

Tragedy of the Commons in Groundwater Resources
And
Evaluating Strategies to Achieve Sustainable Development
(A Case Study of Iran)

Master thesis

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Abstract

At present, many countries (including Iran) face "extremely high" levels of water stress, which means more than 80 percent of the water available to agricultural, domestic, and industrial users is withdrawn from groundwater resources annually. Based on the statistics, the agriculture sector is responsible for consuming more than 90 percent of water in Iran. To date, the growing demand for water in the agriculture sector has largely been met by mining fossil groundwater resources. Indeed, about 90 percent of groundwater use belongs to the agriculture sector. Needless to say, this unsustainable trend cannot continue for a long time since groundwater resources are limited in practice. So, decision-makers need doing some urgent, effective actions to handle this problem. The main objective of this study is understanding the underlying cause of the problem and evaluating usually suggested policies to address the crisis. The SD methodology is used. the model is based on "tragedy of the commons" theory and tries to explain how farms attempt to maximize their profits turns to a serious threat for the sustainability of groundwater resources. In the following, the model has been used to evaluate various strategies for avoiding the depletion of groundwater resources. For this purpose, "gap analysis" has been used. In gap analysis, the future under the present strategy is forecasted. Then, objectives or desired future is identified and the gap between the objectives and the future conditions under the current strategy is determined. Finally, new strategies which will help to close the gap will be designed. In the end, it is concluded that; (1) the government should consider the concept of maximum sustainable yield (MSY) and control the size of irrigated land, share of high-water demand crops, and number of wells (2) improving irrigation efficiency and many other policies are fruitless if the government do not consider the rebound effect and combined policies should be adopted (3) even by changing the water governance to eliminate the tragedy of the commons, overshoot and collapse can happen due to misperception

Key Words: Water Management, Groundwater Resources, Sustainability, Tragedy of the Commons, System Dynamics, Iran, Strategy Planning, Sustainable Water Resources Solutions, Water Resilience, Unsustainable Management Strategies, Systems Thinking, Integrated Water Resources Modeling, Archetypes, Overshoot and Collapse, Rebound Effect, Gap Analysis

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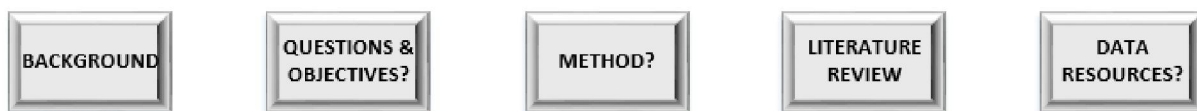
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PART I: Introduction

In this part, first, we bring an introduction to the water consumption and agriculture sector in Iran. Then, we define our purpose of doing this research and the method that we intend to apply. Before going further, to make sure that our efforts are not in vain to reinvent the wheel, we will review the literature and conducted studies. When we ensure that our work is novel, we speak out the resources of needed data. The steps are depicted in the below picture.



1. Introduction

At present, 37 countries (including Iran) face "extremely high" levels of water stress, meaning that annually more than 80 percent of the water available to agricultural, domestic, and industrial users is withdrawn from groundwater resources [1]; 50% of the people in sub-Saharan Africa currently have no access to improved water sources [2]; and it is estimated that by 2025, two billion people will be living in regions with absolute water scarcity [3]. Water crisis is so serious that the former United Nations Secretary-General, Kofi Annan, believes "fierce competition for freshwater may well become a source of conflict and wars in the future"[4], and the "World Economic Forum" survey shows that for the next 10 years, the number one risk is water crisis [5] (the fourth case is food that also is rooted in the water problem).

One of the main culprits of the overconsumption of water in Iran, and the world is the agricultural sector. To illustrate, the water and agriculture sector in Iran will be explained in the following.

1.1. A glance at water consumption in Iran

Based on the FAO report, more than 90 percent of water withdrawal is used in the agriculture sector, and 57% of water withdrawal is from groundwater resources [6]. Going to the depth, based on the report prepared by Stanford University, Iran is known as one of the dry areas of the world. Most of the country (more than 70 percent), is arid and about 25 percent is semi-arid. So Iran has a little precipitation. Moreover, it has a “**spatial**” problem, and only 25% of its precipitation occurs in plains, and 75% does in mountainous and highlands. Worst, it has “**temporal**” problem as well, that is, 75% of the water is falling when we do not necessarily need it for irrigation, and the rainy season does not coincide with the cultivation, and during summer there is no effective rainfall [7]. As a result, while the share of rain-fed food production is 60% in the world, it is only 11% in Iran. So the size of irrigated agriculture is large in Iran, and surface water can support only 38% of that, and the rest 62% is withdrawn from groundwater resources. In other words, agriculture is responsible for more than 90% of groundwater consumption in Iran [6].

Another important feature of water consumption in Iran’s agriculture is that due to high subsidy granted to water and energy, this part has not had enough motivation to become efficient. “Inappropriate crop pattern” and “low irrigation efficiency” cause the efficiency in agriculture to be about 30% percent (about 92% of irrigation technique is surface irrigation) [6].

1.2. A glance at the agricultural sector in Iran

Agricultural production is about 10% of Iran’s GDP, and about 20% of employment is in the agriculture sector. Total cultivated land has increased from 9.47 million hectares in 1978 to 12.16 million hectares in 2013 (Fig.1) [8]. The report released by Iran’s Ministry of Agriculture [8] shows that during the last years, rain-fed farmlands has been constant and the agricultural land has increased only 28%, nevertheless agricultural production has increased more than fivefold (Fig.1 and Fig.2). Another report shows “While the total cultivated cropland area has been fluctuating around 12 million ha over the past 25 years, the average crop yield

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has increased from 2.8 to 6.4 ton/ha — giving rise to an increase in the annual crop production from 29 to 74 million ton between 1990 and 2015. Nevertheless, the yield and production tonnage of the cereals — which account for 80% of the harvested croplands — have virtually stayed flat and the rise in the average crop yield and total production is solely due to the increase in the production of vegetables (sabzijät and jälizi) and fodder. This marked shift in cropping pattern has significantly exacerbated Iran’s water problems as majority of these crops are highly water demanding. In addition to the field crops, horticulture and orchards encompass 2.6 million ha of Iran’s land with an average yield of 6.4 ton/ha, supplying about 16 million ton of orchard products per year”. [7]

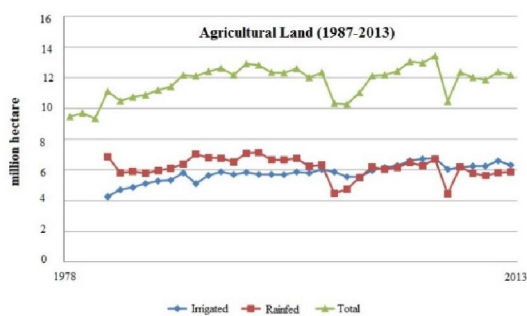


Figure 1: Agricultural Land (1987-2013)[8]

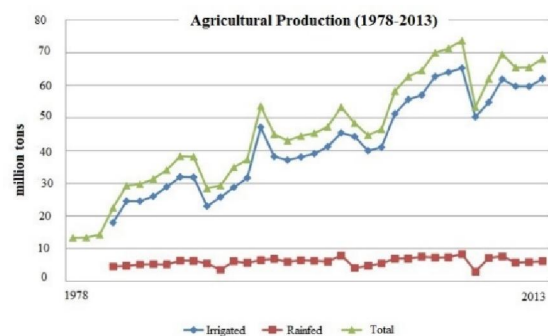


Figure 2: Agricultural production (1978-2013) [8]

Another important feature of Iran’s agriculture sector is that “wheat” is a strategic crop in Iran, and for this reason, about 50% of the cultivated land is allocated to it and it is about 14% of total agricultural products. Other most cultivated crops are maize, sugar beet, tomato, watermelon, alfalfa, potato, sugar cane, barley, and rice. (figure.3, 4) [8]

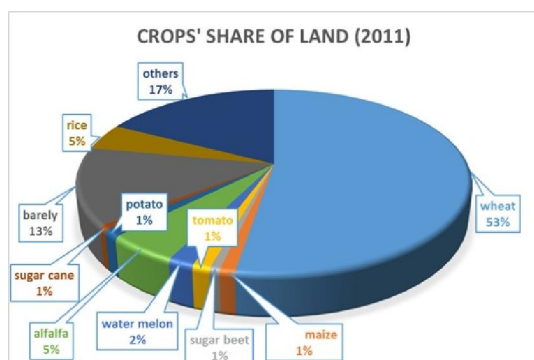


Figure 3: Crops Share of Land (2011) [8]

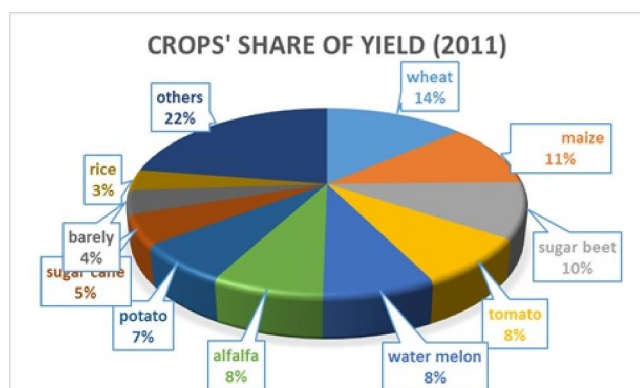


Figure 4: Crops Share of Yield [8]

2. Research Objectives and Research Questions

This research aims to build a quantitative SD model in order to achieve more insight into the underlying structure (mechanism) of the tragedy of the commons in groundwater resources. System dynamics is chosen to study this problem as an essential project deliverable, which is a transparent model of causal mechanisms and the effects of different scenarios. Policymakers need an instrument that helps them to figure out the results of the policies they have in mind. The resulting model should provide the policymakers of Iran with actionable and practical intervention points which can control the groundwater over-withdrawing issue.

The central questions which can steer the studies are as follows:

- 1) What are the most important parameters affecting the groundwater consumption in Iran's agriculture sector?
- 2) How are those affecting parameters dynamically interconnected which lead to over-withdrawing and the tragedy of commons in groundwater resources? (in part II we will elaborate the concept of tragedy of the commons)
- 3) What are the most effective applicable policies to control the tragedy of commons in groundwater resources?

3. Methodology

In this research, the tool of system dynamics is used. SD has been defined as "the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behavior" [9]. It includes problem articulation, boundary selection, formulation of a dynamic hypothesis, simulation model building, use of the simulation model to test the dynamic hypothesis, model validation, policy design and evaluation [10]. This modeling technique helps to understand how the behavior of a particular system is driven by its structure, which is formed by the causal relationships among variables [11].

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SD could be described as a mixed-methods research strategy since it combines qualitative and quantitative elements [12,10]. SD is itself a broad research strategy and includes a range of approaches as classified and described by [13]. Considering the Research Objectives and Research Questions posed above, the SD research strategy to be adopted in this study resembles the “Phenomenon Replicating Explanation Strategy.” This focuses on using existing knowledge and empirical data to build a quantitative model capable of reproducing a reference mode of behavior which is used to compare scenarios for developing new policy insights. In this study, existing knowledge will be synthesized to produce a high-level, aggregated model to clarify the structural mechanisms behind a system’s complex dynamics and identify strategic leverage points of policy interest. Given that an extensive archive of documented information already exists regarding the issue of health reform in Iran, this SD research strategy is considered appropriate for fulfilling the Research Objectives of this study. Components of other SD research strategies will be employed where existing knowledge is unavailable or still emerging. The SD model will be built using the Stella Architect software [14].

4. Literature Review

By searching the keywords of “water” and “agriculture” in the system dynamics bibliography (www.systemdynamics.org/bibliography) more than 300 articles are found. Moreover, since the subject of water and water management are related to many scientific disciplines, by searching those keywords plus “system dynamics” in google scholar, a wealth of studies can be found in the literature, in specialized journals of “sustainability”, “environment”, “water and wastewater”, “hydrology”, “agriculture”, etc. which are not mentioned in system dynamics bibliography. Besides, many articles are published in Persian in domestic journals. In fact, the literature is so vast that it seems to review and to classify those demands Meta-Analysis and other research. In Table.4 (Appendix A), some studies conducted on water issues are listed¹. Then in Table.5 (Appendix A), we will review the studies focusing on the case of Iran. In the next step, we will classify these studies based on the “underlying

¹ To prepare this section, mainly the literature review of these articles are used: Mirchi et al. [60], Soltani and Alizadeh [76], Hosseini and Bagheri [68], Alami et al. [70] Salvitabar et al. [65]

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model structure,” which “tragedy of the commons” is one of them. In the end, studies which are applied “tragedy of the commons” to investigate the water management will be examined.

4.1. Classification of water studies based on Underlying Model Structure

In a general category, regardless of the method of building the model (e.g., participatory model building, combining SD with GIS, multi-criteria decision making, etc.), the studies can be divided into two major categories: (1) those concern about “quality of water” and water salinity and water contamination by fertilizers, solid wastes, sewage drainage, etc. & (2) those concern about the “quantity” of water. The models studying the quantity of water, in turn, can be divided into some categories. As follows, we categorize them in five groups, based on their underlying structure:

i. Supply and Demand Model based on the Water Cycle and Material Flow Structure

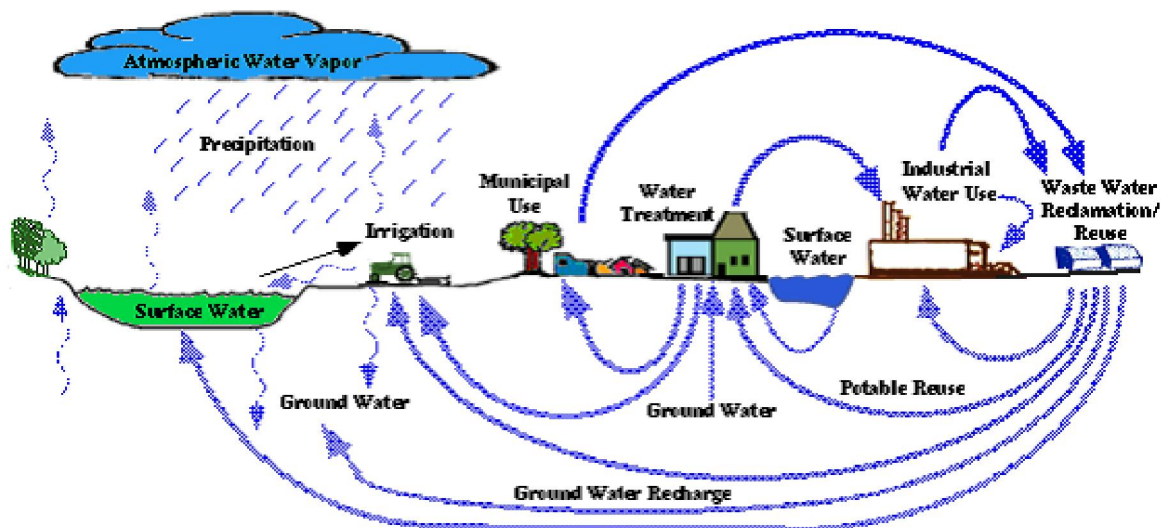


Figure 5: Water Cycle [15]

Many of the models mentioned above are based on the water cycle (Fig.5) and the material flow structure. They attempt to model the supply of water and the dynamics of water demand in different sectors (domestic, industrial, and agriculture). Some of these models are about a basin, river, city, or country, and some of them view the problem in the

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global level and test different policies to bridge the gap between supply and demand. Also, some of them seek for solutions to manage the water crisis in natural disasters such as earthquakes and floods.

ii. Supply and Demand Model considering Behavioral Feedbacks in addition to Material Flow Structure:

In these models, in addition to material flow, the way of decision-making of some stakeholders, and their responses to different policies and situations are included in the model. For example, we can mention the model of Gohari A. et al. [16] (Figure 6). The model is about the Zayandeh-Rud River basin, Iran, and comprises hydrological, socioeconomic, and agricultural sub-systems. Agricultural land-use decisions are assumed to be based on income-maximization. Ten crop types are included in the agricultural sub-system, namely wheat, barley, potato, rice, onion, alfalfa, corn, garden products and vegetables, and cereal and legume. Land area for each crop is defined as a function of the corresponding net economic benefit in the previous year. The expected agricultural water demand is the sum of expected water demand for all crops. Because of water scarcity in the

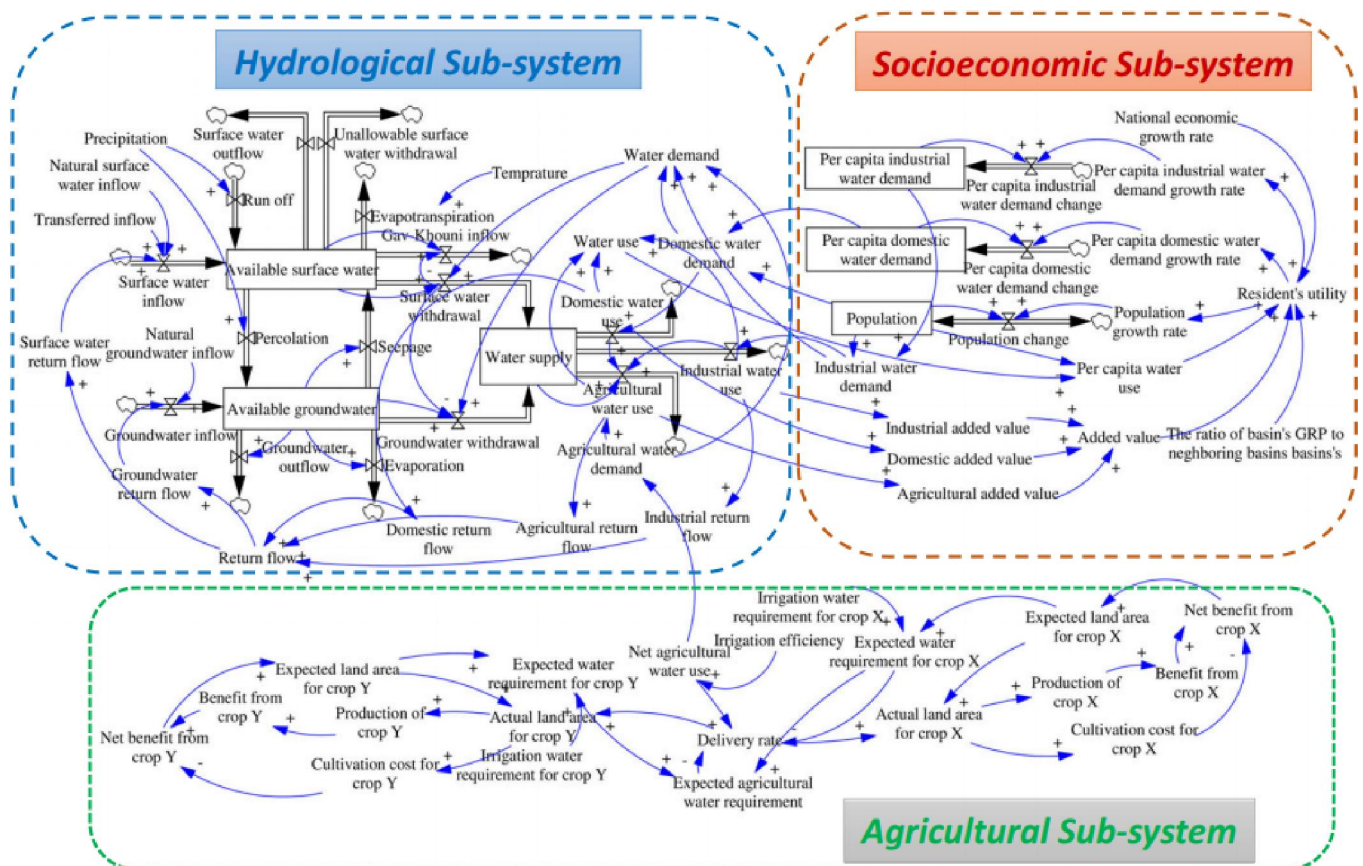


Figure 6: Gohari, et al. model for the water crisis [16]

basin, “delivery rate” is defined as the proportion of agricultural water demand that can be fully satisfied using available water supply. The land area for each crop is estimated by adjusting the expected land area for that crop based on the water delivery rate. Another good example for this category is Langarudi et al. [17] which examine how does socioeconomic feedback matter for water models.

iii. **Water-Energy-Food Nexus:**

These models (for example, Khalkhali et al. [18], & Bhatkoti et al. [19]) investigate the interaction between three sectors of food, energy, and water (Fig.7). The food sector is a large consumer of energy (>30%). Also, water is input to the energy sector as hydropower, cooling, biofuels In addition, energy is an input to water supply (desalination, water transport, air-water ...), and agriculture is input to renewable energy (biofuels). Moreover, Energy is a driver of water use (electrified irrigation), and the agriculture sector is the largest consumer of freshwater.

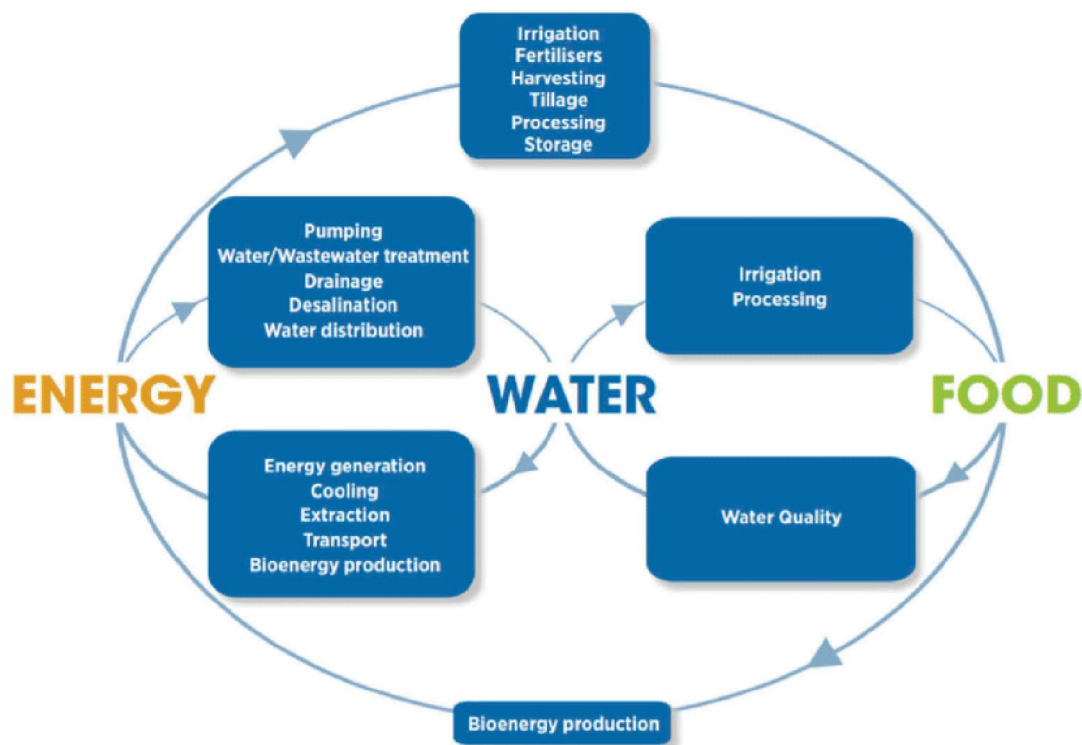


Figure 7: water-food-energy nexus [20]

iv. Hydro-Economy & Agro-Economy model:

The models (e.g. Saysel & Barlas [21] & Saysek, Barlas, & Yenigün [22]) are a micro-founded integrated model of agriculture and water and include crop markets and trade, soil quality, precipitation pattern, temperature, etc. (Fig.8).

