with Historical Data

____Irrigated land data gives information about how much water is required for lands in Kızıltepe Plain. The historical data was taken from Ministry of Food, Agriculture and Livestock of Mardin Branch. As it is seen from below figure 6.10., the behavior of simulated results and historical data are similar to each other, providing further confidence in the performance of the model.

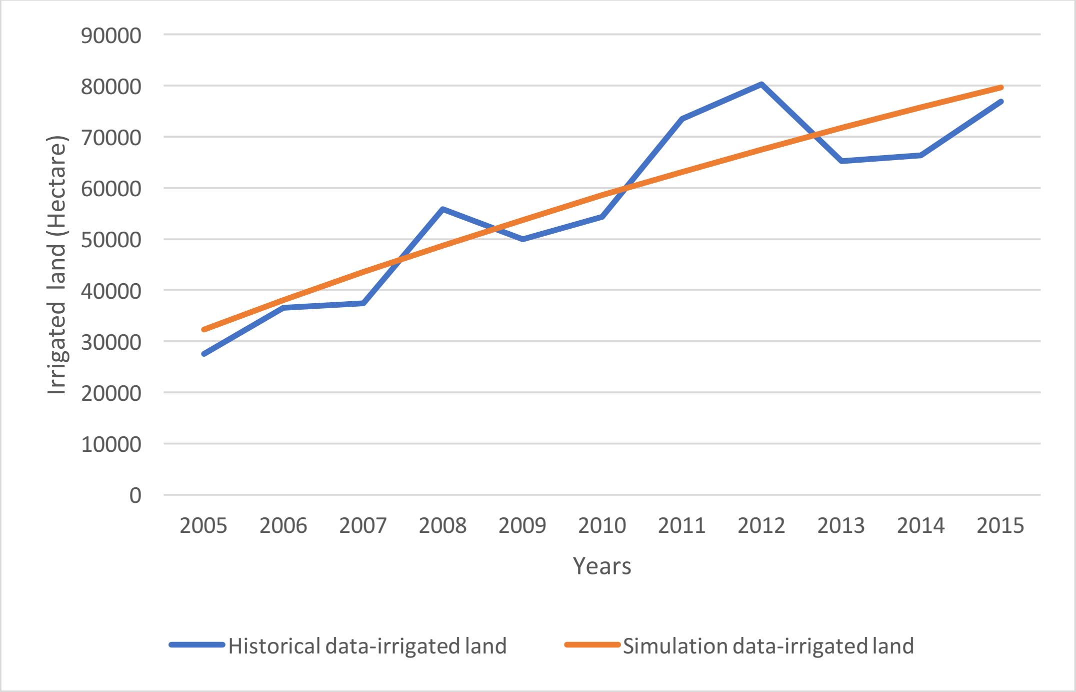

Figure 6.10. Irrigated land historical vs simulation data.

6.2.3. Comparison of Model Output of Water Table Level with Historical Data

Water table level is another important data since it is an indicator of how much water has been extracted and how much water is left in the aquifer for future generations. The historical data shown in Figure 6.11 was taken from Work Hydraulic Works of Diyarbakır Branch and all wells are belong to farmers which are used for irrigation purpose. As shown in below figure 6.11, the behavior of simulation results and historical data are not similar. The underlying reason may be the crop pattern change. Farmers planted cotton in huge amount between 2009 and 2014 and water table increased up to 185 meters during this period. Then, as farmers tended towards corn instead of cotton, water table level decreased. The irrigation requirement in the simulation model is based on the needs of corn and the model structure does not comprise crop choices of farmers Therefore, model output for water table level between 2009 and 2014 is different from historical data.

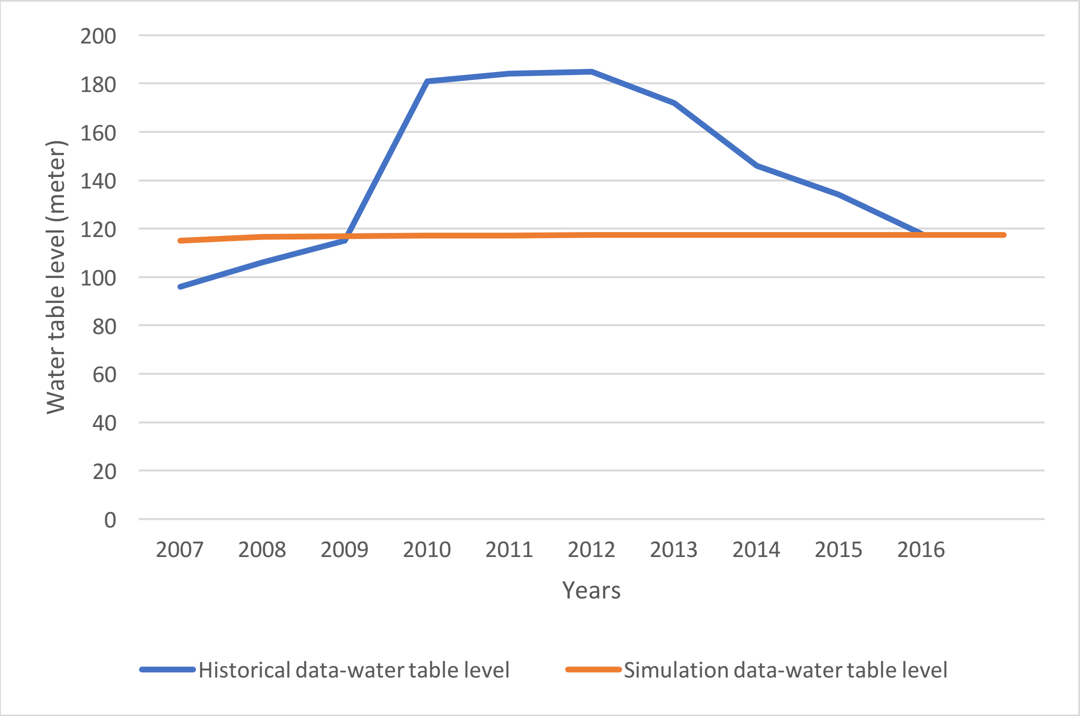

Figure 6.11. Water table level historical with vs simulation data.

7. REFERENCE BEHAVIOR OF THE MODEL

The complete stock-flow equations are given in Appendix A. The simulation runs were for 240 months, starting from year 2005 and finishing at 2025. Month zero represents January 2005 whereas month 240 represents December 2025. The historical data for different variables between 2005 and 2015 were used to compare with simulation data. The details of comparison are shown in previous chapter (Chapter 6) of behavioral validation part.

In Kızıltepe Plain, the amount of irrigated land has been increasing for the last ten years and it is expected to have similar tendency in future as farmers get enough water for irrigation. As there is an increase in irrigated land, there is a decrease in rainfed land since rainfed land is converted to irrigated land as shown in Figure 7.1.

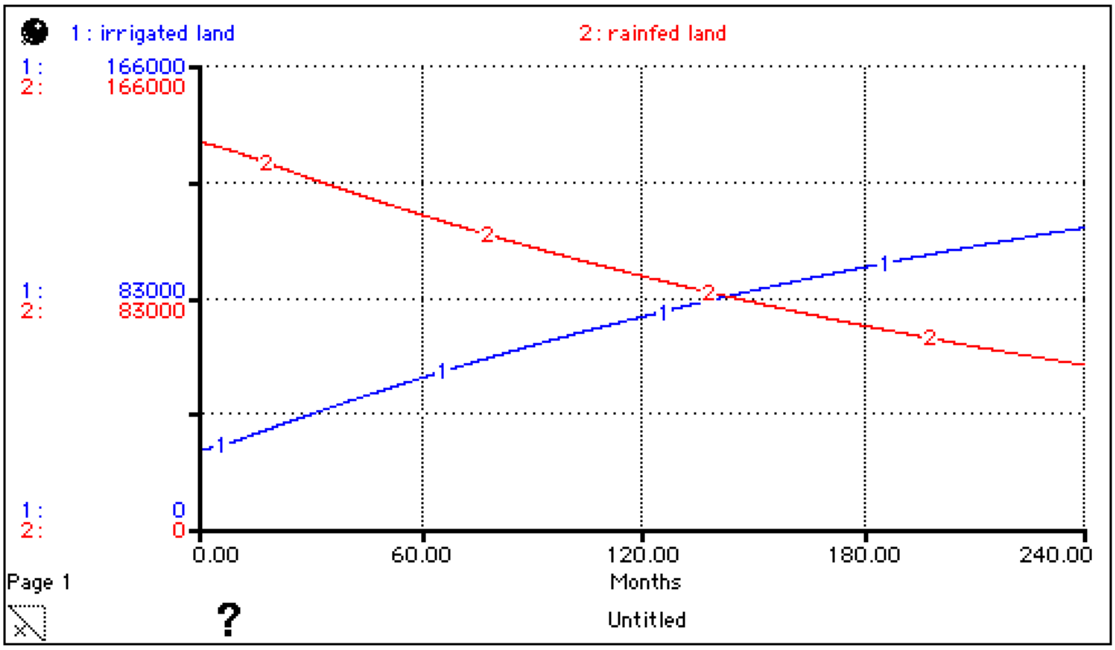

Figure 7.1. Reference dynamics of irrigated and rainfed land change.