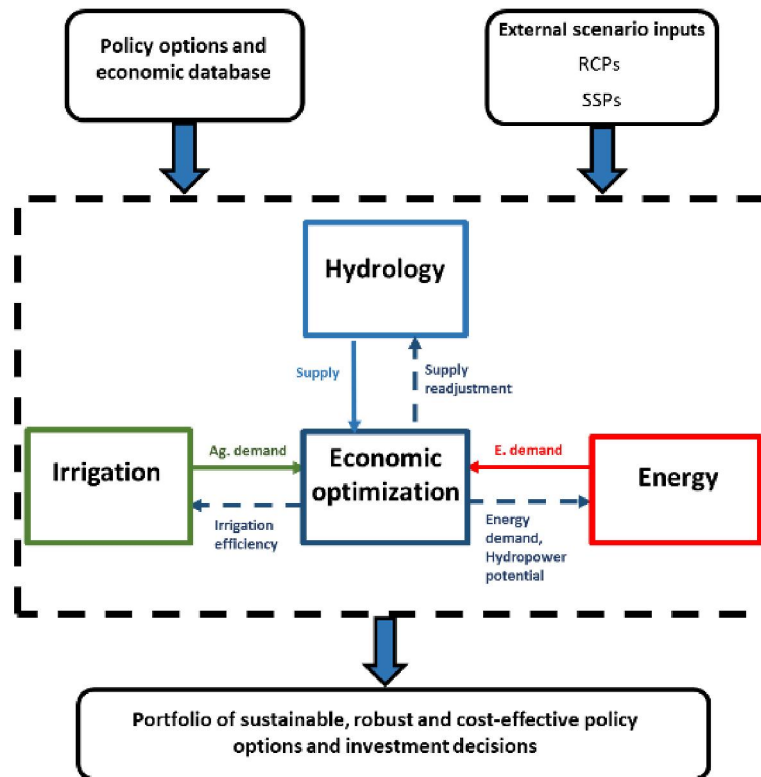


Figure 8: hydro-economic model[23]

v. Tragedy of the commons:

As far as the author finds, there are only two studies which focus on the tragedy of the commons in the case of water consumption; Khalid Saeed [24] and Ali Saysel [25].

In Khalid Saeed’s model, the food production system of the Asian countries is characterized by the feedback loops shown in Figure.9 Food fulfills nutritional needs of the population; hence, food sufficiency is related to the average life expectancy. An increase in population expands the food consumption base. Consequently, food consumption is stepped up through intensive land use, high yielding seed varieties, and extensive irrigation-all of which degrade land in the long run. Yield may also be increased or sustained through investment in land improvement, which is only resorted to after much damage has already

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been caused. The model subsumes three subsystems: population, food production, and ecology. [24]

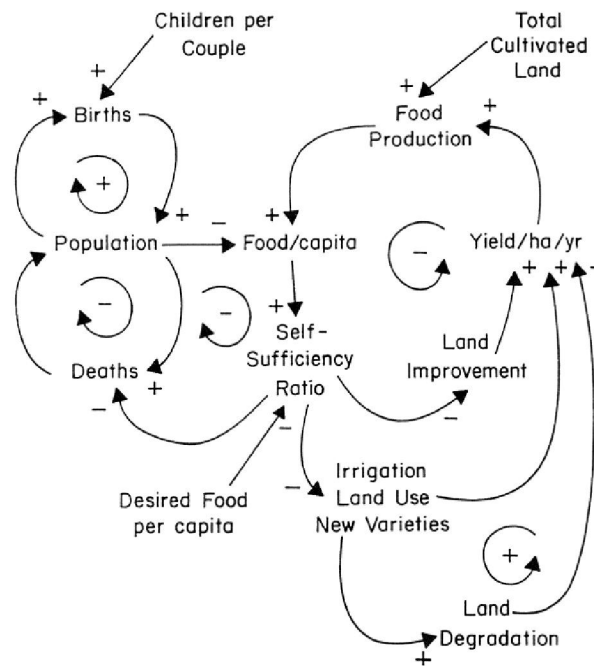


Figure 9: Tragedy of the commons in Asian agriculture-Khalid Saeed (1991)[24]

Saysel & Mirhanoglu's model consists of three subsystems: groundwater resource, irrigated land, and energy. It includes three main reinforcing loops and one balancing loop, as shown in Fig.10.

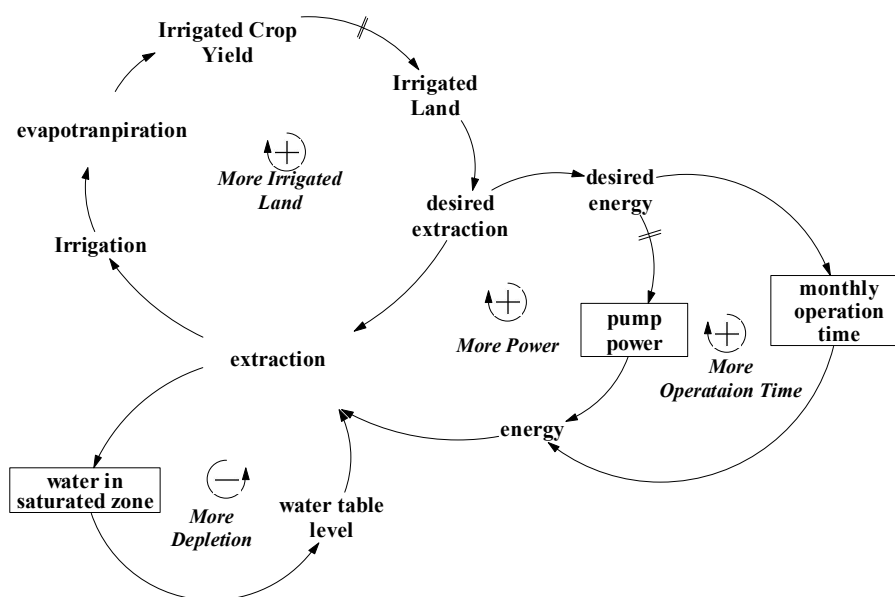


Figure 10: Tragedy of Commons in Groundwater Resources- Ali Saysel (2018)[25]

5. Data Collection

Data which is applied in this research can be divided into three categories:

i. **Structural Data:**

Much of the Structural data were found in the literature. Secondary data were drawn from a literature review. A literature review enabled better understanding and analysis of the elements in the water system and factors that influence water crisis, thereby enriching the author's mental model of the water system. Reviewed literature included academic articles and books, institutional reports, and newspaper interviews with experts and authorities. This literature was obtained from the Internet. Selection of literature from journals was primarily based on the use of keywords (e.g., 'water management'; 'water crisis'; 'agriculture'; 'tragedy of the commons'; 'common-pool resources'). In addition, part of the journal articles is selected by means of backward and forward snowballing (i.e., the use of a paper's reference list to identify additional papers). Besides, wherever it was unclear and ambiguous, we asked them from either agriculture or water experts to gain a better understanding.

ii. **Statistical Data:**

To compare model behavior with real data, this paper employs statistical and time-series data published by FAO, the ministry of agriculture, the Central Bank of Iran, and the Statistical Center of Iran.

iii. **Data to Calibrate the Model:**

Regarding data to calibrate the model & data for table functions, in the first step, is selected by guess. Then after building the running model and doing sensitivity tests, if the system was sensitive to them, we tried to find more accurate data referring to studies and statistics. In some cases that finding real data was very difficult and time-consuming, we assumed different numbers for the parameters and the system behavior is investigated under various scenarios.

PART II: Conceptual Model

In this and two following parts, the five-step disciplined process of building an SD model will be followed, which is (1) articulating the problem to be addressed, (2) formulating a dynamic hypothesis or theory about the causes of the problem, (3) formulating a simulation model to test the dynamic hypothesis, (4) testing the model until you are satisfied it is suitable for your purpose, and (5) designing and evaluating policies for improvement ([10], P.86).

This part contains four sections, including (1) introduction (2) problem definition (3) hypothesis and conceptual model, and (4) boundaries and assumptions



6. Background: Tragedy of the Commons

The problem of excessive exploitation and the depletion of a common-pool resource arises when numerous individuals or communities use at the same time and in a collective way the same resource without excluding anyone of its use and trying to obtain the most advantage of its exploitation, causing the depletion of the common resource. This non-systemic behavior is caused because the individuals that are receiving benefits from the common-pool resource, behave in an individualistic way and care less about the consequences of their actions on the collective well-being [26]. With open access to a common resource, the benefits of over-exploitation accrue to the individual while the costs are borne by all. The inappropriate incentives lead to the "tragedy of the commons" [27].

There are countless examples of overexploitation of renewable resources such as fish, whales, pastures, forests, complex habitats for biodiversity, and groundwater, as well as of

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resources that serve as regenerative sinks for pollution such as SO₂, NO₂, CO₂, industrial chemicals, pesticides, and nutrients. A related economic problem is overbuilding of harvesting capacity and low capacity utilization. Since Aristotle, there has been an awareness of the commons problem as a cause of this overutilization. In modern times, Gordon [28] and Hardin [29] formalized and contributed to awareness of the commons problem or the “tragedy of the commons” [30]. Earlier references such as Aristotle, Lloyd [31], Warming [32] and Pigou [33] indicate that the basic idea is not new. Ostrom [34] uses the term "appropriation problem," indicating the need to design rules and institutions to allocate rights and responsibilities. The commons problem is widely held to be the cause of mismanagement of common renewable resources [27].

7. Problem Definition

As mentioned, Iran is one of those 37 countries which currently faces "extremely high" levels of water stress. In fact, water use has exceeded available surface supply and caused decreasing groundwater tables. The groundwater resources have depleted during the last two decades (figure.11), and if unrestricted groundwater use is continued, available groundwater will most likely be exhausted.

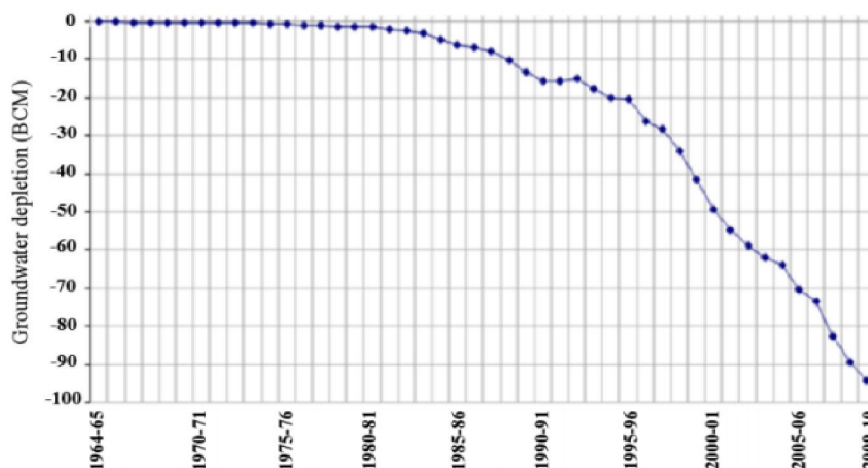


Figure 11: Groundwater Depletion [35]

One of the main reasons for this phenomena is the improvement of water pump technology, which allowed this withdrawal to take place. Besides, As Figure.12 shows, during the last 30 years, the number of wells has also increased from about 90,000 to about 650,000. Increase in number of wells and development in the pump technology has caused about 100

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billion cubic meters of groundwater resources are consumed in less than 50 years. Needless to say, this trend is not sustainable, and sooner or later, Iran will face severe problems in water and food security. [35]

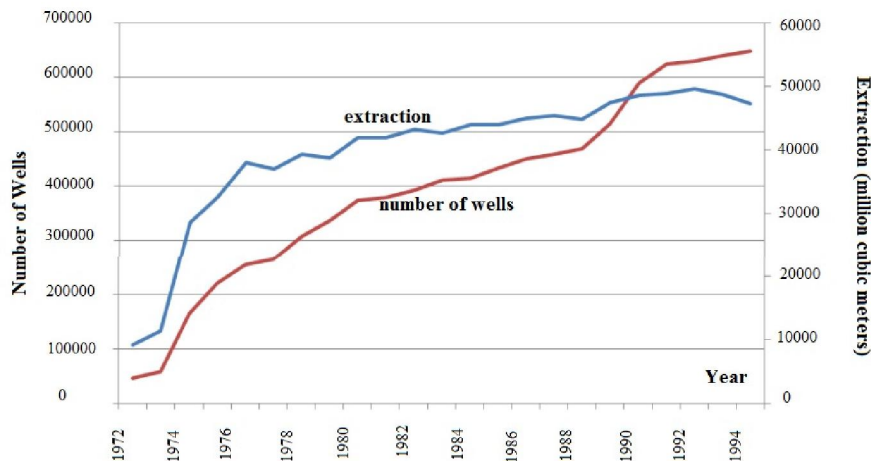


Figure 12: number of wells [35]

8. Dynamic Hypothesis

The logic and the main idea used in this hypothesis is that farmers decide on how much their land is cultivated each year based on "*profitability*" and "*available water*." It is worth noting that farmers, in addition to the size of the farmland, also have to decide on the type of product which is ignored in this model, and to simplify it is embedded in the decision of the size of the land in some way (detailed explanations are brought in the section of Model Boundaries and Assumptions).

Part One: Relationship between "Irrigated Land" & "Water Withdrawal"

Farmers, like other business owners, are interested in raising their production capacity when their business becomes more profitable. As shown in Fig.13, firstly based on the "*profitability*" (that is, "*Revenue-Cost Ratio*" abbreviated by "*R / C Ratio*"), a "*desired Irrigated Land based on Profitability*" is created in the minds of the farmers. This variable, in turn, also indicates the "*desired available water*." Some part of this "*desired available water*" is provided by "*available surface water*" and "*treated and reused wastewater*", and farmers, to provide remaining proportion, will dig wells and withdraw water from "*groundwater resources*." In other words, the "*desired Irrigated Land*" dictates "*desired water*" and subsequently "*desired*

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number of wells". The discrepancy between "*number of wells*" and "*desired number of wells*" makes up a negative loop adjusting "*number of wells*". The "*number of wells*", in turn, determines the amount of "*withdrawal*" and "*available water*".

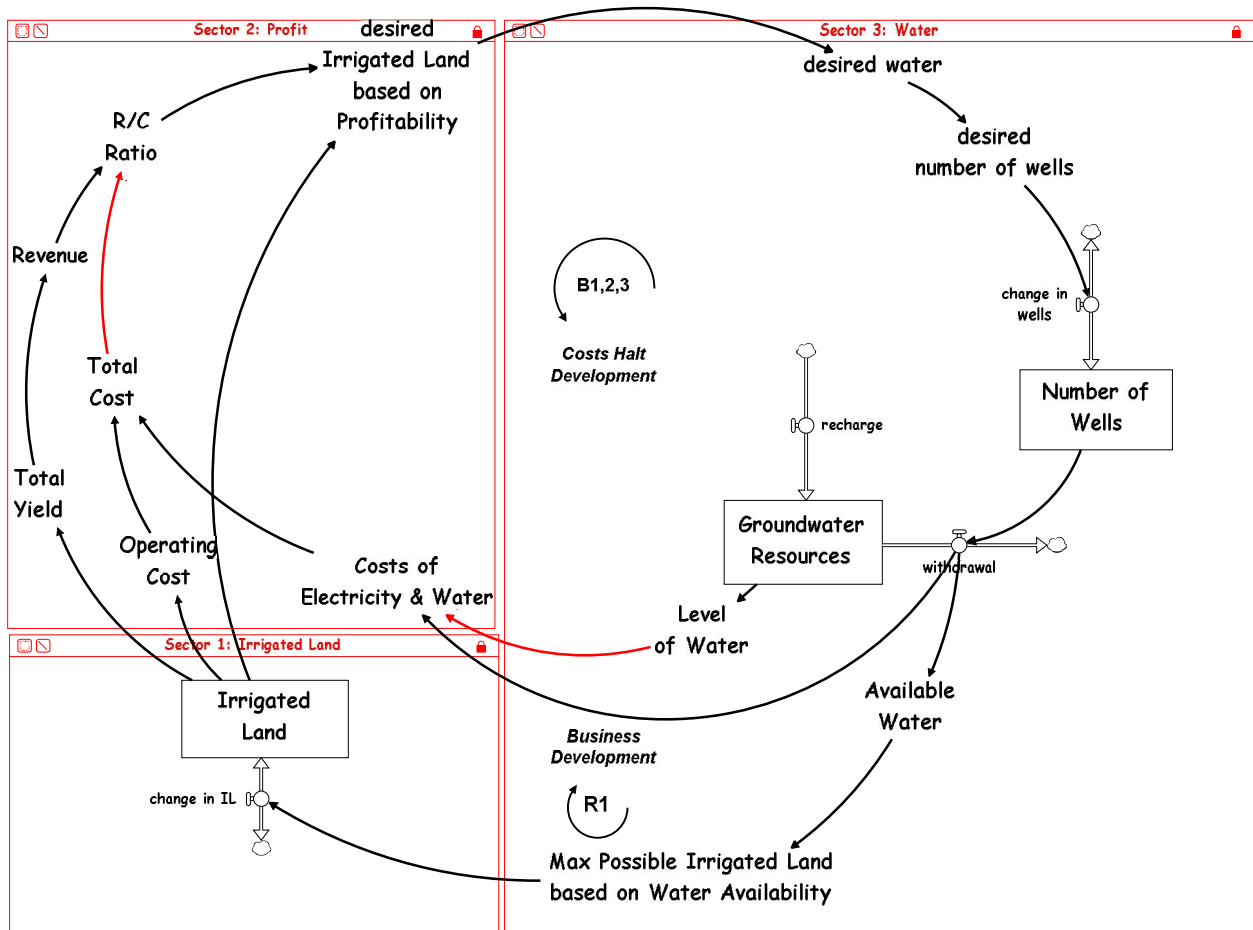


Figure 13: Dynamic Hypothesis-Part (1)

However, "*available water*" does not always equal "*desired water*", and consequently the size of "*Irrigated Land*" does not always same to "*desired Irrigated Land based on Profitability*". Ultimately, the amount of water available to the farmer, that is, "*available water*", will determine "*max possible Irrigated land based on water availability*", and the gap between this number and "*irrigated land*" makes another goal-seeking loop which changes the size of "*irrigated land*". The "*irrigated land*", also, sets "*total yield*" and "*revenue*".

These relationships form a positive loop (R1) that wants to exponentially increase the size of "*irrigated land*" and "*revenue*";

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R1- Business Development: *Irrigated Land & HWD Share* ↑ ⇒ *Total Yield* ↑ ⇒ *Revenue* ↑ ⇒ *R/C Ratio* ↑ ⇒ *Desired Irrigated Land & HWD Share based on Profitability* ↑ ⇒ *Desired Water* ↑ ⇒ *Number of Wells* ↑ ⇒ *Withdrawal* ↑ ⇒ *Available Water* ↑ ⇒ *Possible Irrigated Land & HWD Share based on Water Availability* ↑ ⇒ *Irrigated Land & HWD Share* ↑

On the other hand, by increasing the size of “*irrigated land*”, “*operating costs*” (including the cost of seed, fertilizer, labor recruitment, etc.), the amount of “*withdrawal*” water, the “*cost of consumed water*”, and the “*cost of electricity*”. Obviously, the lower the “*level of water*”, a stronger pump (with higher suction head) will be needed to pump water from groundwater resources on the ground increase, which naturally consumes more electricity. It should be noted that here the amount of withdrawal per well is assumed to be constant, and instead of changing the amount of “*withdrawal per well*” with changing the “*level of water*”, the same amount of water is extracted, by using more powerful pumps consuming more electricity.

These relationships also form three negative loops that attempt to stop and control the exponential growth of R1:

B1: *more Withdrawal* ⇒ *less Groundwater Resources* ⇒ *less Water Level* ⇒ *more Electricity Cost* ⇒ *more Costs* ⇒ *less R/C Ratio* ⇒ *less Desired Irrigated Land & HWD Share based on Profitability* ⇒ *less Desired Water* ⇒ *less Number of Wells* ⇒ *more Withdrawal*

B2: *more Withdrawal* ⇒ *more Water Cost* ⇒ *more Costs* ⇒ *less R/C Ratio* ⇒ *less Desired Irrigated Land & HWD Share based on Profitability* ⇒ *less Desired Water* ⇒ *less Number of Wells* ⇒ *less Withdrawal*

B3: *more Withdrawal* ⇒ *more Available Water* ⇒ *more Possible Irrigated Land & HWD Share based on Water Availability* ⇒ *more Irrigated Land & HWD Share* ⇒ *more Operating Cost* ⇒ *more Costs* ⇒ *less R/C Ratio* ⇒ *less Desired Irrigated Land & HWD Share based on Profitability* ⇒ *less Desired Water* ⇒ *less Number of Wells* ⇒ *less Withdrawal*

Part Two: Recharge of Groundwater Resources

The previous paragraph discussed the factors affecting the amount of extracted water from underground aquifers. Yet, how do underground aquifers feed? And what are the factors and mechanisms behind it?

“Groundwater recharge or deep drainage or deep *percolation* is a hydrologic process, where water moves downward from surface water to groundwater. Recharge is the primary method through which water enters an aquifer. This process usually occurs in the vadose zone below plant roots and, is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface. Groundwater is recharged naturally by rain and snow melt and to a smaller extent by surface water (rivers and lakes). Recharge may be impeded somewhat by human activities including paving, development, or logging.” [36]

In the model, natural recharge are considered by “*total consumed water*” and “*rainwater penetration*”, also artificial recharge is considered by adding variable of “*recharge policy*” to the model. As shown in figure.14, some of “*total consumed water*” for irrigation is absorbed by the plants, some is evaporated, some flowing and joins runoffs, and a percentage of it penetrate the soil and “*recharge*” the aquifers. That what fraction of water will return to groundwater resources depends on the density and permeability of the soil. When the “*level of water*” drops down, land subsides, the soil becomes denser, and the permeability and “*return fraction*” decreases. On the other hand, “*water table capacity*” is not constant but with the consumption of water and the lowering of “*level of water*”, part of the aquifer will be destroyed resulting in shortening the “*water table capacity*”.

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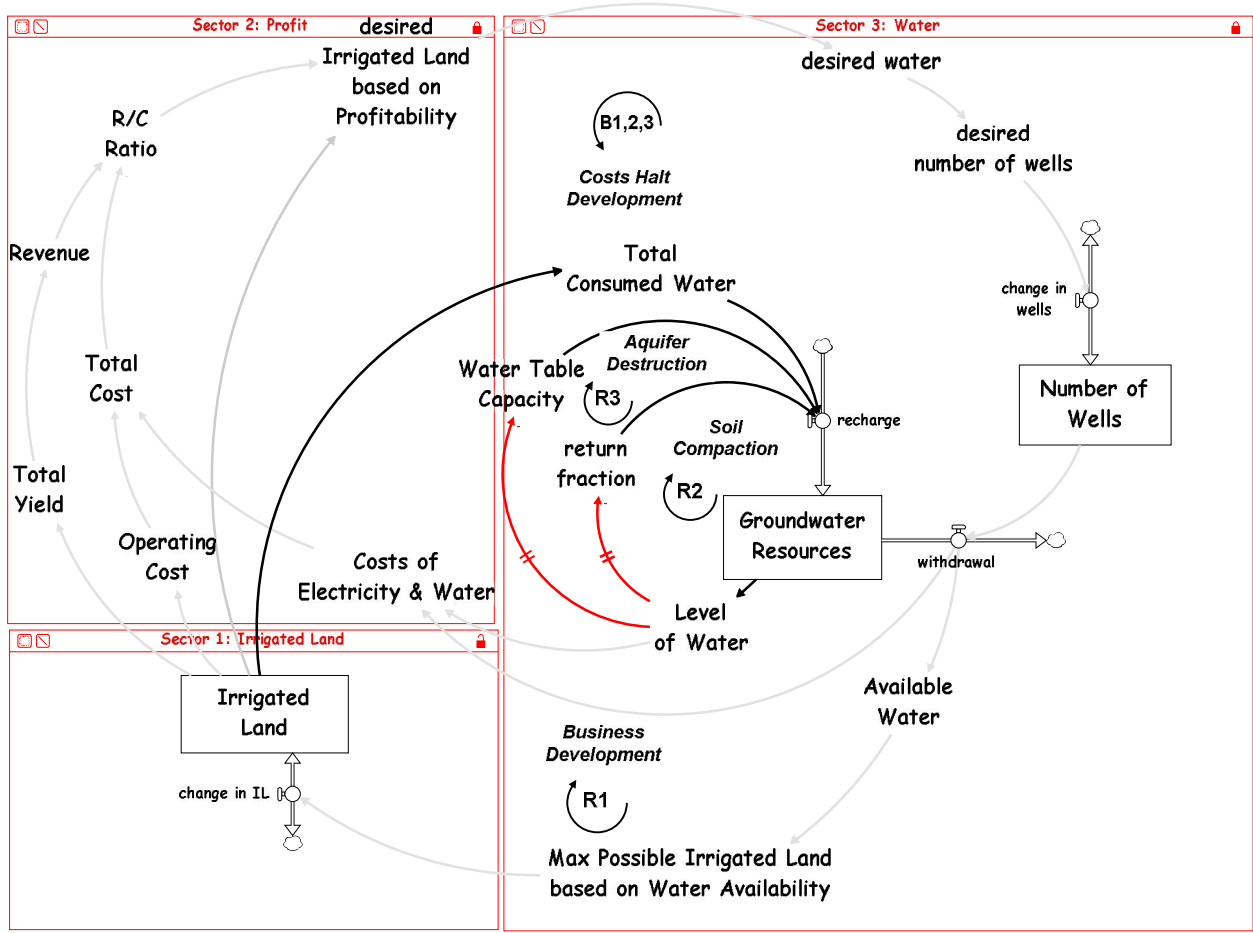


Figure 14: Dynamic Hypothesis-Part (2)

These relationships make two other reinforcing loops (R2 and R3), as follows:

R2- Aquifer Destruction: Groundwater Resources ↓ ⇒ Water Level ↓ ⇒ Land Subsidence ↓ ⇒ aquifer storage capacity ↓ ⇒ Recharge ↓ ⇒ Groundwater Resources ↓

R3- Soil Compaction: Groundwater Resources ↓ ⇒ Water Level ↓ ⇒ aquifer material compaction ↑ ⇒ soil porosity ↓ ⇒ absorption fraction ↓ ⇒ Recharge ↓ ⇒ Groundwater Resources ↓

Part Three: Irrigation Efficiency

Another important variable that should be added to the model is “*irrigation efficiency*”. As shown in Fig. 15, the “*irrigation efficiency*” has an adverse effect on two variables of the model, namely, “*total consumed water*” and “*desired water*”. Also, it has a

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direct impact on “*Max Possible Irrigated Land based on Water Availability*”; to explain, the more irrigation efficiency, the more land can be cultivated, with a constant amount of “*Available Water*”.

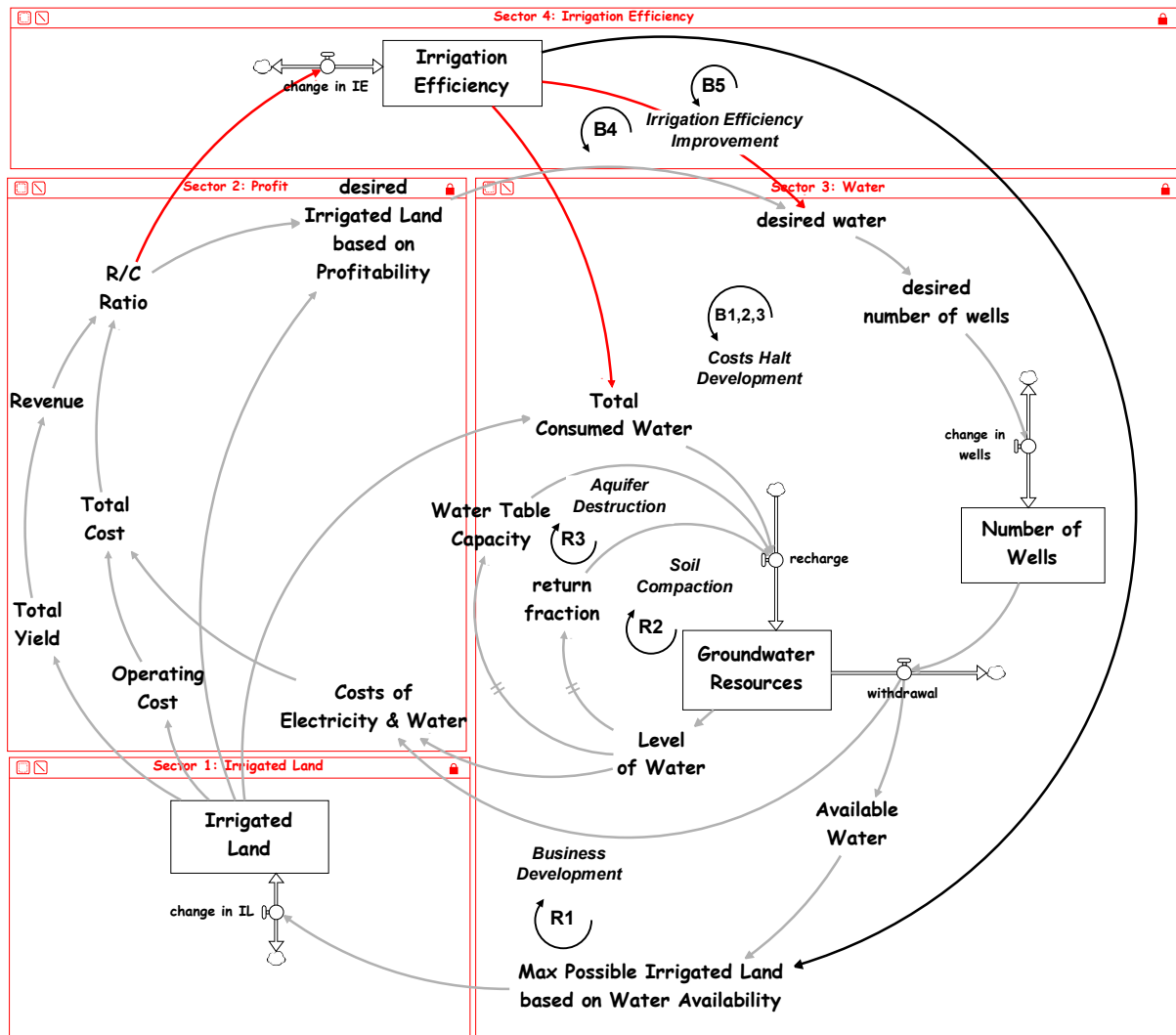


Figure 15: Dynamic Hypothesis-Part (3)

But by what mechanism does irrigation efficiency change? And what factors encourage farmers to improve irrigation technology to increase irrigation efficiency?

One model assumption is that the main reason for the lack of irrigation efficiency improvement in recent decades has been the cheapness and abundance of water. So, as long as the water is abundant and cheap, there is no incentive to increase irrigation efficiency. But with rising costs, farmers will try to get the most benefit from the expensive extracted water

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and will try to produce the most possible product and income to meet the costs. Thereby, a decrease in “*R/C Ratio*” encourage them to upgrade irrigation technologies and increase “*irrigation efficiency*”.

Adding these relationships to the previous relationships, two more negative loops (B4 and B5) are added to the model that affect the irrigation efficiency:

B4: Efficiency of Irrigation↑ ⇒ Desired Water↓ ⇒ Number of Wells↓ ⇒ Withdrawal↓ ⇒ Costs↓ ⇒ R/C Ratio↑ ⇒ Efficiency of Irrigation↓

B5: Efficiency of Irrigation↑ ⇒ Possible Irrigated Land & HWD Share based on Water Availability↑ ⇒ Irrigated Land & HWD Share↑ ⇒ Total Yield↑ ⇒ Revenue↑ ⇒ R/C Ratio↑ ⇒ Efficiency of Irrigation↓

9. Model Boundaries & Assumptions

9.1. Model Boundaries:

1. This research is about “**quantity**” of water, not “**quality**”, so water “salinity” and “contamination” are out of our boundary.
2. It is about “**groundwater**” and does not include dynamics of “**surface water**”
3. Our focus is on farmers’ behavior regarding “water extraction” to increase their production and maximize their profits, so other affecting factors like “soil quality”, “fertilizer”, “working force”, “machinery”, etc. are out of our boundary.

9.2. Basic Assumptions

1. As mentioned earlier, farmers should make two major decisions based on “*profitability*” and “*available water*”: (1) the size of land under cultivation (2) type of crops to cultivate. To understand how farmers make decisions, we need to know how they will react when more water is available. Do they increase the size of land under cultivation or switch to higher water demand crops?

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The 2015 Iran's ministry of Agriculture report [8] shows that despite the increasing number of wells, agricultural water consumption, and a fivefold increase in crop yields, over the past 30 years, the size of land under cultivation has increased by only 28% (Fig.16 and Fig.17).

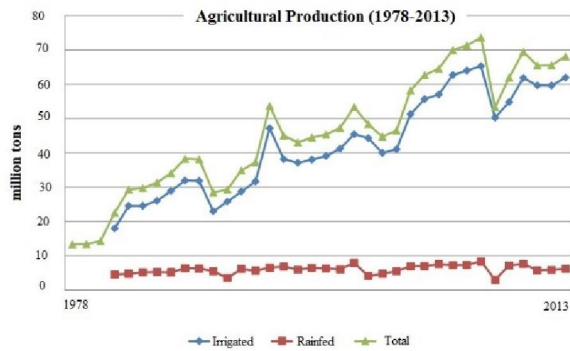


Figure 17: Agricultural Production (1987-2013) [8]

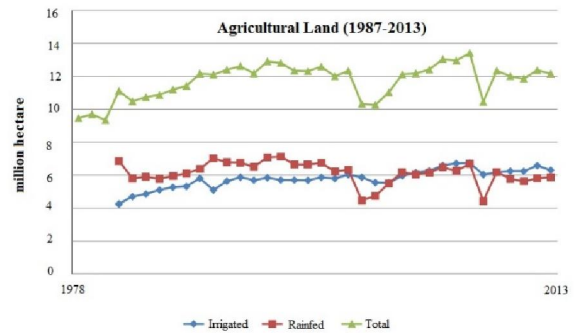


Figure 16: Agricultural Land (1987-2013) [8]

This indicates that farmers are moving towards crops that have higher water consumption and higher yields per hectare, rather than increasing the size of land under cultivation.

But what is the cause of this reaction? Why are farmers turning to high-water-demand crops if available water increases? Whether they have a higher price?

Table 1: no correlation between Water Footprint and price [37]

Crop Type	Price (\$/kg)	Water Footprint (m ³ /ton)
wheat	0.285	1827
maze	0.27	1222
barely	0.25	1423
tomato	0.34	214
potato	0.35	287
cucumber	0.35	353
water melon	0.32	235

As shown in Table.1, there is no meaningful relationship between water footprint and the price of crops. Therefore, the tendency towards to plant more water-consuming crops cannot be due to higher prices. Albeit, it seems to be rational, because when water is very cheap, naturally the amount of water consumption has no significant impact on the price of crops.

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Another potential reason can be since “Profit = Land * Yield per ha * Price” farmers cultivate crops with higher yield per hectare (which consume more water) to maximize their profit.

Table.2 confirms this claim. It shows that crops with higher water consumption give more crop per hectare (in terms of weight), which can increase farmers' income. For example, the tomato and potato crops that have grown the most in the last 36 years (6.5 percent and 5.5 percent per year, respectively) produce 29 and 21 tons per hectare, respectively².

Table 2: correlation between growth rate and water footprint (m3/ha) [8]³

Crop Type	Yield (ton/ha)	Water Footprint m ³ /ton	Water Footprint (m ³ /ha)	Average Growth Rate during recent 36 Years
tomato	29	214	6200	6.56 %
potato	21	287	6027	5.54 %
barely	2.5	1423	3557	2.63 %
wheat	2.7	1827	5000	2.6 %

Regarding “crop selection”, to simplify, it can be assumed that farmers have to choose only between cultivating of two crops instead of choosing among more than 100 crops; one is the low-water-demand crop (LWD) crop and the other is the high-water-demand crop (HWD). In fact, in SD, agents often aggregate, and although this can reduce model accuracy, it also makes the model easier to understand. In SD models, we do not seek to accurately predict numbers but seek to understand and more insight regarding the problem. Which is why in many cases, we are willing to sacrifice model accuracy for more insight, of course to the extent that it does not impair the validity of the model. For this reason, here, considering only two HWD and LWD products instead of the tens of products, seems to be a logical solution for model simplification.

However, including both decisions of “the size of irrigated land” and “share of HWD of irrigated land” not only makes the model a little messy but also creates some computational problems that we do not want to speak about here. What did we do to handle this problem? Some of the variables in the data can be aggregated to create appropriate model variables,

² Please note the difference between water footprint (m3/ha) and water footprint (m3 / ton) in the table above.

³ The resource for the amount of “water footprint” is [38] and “average growth rate” is extracted by the author from [8]

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and *some of these aggregations might even create abstract, intangible variables markedly different from those in the data* (Khalid Saeed, 2003) [39].

What we did is that we tried to merge both decisions into one. In a way that instead of having to decide about both the size of the land and the type of crop, the farmer only has to decide on one. For this purpose, for example, we can assume that *“the size of land under cultivation is constant”*, and the only decision farmers have to make is to choose between the share of each crop (HWD and LWD). Also, in order to see the impact of the increase in irrigated land size, *“maximum amount of HWD considering the market demand”* can be a little more than statistics.

As the second option, we can suppose *“there is only one crop,”* and the farmer only has to decide on the size of the land. In this case, in order to see the effect of cultivating HWD crop, we need to multiply the actual size of the land by a factor, to make equal water consumption (which is the main variable of our model). In this model used the second solution, and assume that there is only one crop and the farmer only has to decide on the size of the land.

2. We assume that **“price”** is constant, and ignore **“inflation”**, because *“inflation”* affects both *“revenue”* and *“costs”* at the same time, and we use **“revenue costs ratio”**, so including or excluding it does not influence our results
3. How much farmers produce, there is **“demand”** for it, and the increase in production will not lead to *“supply surplus”* and *“price reduction”*. Indeed, it is not much far away from reality; according to the project of Iran 2040 conducted by Stanford University [7] *“the increase in agricultural productions over the past quarter century has not been able to keep pace with the increasing demands caused by rapid population growth, resulting in a downward trend in the net international trade of the country in this sector. In rough terms, the net value of agricultural import (i.e., ~ \$5B) is equal to 14% of Iran’s current oil export gross revenue”* (Fig.18).

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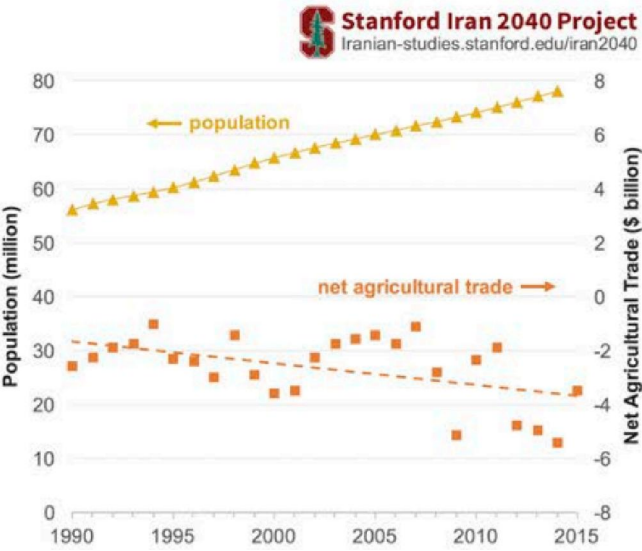
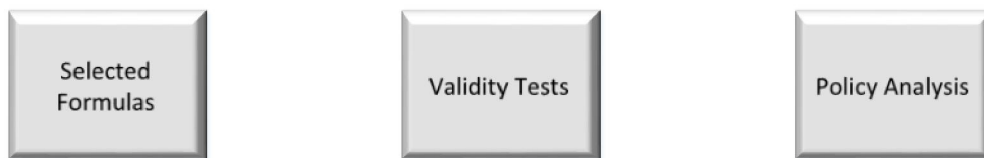


Figure 18: trend of population and net agriculture trade[7]

PART III: Simulation Model

The third part of this thesis presents the simulation model as a product of the data collection and analysis in the second part of this thesis and refers back to the foundation that is established in the first part of this thesis.

This part, as shown in the below picture, contains three sections. First, we present selected model formulas. Then, we assess the credibility of the model by doing internal and external validity tests. When we become sure that the model generates the “right output behavior for the right reasons,” we will run the model to find out what will happen if we do nothing (‘business-as-usual’ scenario). Afterward, we will test suggested proposals to investigate their effectiveness and discover the best policy(s) to manage the over-extraction of groundwater resources.



10. Running Model & Selected Model Formulations

To see the running model and full model documentation please refer to Appendix (B) and Appendix (C).

11. Model Credibility

System dynamics modelers have developed a wide variety of specific tests to uncover flaws and improve models ([10], p.858). Model credibility testing aims to assure that the model is an acceptable description of the real system with respect to the dynamic problem. Model testing is executed in two steps: structure and output behavior testing. Behavior pattern tests are designed to measure how well the model can reproduce the major behavior patterns of the real system. Structure test checks whether the structure of a model is a meaningful description of the real relations that exist in the problem. In the model, all

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parameters and variables have real-life counterparts. The model is dimensionally consistent in all equations. These are examples of direct structure tests. One typical indirect structure testing is an extreme condition simulation. In order to check the validity of model structure, selected extreme conditions are simulated [40].

An important point in this regard is that similar to the quality of the product that must be “built into” the product in the design phases (both product design and process design) and the quality cannot be “inspected in”, model credibility as a process, rather than an outcome as well (Barlas, 1996) [40]. Although some degree of validation takes place in every stage of modeling (and that validation cannot be entirely formal and objective), it is safe to state that a significant portion of “formal” validation activities take place right after the initial model formulation has been completed and before the policy analysis/ design step [40].

Among many tests for model validation, seven most used are selected, namely, (1) Boundary Adequacy (2) Structure and Parameter Confirmation (3) Dimensional Consistency (4) Integration Error (5) Extreme and Direct Extreme Conditions (6) Behavior sensitivity (7) Behavior Reproduction. In this research, I will apply all of them to test the validation of the model.

11.1. Boundary Adequacy:

For the boundary adequacy test, the guiding question is: does the model include all relevant structures needed for fulfilling the purpose of the model? Therefore, the purpose of the model is reviewed. The purpose of the model is to answer the research question: “how are the factors associated with the groundwater over-withdrawing dynamically interconnected?” In addition, it needs to be possible to test policies. For every policy, one or multiple model elements have been introduced (i.e., irrigation efficiency, land size, etc.), thereby satisfying the purpose of the model. In addition, an assessment of possible model extensions based on data collection is performed. It is certain that the implementation of additional qualitative and quantitative data (e.g., those are brought in suggestions for future research) would make the model fit better with reality and thus improve validity. However, the increase in understanding of the dynamics to which the system is subject in comparison

with required additional data is expected to merely contribute. Based on these arguments, it can be concluded that the model boundary is adequate for the purpose of the model.

11.2. Structure and Parameter Confirmation:

The test checks that the model has no dummy “scaling” parameters that have no meaning in real life [41]. The model passes this test since its structure consistent with relevant descriptive knowledge of the system, and all parameters have operational, physical meaning and real-world counterparts.

11.3. Dimensional Consistency:

This test checks whether all equations are dimensionally consistent without the use of parameters having no real world meaning. Key in the dimensional consistency test is consistent use of units from input values (exogenous parameters and stocks) when writing equations in the model. With the help of the ‘Units check’-function in the software, the reported outcome is ‘Units are OK.’

11.4. Integration Error:

The results are not sensitive to the choice of time step or numerical integration method (Euler, RK2, RK4, and Cycle Time).

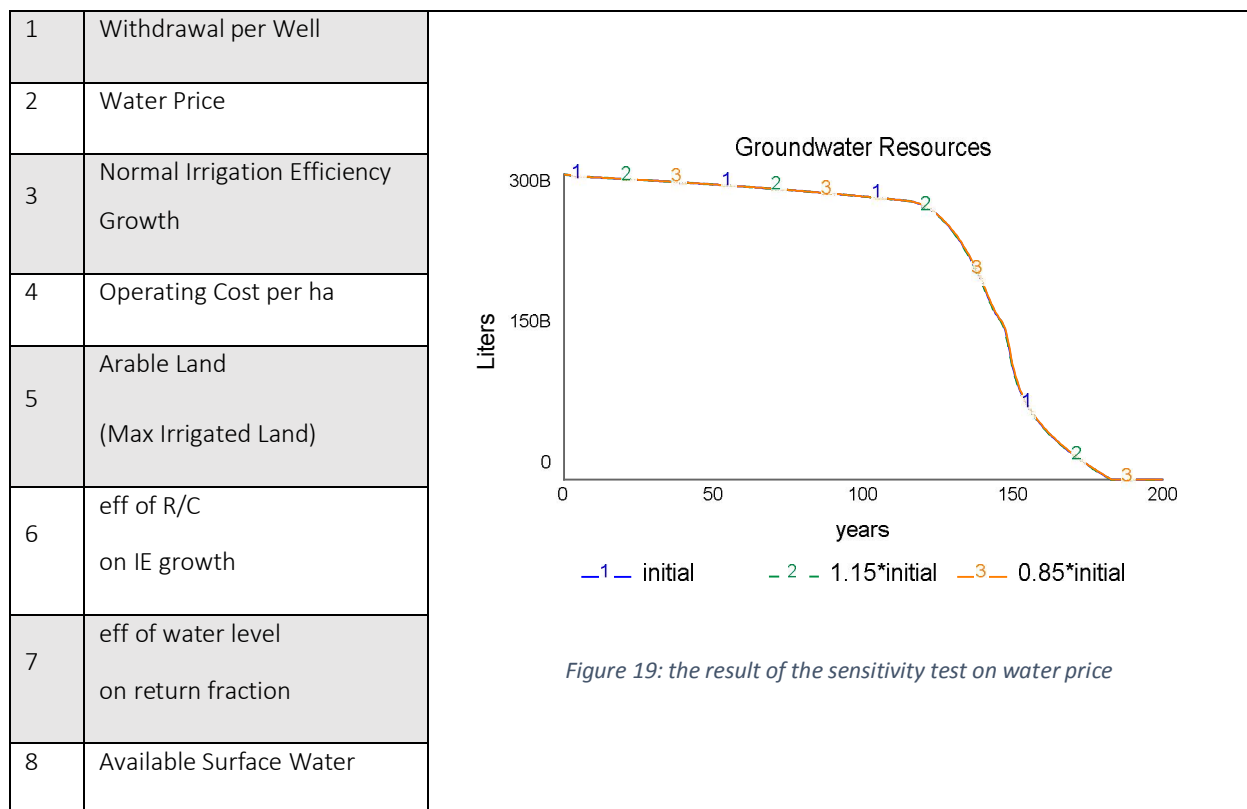
11.5. Extreme Conditions:

The extreme-condition test is about verifying the response of the model to extreme conditions of each model parameter. All equations make sense even when their inputs take on extreme values, and the model responds plausibly when subjected to extreme policies, shocks, and parameters. In this part, selected extreme conditions are simulated. For example, if the groundwater resources is zero then number of wells will be zero & the irrigated land will only be to the extent that available surface water is able to support it, and if groundwater resources and available surface water are zero at the same time, the total yield & irrigated land will be zero. Extreme condition tests are also applied to Irrigated land. When it is zero, “total yield”, “number of wells”, and the amount of withdrawal are all zero. These and many other extreme condition tests yield results consistent with real-life information

11.6. Behavior Sensitivity:

Assumptions about parameters were changed over the plausible range of uncertainty ($\pm 15\%$) to check whether outcomes change significantly or not. Sensitivity tests were done on (1) initial value of stocks, (2) exogenous variables, & (3) lookup table functions, and the result was as follow:

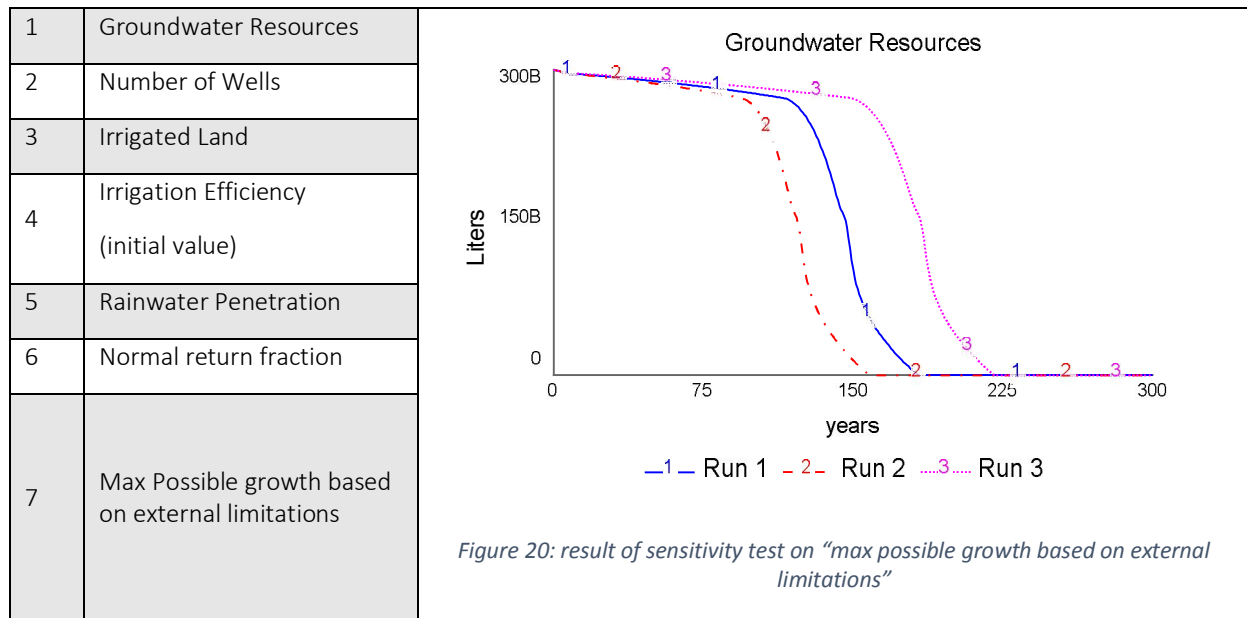
A. Variables to them the system shows no/small numerical sensitivity



- These parameters are neither attractive in terms of policy-making, nor do we need to be obsessive about their numerical value and spend much time and energy to find their exact value.