As irrigated land changes, water in root zone and water in saturated zone also change. Moreover, change in water in saturated zone directly affects water table level. Figure 7.2. shows simulated change of these parameters with time. Change in water in root zone reaches its maximum level for every irrigation season i.e., between April and September whereas water in saturated zone decreases because the water extraction increases every year. Since the desired extraction increases every year, water table level increases and there is less water in saturated zone.

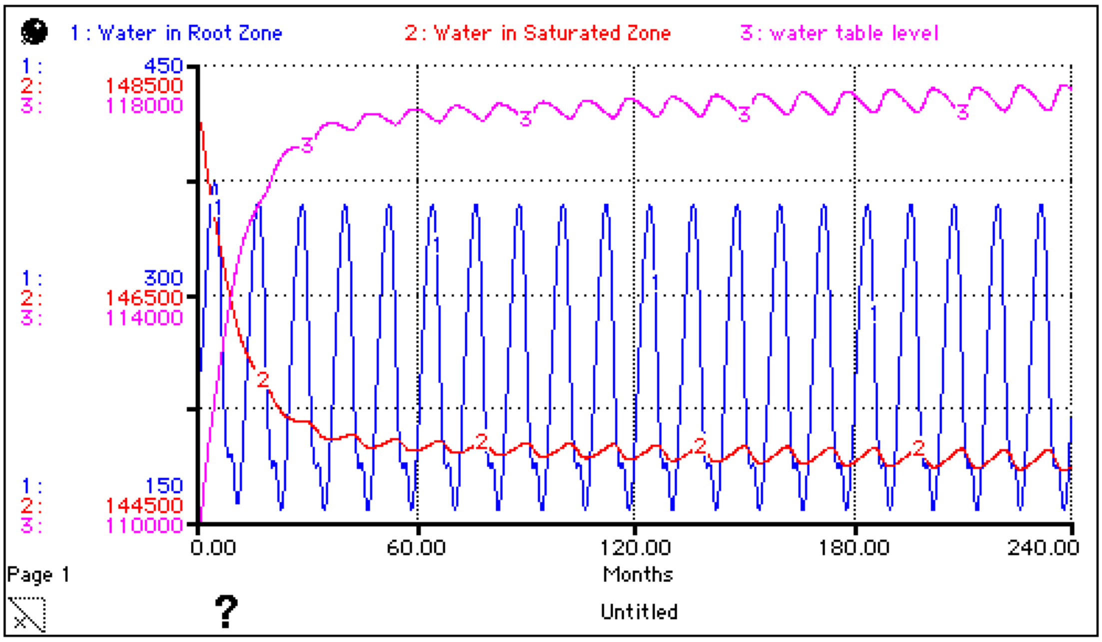

Figure 7.2. Reference dynamics of water in root zone, water in saturated zone and water table level.

Moreover, extraction directly affects monthly operation time of pumps and their power. Figure 7.3. shows the peak values of monthly operation time and pump power for every irrigation season. Monthly operation time and pump power have similar behavior and both of them tend to be stable.

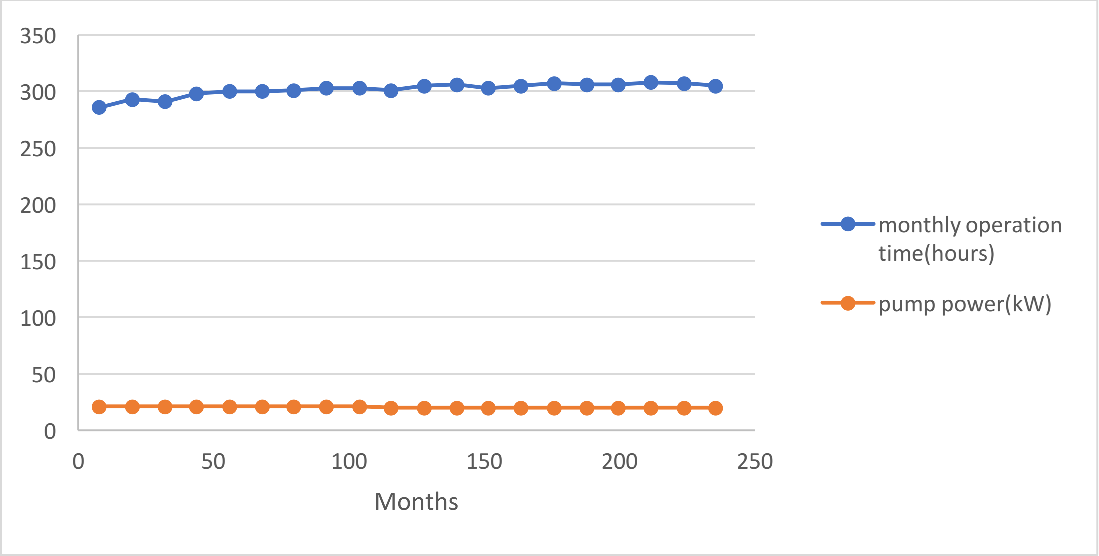

Figure 7.3. Reference dynamics of monthly operation time and pump power.

The energy consumed is the multiplication of monthly operation time and pump power. As shown in Figure 7.4, the change in energy per hectare is between 403 and 419 kWhours per month.

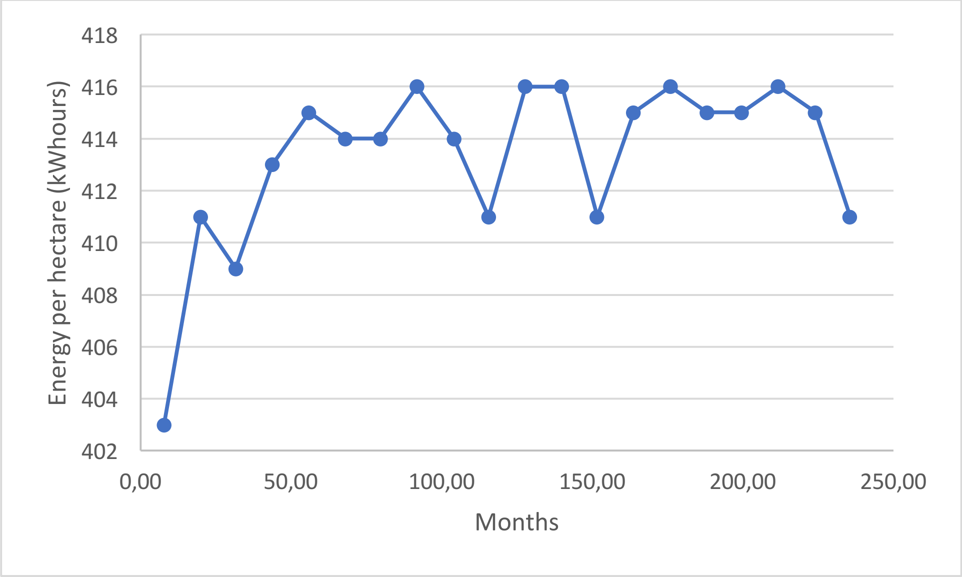

Figure 7.4. Reference dynamics of energy per hectare.

Consuming energy is directly related to groundwater extraction which depicted in Figure 7.5. The change in extraction per hectare is between 1275 and 1291 cubic meters per month.

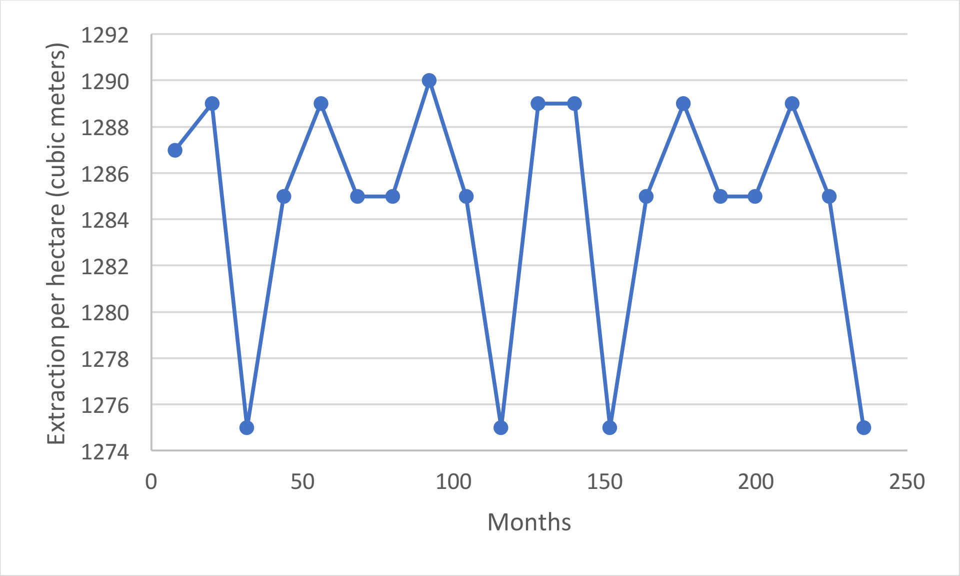

Figure 7.5. Reference dynamics of water extraction per hectare.