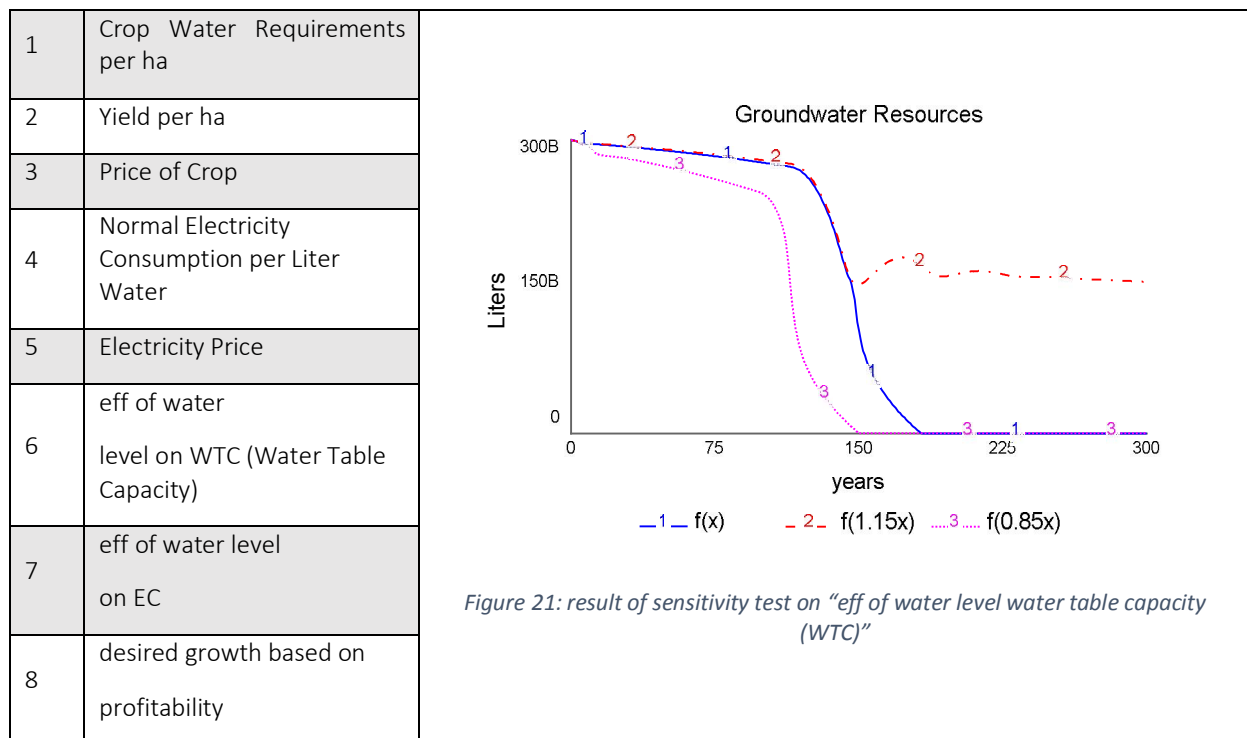
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B. Variables to them the system shows considerable numerical sensitivity



- The general pattern of model behavior (overshoot & collapse) does not change, but the time of overshoot and deletion changes. For example, the higher the water resources, the later groundwater resources will be depleted (when it is the infinity, it never gets depleted)

C. Variables to which the system is very sensitive (numeric or behavioral)



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- Parameters that showed high sensitivity were checked in the first step if the real system would exhibit similar high sensitivity to the corresponding parameters. After that, once we ensured, we spent more time and effort to estimate their value more accurately. On the other hand, highly sensitive parameters were selected as candidates for policymaking (we will refer to them in the last section, that is, “policy analysis” and talk about them in more detail). In cases, that system is highly (behavioral or numerical) sensitive, and we could not find exact values, we work with different assumptions there and use these assumptions as scenarios.

11.7. Behavior Reproduction:

The model reproduces the behavior of interest in the system (Figure.22). This test is done to measure how accurately the model can reproduce the major behavior patterns exhibited by the real system. It is crucial to note that the emphasis is on pattern prediction (periods, frequencies, trends, phase lags, amplitudes ...), rather than point (event) prediction. This is a logical result of the long-term policy orientation of system dynamics models. Furthermore, since such models, starting with a set of initial conditions, create the dynamic behavior patterns endogenously (not dictated by external input functions), it can be shown that even “perfect” structures may not yield accurate point prediction [40].

Note that, if a model is judged to fail the behavior pattern tests, we return once again back to work on “model revisions.” But in this case, since confidence in the model structure must have been already established, model revisions involve parameter/input changes, rather than structural revisions.

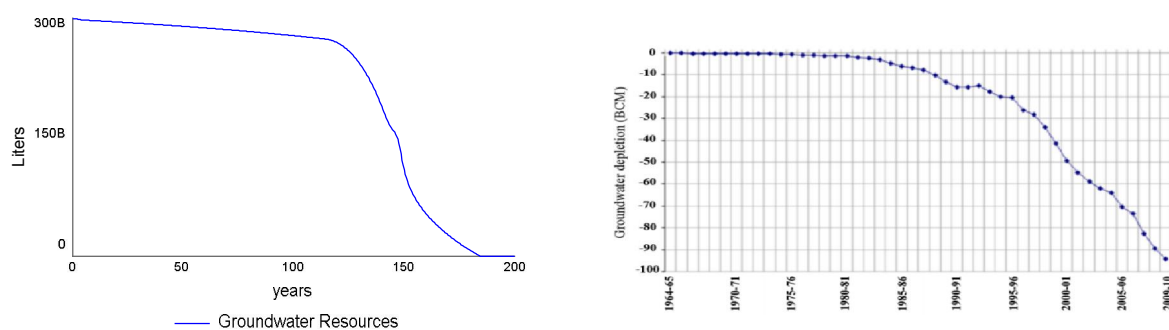


Figure 22: behavior reproduction test

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(the left picture is the output of the model and the right one is the reference mode)

Regarding behavior reproduction test we should notice some important points. One, a model can never really reproduce the data. It should reproduce relevant behavior but this relevant behavior might be only partially reflected by the data. Indeed, it is crucial to note that the emphasis is on pattern prediction (periods, frequencies, trends, phase lags, amplitudes ...), rather than point (event) prediction. This is a logical result of the long-term policy orientation of system dynamics models. Furthermore, since such models, starting with a set of initial conditions, create the dynamic behavior patterns endogenously (not dictated by external input functions), it can be shown that even “perfect” structures may not yield accurate point prediction [40]. another point is that a reference mode is different from a precise time history in that it represents a pattern incorporating only a slice of the history [42]. Although historical behavior and a reference mode can be expressed in either quantitative or descriptive terms, a reference mode is essentially a qualitative and intuitive concept because it represents a pattern rather than a precise description of a series of events [43]. Simply stated, reference mode is a “qualitative pattern”. The graphs included in it should explain all “turning points” in it and lead to the dynamic hypothesis. Your model must replicate the qualitative pattern articulated in the reference mode. Matching historical data would be irrelevant as historical data is generated by a very complex system of relationships and you sliced and diced model is a small subset of it.

12. Policy Analysis

In the following, the built model has been used to evaluate various strategies for avoiding the depletion of groundwater resources. For this purpose, “gap analysis” has been used. In gap analysis, the future under the present strategy (business as usual) is forecasted. Then, objectives or desired future is identified and the gap between the objectives and the future conditions under the current strategy is determined. Finally, new strategies which will help to close the gap will be designed [44].

So, in the following lines, we first discuss what will happen if we do nothing. Then, we will list a collection of intervention policies. And in the end, we will examine the impact of these policies to find the best ones.

12.1. Business-as-Usual (B.a.U.) Scenario

One of the conclusions gained in the sensitivity analysis is that the fate of groundwater resources depends on the soil properties, which manifest itself in “*eff of water on WTC*”. If the soil is loose and the reservoir resistance against destruction is low, it is expected that the reservoir easily degrades and dies by lowering the water level in the reservoir. But what about when the soil is very hard?

Since the soil properties can considerably affect the behavior and upshot of the system, and it is not so easy to find accurate data for that, we investigate business-as-usual scenario under two different conditions: (1) when the aquifer wall is very hard (like a rock), and will not destruct when the water level goes down, in other words, the water table capacity is fixed; (2) when water table capacity is eroded. The advantage of this work is that the model results can be applied to different regions of the world with different soil strength.

12.1.1. Business-as-Usual Scenario (I) - CC is fixed:

As can be seen in the figure.23, in this case initially the reinforcing loop of R1 is dominant and “*number of wells*” increases exponentially. But no growth can continue to infinity without being constrained. Meanwhile, the power of negative loops is increasing gradually from moment to moment. These negative loops try to limit the exponential growth to carrying capacity, so after a specific point, dominant loop shifts, and the model starts to show an S-shaped behavior. Nevertheless, due to the existence of time delays in these negative loops, the state of the system will overshoot and oscillate around the carrying capacity (400,000 wells & $150 \cdot 10^9$ m³ groundwater resources). To make sure this equilibrium is stable, we increased the model time horizon to 1000 and no change was observed. The number of wells and groundwater resources tends to oscillate with an average periodicity of

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about 40 years. The oscillation is quite lightly damped, requiring about 100 years for groundwater resources start to settle within 56% of the new equilibrium.

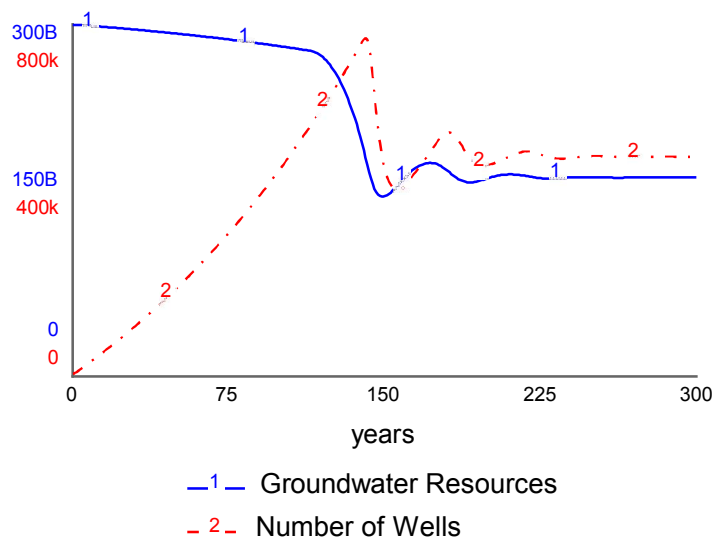


Figure 23: business-as-usual scenario-CC is fixed

Figure.24 can help us to understand the sources of the damped oscillation. The phase plot shows how the change in wells is related to the number of wells itself.

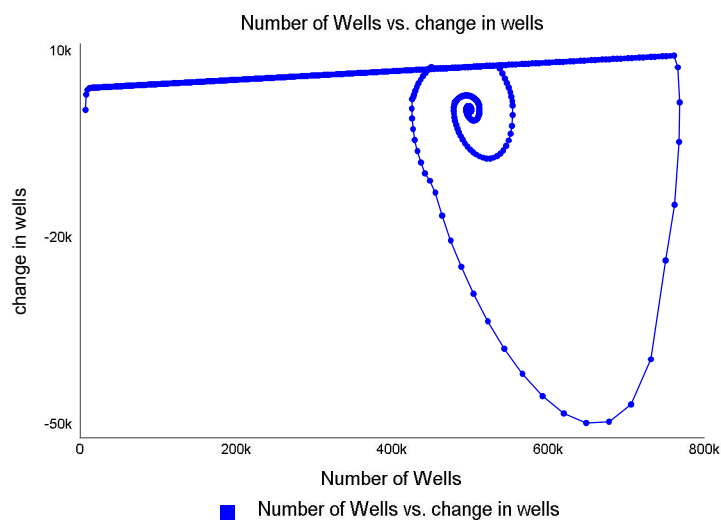


Figure 24: phase plot for the number of wells

12.1.2. Business-as-Usual Scenario (II) - Water Table Capacity is eroded

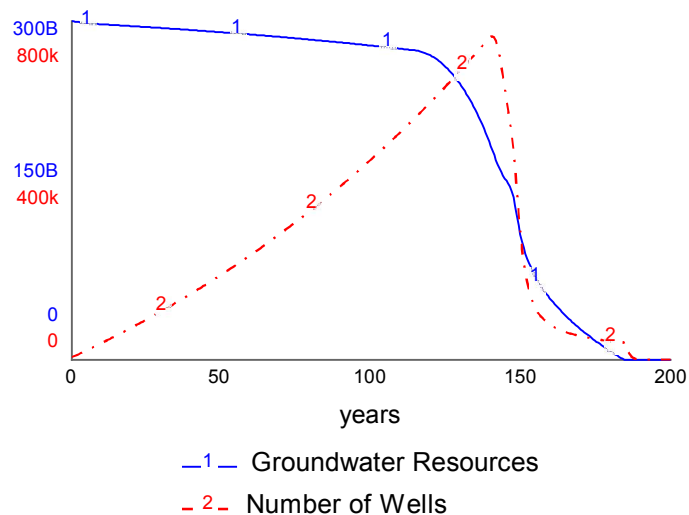


Figure 25: business-as-usual scenario-water capacity is eroded

In this case, the positive loop is dominant at the first, farmers are constantly extracting more water, making more profit, and cultivating more land. Withdrawn water is offset by “recharge” and no noticeable change is seen in “groundwater resources”. But suddenly when it passes the maximum sustainable yield (MSY)⁴ point, it collapses. Since in practice the capacity of the table is not constant, based on what is shown in the picture.²⁵, it can be concluded that if the government does not take urgent measurements, overshoot and collapse will occur, groundwater resources will be depleted, and the country will face serious food and water insecurity.

As mentioned, the second scenario is nearer to the reality, so in the following we will use the second one for policy analysis. Albeit, in the end, we can check how the following policies can affect the system under the first scenario, then compare how the promising policies are robust under these two different constellations of water table capacity.

12.2. Policies to Manage Groundwater Crisis

The proposed policies can be broadly divided into three categories:

⁴ https://en.wikipedia.org/wiki/Maximum_sustainable_yield

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(1) Policies that focus on a particular parameter of the model and attempt to control the behavior of the model by strengthening or weakening the existing loops. These policies seek to weaken loops that intensify water withdrawing and, on the other hand, to strengthen loops that seek to control withdrawal. The following table lists the names of the loops, the manipulable and policy variables within those loops, and the possible policies for managing those variables.

Table 3: suggested policies to manage over withdrawal of groundwater resources

Loop	Variable	Policy
R1	Max Land Under Cultivation	<ol style="list-style-type: none"> shrinking agriculture size virtual water trade and shrinking the share of crops with higher water footprint
	max growth based on external limitations (embedded in desired growth based on profitability & external limitations)	external limitations
	Price of Crop	price determination
	Yield per ha	production efficiency by cultivation or harvesting technology or by genetic engineering
	Crop Water Requirements per ha	genetic engineering
	Number of Wells	limiting the number of wells & blocking unauthorized wells
	Available Surface Water	<ol style="list-style-type: none"> increasing the share of surface water for the agriculture sector treated wastewater for agriculture
B1,2,3	Water Price	price determination
	Electricity Cost	price determination
	EC per liter water	pump efficiency
	operating cost	price determination
B4, 5	Irrigation Efficiency	modernization of irrigation

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(2) Combined Policies: these policies aim to control system behavior by simultaneously managing multiple variables and the power of different loops. After investigating the above-listed policies separately, and gaining more insights, we will decide which policies could be combined.

(3) Changing the current structure: one solution in this category can be changing water governance and constitution of the water market

12.3. Evaluation of the Suggested Policies

We will elaborately discuss each of the above-mentioned policies as follows:

12.3.1. Policy (1): Shrinking Agriculture Size

Not surprisingly shrinking agriculture can ameliorate groundwater depletion. In other words, having sustainable natural capital, the scale of human activities should be limited to a level that is compatible with the carrying capacity of natural capital. Excess expenditure over income will lead to bankruptcy. MSY is required to calculate the maximum irrigated for the system to remain stable. As shown in figure.26, if the size of irrigated land exceeds even slightly the MSY, system will be highly unstable and will collapse rapidly.

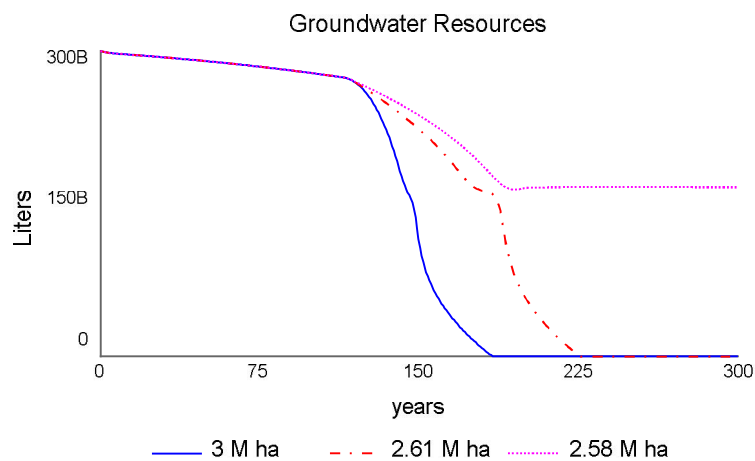


Figure 26: effect of irrigated land on groundwater resource sustainability

As noted earlier, the size of the irrigated land is actually representative of two parameters: (a) the actual size of the irrigated land, and (b) the share of the high-water

demand crops. So when it comes to agricultural downsizing, it can be implemented by either reducing the actual size of irrigated land or reducing the share of high-water demand crops. Which of course, both of them have their own implementation challenges. Before more explanation, it worth-mentioning that the concept of maximum sustainable yield is not always easy to apply in practice. Estimation problems arise due to poor assumptions in some models and lack of reliability of the data.

➤ Implementation Challenges

(i) Implementation challenges of virtual water trading:

To reduce the share of high water footprint crops, the government can guarantee the purchase of low water footprint crops at a higher price than high water footprint crops or can impose a higher tax on high water footprint crops. In addition, the government can prohibit the export of high-water footprint crops (such as watermelon), or can import high-water footprint crops at a lower price, leading to farmers have no incentive to cultivate them in the country. Nevertheless, there is some objection and insecurities in the virtual water trade. First of all, some countries which have a lot of water suffer from lack of proper land for agriculture (like Canada). Some other countries although benefit from enough water and land, due to the high salary of labors and environmental concerns they prefer to import agricultural products as well (like Japan). Moreover, besides 37 countries which face with high water stress, many other countries will face the same problem in near future (like China), which shift and impose a huge pressure on countries that export crops and virtual water (like Brazil), so, this trend is not sustainable.

(ii) Implementation challenges for shrinking the actual size of irrigated land:

1. **Conflict of interest** between Agriculture Ministry and Energy Ministry: the main goal of agriculture ministry is food security and self- sufficiency. So, whether both aims of water security and food security are achievable at the same time or not and they are mutually exclusive? They are not mutually exclusive if we can manage the “demand” by the following six proposed ways:

1.1. Revising population growth policy: After the war with Iraq, due to the adopted population growth policies, the population of Iran has doubled (in 1980 it was 40 million, and in 2016 it is 80 million). After the baby boom, Iran’s authorities adopted population reduction policies. Yet, after a while, as shown in below picture again they started encouraging people to have more children. One of their reasons is when the baby boom generation becomes retired need backing population (Fig.27 and Fig.28).

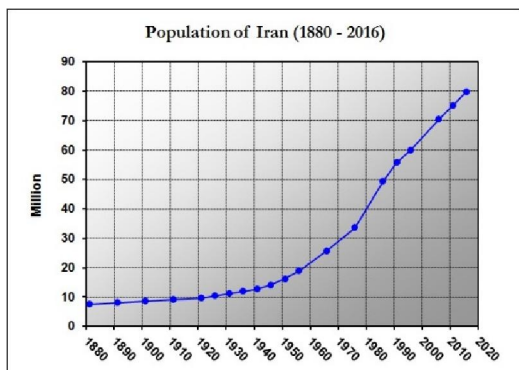


Figure 27: Iran's Population [45]

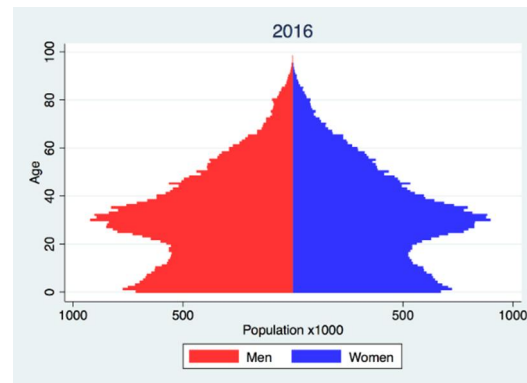


Figure 28 Iran Population Pyramid [45]

There is an urgent need for revisiting the new population growth policy in Iran. While the current age distribution of Iran’s population is undesirable and can have some long-term socioeconomic impacts, the negative consequences of uncontrolled population growth and rapid urbanization can be much more significant. Optimizing the spatial distribution of the current population should be prioritized over improving the age distribution of the population. Major urban areas in Iran are already challenged by satisfying the needs of the existing population. Without major socioeconomic and political reforms to address the current imbalance of power and services throughout the country migration to major metropolitans will continue. So, the new population growth policies will just exacerbate the situation.[46]

1.2. Consuming less meat: Nowadays in most parts of the world people prefer meat to vegetables and this is bad news for water sources, as vegetables consume about 2000 liters per kilo while red meats consume 15,000 kilos per kilo (more than 7 times). Vanham

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D. et al (2013) [47] by using the concept of "virtual water" show that people's "current diet" is 1000 liters more than a "healthy diet" and 1600 liters more than a "vegetarian diet". That is, if people reduce their consumption of red meat and stick to a healthy diet, it can not only alleviate many health problems, including overweight and cardiovascular disease, which puts a lot of pressure on the Ministry of Health and the health budget. But it can greatly solve the problem of groundwater over-extraction. However, in some places encouraging this policy may lead to other problems, such as overfishing, so it is necessary to formulate some plans for managing side effects beforehand.

1.3. Decreasing the food waste: Based on statistics, 35% of agricultural products is wasted which is equal to 3.9 billion cubic meters of water. For this purpose, the mentality and culture of people should be changed.

1.4. Using new food sources that consume less water, such as insect bread instead of wheat bread

1.5. Finding a new method of agriculture by salty water^Δ

1.6. Changing the definition of "self-sufficiency". It is not possible and rational to be 100% self-sufficient in all **agricultural products. Groundwater resources should be considered as strategic reserves for critical conditions and they should be maintained for times when the country may be under food siege.**

2. Unemployment rate: Agriculture is "labor-intensive" and there are about 4 million farms in Iran, the shrinking agriculture sector will increase the unemployment rate dramatically. In fact, the current unemployment rate is about 12% and government cannot manage it, because creating jobs needs budget and government right now suffers deficit budget, and due to sanctions foreign investors are not willing to invest in Iran as well. Moreover, even the government can create job opportunities, farmers' average ages is more than 50 in Iran, most of them are illiterate, and cannot do anything else farming.

^Δ please visit www.biosaline.org

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3. Another challenge is the way of implementation. How does the government want to shrink the agricultural sector? Two approaches come to mind:

- a) Paying Money to farmers for “No Cultivation”; Lack of trust to the financial power of “Social Security” and income heterogeneity in different regions are two important challenges for this method.
- b) Buying farmlands; bargaining after buying farmlands of the first village and unemployment rate are important challenges in this method [48].

12.3.2. Policy (2): External limitations

The lookup function defined for “desired growth based on profitability” also implicitly applied “max possible growth based on external limitations”. There are a number of external constraints that limit the growth of cultivated land, and if the “R/C Ratio” is ten, farmers cannot increase the cultivated land 10 times overnight. Sensitivity analysis shows that this constraint and ceiling for irrigated land growth can have a significant impact on model behavior. That is to say, imposing restrictions on irrigated land growth per year and the growth of the share of high-water demand (HWD) crops per year has a significant impact on system behavior. From another perspective, this variable can be considered as an indicator of the *aggressiveness* of farmers. If farmers are not too aggressive, and when their business is profitable, do not expand their irrigated land and HWD share maximally, as shown in figure.29, it seems the problem of groundwater depletion will be controlled, and at one point it will be stabilized.

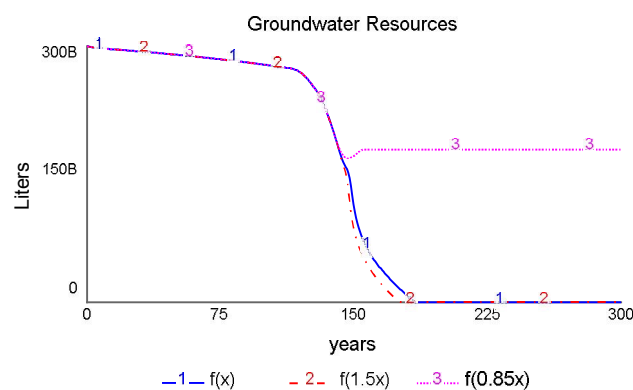


Figure 29: effect of max possible growth based on external limitations on groundwater resource sustainability

(Time period = 300 years)

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Since the degree of farmers’ aggressiveness is an important variable, different scenarios can be analyzed in the business-as-usual section, based on the degree of aggressiveness of the farmers. The important question here is whether this solution to restrict growth by applying external constraints is a sustainable solution. To answer this question, we increase the time period from 300 to 600 years and see (figure.30) although this problem can be controlled for a longer time, it cannot be sustained forever and collapses again after a few decades.

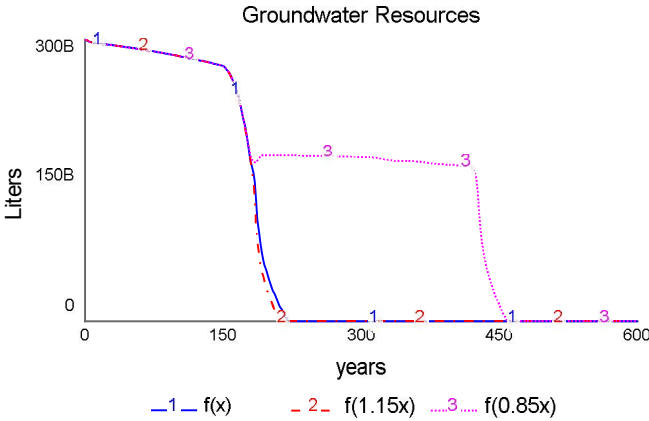


Figure 30: effect of max possible growth based on external limitations on groundwater resource sustainability (Time period = 600 years)

This conclusion seems reasonable since the main reason for the collapse is crossing the MSY. In this policy we do not consider the MSY, just slow down the speed of growth, but do not prevent it from crossing the MSY, and collapse will occur whenever it crosses that point.

12.3.3. Policy (3): Price of Crop

In Iran, most farmers belong to the lower class of society who need to produce as many crops as possible to support their families. For this purpose, they have no way else digging more wells (authorized or unauthorized). In other words, digging well is often not because of the greed of the farmers and effort to accumulate more wealth, but because of the poverty and the need to dig wells to earn a living. With these explanations, it appears that an increase in the price of agricultural products by the government can not only improve the living condition of farmers but also eliminate their need to dig more wells to increase

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production and provide a minimum standard of living. But can the policy of increasing the price of crops really prevent digging more wells and control the over-extraction?

As can be seen in the figure.31, contrary to the above argument, the increase in the price of agricultural products not only does not control over-extraction but also exacerbates the problem and groundwater resources will be depleted in a shorter time. The reason is that rising crop prices make the reinforcing loop of R1 more powerful. Therefore, it seems that in order to control over-extraction, the prices of agricultural products should decrease, leading to decrease in profitability and attractiveness of agriculture. Figure.9 shows when the price of crops drop by 15%, the behavior of system changes and no longer collapse, and reaches a stable equilibrium (time horizon increased to 1000 years, but no change happened).

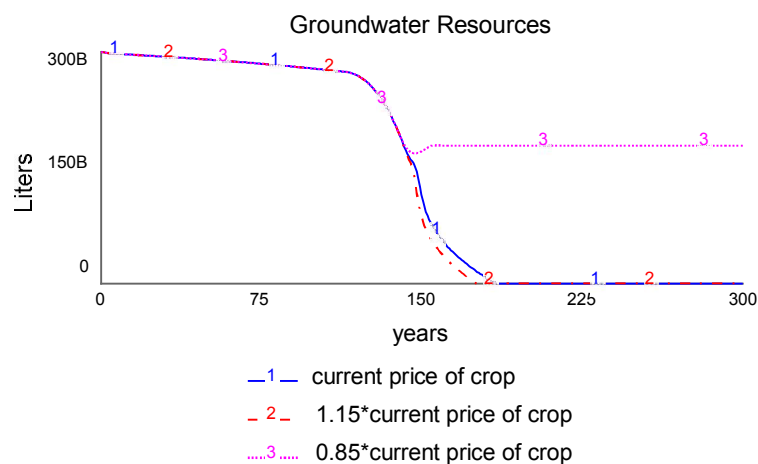


Figure 31: effect of crop price on groundwater consumption

12.3.4. Policy (4): Yield per ha

Another solution to reduce water consumption is to increase productivity by improving cultivation and harvesting technology, or using genetic engineering. By this way, with less water, more crop is produced, and since the increase in production will cause reach to the demand saturation point sooner. Contrary to this argument, the model shows (Figure.32) that with increasing agricultural productivity will exacerbate the over-extraction problem.

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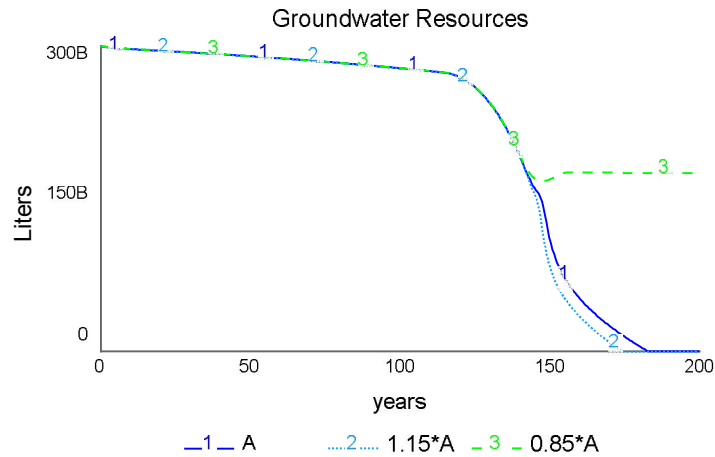


Figure 32: effect of agricultural productivity on water consumption

The reason is that by improving agricultural productivity, the reinforcing loop of R1 will be amplified. So, it seems that controlling agricultural productivity will weaken this positive loop and postpone groundwater depletion. Amelioration of agricultural productivity although increase production (which seems to be a reasonable solution to meet growing demand), it increases “R / C Ratio” and disrupts one of the main growth, and worsens the over-extraction problem.

In order to see the impact of this policy over a longer timeframe, the timeframe was extended to 1000 years but no change in model behavior was observed. *It should be added that it is assumed that “crop price” is fixed and the amount of production has no effect on the price, also there is no demand saturation point and there is demand for whatever is produced (this was stated in the model assumptions). However, to improve the model results, we can add the effects of supply and demand on crop price.*

12.3.5. Policy (5): Crop Water Requirements per ha

Can genetic changes in crops, in a way that they consume less water for the same amount of yield, prevent groundwater depletion? It seems rational, since when we do an extreme test and assume “Crop Water Requirements per ha = 0”, water withdrawal will be zero, and the groundwater resources will remain pristine.

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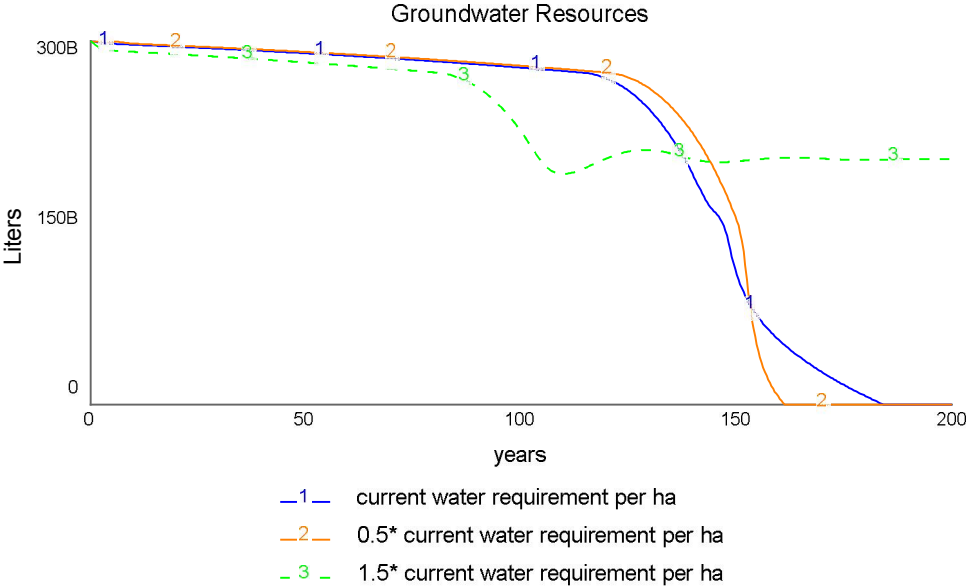


Figure 33: effect of crop water requirement per ha on groundwater resources

However, when we change the amount of water needed per hectare to $\pm 50\%$, it is found that by decreasing the water requirement per hectare again the system will collapse (Figure.33). Interestingly, when we decrease the water requirement per ha, the starting time of collapse will be slightly delayed, but the speed and slope are higher than the initial state, and sooner the resources will be depleted and reach zero. Why? With the decrease in water requirement per hectare, the negative loops of B1 and B2 (driven by the costs of water and electricity) will be weakened, the reinforcing loop of R1 will be dominant more time, and the size of irrigated land and share of HWD will be greater, causing more water extraction.

Two noteworthy points that, we increased the time period to 1000 and no change in behavior was seen. Second, why and to what extent does the reduction in the water needed per hectare not lead to improvement? We will answer these questions in evaluating policy 13 (irrigation efficiency). In fact, we can decrease needed water per hectare both by genetic engineering and improving irrigation efficiency.

12.3.6. Policy (6): Permission for digging Wells

This method is similar to the shrinking of the agricultural sector (policy 1), and if the number of wells is defined to be smaller than the MSY, the groundwater problem can be controlled.

➤ **Implementation Challenges**

1. Politicians' desire for solutions that solve the problem faster (but not more radically): When there is a problem of water scarcity, the government can offer two solutions; one is creating new job opportunities for farmers and shrinking the size of the farm, and two is allowing digging more wells to meet needed water for agriculture. The first is time-consuming and costly, so it is not desirable for politicians seeking solutions to solve the problem quickly. Such short-term solutions not only do not address the root cause of the problem but also allow it to go further and deeper (shifting burden or fix-that-fails archetype, Fig.34)

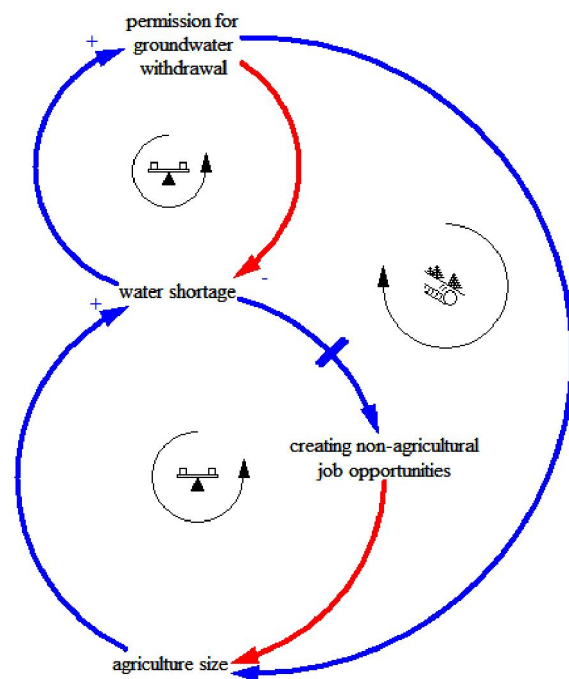


Figure 34: shifting burden archetype in agriculture sector

2. Increasing the number of unauthorized wells by decreasing the number of permitted wells, due to its light penalties and low risk. Increasing the number of unauthorized wells eliminates its ugliness and fear of digging illegal wells, and creates a positive loop as shown in figure.35.

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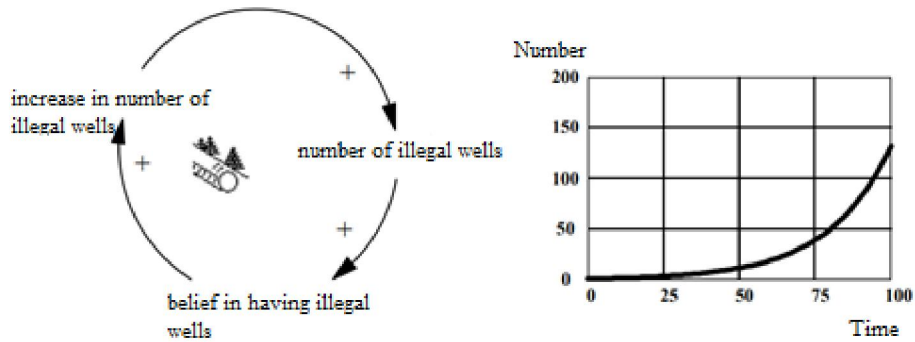


Figure 35: reinforcing loop of perception about having illegal well

3. **law enforcers'** lack of understanding about the importance of these rules and corruption [49].
4. Farmers' Resistance to blocking illegal wells: based on interviews, the livelihood of farmers is one of the most influential aspects of conservation measures and a significant proportion of farmers (according to interviewees ranging from 10% to 90%) depends on illegal wells to maintain their family's livelihood. One of the managers of the Ministry of Energy described the issue of farmers' dependence on illegal wells in this way: "The farmer has his child's hand, hung over the well, saying either go or I will throw him into the well. Because that well is also his whole life ... " [49]

12.3.7. Policy (7): increasing the share of surface water for agriculture sector

Could allocating more surface water reduce groundwater withdrawal and prevent it from being depleted? Contrary to the perception, as seen in figure.36, increasing the share of agriculture in surface water exacerbates the problem and speeds up groundwater over-extraction, and resources come to an end sooner.

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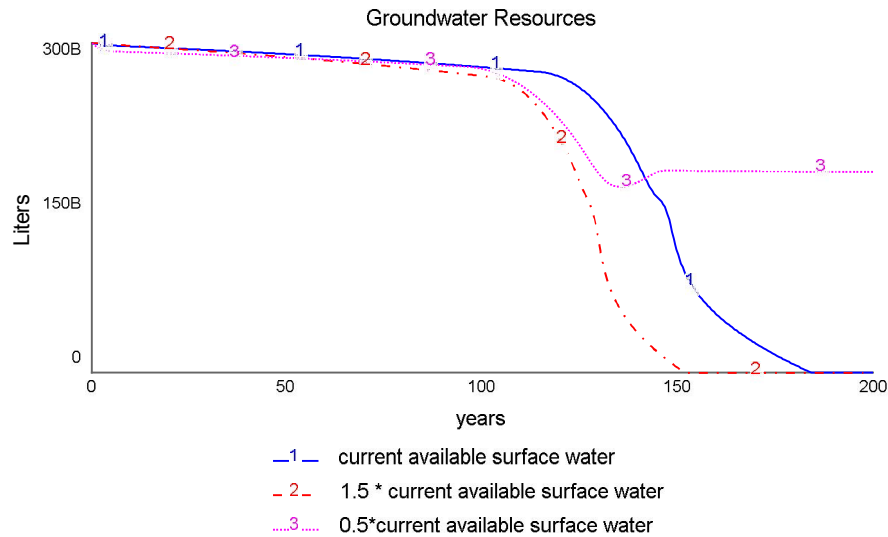


Figure 36: effect of allocating more surface water to the agriculture sector

The reason for this observation is when more surface water is available, farmers will not have to pay money for electricity and pumping water to the surface of ground, that is, R/C Ratio will become larger, the later costs will exceed revenues, and the later shifting dominant loop from the reinforcing loop R1 to negative loops happens. Which means, the reinforcing loop R1 will be dominant for a longer time, and more water will be extracted. Conversely, as can be seen in the above figure, with the reduction of the surface water, the negative loops gain more power and can prevent collapse behavior. We checked the outputs by expanding the time horizon to 1000 years and no change in behavior observed. In order to this policy to be effective, it is necessary to control the size of irrigated land and the share of HWD crops, in this way by increasing the available surface water, the farmer cannot cultivate more land and HWD crops, therefore there is no reason to extract water from groundwater resources. Because excessive discharge will have an adverse impact on their harvest and profit (figure.37)

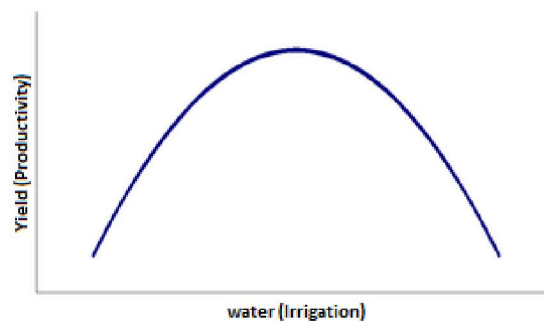


Figure 37: relationship between water used in irrigation and yield (productivity)

➤ Implementation Challenges

Allocating more surface water to agriculture sector not only exacerbates the problem of over-extraction, but it also accompanies some implementation problems and environmental consequences. Surface water is limited, and increasing the share of agriculture means decreasing the share of household, industry, or environment. Household share due to exponentially increase in population and urbanization not only is not reducible but also is increasing exponentially. But if people decrease their personal water consumption, this policy can be applied. Nevertheless, we should remember that household consumption is only 6% of total water consumption, and decreasing it cannot create a big effect on the depletion of groundwater which is used by agriculture. Another way is reducing the leakage in the distribution network. Regarding the industry share of surface water, similarly, since the government wants to improve GDP and decrease the unemployment rate for exponentially growing population, the industry share of surface water has been increasing during recent decades. So, the only practical way to increase the share of agriculture from surface water is decreasing the water share of the environment. The government by building dams over the last decades has tried to meet the water demand of agriculture and household, and caused serious environmental problems; the tragedy of Urmia is one of them. The shrinking the Lake is obvious in Fig.38:

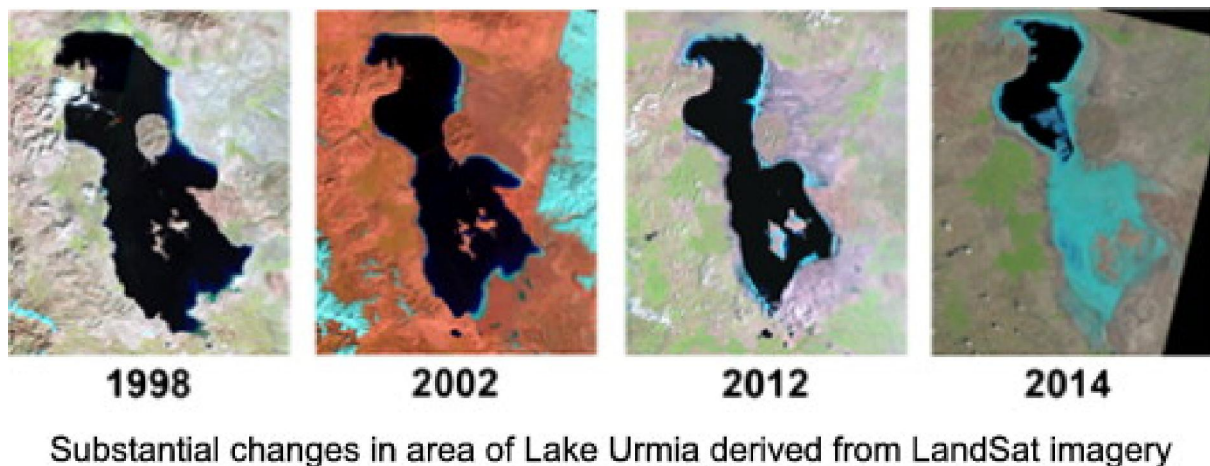


Figure 38: Gradual shrinkage of Lake Urmia in less than 15 years [50]

This drying up of lakes and wetlands has led to salt and dust storms in many parts of Iran that have created serious respiratory problems for people. Salt storms, in turn, are destroying the surrounding farmland, which could eventually force villagers and farmers to

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migrate to cities, which in turn could exacerbate the water crisis in big cities, on the one hand, and expand shantytown and slum areas around big cities, causing more social problems.

12.3.8. Policy (8): Treated Waste Water for Agriculture

Wastewater treatment and use that for agriculture, although does not have the environmental impacts mentioned above, it is still can aggravate the problem of over-extraction of groundwater resources unless the size of irrigated land and the share of HWD crops is controlled. The reason is that this policy will decrease the cost of electricity, increase R/C Ratio, and postpone shifting dominant loop from R1 to negative loops. Another point to note is that even with the control of irrigated land size and HWD crop share, this policy cannot make a paradigm shift in depletion of groundwater resources. Since as it was mentioned earlier, domestic water consumption is only 6% and this is a small number compared to the water consumed in agriculture (1.5 percent belongs to industry and the rest belongs to the agricultural sector).

➤ Implementation Challenges

Financial Problem: due to sanctions Iran was not able to finance these projects from international banks, and at the same time since the water is almost free in Iran, no domestic investor is willing to invest in this industry. As seen before, the low price of water not only has caused inefficiency in agriculture but also hindered the development of water treatment

12.3.9. Policy (9): Water Price

Another way to control the reinforcing loop ending to groundwater depletion (R1) is empowering the balancing loops by increasing the water and electricity prices. Figure.39 depicts the water price for the agriculture sector in comparison to household and industry sectors; it shows except a few countries (like Netherlands and Austria) water for irrigation is very cheap. In Iran, despite the scarcity of water resources, the price of water for irrigation is 0.0025 dollars/liter [52] and the price of electricity is 0.002 dollars/kwh [53].

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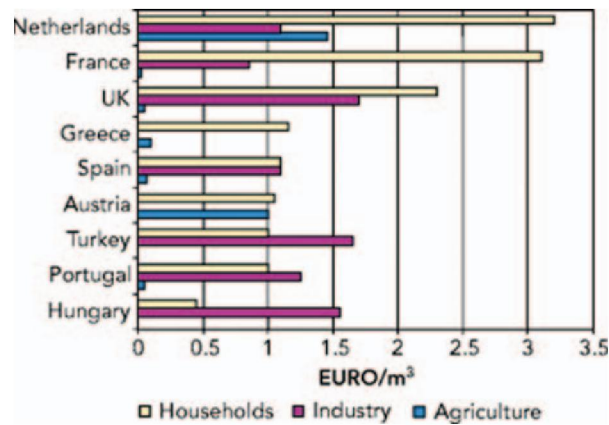


Figure 39: water price in different countries [51]

Can rising water prices prevent over-extraction? The figure.40 shows that the increase in agricultural water prices despite the heavy costs for the government (farmers' dissatisfaction and strikes), the system is not sensitive to that and does not make a big change, and if the government insists on controlling water extraction by this policy, it should make the water price at least five times. As can be seen, when the water price is four times higher, there is still no change, but when the water price is five times higher, the behavior of the model changes and reaches equilibrium instead of collapse. Increasing this number from 5 to 20 (Run 4) also shows a higher equilibrium point and a damped oscillation behavior.