Reference dynamics of crop yields are also important because they reveal whether water extracted and the amount precipitation are enough for crops. Crop yields for both irrigated and rainfed are depicted in Figure 7.6.

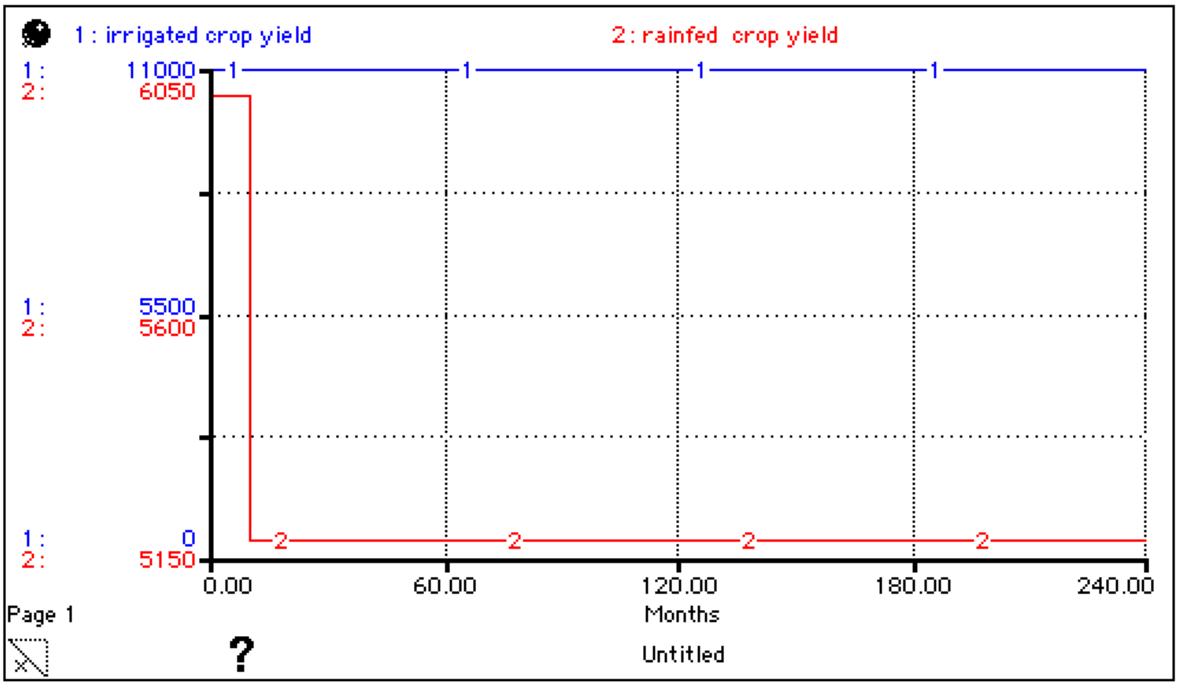

Figure 7.6. Reference dynamics of irrigated crop yield and rainfed crop yield.

As shown in Figure 7.6., extracted water is enough for irrigated crop and it reaches its attainable yield. However, precipitation is not enough for rainfed crop and its crop yield is below attainable yield.

Crop yields directly affect crop revenues. As shown in Figure 7.7., irrigated crop revenue is more than rainfed crop revenue although their prices are very close to each other i.e. irrigated crop (corn) price is 0. 87 tl/kg and rainfed crop (wheat) price is 0.9 tl/kg.

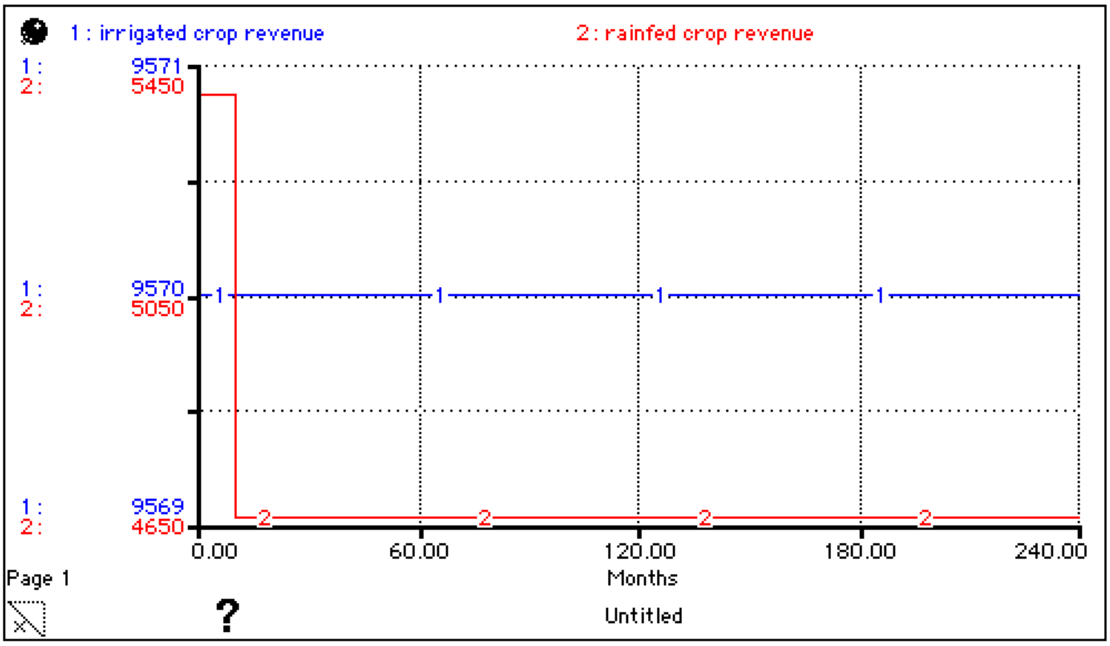

Figure 7.7. Reference dynamics of irrigated crop revenue and rainfed crop revenue

8. SCENARIO ANALYSIS

Several scenario analyses were performed with the model in order to gain further insight into the complex human-groundwater system. Each scenario and its impact on the model are illustrated below in detail.

8.1. Scenario Analyses Related to Irrigation Efficiency

Irrigation efficiency is taken as 0.65 for the reference run since farmers in Kızıltepe Plain mainly practice flood irrigation and irrigation efficiency for flood irrigation is 0.65 Sharmasarkar et al. (2001). However, there are more efficient practices and change in irrigation efficiency has direct effect on model behaviors. For example, sprinkler irrigation has 0.75 efficiency and drip irrigation's efficiency is 0.9 which is the highest compared with flood and sprinkler irrigation (Irrigation efficiencies, 1989).

8.1.1. Irrigation Type is Changed to Drip Irrigation

For this scenario, irrigation type is changed to drip irrigation which means irrigation efficiency is increased to 0.90. The base dynamics figures are simulated again and new outputs are presented.

First of all, below Figure 8.1. is compared with Figure 7.4. which shows reference dynamics of energy per hectare. As it is seen from these both figures have similar behaviors and there is a decrease in energy per hectare for every irrigation season which is an expected change.

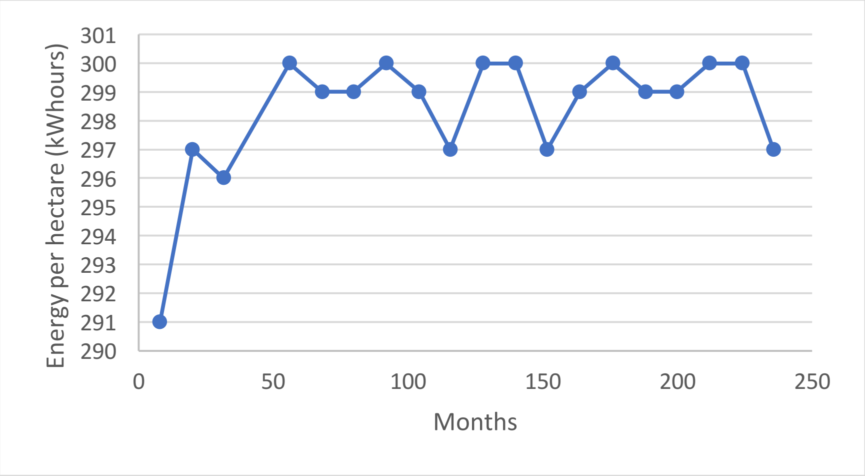

Figure 8.1. Behavior of energy per hectare (irrigation efficiency=0.9)

There is a similar decrease in extraction per hectare, shown in Figure 8.2., compared to Figure 7.5. which is reference dynamics of energy per hectare are compared with each other.