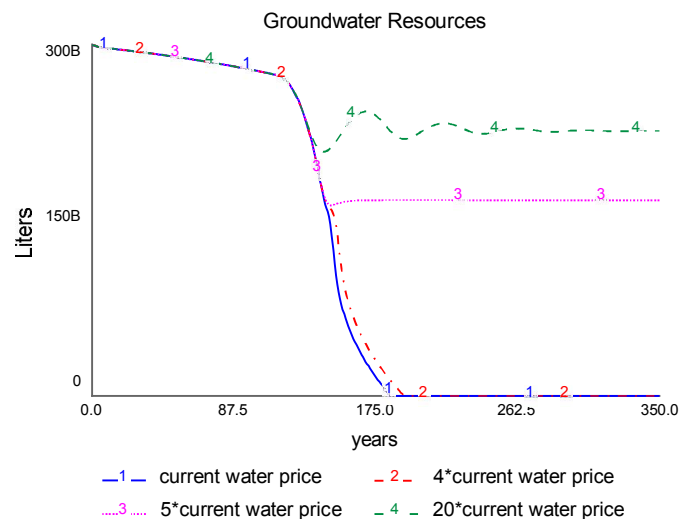


Figure 40: effect of water price on groundwater withdrawal

Of course, it should be noted that this model assumes the crop price is fixed. However, with the decline in water availability or rising price of water and other production

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inputs (such as electricity, etc.), the crop price will also be expected to rise. So, by adding the effect of production costs on crop price a more accurate result can be obtained from the model.

12.3.10. Policy (10): Electricity Price

Due to the high subsidy of the government for water and electricity in agriculture and their very low price, water and electricity consumption is far from the optimal mode. As shown in Figure.41, the consumption of electricity in the agriculture sector has been ever increasing over the recent decades and currently the agricultural sector accounts for about 15% of the country's electricity consumption [54]:

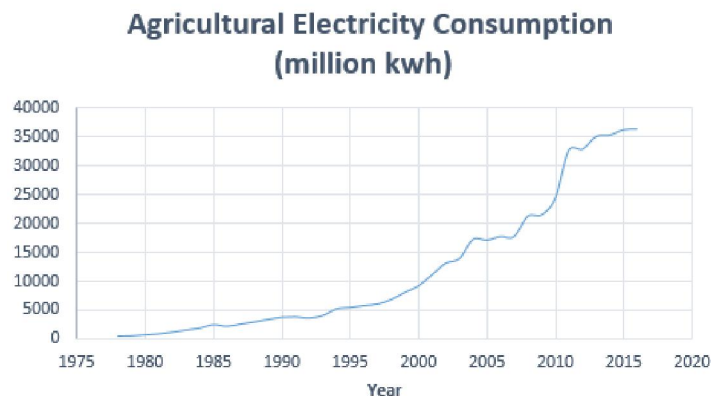


Figure 41: Electricity consumption in agriculture sector (1978-2016)

Due to the increasing electricity demand in the agricultural sector, the Ministry of Energy is keen to encourage farmers to use solar panels. Another way to control electricity in the agricultural sector could be to raise the electricity price. Which of the two is the preferred option? If the system is not sensitive to the price of electricity (as it was not to water price), using solar panels seems to be a reasonable option and can at least reduce power consumption. As can be seen in figure.42, lower electricity prices can exacerbate the problem and accelerate groundwater extraction. on the other hand, with a 15% increase in the price of electricity, the behavior of the system changes, and after an initial overshoot, the system reaches an equilibrium point (time horizon has increased to 1000 years and no change has been observed).

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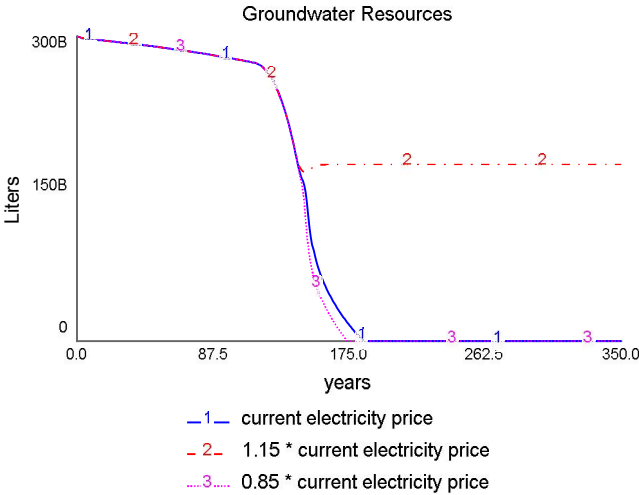


Figure 42: effect of electricity price on groundwater withdrawal

Rising electricity price has two major effects on the system. First, it reinforces the negative loop of B2 controlling the positive loop of R1. Besides, it will reduce the profitability (R/C ratio) which will encourage farmers to improve irrigation methods and increase irrigation efficiency, and the increase in irrigation efficiency has its effects which we will discuss it later (policy 13). With this explanation, it can be seen that encouraging farmers to use solar panels although reduce the electricity consumption (which is favorable for the Ministry of Energy), it will exacerbate the problem of groundwater depletion. Because it will weaken the B2 balancing loop and increases water extraction. Another drawback is that the best time for irrigation is night-time when there is no sunlight, the worst time for irrigation is noon when sunlight and evaporation is maximum (though adding a battery to the system which stores the electricity to use it in the night-time, because of its high cost it is not welcomed by farmers)

➤ Implementation Challenges

1. Farmers’ resistance and strike: Previous increases in agricultural water price have resulted in farmers’ strikes. “Agricultural water use, which amounts to about 90% of the total consumed water, is very cheap and the government cannot easily raise the price due to political obstacles. Water and energy prices should be raised meaningfully to be reflective of the true cost of water and energy in each region across the country. This, of course, can

have serious negative impacts on the socioeconomic conditions of farmers in the short-run and is associated with a high political cost for the government. To prevent such impacts, the government should finance the modernization of agricultural practices that help farmers cut water and energy usage effectively. Although this strategy requires large initial investments, in the long-term, it is expected to cost less than the current government policy, which heavily subsidizes the increasing water and energy use in the agricultural sector.” [46]

2. Measurement and water extraction monitoring technologies: for solving this challenge the government has started to sell a specific water and electricity meter to farmers which can measure water and electricity consumption at the same time [77], and farmers can pay for it by monthly installments.
3. Increase in **electricity theft**
4. **Populism**: Populist actions of the Iranian decision-makers, such as substantial subsidization of water and energy, to support farmers have failed to increase welfare in this sector. Given the existing political instability and insecurity within the system, decision-makers are more interested in populist development actions which produce immediate economic impacts. For example, the representative of a region in the parliament can pressure the water authorities to finance a dam construction project to help the farmers in his region. If the project is successful, it can boost the regional economy alongside the legitimization of the representative. Locals would then be willing to support the same person and send him to the parliament in the next round. The long-term environmental impacts are not associated with immediate economic benefits and political popularity. Thus, ecosystem preservation remains overlooked when pursuing populist development agendas. Similar development initiatives by other elected officials in the shared river basin will eventually create significant externalities, resulting in long-term losses for all parties. A good example of this situation is the Lake Urmia tragedy, which is perhaps the most catastrophic water problem, experienced by the Iranians to date. The lake has almost dried up because of the anthropogenic effects of selfish and uncoordinated upstream development activities by three provinces in a competitive environment. Locals would then be willing to support the same person and send him to the parliament in the next round. The long-term environmental impacts are not associated with immediate economic benefits and political

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popularity. Thus, ecosystem preservation remains overlooked when pursuing populist development agendas. Similar development initiatives by other elected officials in the shared river basin will eventually create significant externalities, resulting in long-term losses for all parties. A good example of this situation is the Lake Urmia tragedy, which is perhaps the most catastrophic water problem, experienced by the Iranians to date. The lake has almost dried up because of the anthropogenic effects of selfish and uncoordinated upstream development activities by three provinces in a competitive environment. [46]

5. Increase in people's dissatisfaction due to the increase in crops prices and inflation
6. There is a direct correlation between water scarcity and level of poverty, and if the water is priced based on scarcity, poorer farmers living in the area of low water have to pay more for water [48]

12.3.11. Policy (11): EC (electricity consumption) per liter water

As shown in figure.43, the function determining the relationship between energy consumption and water depth is an important and influential function on the fate of groundwater. With the technology advancement in water pumps and improving the efficiency of pumps, less electricity will be consumed to pump needed water, so the balancing loop of B2 will be weakened, shifting dominant loop will be postponed, and groundwater resources will be depleted faster.

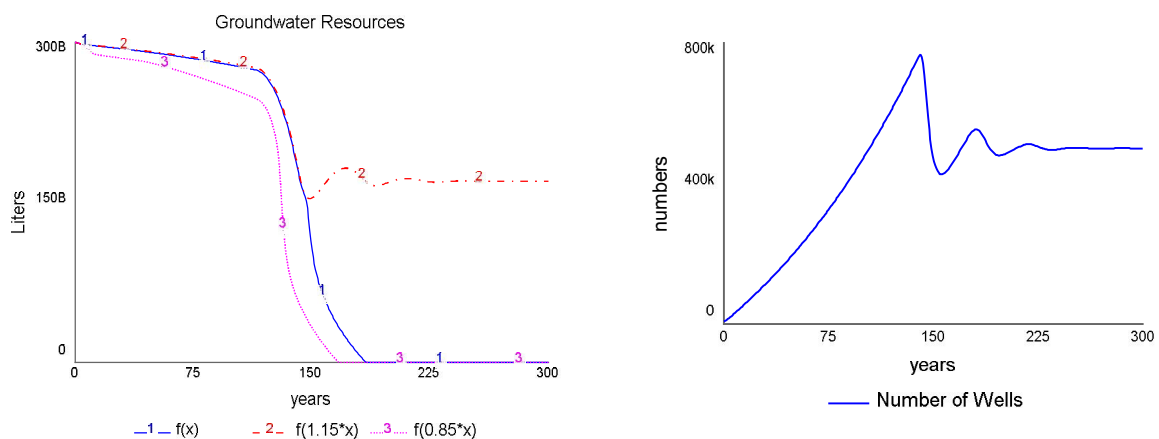


Figure 43: effect of pumps technology and efficiency on groundwater withdrawal

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Conversely, low-efficiency pumps will be a barrier to groundwater extraction, and as can be seen, by reducing the pump's efficiency, after an overshoot, the system will balance with a damped oscillation. Therefore, banning high-efficiency pumps, although seemingly increasing the electricity consumption in the agricultural sector, will control groundwater extraction.

Two points worth mention here. One, to ensure that this behavior is sustained, the time period was increased to 1000 years and no change was observed. Second, in this model, the relationship between electricity price and pump efficiency is ignored. In policy 10, we reached to the conclusion that electricity price can control water consumption. But, at the same time, farmers will shift to use the more efficient pump, consuming less electricity, and will neutralize the effect of electricity price on water extraction (what was explained in policy 10). So, to have better output from the model, we can add this effect to the model.

12.3.12. Policy (12): Operating cost

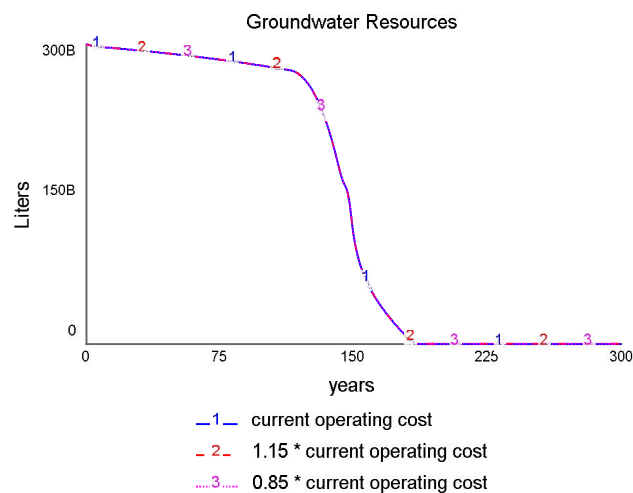


Figure 44: effect of operating cost on groundwater withdrawal

As can be seen in figure.44, the system is not at all sensitive to operating costs. It can be concluded that if the government is interested in subsidizing farmers, it could be a subsidy for water and operating costs, and should not be for electricity at all.

12.3.13. Policy (13): Irrigation Efficiency

To support this sector, the government has heavily subsidized agricultural water and energy use. The significantly cheap prices have not provided any motivation for increasing the production efficiency in this sector. The average irrigation efficiency is about 40 % (while it is 45% in advance countries and 65% in advanced countries). Only 5 % of the farmed area is under pressured irrigation and 95% is surface irrigation. During the last 30 years, irrigation efficiency has improved by only 1% (0.001) yearly [55].

One solution that almost all experts agree on is to improve irrigation efficiency. But whether government-subsidized improvements in irrigation efficiency really led to a decrease in water scarcity? Our model shows that this policy is completely useless (figure.45)

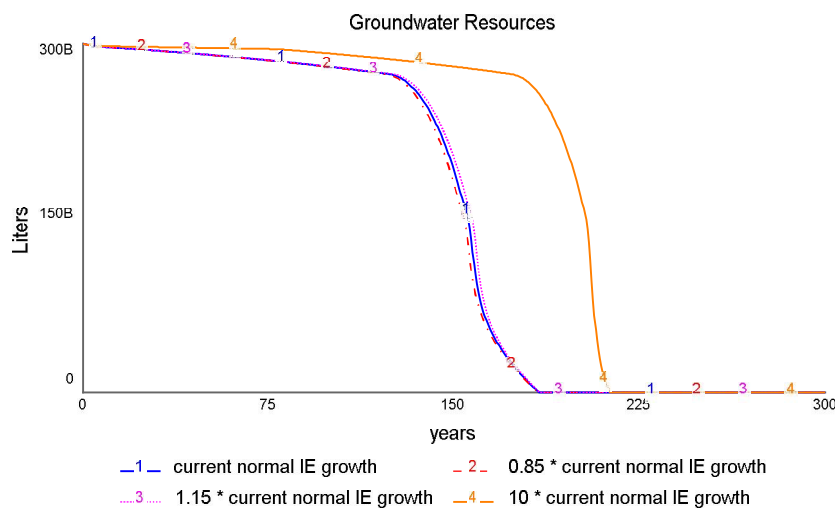


Figure 45: effect of irrigation efficiency (IE) on groundwater withdrawal

At first, normal IE (irrigation efficiency) growth was changed to $\pm 15\%$, but it was observed that the system had no sensitivity to this variable. Even when the initial value multiplied by 10, it can be seen that the policy does not prevent the groundwater depletion, and collapse occurs anyway. But what is the reason? Why cannot an increase in irrigation efficiency handle over-extraction? As can be seen in the figure.46, the main reason is that as irrigation efficiency increases, the size of irrigated land (and the share of HWD crops) is also increasing.

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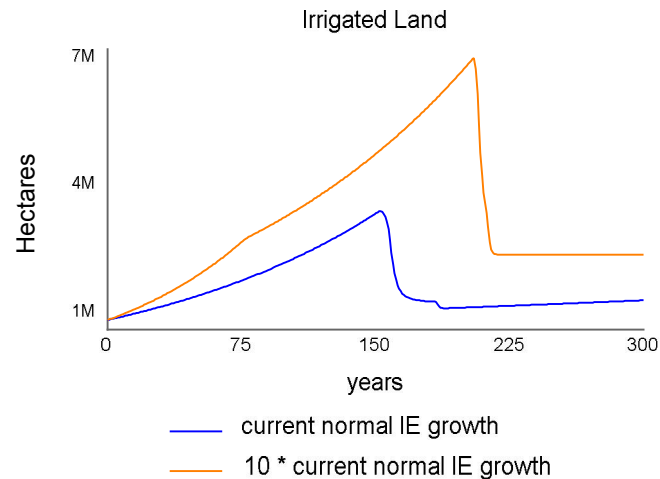


Figure 46: effect of irrigation efficiency on irrigated land

Referring to the model, we can see it is true that there is a negative link between “irrigation efficiency” and “desired water” and it is expected that by increase in “irrigation efficiency”, “desired water”, “desired number of wells”, “number of wells”, and “withdrawal” decrease consequently. But, at the same time, there is a positive link between “irrigation efficiency” and “Max Possible Irrigated Land Based on Water Availability”, which can increase the size of “irrigated land” (and the share of HWD crops). Because the first link is “accumulating cause and effect” and the second link is “instantaneous cause and effect”, it causes the second link makes a short circuit, and in practice instead of reducing “desired water” (what policymakers intent), the size of the irrigated land (and HWD crop share) expand, and water consumption is not reduced at all. This effect is called “**rebound effect**” or “**Jevons Paradox**”⁶. In economics, the Jevons paradox occurs when technological progress or government policy increases the efficiency with which a resource is used (reducing the amount necessary for any one use), but the rate of consumption of that resource rises due to increasing demand [56]. The Jevons paradox is perhaps the most widely known paradox in environmental economics [57]. However, governments and environmentalists generally assume that efficiency gains will lower resource consumption, ignoring the possibility of the paradox arising [58].

So until when irrigated land (and the share of high-water demand crops) are unconstrained, modernization of irrigation methods is fruitless and cannot manage over-

⁶ https://en.wikipedia.org/wiki/Jevons_paradox#cite_note-York-2

extraction. How can we avoid the rebound effect? Julio Berbel et al. (2015) proposes three methods, namely, (1) the strict limitations placed on the size of the irrigated area, (2) the reduction of former water rights, and (3) the re-assignment of water savings to achieve environmental goals [59].

12.3.14. Policy (14): Combined Policies

As we witnessed in the evaluation of the single-parameters policies, the output of many of them differed with our expectation. For example regarding policy 5 (Crop Water Requirements per ha), policy 7 (increasing the share of surface water for agriculture sector), policy 8 (Treated Waste Water for Agriculture), and policy 13 (Irrigation efficiency), we saw they are fruitless, due to an increase in irrigation land size (and HWD crop share). So one of the combined policies could be to limit the irrigated land size (and HWD crop share) and implementing one of these four policies. In the following, we will combine policy 1 (limiting agriculture size) and policy 13 (improving irrigation efficiency). We increased the normal irrigation efficiency from 1% to 3.5% and shrank permitted irrigated land from 20 million hectares to 5 million hectares and the result was figure.47.

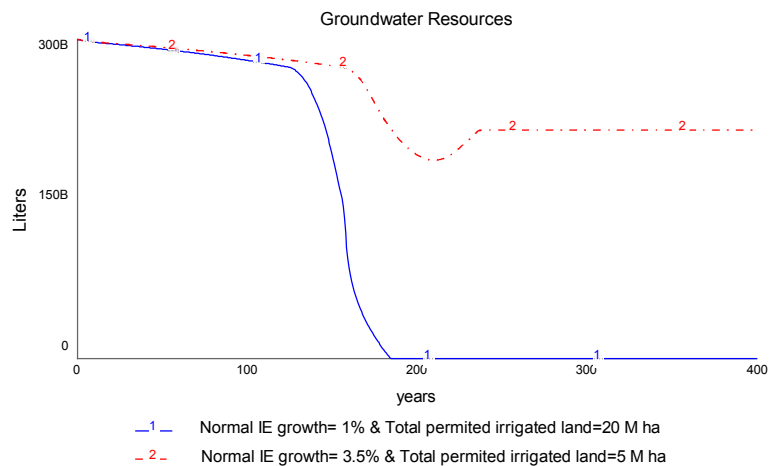


Figure 47: effect of shrinking irrigated land size and improving irrigated efficiency at the same time on groundwater withdrawal

In another scenario, in the year 150, when groundwater resources are declining rapidly, if the government starts a comprehensive plan to increase the irrigation efficiency to

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the maximum possible (65%)⁷, we will see in figure.48 that the first few years the situation gets a little better, but suddenly we see a free fall

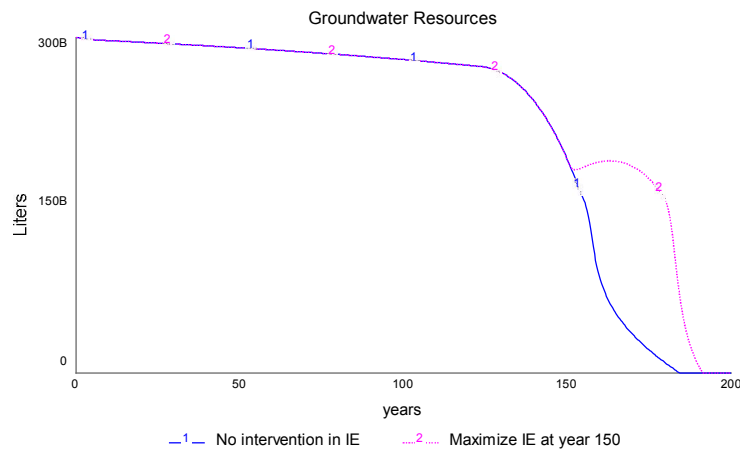


Figure 48: result of comprehensive plan to maximize irrigation efficiency in the year 150

But if at the same time in the year 150, the project of restricting the irrigated land is implemented⁸, and not allowing more land to be irrigated (and more HWD crops cultivated), then the tragedy of groundwater depletion can be prevented (figure.49).

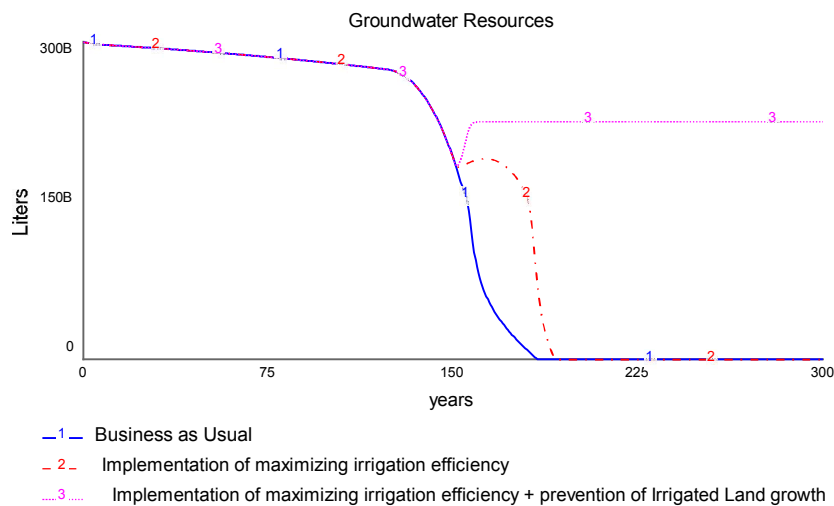


Figure 49: maximization of irrigated efficiency and keeping irrigated land constant

⁷ change in IE= ((MIN(Max_IE-Irrigation_Efficiency, IE_growth*Irrigation_Efficiency))/AT)+(STEP(-Irrigation_Efficiency+Max_IE,150))

⁸ desired IL based on all limitations = (Max_Possible_Irrigated_Land_based_on_Water_Availability)+(STEP(-Max_Possible_Irrigated_Land_based_on_Water_Availability+policy_intervention_Max_allowed_irrigated_land, 150))
 policy intervention (Max allowed irrigated land) = Irrigated Land

Other combined policies can also be tested in the same way.

An important point should be mentioned here is the relationship between “irrigation efficiency” and “electricity consumption” is ignored in this model. Indeed, modernizing irrigation equipment, in turn, will lead to an increase in electricity consumption. This is another factor that can reduce farmers' incentives to improve irrigation efficiency, especially when the initial cost of buying new equipment and electricity price is high. Fernández García et al. (2014) shows “increasing of water use efficiency has been a key strategy for dealing with water scarcity in semiarid countries. In Spain modernization of irrigation schemes has consisted in the substitution of old open channels systems by pressurized networks. However, this improvement has represented a significant increase in water costs, mainly due to the higher energy requirements.”[75]

➤ Implementation Challenges

The challenges of shrinking agriculture size were discussed earlier (in policy 1). But increasing irrigation efficiency also has its challenges, including:

1. Cost: improving the technology of 6 million hectares irrigated land needs a huge amount of money while at the present the government suffers from financial problems and budget deficit
2. Small size and a large number of farmer: After Iran’s revolution (40 years ago) the new government split farmlands and divided them among peasants. Now, the average of farmlands in Iran is under 5 hectare, while in successful countries it is above 80 hectares. For this reason, not only the number of stakeholders (farmers) are too much, but only due to the small size of farmlands, the penetration impact of technology is low. So, for a better result, the government should aggregate them again in the form of cooperative companies [48].