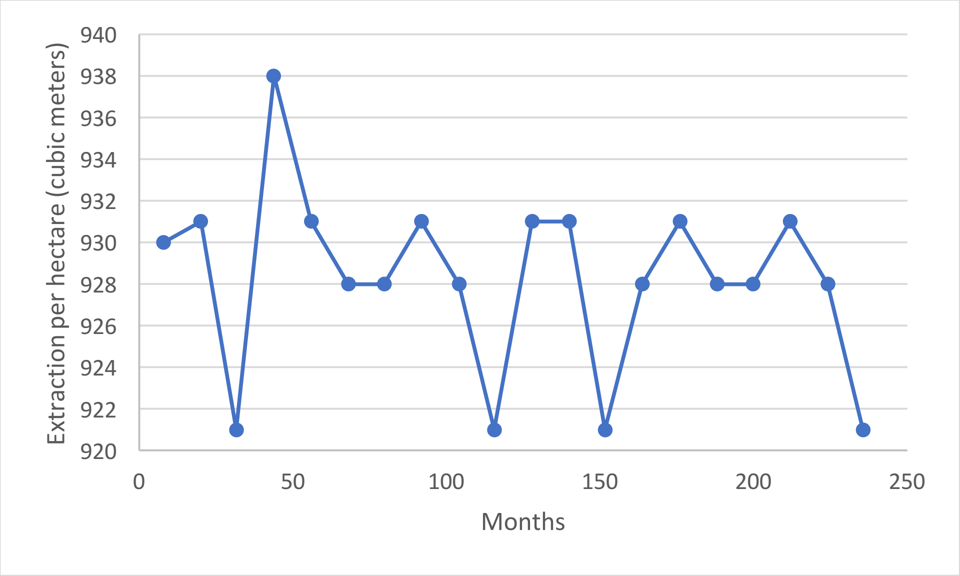

Figure 8.2. Behavior of extraction per hectare (irrigation efficiency=0.9).

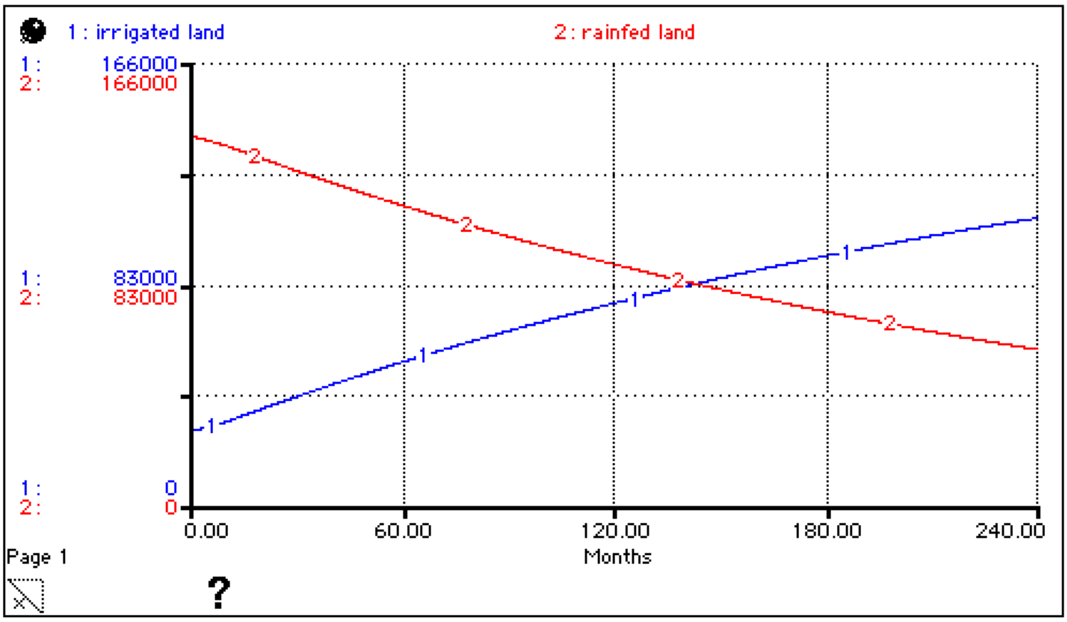

Figure 8.3. Behavior of irrigated and rainfed lands (irrigation efficiency=0.9).

However, there is a slightly increase in irrigated land and decrease in rainfed land, shown in Figure 8.3., compared to Figure 7.1. which is the reference dynamics of irrigated and rainfed land change.

Moreover, the behavior of water in root zone, water in saturated zone and water table level are analyzed after increasing irrigation efficiency. When below Figure 8.3. and Figure 7.2. is compared, it is seen that there is a change in amount of water in root zone. As irrigation efficiency increases, less water is required and there is less water left in water in root zone stock especially during periods when irrigation is not applied.

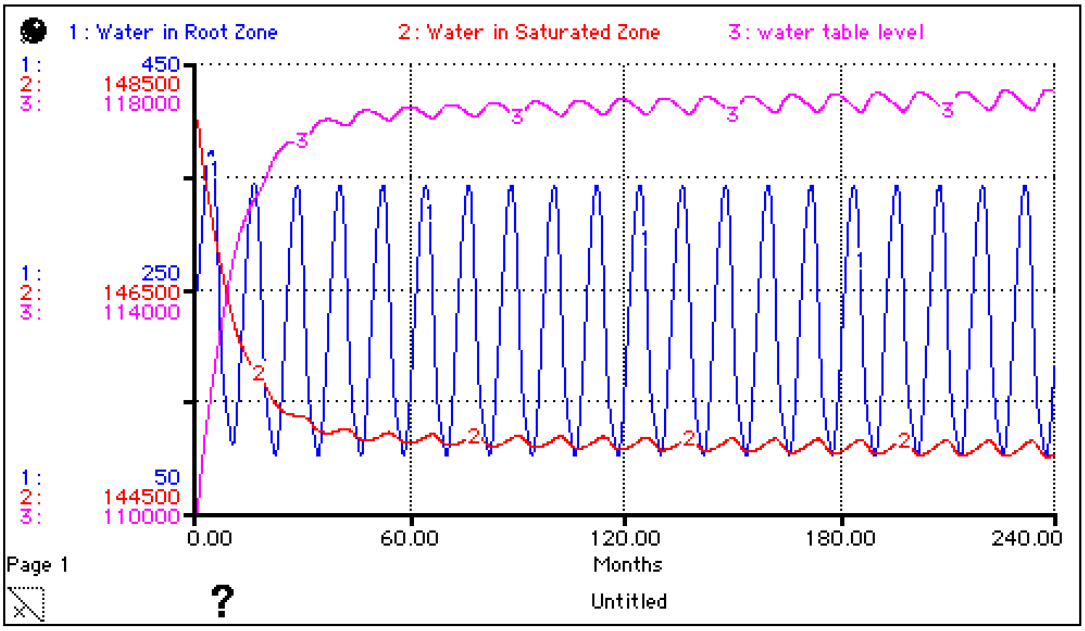

Figure 8.4. Water in root zone, water in saturated zone and water table level (irrigation efficiency=0.9).

The monthly operation time and pump power also decrease when the irrigation efficiency is increased. The decrease can be seen if below Figure 8.4. and Figure 7.3. which is reference dynamics of monthly operation time and pump power are compared with each other.

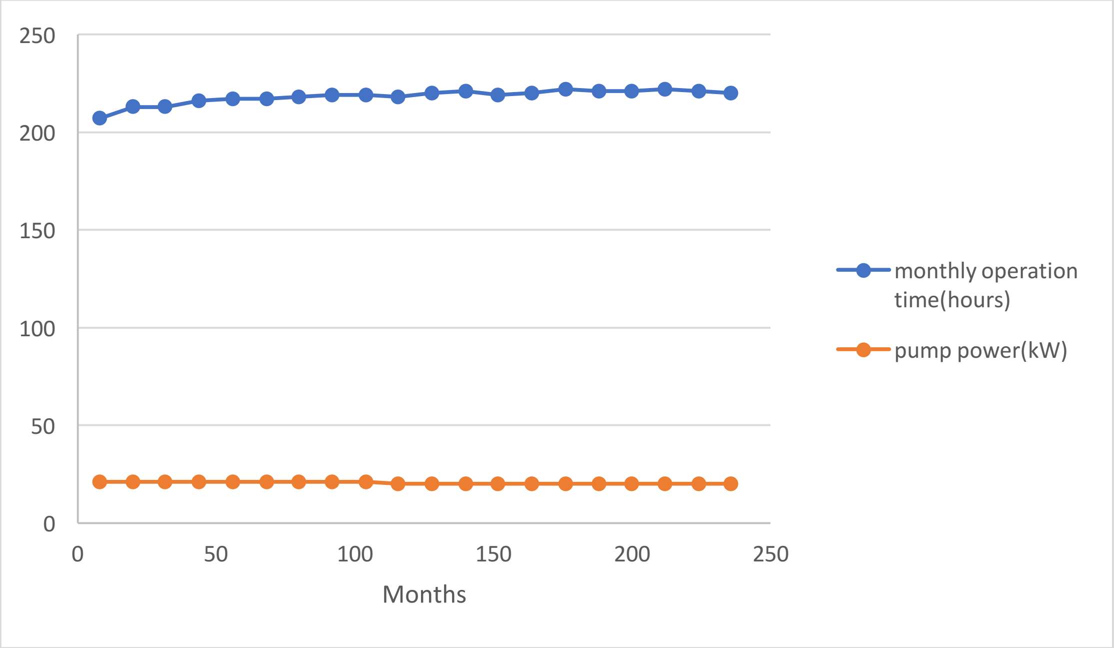

Figure 8.5. Behavior of monthly operation time and pump power (irrigation efficiency=0.9).

Irrigated crop yield and irrigated crop revenue remain same after an increase in irrigation efficiency because they reach their attainable values when irrigation efficiency is equal to 0.65 i.e. reference run.

8.2. Scenario Analysis Related to Reference Fraction from Rainfed to Irrigated Land

8.2.1. Reference Fraction from Rainfed to Irrigated Land is Changed

For this scenario, reference fraction from rainfed to irrigated is doubled. The underlying reason of this scenario can be state incentives. The state may have policies to increase amount of corn, which is an irrigated crop, if it is forecasted that the demand for corn will increase.

If reference fraction from rainfed to irrigated land is doubled, the amount of irrigated land will be increased in same period (Figure 8.5.) when it is compared with the reference dynamics of irrigated and rainfed land shown in Figure 7.1.

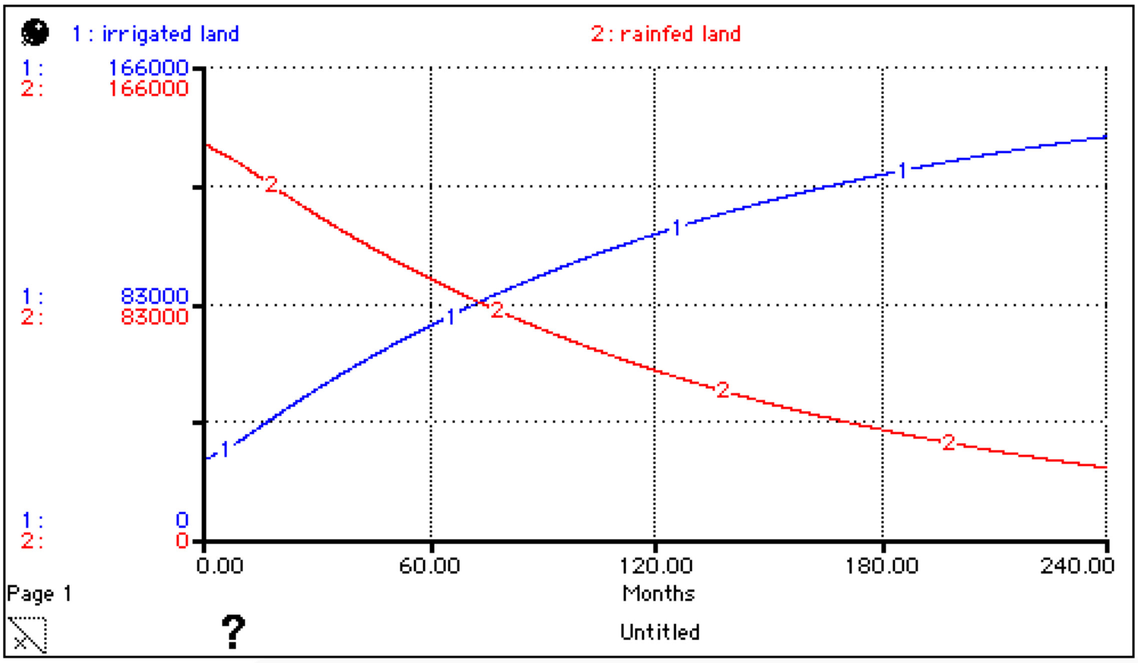

Figure 8.6. Irrigated and rainfed land change (reference fraction from rainfed to irrigated=0.002).

The rest of the variables shown in reference behavior chapter remain same after increasing reference fraction from rainfed to irrigated since reference fraction from rainfed to irrigated affect only irrigated land and rainfed land.

8.3. Scenario Analysis Related to Irrigated Crop Price

8.3.1. Irrigated Crop price is Doubled

For this scenario, irrigated crop price is doubled. This scenario may occur if the yield of irrigated crop decreases because of several reasons such as having less precipitation or problems occur with irrigation. If irrigated crop price is doubled, then irrigated land increases as shown in below Figure 8.6 when it is compared to Figure 7.1. which is the reference dynamics of irrigated land and rainfed land. As irrigated land increases, rainfed land decreases for the same period.

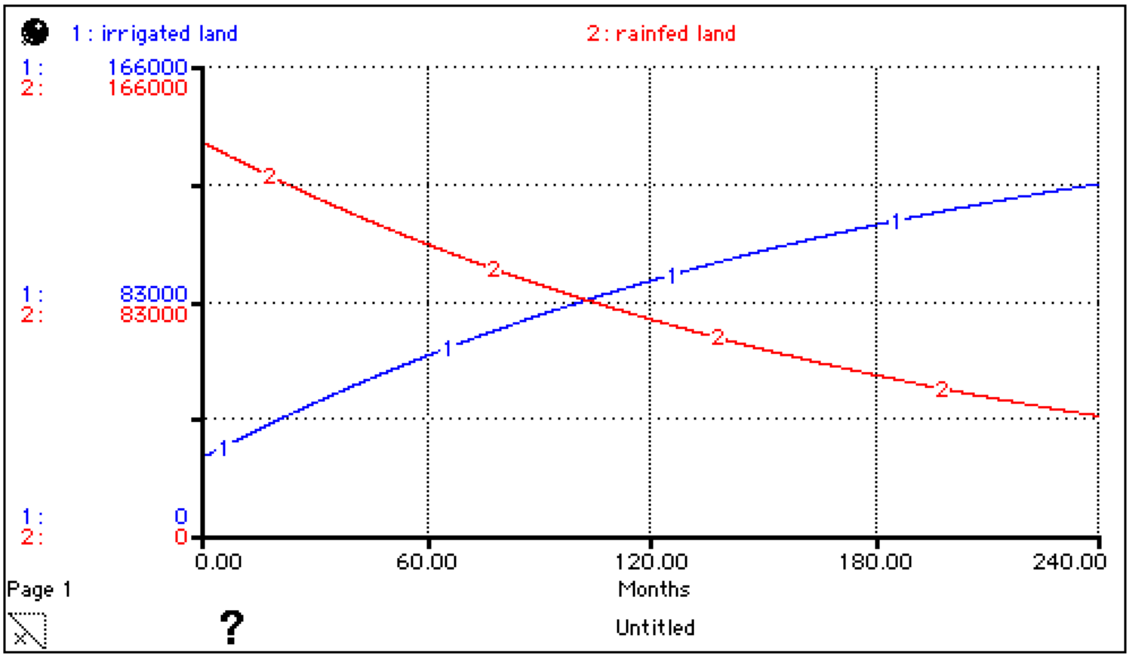

Figure 8.7. Irrigated and rainfed land change (irrigated crop price is doubled).

As crop price increases, farmers will make more profit. Figure 8.7. shows the increase in crop revenue when it is compared with Figure 7.7 which is reference dynamics of crop revenue.

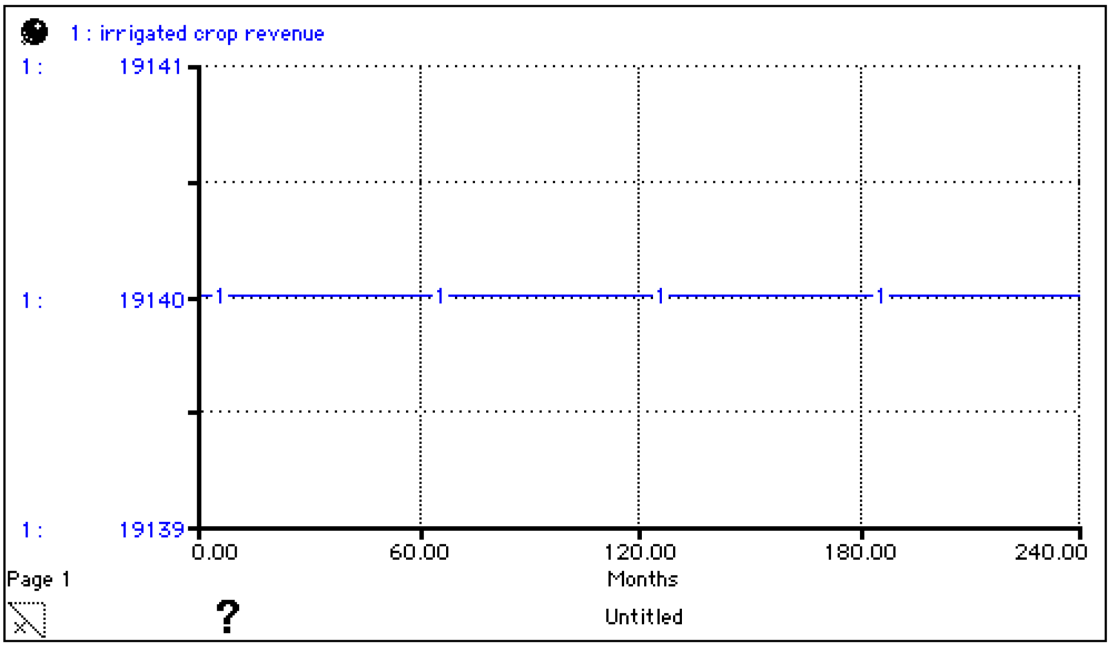

Figure 8.8. Behavior of irrigated crop revenue (irrigated crop price is doubled).