12.3.15. Policy (15): Water Governance (changing the current structure)

The main reason for the "tragedy of the commons" is that the ownership of water is in the hands of the government. When farmers own the water, they will try to conserve it and think about the long-term benefit, not just the short-term benefit. In this particular case,

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when the groundwater level drops below a specific level, farmers feel threatened, increase irrigation efficiency, and maintain or even reduce the size of irrigated land (and the share of HWD crops). They will give groundwater resources an opportunity to recover themselves. In similar situations, when farmers are not privately owned water, they do not reduce the size of irrigated land (and the share of HWD crop), because they think that this will reduce their profits, but give competitors the opportunity to extract more water and make more profit. Especially farmers, who recently have started their activities, will try to extract as much water as they can before water depletion because they want to gain their initial investment at least and not going bankrupt. In other words, by decreasing groundwater, not only farmers do not reduce their water consumption, but they will try to gain maximum benefit in the remaining time before their competitors do that. It is almost similar to “prison dilemma” in game theory. Each player cares only about his/her profit and wants to achieve the highest possible profit. Although it is better for all farmers to reduce water consumption, the situation of (low withdrawal, low withdrawal) is not a Nash equilibrium, and both players have an incentive to deviate from this strategy.

If we have “**water bank**” (like California), and farmers have the ownership of water not only they will consume it more efficiently but also they can decide to sell their water to sectors with higher productivity (industry sector for instance); as an example, for producing 1000kg wheat, 1,000,000 kg water is consumed while for producing 1000 kg steel, just 14,000 kg water is consumed while. Also, the government should make involved other stakeholders in decision makings and the “top-down” approach not only is not effective but also it has to allocate a lot financial and human resources to dictates its regulations. Whilst participatory decision making can minimize the resistance of the stakeholders. A reliable **water market** will increase the economic efficiency of water use. The implementation of a water market requires serious regulation and monitoring of water uses as well as creating a financial mechanism to support water trades. To overcome the current crisis, the government should also pursue setting up environmental water and try to purchase water from farms with low economic efficiency to recharge aquifers and recover damaged ecosystems. [46]

To investigate whether the change in water governance can prevent groundwater over-extraction, we change the model structure and add a link from “*the water level*” (normalized water level) variable to “*desired number of wells*”. So when the groundwater level

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drops below a certain level, farmers will no longer dig a new well⁹. But how much should this “min water level” (min normalized water level) be?

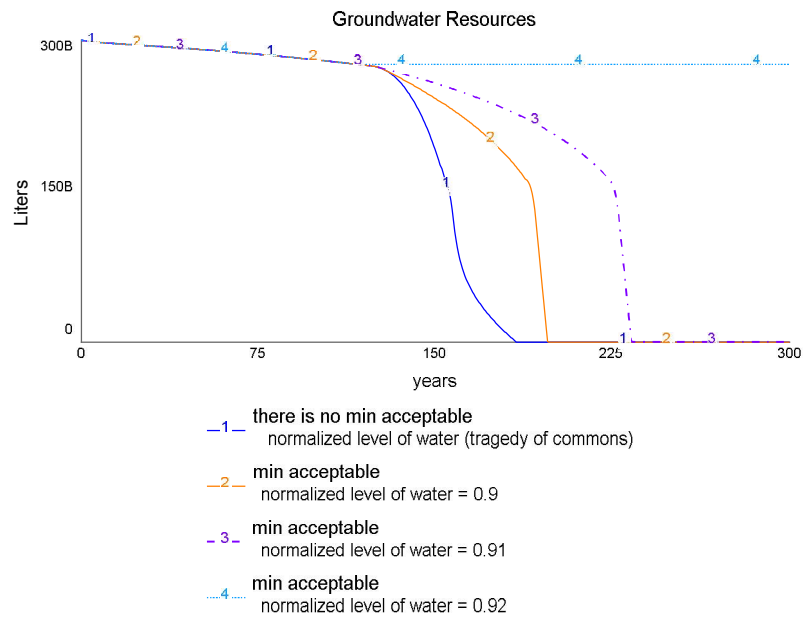


Figure 50: effect of changing water governance on groundwater withdrawal

In figure.50, it can be seen when the “water level” reaches 90% or even 91% of the initial level, keeping constant “number of wells” and not digging new wells will not prevent groundwater depletion; and for this purpose, digging new wells must be stopped before the groundwater level reaches below 92% of the initial level. The reason for this observation goes back to the *MSY* concept. As long as the *outflow* is larger or equal to the *inflow*, there is no risk and the number of wells, irrigated land size, and the share of HWD crops can be increased. But when, even a trivial amount, *outflow* exceeds the *inflow* (netflow <0), inventory will decline and will sooner or later come to an end.

In fact, it can be concluded that not only the tragedy of the commons but also misperception about the amount of groundwater availability, the amount of remaining water, , and the amount of groundwater withdrawal and recharge can also lead to overshoot and collapse behavior. And it is highly probable since these amounts are unclear and hard to measure. This result is also consistent with research conducted by Moxnes (1998) [27]. So,

⁹ Desired number of wells =

IF (Normalized_Level_of_Water > "min_acceptable_normalized_level_of_water_(STOP_digging_new_wells)")
THEN ((desired_water - Available_Surface_Water) / withdrawal_per_well) ELSE (Number_of_Wells)

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even in the case of private ownership of water, should be informed about the effect of these misperceptions otherwise it can again lead to overshoot and collapse.

PART IV: Conclusion & Discussion

The fourth and final part of this thesis includes a brief summary of this research and its outcomes. Also, some suggestions will be offered at the end for further studies.

13. Summary:

The problem of water scarcity is a crucial issue that is one of the most important humanitarian challenges not only nationally (Iran) but globally. Water resources are going fast, and the picture is alarming in many places around the world. From India to Iran to Botswana, 17 countries around the world are currently under extremely high water stress. In those countries are several big, thirsty cities that have faced acute shortages recently, including São Paulo, Brazil; Chennai, India; and Cape Town, which in 2018 narrowly beat what it called Day Zero — the day when all its dams would be dry. Mexico's capital, Mexico City, is drawing groundwater so fast that the city is literally sinking. In many countries, farmers are draining aquifers to grow water-intensive crops like cotton and rice. Many US states, including New Mexico, also face a similar problem. By 2030, the number of cities in the extremely high stress category is expected to rise to 45 and include nearly 470 million people, with repercussions for public health, food insecurity, poverty, and social unrest. [80]

The big question is how we can address the problem? Although the broad policies have been implemented over the past several decades, the problem continued to persist or even become worse. Why are not those policies effective and do end in failure to address the problem? Whether the policies were not properly designed or it was a problem of their implementation? To answer these questions, we deployed the system dynamics approach. Building a qualitative SD model helps us to visualize our mental models, makes us contemplate our mental model and accurately articulate our opinions. This process can uncover and challenge our implicit assumptions. At the next step, when we quantify, test and analyze the model, some other bugs in our mental model are discovered and removed.

In this study, also the concept of “tragedy of the commons” is used to explain the problem of over-extraction of groundwater resources in the agriculture sector, which is responsible for more than 90 percent of water withdrawal. The issue of excessive exploitation

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and the depletion of a common-pool resource arises when numerous individuals or communities use at the same time and in a collective way the same resource without excluding anyone of its use and trying to obtain the most advantage of its exploitation, causing the depletion of the shared resource. The tool of system dynamics is used to uncover and understand endogenous sources of the system behavior. Our SD model consists of four sectors (namely, irrigated land, profit, water, and irrigation efficiency), three reinforcing loops, and five balancing loops. Then 15 policies are evaluated to find the best policy. Thirteen of these policies just focus on one parameter, which by weakening the reinforcing loop and strengthening the balancing loops try to stabilize the system behavior and prevent groundwater depletion. One evaluated policy is a combined policy, and the last one is the policy which suggests changing the water governance and system structure.

To put it in a nutshell, the key finding is that if the government wants to control the size of irrigated land, share of HWD crops (policy 1), and number of wells (policy 6), it should consider the concept of maximum sustainable yield (MSY), and if these numbers slightly exceed MSY, system sooner or later will collapse. Also, if the government wants to manage the problem by manipulating the prices, it has four options; price of crops (policy 3), water price (policy 9), electricity price (policy 10), and operating cost (policy 12). Among these four policies, increasing the price of crops will worsen the situation. In addition, the system is not sensitive to water price and operating cost. Therefore, increasing these prices just increases the dissatisfaction of farmers. On the other hand, system is very sensitive to electricity price, and the government should decrease the subsidy allocated to electricity price in agriculture. Besides, using solar panels in agriculture although it can decrease electricity consumption, it will exacerbate the problem of over-extraction. In sum, we suggest to the government that if it wants to give subsidy to agriculture, it can be a subsidy for water and operating costs (since make farmers satisfied but have no effect of water consumption). Also, it should not at all give subsidy to electricity or try to encourage farmers to use the solar panels. Endeavors for handling the problem by controlling the parameters of Crop Water Requirements per ha (policy 5), the share of surface water for agriculture sector (policy 7), Treated Waste Water for Agriculture (policy 8), and policy Irrigation efficiency (13), are fruitless because of partial thinking and ignoring the “rebound effect”. For example, policy-makers think increasing

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irrigation efficiency will decrease water withdrawal since there is a linear relationship like below (Fig.51) between them.

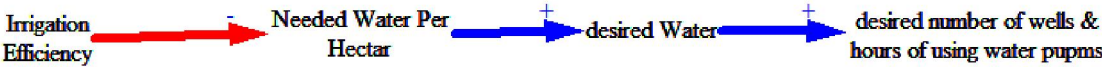


Figure 51: linear thinking about the effect of improving irrigation efficiency

But, we showed that there is another instantaneous link in the model that creates a short circuit causing above depicted intentions does not happen. An increase in irrigation efficiency will cause an increase in “max possible irrigated land based on water availability” (Fig.52), and increasing every variable of a positive loop will lead to increasing of all other variables in the loop, and amplification of the reinforcing loop.

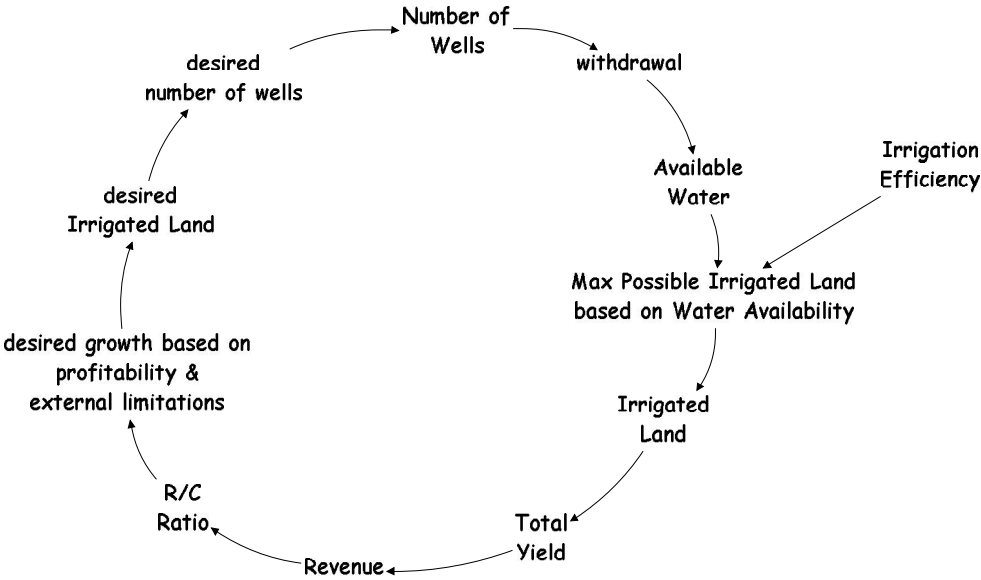


Figure 52: how improving irrigation efficiency worsens the water over-pump

So, we recommend the government for implementing combined policies that is, it should first control the size of irrigated land and the share of HWD crops, then apply one of these four policies. To examine, we combine two policies of shrinking irrigated land size (policy 1) and increasing the irrigation efficiency (13) and show how much this combined policy can be effective. In the end, we evaluate the policy of changing the water governance and show that not only the tragedy of the commons but also misperception about the amount of

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groundwater availability, the amount of remaining water, and the amount of groundwater withdrawal and recharge can also lead to overshoot and collapse behavior.

To sum up, if we want to highlight how system dynamics was useful in adding value to the tragedy of the commons issue in groundwater extraction in Iran, we can mention the following:

1) Holistic view:

The lack of a holistic view and ignoring feedback loops, delay, accumulation, and nonlinearity will end into piecemeal solutions, which may alleviate the problem for a short time but in the longer horizons can lead to unintended consequences, create new problems, or exacerbate the previous problems.

We saw how linear thinking and ignoring the rebound effect can make many policy interventions useless. Also, we saw how dynamic relationship between positive and negative loops can lead to some unexpected and counterintuitive results which human's mind, due to its intrinsic limitations, is not able to reach without the help of SD and computer models. For instance, although it seems that subsidy for water will make water less costly, make it seem less scarce, and will decrease water use efficiency, one way or the other, we saw that it is better for the government to do not eliminate the water subsidy, since it can cause many political and social pressure for the government, but it has a trivial effect on diminishing water scarcity.

2) Shared understanding:

The model can create a shared understanding among different stakeholders (farmers, ministry of energy, ministry of agriculture, ...) with diverse interest. Consensus and mutual understanding can mitigate stakeholders' resistance and promote their commitment, which is a prerequisite for alleviating water scarcity.

In the end, as the last word, I would like add two points:

1. SD models are transparent boxes; this advantage causes other researchers to be able to easily adjust the model and use for other countries, by changing numbers and assumptions.

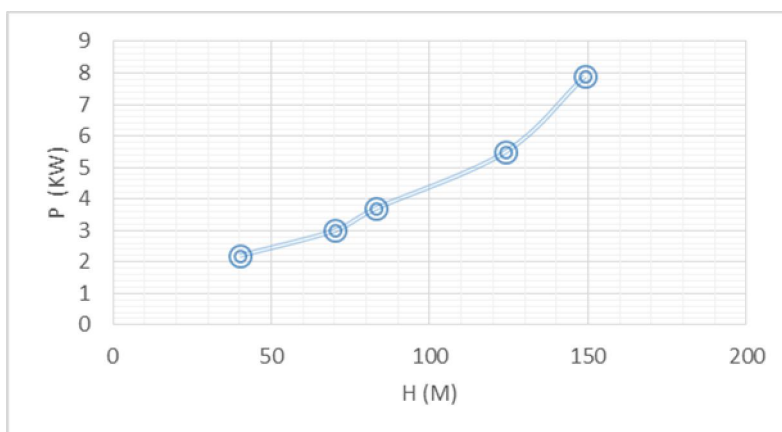
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2. Another advantage of SD models is applying operational thinking, which makes the model easily expandable. As follows, some suggestions are offered to expand and improve the model.

14.Suggestion For Future Studies

1. Working on the lookup functions outlined in Appendix (C) to improve the results of the model. In fact, I didn't find accurate functions for them until I wrote this thesis (I am still working on them), and I had no way than to make some educated guesses. For example, we assumed that there is nonlinear relationship between “level of water” and “electricity consumption”. in the World Bank report (2010) [78], although this relationship is assumed linear, the author mentions that “it is not always reasonable to assume full smoothness of the pumping cost function, as I do. As pumping depths increase, one may need, at some point, to switch from simple (surface) pumps to much more expensive submerged pumps, this increasing the overall pumping cost drastically at one (or more) discrete point(s). This complication is ignored here.”

I also referred to the catalog of submersible pumps for PUMPIRAN company [79] to check the relationship between H (head of pump) and P (pump power) when the flow (Q) is constant. I extracted the below figure:



Q = 10 (m ³ /hr)	
H (m)	P (KW)
40	2.2
70	3
83	3.7
124	5.5
149	7.9

Figure 53: relationship between “pump head” and “pump power”

Although this figure demands more work, at least it shows that our assumption about nonlinear relationship between “pump suction head” and “pump power” is not irrational.

2. Adding those highlighted suggestions offered in Part III:

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- effects of supply and demand on crop price
 - impact of production costs on crop price
 - the relationship between electricity price and pump
 - The relationship between “irrigation efficiency” and “electricity consumption.”
3. adding the mechanism of “land price” which can affect “crop price”
 4. we assume that the “water price” is constant but in practice the fewer water resources, the more water prices, which in turn, will affect the “price of crops”
 5. For “irrigation efficiency”, we ignored the depreciation and lifetime of irrigation facilities.
 6. To simplify the model we merged the share of HWD crops with the size of the irrigated land. They can be separated, and instead of two stocks of “arable land” and “irrigated land”, we can three stocks of “arable land”, “land for LWD crops”, and “land for HWD crops”.

In this case, maybe other factors that influence farmers' decision should be considered. For example, their perception about prices, since if all farmers cultivated HWD crops, their price will drop and the price of LWD will go up. In addition, LWD and HWD crops should be cultivated *periodically*, otherwise, the soil will be weakened and productivity will drop.

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Appendices

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Appendix (A): Literature Review

Table 4: Some studies in the field of water management using the dynamics of a systems approach

	Author(s)	Case Studied	Explanations
1	Forrester (1973)	---	The World 3 model was developed by Forrester in 1973. This model examines the changes in mineral, organic, and human resources based on human activities on Earth.
2	Meadows et al. (1974, 1992)	---	The World3 model was completed by Meadows and her colleagues in the 1974 and 1992 at Massachusetts Institute of Technology
3	Cassell, E.A., Clausen, J.C. (1993)	---	They developed a model called "Field Phosphorus." This model simulates the use of phosphorous materials in a region's agriculture and its impact on the quality of groundwater and surface water. This model examines the impact of agricultural optimization programs on reducing phosphorus in water resources
4	Ruth, M., and Pieper, F. (1994)	USA	Investigating the shape of Cape Cod in Massachusetts, USA. With regard to climate change in the world, this model deals with the progress of seawater in the cape. Coastal erosion is a dynamic issue, and the dynamics-based model makes a significant contribution to simulating the changes in the process for the next years. This study is, in fact, the integration of geographic information systems (GIS) with the dynamics of the system.
5	Ford (1996)	USA	This model is built through a participatory model building process and addresses the issue of over-allocation of river flows to various types of stakeholders from farmers to energy generation.
6	Rotmans, I., and Devries, B. (1997)	Netherlands	The "Target" model was developed by the Dutch National Environmental and Public Health Institute in 1997. The model consists of several parts: population, health, energy, land, food, water and circulation of biological elements. The water sector has humanitarian functions, including water supply for urban use, industry, agriculture, electricity, and coastal protection. Environmental functions include water supply for the land ecosystem and the maintenance of the water ecosystem quality, and also includes the impact of social, economic, and environmental stresses on the water system. The structure of this model is largely dependent on climate change
7	Sudhir, V., Srivivasan, G., Muraleedharan, V.R. (1997)	India	For sustainable management of solid wastes, they have built a model based on SD. This model is tailored to Indian cities, in which the dynamics of the health, economy, environment, and human behavior cycles are set. This model can simulate the results and effects of management plans.
8	Vezjak et al. (1998)	Slovenia	This model deals with the effects of the aggregation of phosphorus and nutrients from agricultural runoff and sewage drainage
9	Bala & et al. (1998)	---	Using the SD method, they presented a model that predicted the volume of water needed for the farm, the irrigation time, and its effect on the yield of the product.
10	Forester (1999)	---	In the book "Urban Dynamics," in 1999, Forester explores the social and economic dynamics of a city and the impact on resources.
11	Simonovic and Fahmy (1999)	Egypt	Water resources policy analysis deals with the protection of people from the harmful effects of water and assurance of a consistent, adequate supply of usable water. Population and regulatory pressures, political and economic instabilities, and climatic variations can all be expected to further stress water supply resources. Developing policy for managing water systems for human needs in such an environment is difficult, slow, and very costly. The approach to water resources policy analysis developed in this paper is that of the rational decision-maker who lays out goals and uses logical processes to explore the best way to reach those goals.
12	Wolfenden, J.A.J. (1999)	---	The model has been developed for the management of the resource in the catchment area. Characteristics of this model are modeling complex environments, participation and learning participants, and taking into account multiple criteria.
13	Ahmad and Simonovic (2000)	Canada	Using SD, the behavior of a reservoir (dam) is simulated for rainy years and flood
14	Huerta, J.M.,	Mexico	Manage a basin in Mexico. The prepared model has been a powerful tool for solving

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	Serra, M., Sandoval, R. (2001)		disputes between the five provinces and national water departments on the distribution of surface water.
15	Guo et al. (2001)	China	This model has been developed to examine the changes in the quality of lake water in China. The negative effects of rapid socio-economic development on the quality of the lake cause concerns among regional executives. In this model, a comprehensive system of environmental, economic, and social components of the lake has been developed, and the effects of four management plans have been reviewed. The advantage of this model is the reflection of the results of simulating water quality decisions for managers.
16	Xu et al. (2002)	China	Seeking for sustainable management of water resources in response to ever-increasing demand, taking into account different scenarios (such as climate, etc.), and giving readers an overview of the factors affecting both sides of supply and demand and the road map for water management.
17	Saysel (2002)	Turkey	Using the SD method, they simulated the crop pattern, crop rate, and agricultural pollution in southern Turkey. Their results showed that the current policies adopted in managing the projects would have serious environmental damages.
18	Simonovic and Li (2003)	Canada	The model of Canada's Water considers the entire Canadian region and a part of the United States in an area of 10 million square kilometers. To achieve this regional model, the "World" model has been used. The Canadian model takes into account nine sub-systems; population, capital, agriculture, food, water, water quality, energy, persistent pollution, and non-renewable resources, in an interconnected way. The purpose of this model is to simulate Canadian water quality and quality relationships with major socio-economic variables over a period of more than 100 years. Twelve scenarios have been simulated for various policies: available water changes, sewage treatment, economic growth, energy production, and food production. The results of this model indicate a shortage of gas for energy production and a sharp drop in water quality in the coming years.
19	Tangirala et al. (2003)	USA	The Effect of Nutrients on Water Quality
20	Stave (2003)	USA	Using participatory model building, Las Vegas's water scarcity has been modeled in the state of Nevada. In this model, different ways of managing demand are reviewed from the viewpoint of the people, and their results and impacts on reducing the gap between supply and demand are examined. The advantage if this model is the ability to deliver decision-making results before the decision is made.
21	Ahmad and Simonovic (2004)	Canada	Flood damage estimation
22	Simonovic and Rajasekaram (2004)	Canada	Investigating socio-economic plans for managing water availability at the country level
23	Stewart et al. (2004)	Mexico	Planning and managing water resources in a catchment area using hydrological simulation
24	Tidwell et al. (2004),	USA	Using participatory modeling to introduce key hydrological, social, and environmental factors in the model to examine proposed water management options.
25	Fernandez and Selma (2004)	Spain	The dynamic model of environmental sustainability for agriculture and land-use change was presented in Spain. The research results showed that reducing irrigated lands in order to balance the supply and demand of water not only eliminates the problem of water scarcity but also improves the environmental problems caused by irrigation of agricultural lands.
26	Habron, G. B., Kaplowitz, M. D., and Levine, R. L. (2004)	---	In this research, based on the results of previous researches, a conceptual framework that can provide a link between social sectors and environmental processes in the planning of basin management is developed.
27	Simonovic and Ahmad (2005)	Canada	Effective management of crisis during floods by modeling human behavior
28	Sehlke and Jacobson (2005)	USA	Planning and managing water resources in a catchment area using hydrological simulation
29	Chen, C. H., Liu, W. L., Liaw, S.	China	Chen and his colleagues presented the study entitled "Development of Theory and Dynamic Planning System for Sustainable Management at River Basin Levels." In this

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	L., (2005)		work, the goal was to determine how to create integrated management of groundwater resources and climate in the basin area
30	Winz (2005)	New Zealand	Applying SD, they developed a framework for a water supply system for managing and sustainable development water resources in New Zealand.
31	Ho, C. C., (2005)	Taiwan	The effects of water management decisions for South Taiwan have been used. The proposed model examines the effect of an increase in the capacity of water facilities, water treatment, and groundwater.
32	Ewers, M. (2005)	USA	This model is provided to optimal water allocation in the San Wan Basin, between Colorado and Mexico, and various stakeholders. The model quantifies the economic interactions of various water uses. Also, this model estimates the impact of climate change on the main river.
33	Sahlke, G., and Jacobson, J. (2005)	USA	The model is about a basin located between three states. This model is designed for integrated management of groundwater and surface water of this basin by integrating hydrological information with other information (social, economic, and political).
34	Leal Neto et al. (2006)	Brazil	Water quality and environmental degradation due to social and economic growth
35	Leaver and Unsworth (2006)	New Zealand	The process of influencing hot springs
36	Langsdale et al. (2007)	Canada	Group model building and including climate change in the planning and management of water resources
37	Croke et al. 2007	Australia	This model offers an integrated assessment of water resources management in Australia and suggestions solutions in order to achieve more sustainability at the basin level.
38	de Fraiture, C. (2007)	---	The "WaterSim" model analyzes water and food security in the regional and global levels.
39	Yang et al. (2008)	Taiwan	Using SD, they study the challenges of water scarcity in Taiwan. In this research, a combined process of system dynamics approach and analysis of impacts are presented for systematic and quantitative evaluation of water sector strategies. Water shortages and total financial costs as reference variables are mentioned in this research
40	Prodanovic, P., and Simonovic, S. P. (2009)	---	They provided an operational model for supporting interconnected river basin management. In this research, a simulation based on the dynamics of the systems approach is presented. In this approach, the concepts of feedback are used to express social, economic, and environmental processes in the basin.
41	Li & et al. (2009)	---	They used the concept of SD for the rice fields. The model evaluated different components of water balance, such as actual evapotranspiration, deep penetration, surface runoff, and climbing of valleys on a daily scale of simulation and scenarios for dealing with water resource constraints.
42	Chao, B., and Chuanglin, F. (2009)	China	The model is an integrated assessment tool for water resources under the development of urbanization in arid areas. This research explains the benefits of using an integrated assessment approach as an effective tool for analyzing the challenge and conflict between water resource systems and urbanization systems in arid areas.
43	Winz, I., Brierley, G., and Trowsdale, S. (2009)	---	In this research, using SD and attention water use in agricultural, industrial, urban and environmental sectors, some solutions have been developed for water resources management
44	Ahmad and Prashar (2010),	USA	This study deals with dynamic simulation in South Florida. This model outlines the interconnections between access to water and competition for increasing water demand in urban, agricultural and environmental sectors
45	Davies and Simonovic (2011)	---	Exploring the scourge of increasing water scarcity in the world by simulating different subsystems, including climate, food production, resources and water consumption, and water quality
46	Venkatesan et al. (2011a, b)	USA	Salinity of water
47	Kaiser et al. (2011)	USA	Seeking sustainable management of water resources in response to increasing demand, taking into account different scenarios (such as climate, etc.), and giving readers an overview of the factors affecting both sides of supply and demand and the road map for water management.