The rest of the variables shown in reference behavior chapter remain same after increasing in crop price since crop price affect only crop revenue, crop profit and the amount of both irrigated and rainfed lands.

9. RESULTS

The reference behavior of the model points to many problems related to irrigated land, water in saturated zone, water table level and pump power. According to the model reference run, there is a huge increase in irrigated land. This uncontrolled and unplanned increase may have negative effects on local aquifers. Also, since there is a drastic decrease in rainfed land, the amount of rainfed crop which is a basic need is reduced and the demand and price of rainfed crop may increase in future .

In the long term, as irrigated land increases, more water is needed for irrigation. This leads to a decrease in saturated water zone as pointed out by the model reference simulations. The decrease in saturated water zone directly affects water table level which makes it difficult and costly for farmers to access required water. Also, excessive extraction of water will have negative effects on dynamics of groundwater resources and aquifers.

According to model reference behavior, the pump power is used extensively. Farmers need a great amount of electrical power in order to extract water from deep wells. This is not a sustainable way of using electric power for irrigation and it causes lots of problems among farmers, local people and electric supply company during irrigation season.

Several Scenario analyses are performed on the model in order to gain insight into the system better. The first scenario which is related to irrigation efficiency reveals the change in energy per hectare and extraction per hectare, water in root zone, monthly operation time and pump power. Irrigation efficiency type is changed to drip irrigation assuming that all farmers give up flood irrigation and build infrastructure for drip irrigation which means that irrigation efficiency increases from 0.65 to 0.9. After this change, both energy per hectare and extraction per hectare decrease. Also, the amount of water in root zone becomes less especially during periods when there is no irrigation. Moreover, less monthly operation time and pump power. This scenario can be considered as one of the most important and effective scenario that can be taken in order to achieve a sustainable management system in Kızıltepe Plain.

In second scenario, government incentives for irrigated land is performed. In this case, the reference fraction from rainfed to irrigated is doubled which means farmers transform their rainfed lands to irrigated lands at a higher rate. This situation can occur if government gives incentives for irrigated land. An increase in reference fraction from rainfed to irrigated causes an increase in irrigated land which reduces rainfed land and causes a decrease in rainfed crop.

As a last scenario, irrigated crop price is doubled. As a result, there is an increase in irrigated land as expected since relative profitability irrigated parameter also increases. Moreover, farmers may give up planting rainfed crops which are the basic required crops. This will result in an increase in the price of rainfed crops. Therefore, this scenario cannot be a good option for sustainable irrigation of groundwater in Kızıltepe Plain.

10. CONCLUSION

In this research, the effects of groundwater fed irrigation on local aquifers and farmers choices in Kızıltepe Plain are analyzed in a long-term perspective. A dynamic simulation model is developed for this analysis. The model is based on system dynamics methodology, which provides us tools to explore and understand the complexity of hydrology of groundwater resources and the impact of human activities on groundwater exploitation. For this purpose, the dynamic model is developed in four different sectors representing groundwater resources, water extraction, land use and crop profitability.

The developed model is first tested by a series of structural and behavioral tests, which can be considered as standard validation procedure. First, each model sector is structurally validated by different extreme condition tests and parameter sensitivity tests. Then, the same procedure is applied to the whole model in order to test the model in a holistic way. Second, each model sector and then whole model is behaviorally validated. During this procedure, available data between 2005 and 2015 is used for model calibration purposes. By using this comparison, model behavior, which concerns number of wells, land use and water table level are validated.

The dynamic simulation model provides a platform where several scenarios can be analyzed. The model helps us improve our understanding of groundwater use in Kızıltepe Plain as a socio-ecological system. The research results are hoped to guide policy makers and farmers in achieving sustainable management of groundwater use in Kızıltepe Plain. Also, the simulation model developed in this research aims to contribute to system dynamics literature. The results of the model eventually will be shared with Ministry of Food, Agriculture and Livestock, State Hydraulic Works, Mardin Metropolitan Municipality, Tigris Development Agency (DİKA), local farmer organizations and other interested institutions.

Further research may concentrate on detail analysis of each sector in order to have a more useful model. For groundwater resources sector, choosing different irrigated and rainfed crops data would be useful as well in case there is a change in farmers crop choice in future. Testing the model under different climatic conditions would help us understand the dynamics of groundwater resources better. Also, the effect of precipitation on recharge would make the model more realistic since recharge changes as precipitation changes. For water extraction sector, adding the effect of well crowding would make the model more challenging but also more interesting since each neighbor well affects each other's extraction yield. For land use sector, adding uncultivated land stock would make land use model in detail and help us understand the interaction between irrigated, rainfed and uncultivated lands better. Also, collecting field data for certain variables such as infiltration, recharge, discharge and exact number of wells would be useful for further research. Finally, converting the model to a simulation game would be really helpful for policy makers and farmers to capture the dynamics of groundwater resources and the impact of human activities on groundwater exploitation.

REFERENCES

Bagheri M. H, Neychalani T. M, Farhian F., Bagheri A., 2015. Groundwater level modeling using system dynamics to investigate sinkhole events. International Journal of Hydrology Science and Technology, 5, 4.

Barlas, Y., 1989a. Multiple tests for validation of system dynamics type of simulation models. European Journal of Operational Research, 42, 59-87.

Barlas, Y., 1989b. Tests of model behavior that can detect structural flaws: demonstration with simulation experiments. In Computer-Based Management of Complex Systems, 246-254. Springer, Berlin, Heidelberg, Germany.

Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. System Dynamics Review, 12, 183-210.

Barlas, Y., 2007. System dynamics: systemic feedback modeling for policy analysis. System, 1, 59.

Barlas, Y., Carpenter, S., 1990. Philosophical roots of model validation: two paradigms. System Dynamics Review, 6, 148-166.

Briggs, A. C., 2010. Water shortages: Environmental, Economic and Social Impacts. Nova Science Publishers, New York, U.S.A.

Bueno N. P., 2014. Misperceptions of feedbacks and the resilience of common-pool resource systems: a discussion for irrigation systems based on loop dominance analysis, International Journal of the Commons, 8, 79-106.

Çakmak, B., Yapılar, T., Yıldırım, M., Aküzüm T., 2008. Türkiye'de tarımsal sulama yönetimi, sorunları ve çözüm önerileri. TMMOB II. Su Politikaları Kongresi, Ankara, Turkey.

Dedaş çiftçiye borcu için süre verdi, 2016. http://www.enerjigunlugu.net/icerik/18461/dedas-ciftciye-borcu-icin-sure-verdi.html. Date accessed December 2017.

Domenico, P. A., Schwartz, F. W., 1998. Physical and chemical hydrogeology. John Wiley and Sons, Inc., New York, U.S.A

Doorenbos, J., Kassam, A. H., 1979. Yield response to water. Irrigation and drainage paper, 33-257, FAO, Rome, Italy.

Eamus, D., Froend, R., Loomes, R., Hose, G., Murray, B., 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Australian Journal of Botany, 54, 97-114.

Fernández, J. M., Selma, M. A. E., 2004. The dynamics of water scarcity on irrigated landscapes: Mazarrón and Aguilas in south-eastern Spain. System Dynamics Review, 20, 117-137.

Ford, A., 1996. Testing snake river explorer. System Dynamics Review 12, 305-329.

Forrester, J. W., 1968. Industrial dynamics—a response to Ansoff and Slevin. Management Science, 14, 601-618.

Forrester, J. W., 1997. Industrial dynamics. Journal of the Operational Research Society, 48, 1037-1041.

Forrester, J. W., Low, G. W., Mass, N. J., 1974. The debate on world dynamics: a response to Nordhaus. Policy Sciences, 5, 169-190.

Gap Teyap Sulama Zaman Planlaması., 2015. http://www.gapteyap.org/wp-content/uploads/2015/02/BİTKİ-SU-TÜKETİMİ-GAP-TEYAP-.pdf. Date accessed December 2017.

Hardin, G., 1968. The tragedy of the commons. Science, 162, 1243–1248

IPCC, 2014. Climate change: Impacts, Adaptation and Vulnerability. http://www.ipcc.ch/report/ar5/wg2/. Date accessed December 2017.

Irrigation efficiencies., 1989. http://www.fao.org/docrep/t7202e/t7202e08.htm. Date accessed December 2017.

Kızıltepe., 2017. http://kiziltepetb.org.tr/site/default.asp?lang=tr. Date accessed December 2017.

Lowi, M. R., 1995. Water and power: The politics of a scarce resource in the Jordan River Basin. Cambridge University Press, Cambridge, UK.

Mardin Mevsim Normalleri 1981-2010., 2017. https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=H. Date accessed December 2017.

Mardin Büyükşehir Belediyesi Su ve Kanalizasyon İdaresi Genel Müdürlüğü. http://www.marsu.gov.tr/menu.aspx?parentID=34&menuID=146&lang=1. Date accessed December 2017.

Mardin İli 2014 Yılı Çevre Durum Raporu. http://www.csb.gov.tr/db/ced/editordosya/MARD%C3%84%C2%B0N-2014.pdf. Date accessed December 2017.

Meadows, D. L., Fiddaman, T., Shannon, D., 1993. Fish banks, LTD. Game administrator's manual. Laboratory for interactive learning, Institute for Policy and Social Science Research Hood House, University of New Hampshire, Durham, USA.

Mirchi, A., Madani K., Watkins D., Ahmad S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems, Water Resources Management, 26, 2421-2442.

Moxnes, 2015. http://www.uib.no/en/course/GEO-SD660. Date accessed March 2017.

141 büyük ova, koruma alanı olarak belirlendi., 2017. http://tarim.gov.tr/Haber/1102/141-Buyuk-Ova-Koruma-Alani-Olarak-Belirlendi. Date accessed July 2017.

Ostrom, E., Gardner, R., Walker, J., 1994. Rules, games, and common-pool resources. University of Michigan Press. U.S.A.

Richardson, G. P., 1986. Problems with causal-loop diagrams. System Dynamics Review, 2, 158-170.

Rushton, K. R., 2004. Groundwater hydrology: Conceptual and computational models. John Wiley and Sons, Inc., U.S.A.

Sampat, P., 2000. Groundwater shock: The polluting of the World's major fresh water stores. World Watch, 13, 10–22.

Saysel, A. K., Barlas, Y., Yenigün, O., 2002. Environmental sustainability in an agricultural development project: a system dynamics approach. Journal of Environmental Management, 64, 247-260.

Senge, P. M., Forrester, J. W., 1980. Tests for building confidence in system dynamics models. System Dynamics, 14, 209-228.

Sharmasarkar, F. C., Sharmasarkar, S., Miller, S. D., Vance, G. F., Zhang, R., 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugar beets. Agricultural Water Management, 46, 241-251.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F. T., 2010. Groundwater use for irrigation – a global inventory. Hydrology and Earth System Sciences, 14, 1863-1880.

Sönmez, M. E., 2012. Kızıltepe ilçesinde bitkisel ürün deseninde meydana gelen değişimler ve olası olumsuz sonuçları. Coğrafi Bilimler Dergisi, 10, 39-62.

Stave, K. A., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. Journal of Environmental Management, 67, 303-313.

Sterman, J. W., 2000. Business dynamics: Systems thinking and modeling for a complex world, McGraw-Hill., U.S.A.

Sterman J, King A., 2011. Fishbanks simulation instructors' guide: Setup and player briefing. MIT Sloan School of Management, 11-131.

The world's water., 2016 https://water.usgs.gov/edu/earthwherewater.html. Date accessed May 2017.

Türkiye'de Sulanan Bitkilerin Bitki Su Tüketimi Rehberi., 2016. https://www.tarim.gov.tr/TAGEM/Belgeler/Türkiyede%20Sulanan%20Bitkilerin%20Su%20Tüketimi%20Rehberi%205-9-2016.pdf. Date accessed June 2017.

Van den Belt, M., 2004. Mediated modeling: a system dynamics approach to environmental consensus building. Island Press., U.S.A.

Walker, B., Salt, D., 2006. Resilience thinking: sustaining ecosystems and people in a changing world. Island Press., U.S.A.

Water. http://www.wri.org/our-work/topics/water. Date accessed October 2017.

Winz, I. ve G. Brierley, 2007. The use of system dynamics simulation in integrated water resources management, Proceedings of the 25th International Conference System Dynamics, July 29 – August 2, 2007, Boston, U.S.A.

APPENDIX A: LIST OF EQUATIONS FOR THE WHOLE MODEL

Water_in_Root_Zone(t) = Water_in_Root_Zone(t - dt) + (irrigation + precipitation - runoff - evapotranspiration__ETa - infiltration) * dt
INIT Water_in_Root_Zone = 248
INFLOWS:
irrigation = MIN(irrigation_requirement,available_irrigation_water)
precipitation = monthly_average_precipitation
OUTFLOWS:
runoff = Water_in_Root_Zone*fractional_runoff
evapotranspiration__ETa =
MIN(monthly_theoretical___evapotranspiration_corn,max_evapotranspitarion)
infiltration = Water_in_Root_Zone*fractional_infiltration
Water_in_Saturated_Zone(t) = Water_in_Saturated_Zone(t - dt) + (infiltration + recharge - discharge - extraction) * dt
INIT Water_in_Saturated_Zone = 148000
INFLOWS:
infiltration = Water_in_Root_Zone*fractional_infiltration
recharge = 14500
OUTFLOWS:
discharge = Water_in_Saturated_Zone*fractional_discharge
extraction = extraction_by_volume/total_land/10
annual_actual_evapotranspiration_corn(t) = annual_actual_evapotranspiration_corn(t - dt) + (Flow_3 - Flow_4) * dt
INIT annual_actual_evapotranspiration_corn = 323
INFLOWS:
Flow_3 = IF month_count=9 THEN annual_total_evapotranspiration_corn/DT ELSE 0
OUTFLOWS:
Flow_4 = IF month_count=9 THEN annual_actual_evapotranspiration_corn/DT ELSE 0
annual_actual_evapotranspiration_wheat(t) = annual_actual_evapotranspiration_wheat(t - dt) + (Flow_5 - Flow_8) * dt
INIT annual_actual_evapotranspiration_wheat = 158

INFLOWS:

Flow_5 = IF month_count=9 THEN annual_total_evapotranspiration_wheat/DT ELSE 0

OUTFLOWS:

Flow_8 = IF month_count=9 THEN annual_actual_evapotranspiration_wheat/DT ELSE 0

annual_theoretical_evapotranspiration_corn(t) = annual_theoretical_evapotranspiration_corn(t - dt) + (Flow_1 - Flow_2) * dt

INIT annual_theoretical_evapotranspiration_corn = 323

INFLOWS:

Flow_1 = IF month_count=9 THEN annual_total_theoretical_evapotranspiration_corn/DT ELSE 0

OUTFLOWS:

Flow_2 = IF month_count=9 THEN annual_theoretical_evapotranspiration_corn/DT ELSE 0

annual_theoretical_evapotranspiration_wheat(t) = annual_theoretical_evapotranspiration_wheat(t - dt) + (Flow_7 - Flow_6) * dt

INIT annual_theoretical_evapotranspiration_wheat = 158

INFLOWS:

Flow_7 = IF month_count=9 THEN annual_total_theoretical_evapotranspiration_wheat/DT ELSE 0

OUTFLOWS:

Flow_6 = IF month_count=9 THEN annual_theoretical_evapotranspiration_wheat/DT ELSE 0

annual_total_evapotranspiration_corn(t) = annual_total_evapotranspiration_corn(t - dt) + (increase_ann_evapot_corn - decrease_annual_evapot_corn) * dt

INIT annual_total_evapotranspiration_corn = 0

INFLOWS:

increase_ann_evapot_corn = evapotranspiration__ETa

OUTFLOWS:

decrease_annual_evapot_corn = IF month_count=10 THEN annual_total_evapotranspiration_corn/DT else 0

annual_total_evapotranspiration_wheat(t) = annual_total_evapotranspiration_wheat(t - dt) + (increase_annual_evapot_wheat - decrease_annual_evapot_wheat) * dt

INIT annual_total_evapotranspiration_wheat = 0

INFLOWS:

increase_annual_evapot_wheat = reinfed_evapotranspiration

OUTFLOWS:

decrease_annual_evapot_wheat = IF month_count=10 THEN annual_total_evapotranspiration_wheat/DT else 0

```
annual_total_theoretical_evapotranspiration_corn(t) =
annual_total_theoretical_evapotranspiration_corn(t - dt) + (increase_ann_theor_evapot -
decrease_ann_theor_evapot) * dt
INIT annual_total_theoretical_evapotranspiration_corn = 0
INFLOWS:
increase_ann_theor_evapot = monthly_theoretical___evapotranspiration_corn
OUTFLOWS:
decrease_ann_theor_evapot = IF month_count=10 THEN
annual_total_theoretical_evapotranspiration_corn/DT ELSE 0
annual_total_theoretical_evapotranspiration_wheat(t) =
annual_total_theoretical_evapotranspiration_wheat(t - dt) + (increase_annual_theor_evapot_wheat -
decrease_annual_theor_evapot_wheat) * dt
INIT annual_total_theoretical_evapotranspiration_wheat = 0
INFLOWS:
increase_annual_theor_evapot_wheat = monthly_theoretical_evapotranspiraion_wheat
OUTFLOWS:
decrease_annual_theor_evapot_wheat = IF month_count=10 THEN
annual_total_theoretical_evapotranspiration_wheat/DT ELSE 0
irrigated_land(t) = irrigated_land(t - dt) + (rainfed_to_irrigated - irrigated_to_rainfed) * dt
INIT irrigated_land = 27560
INFLOWS:
rainfed_to_irrigated = rainfed_land*fraction_from_rainfed_to_irrigated
OUTFLOWS:
irrigated_to_rainfed = Irrigated_Land*fraction_from_irrigated_to_rainfed
Monthly_Operation_time(t) = Monthly_Operation_time(t - dt) +
(monthly__operation_time_adjustment) * dt
INIT Monthly_Operation_time = 450


INFLOWS:
monthly__operation_time_adjustment =
MIN(monthly_operation__time_gap/adjustment_time_for_monthly_operation_time,possible_mont
hly_operation_time_adjustment)
pump_power(t) = pump_power(t - dt) + (pump_power_adjustment) * dt
INIT pump_power = 100
```

```
INFLOWS:
pump_power_adjustment =
MIN(pump_power__gap/pump_power__adjustment_time,possible_pump_power_adjustment)
rainfed_land(t) = rainfed_land(t - dt) + (irrigated_to_rainfed - rainfed_to_irrigated) * dt
INIT rainfed_land = 138440
INFLOWS:
irrigated_to_rainfed = Irrigated_Land*fraction_from_irrigated_to_rainfed
OUTFLOWS:
rainfed_to_irrigated = rainfed_land*fraction_from_rainfed_to_irrigated
Year_Count(t) = Year_Count(t - dt) + (increase_year_count) * dt
INIT Year_Count = 0
INFLOWS:
increase_year_count = if month_count = 11 THEN 1/DT ELSE 0
adjustment_time_for_monthly_operation_time = 1
agricultural_irrigation__subsidy = 0.35
aquifer_depth = 480000
aquifer_thickness = Water_in_Saturated_Zone/porosity__saturated_zone
attainable_irrigated___crop_yield = 11000
attainable_rainfed___crop_yield = 6000
available_irrigation_water = extraction_by_volume/Irrigated_Land/10
desired_energy_per_well =
(0.001*water_table_level)*9.8*(1000*desired_extraction_by_volume_per_well)/(3.6*10^6)/Pump_
efficiency
desired_extraction = irrigation_requirement
desired_extraction_by_volume_per_well = desired_extraction__by_volume/Wells
desired_extraction__by_volume = Irrigated_Land*desired_extraction*10
effective_precipitation_coefficient = 0.8
effective__precipitation = precipitation*effective_precipitation_coefficient
effect_of_relative_profitability_on_irrigated_to_rainfed_land =
GRAPH(relative_profitability_irrigated)
(0.00, 5.00), (0.2, 3.63), (0.4, 2.59), (0.6, 1.98), (0.8, 1.43), (1.00, 1.00), (1.20, 0.611), (1.40, 0.37),
(1.60, 0.177), (1.80, 0.0514), (2.00, 0.00)
effect_of_relative_profitability_on_rainfed_to_irrigated_land =
GRAPH(relative_profitability_irrigated)
```

(0.00, 0.00), (0.5, 0.402), (1.00, 1.00), (1.50, 1.83), (2.00, 2.62), (2.50, 3.63), (3.00, 4.26), (3.50, 4.65), (4.00, 4.84), (4.50, 4.94), (5.00, 5.00)
energy_cost_for__irrigated_crop = energy_per_hectare*energy_price
energy_gap = desired_energy_per_well-energy_per_well
energy_per_hectare = energy_per_well*wells_per_hectare
energy_per_well = pump_power*Monthly_Operation_time
energy_price = energy_price__per_kW*agricultural_irrigation__subsidy
energy_price__per_kW = 0.39
extraction_by_volume = extraction_by__volume_per_well*Wells
extraction_by__volume_per_well =
IF aquifer_depth>=water_table_level THEN
energy_per_well*3.6*10^6*Pump_efficiency/(0.001*water_table_level+0.001)/9.8/1000 ELSE 0
extraction_per_hectare = extraction_by__volume_per_well*wells_per_hectare
fractional_discharge = 0.1
fractional_evaportranspiration = 1
fractional_infiltration = 0.1
fractional_runoff = 0.1
fraction_from_irrigated_to_rainfed =
effect_of_relative_profitability_on_irrigated_to_rainfed_land*refrence_fraction_from_irrigated_to_rainfed
fraction_from_rainfed_to_irrigated =
effect_of_relative_profitability_on_rainfed_to_irrigated_land*referencefraction_from_rainfed_to_irrigated
irrigated_crop_cost = energy_cost_for__irrigated_crop+other_costs_for__irrigated_crop
irrigated_crop_price = 0.87
irrigated_crop_profit = MAX(0,irrigated_crop_revenue-irrigated_crop_cost)
irrigated_crop_revenue = irrigated_crop_price*irrigated_crop_yield

irrigated_crop_yield = attainable_irrigated___crop_yield*(1-irrigated_yield_response_factor_Ky+irrigated_yield_response_factor_Ky*relative__irrigated_evapotranspiration)
irrigated_yield_response_factor_Ky = 1.25
irrigation_efficiency = 0.65
irrigation_requirement = MAX(0,(monthly_theoretical___evapotranspiration_corn-effective__precipitation)/irrigation_efficiency)

maximum_monthly_operation_time = 720

maximum_pump_power = 220

max_evapotranspitarion = Water_in_Root_Zone*fractional_evaportranspiration

monthly_average_precipitation = GRAPH(TIME MOD 12)

(1.00, 97.9), (2.00, 110), (3.00, 91.1), (4.00, 73.3), (5.00, 36.3), (6.00, 7.10), (7.00, 1.70), (8.00, 0.4), (9.00, 2.50), (10.0, 34.2), (11.0, 67.2), (12.0, 98.7)

monthly_operation__time_gap = energy_gap/(pump_power+0.001)

monthly_theoretical_evapotranspiraion_wheat = GRAPH(TIME MOD 12)

(1.00, 9.00), (2.00, 14.0), (3.00, 28.0), (4.00, 44.0), (5.00, 56.0), (6.00, 2.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)

monthly_theoretical___evapotranspiration_corn = GRAPH(month_count)

(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 8.00), (5.00, 37.0), (6.00, 90.0), (7.00, 100), (8.00, 82.0), (9.00, 14.0), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)

month_count = time mod 12

other_costs_for__irrigated_crop = 1410

porosity__saturated_zone = 0.4

possible_monthly_operation_time_adjustment = (maximum_monthly_operation_time-Monthly_Operation_time)/adjustment_time_for_monthly_operation_time

possible_pump_power_adjustment = (maximum_pump_power-pump_power)/pump_power__adjustment_time

Pump_efficiency = 0.85

pump_power__adjustment_time = 36

pump_power__gap = energy_gap/(Monthly_Operation_time+0.001)

rainfed_crop_cost = 1410

rainfed_crop_price = 0.9

rainfed_crop_profit = MAX(0, rainfed_crop_revenue-rainfed_crop_cost)

rainfed_crop_revenue = rainfed_crop_price*rainfed__crop_yield

rainfed_yield__response_factor_Ky = 1.05

rainfed__crop_yield = attainable_rainfed___crop_yield*(1-rainfed_yield__response_factor_Ky+rainfed_yield__response_factor_Ky*relative_rainfed_evapotranspiration)

referencefraction_from_rainfed_to_irrigated = 0.001

refrence_fraction_from_irrigated_to_rainfed = 0.001

reinfed_evapotranspiration = MIN(effective__precipitation, monthly_theoretical_evapotranspiraion_wheat) relative_irrigated__yield = irrigated_crop_yield/attainable_irrigated___crop_yield

relative_profitability_irrigated = irrigated_crop_profit/(rainfed_crop_profit+0.001)

relative_rainfed_evapotranspiration = annual_actual_evapotranspiration_wheat/annual_theoretical_evapotranspiration_wheat

relative_rainfed_yield = rainfed__crop_yield/attainable_rainfed___crop_yield

relative__irrigated_evapotranspiration = annual_actual_evapotranspiration_corn/annual_theoretical_evapotranspiration_corn

total_land = rainfed_land+Irrigated_Land

water_table_level = IF aquifer_depth>=aquifer_thickness THEN aquifer_depth-aquifer_thickness ELSE 0

wells = Irrigated_Land*wells_per_hectare

wells_per_hectare = 1/15

APPENDIX B: HYDROGEOLOGICAL MAP OF KIZILTEPE PLAIN