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48	Shrestha et al. (2011, 2012)	USA	carbon footprint and energy consumption of different water supply methods
49	Mirchi A. et al., (2012) [60]	---	In this paper, they tried to explain the problems associated with water resource management in the language and archetype of SD
50	Langarudi et al. (2019) [17]	---	This paper responds to this theoretical gap by developing a SD model that takes into account key feedback loops in a socialhydrology system to enable us to look at longer term trends (e.g. over ten years), as well as shorter term trends. The objective is to evaluate policy sensitivity of the model to its socioeconomic feedback structure

Studies focused on cased of Iran

Table 5: studies in the field of water management using the dynamics of systems focusing on the case of Iran

	Authors	Cased Studied	Explanations
1	Ali N. Mashayekhi, (1990)[44]	Iran	The model consists of ten endogenous sectors and two exogenous sectors. Exogenous sectors include "population" and "underground resources", and endogenous sectors include (1) water supply equipment (2) water distribution channels and sewage collection (3) water supply facilities to cities (4) Water distribution equipment in the city (5) Surface water (6) Government (7) Water resources management (8) Industrial and urban sector (9) Agricultural sector (10) Borrowing services. Among the ten mentioned exogenous sectors, the first four sectors, which represent water resources equipment, include five stages of planning, feasibility, engineering design, construction, and operation . In this model, using gap analysis, he examines the effectiveness of various strategies on the progress of water supply projects.
2	Mojtahedzadeh, Mohammad T. (1992)[61]	City of Yazd	The model includes five sectors; (1) industry (2) agriculture (3) urban development (4) water (5) population. It deals with water scarcity in the city of Yazd, and evaluates the impact of five following solutions: (1) Control of population growth and growth of industrial development (2) transfer of water from other areas to Yazd (3) restrict the size of agriculture sector (4) improve irrigation methods (5) avoidance of water transmission
3	Sadeghi et al. (2005)[62]	Sistan	Modeling the exploitation of Sistan water reservoirs in order to control the flood
4	Jalali & Afshar (2005)[63]	---	To exploit hydropower dams, an SD model is applied to evaluate management scenarios
5	Golian et al. (2006)[64]	Urmiah Lake Basin and the Aji Chai River Basin	The study analyzes the utilization of water resources in the Aji-Chai basin and introduces the most appropriate policy that satisfies the interests of all uses and development goals.
6	Salvitabar A. et al., (2006)[65]	Tehran	it addresses the urban water management problem in Tehran, simulates the behavior of groundwater variables by 2020, and investigate the changes in the future water bill and the impact of management scenarios such as inter-basin transfer of water, implementation of sewage collection and treatment scheme and demand management.
7	Madani K, Marino MA, (2009)[66]	Zayandeh-Rud River	Zayandeh-Rud catchment area is modeled, and its fate is investigated in different scenarios, including: (1) Continued current trends (2) climate change, (3) demographic changes (4) economic recession (& 5) changes in surface water. In this study, different social, economic, political, and physical interactions of the basin were considered. Using causality circles and a simulation method, they concluded that the transfer of water from the basin was not the only

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			solution to the problem.
8	Zarghami M, Akbariyeh S, (2012)[67]	city of Tabriz	The model addresses the urban water problems of Tabriz. it includes potential sources of water supply (groundwater, imported fresh water, and refined wastewater), and potential water users (households, industry, and agriculture) and management tools (sewage treatment, water transfer between water basins, price Water, protective devices)
9	Seyed Ahmad Hosseini and Ali Bagheri (2013)[68]	Mashhad	This paper seeks to analyze the sustainable development strategies of Mashhad plain water resources, and to develop policy packages with triple strategies (economic growth with a water resource constraint approach, allocation of water resources with value-added approach, and changing the pattern of cultivation) and their impact on selected indicators including: aquifer level, source stress, resource economic efficiency, water shortage, and average water requirement of the plain are investigated.
10	Gohari A. et al., (2013)[69]	Zayandeh-Rud River	effectiveness of water supply projects for Zayandeh-Rud Basin
11	Alami et al. (2014)[70]	Golak Dam	In this paper, the effects of Golak reservoir dam in collecting flood flows during rainy days, supplying the needs of the area and feeding the aquifer in the lower plain aquifer were investigated.
12	Fartookzadeh et al. (2014)[71]	Tehran	Results derived by the model of water management in Tehran show that population and technology control policies can be combined with policies such as taxation and tariffs to work more efficiently.
13	Qashqai & et al. (2014)[72]	Tehran	Study of the average changes in groundwater level in Tehran plain
14	M. Zarghami, M.A. Rahmani (2015)[73]	Urmia lake	Investigating the effectiveness of methods to revive Urmia lake, including increasing irrigation efficiency, minimizing agricultural sector, fertilizing clouds, and transferring water
15	Gohari A. et al., (2017)[16]	Zayandeh-Rud River	The model is about the Zayandeh-Rud River basin, Iran, and comprises hydrological, socioeconomic, and agricultural sub-systems. Agricultural land-use decisions are assumed to be based on income-maximization. Ten crop types are included in the agricultural sub-system, namely wheat, barley, potato, rice, onion, alfalfa, corn, garden products and vegetables, and cereal and legume. Land area for each crop is defined as a function of the corresponding net economic benefit in the previous year. The expected agricultural water demand is the sum of expected water demand for all crops. Because of water scarcity in the basin, "delivery rate" is defined as the proportion of agricultural water demand that can be fully satisfied using available water supply. The land area for each crop is estimated by adjusting the expected land area for that crop based on the water delivery rate.
16	Mahdavinia & Mokhtar (2018)[74]	Firuzabad plain (Fars province)	the model consists of 2 reinforcing loops and 6 balancing loops. feedback loops (R1, R2) represent the interaction between groundwater level and groundwater lost. The first two negative feedback loops (B1, B2) represent the interaction between groundwater volume and total GW discharge. the third balancing loop (B3) considers the interactions between immigration and per capita water consumption. the fourth balancing loop (B4) represents the interaction between employment in agriculture and labor cost. B5 shows having less groundwater level, pumping cost will escalate which causes higher cost of goods sold. And the last balancing loop (B6) implies the interaction of water per capita and net immigration. The results show that the policy of combination of budget allocation for conservation education and modification in water tariffs might be more effective in improvement of the target indicators

Appendix (B): Simulation model

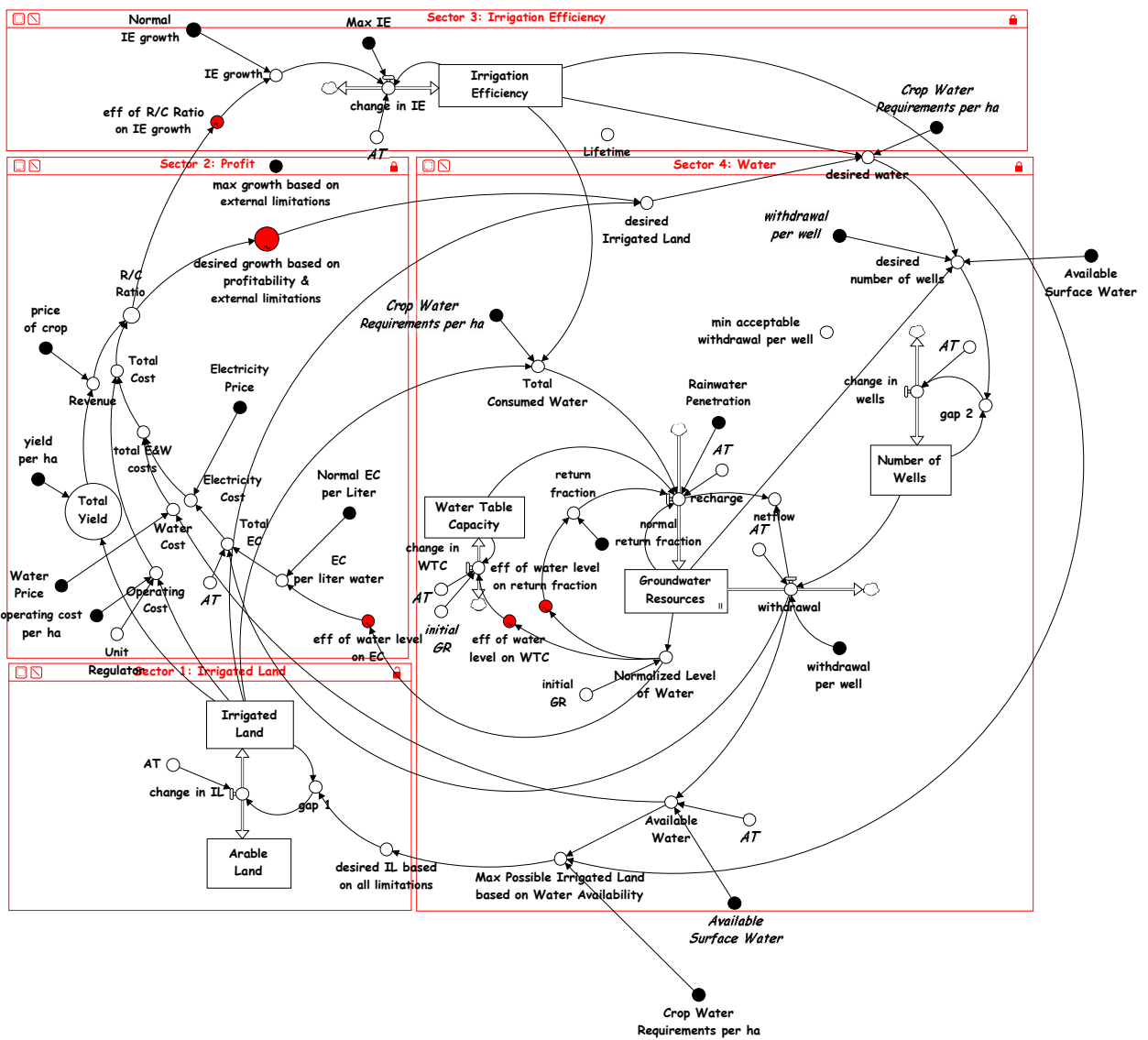


Figure 54: Running Model

Appendix (C): Documentation of simulation model

In this section, we present the selected non-trivial formulations that play an important role in the model, which the reader may be interested in knowing. Also in table.6, all the equations are listed.

1. Water Table Capacity:

Instead of “*level of water*” variable, variable of “*normalized level of water*” is used, which is equal to ‘*Normalized Level of Water = Groundwater Resources / initial GR*’ and is unitless. This variable affects the “*water table capacity*” non-linearly as shown in Fig.51.

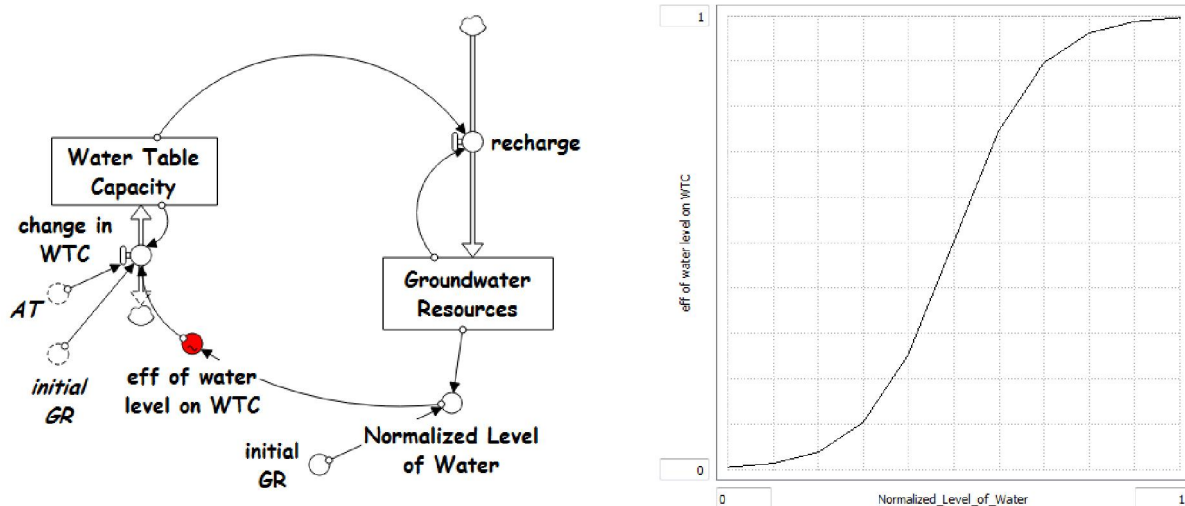


Figure 55: Water Table Capacity

When ‘*Groundwater Resources / initial GR = 1*’, “*effect of water level on WTC*” is also one (that is, makes no change). But as the water level decreases, the land subsides, and the table is destroyed over time. At first, the groundwater reservoirs are resilient and resist destruction. But over time, they lose their resistance and begins to destruct. For this reason, the graph slope is not too steep at first, but gradually it becomes steeper, and reservoirs are destroyed more rapidly. In the end, again the slop decreases, and with the complete depletion of the source, the groundwater reservoir is almost completely destroyed, and the capacity will become zero. Of course, we have assumed that this destruction occurs continuously, while it might depend on Soil characteristics and other factors, and for example, may fall in the form of a step function. “*water table capacity*” is calculated by the below formula;

Water Table Capacity =

$$(-\text{Water_Table_Capacity} + \text{MIN}(\text{Water_Table_Capacity}, \text{initial_GR} * \text{eff_of_water_level_on_WTC})) / \text{AT}$$

According to this formula, in each run, the value of “*water table capacity*” stock is replaced by the minimum between its current value and “*initial_GR * eff_of_Water_Level_on_WTC.*” Please note that according to this formula, this change is irreversible. Although this change can be reversible over hundreds of years, it is far beyond our model time period.

2. Return Fraction:

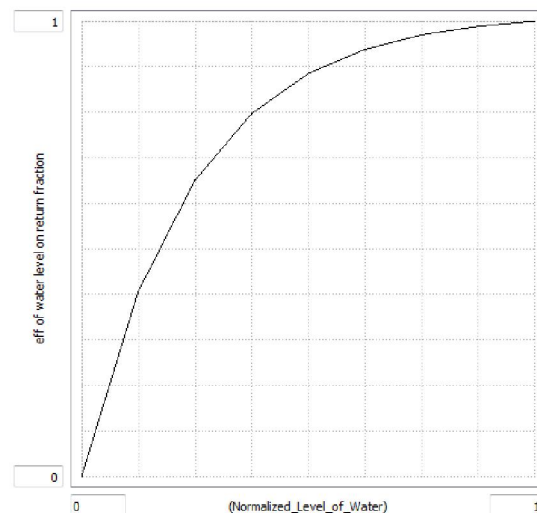
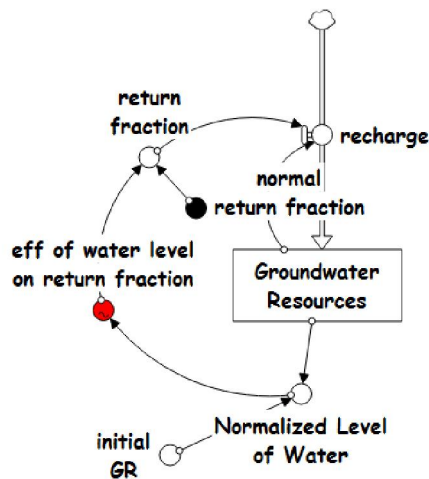


Figure 56: Return Fraction

It is assumed that, under normal conditions, one-third of the water used to irrigation will pass back to groundwater by passing through the soil pores (*normal return fraction = 1/3*). However, this number is not constant, but a non-linear function of the water level (*Normalized Level of Water*):

$$\text{return fraction} = \text{normal fraction} * \text{eff of Water Level on return fraction}$$

As shown in Fig.52. When ‘*normalized level of water = 1*’, “*eff of water level on return fraction*” is also one, that is, the return fraction equals “normal return fraction.” With the decrease in groundwater levels, the land will subside, and soil will become more compact, and the return fraction decreases. Again, in the first, the land shows more resilience, and the slope is gentle, but gradually, it loses its initial resistance.

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3. Electricity Consumption and Electricity Cost:

“Electricity Cost” is calculated by this formula;

$$\text{Electricity Cost} = \text{Total Electricity Consumption (EC)} * \text{Electricity Price}$$

That;

$$\text{Total Electricity Consumption} = \text{Withdrawal} * \text{Electricity Consumption (EC) per liter water}$$

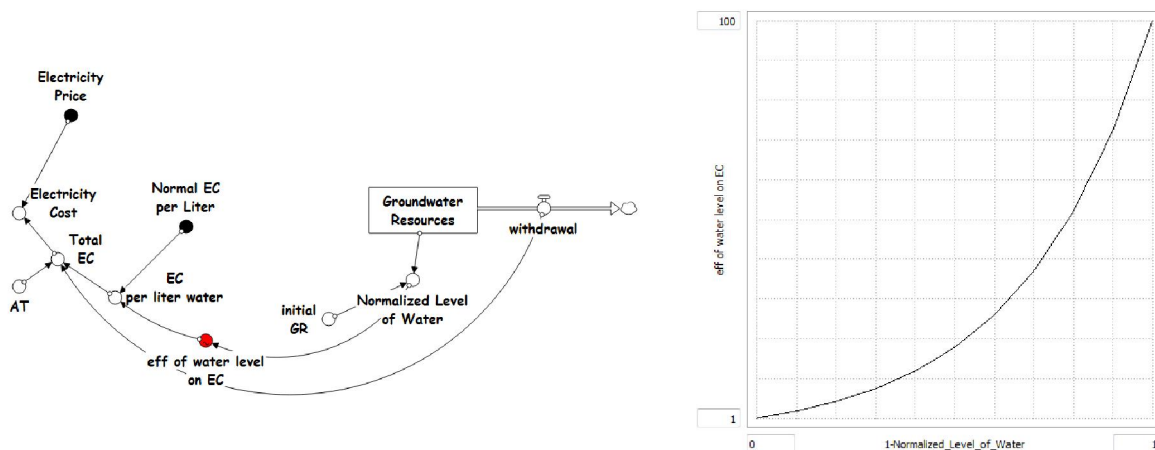


Figure 57: Electricity Consumption

Yet, “Electricity Consumption per liter water” is not a fixed number, and the lower the water level, the stronger pumps should be used, and the more electricity will be consumed per liter water;

Electricity Consumption (EC) per liter water =

$$\text{Normal Electricity Consumption per Liter} * \text{eff of Water Level on Water consumption}$$

As shown in Figure.53, “Electricity Consumption (EC) per liter water” is a nonlinear function of “1-Normalized Water Level”. When “1-Normalized Level of Water” = 0, that is, the reservoir is full, “eff of water level on EC” is one, and electricity consumed per liter water is equal to “normal EC per liter,” and this amount increases exponentially as the water level drops.

4. Irrigation Efficiency:

Irrigation Efficiency is changing with the variable rate of “*change in IE (Irrigation Efficiency),*” and there is a maximum value for it (since in developed countries it is 0.65, we take it 0.65 in the model);

$$\text{change in Irrigation Efficiency} = \frac{(\text{MIN}(\text{Max_IE} - \text{Irrigation_Efficiency}, \text{IE_growth} * \text{Irrigation_Efficiency}))}{AT}$$

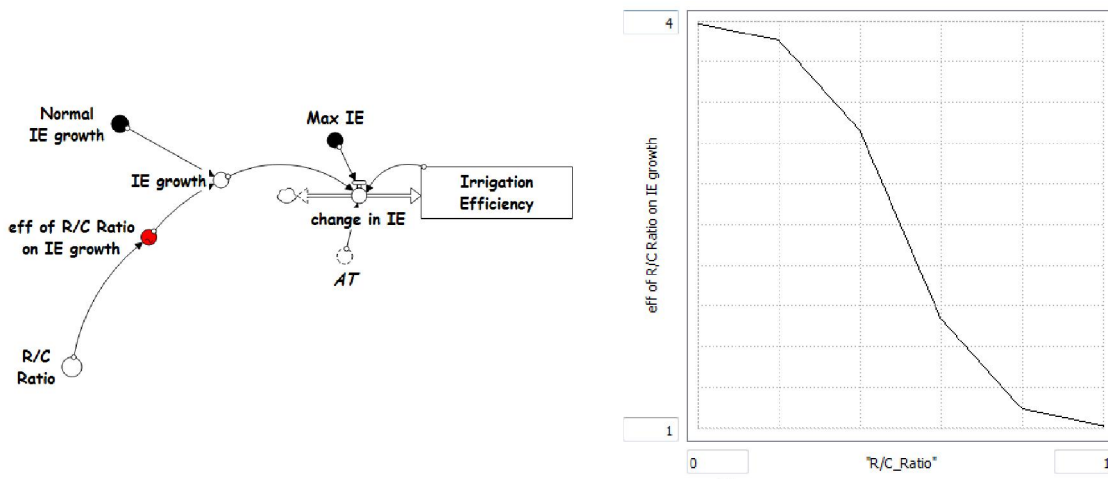


Figure 58: Irrigation Efficiency

The amount of “*IE growth*” is not constant and depends on “*Revenue-Cost (R/C) Ratio.*” The cheaper the water and electricity, and the bigger “*R/C Ratio,*” the fewer incentive farmers have to invest in improving irrigation technology, but when R/C goes down, the farmer will try to improve IE and decrease lost water to make more money from expensive water.

$$\text{Irrigation Growth} = \text{Normal_IE_growth} * \text{eff_of_R/C_Ratio_on_IE_growth}$$

5. desired irrigated land:

$$\text{desired Irrigated Land} = \text{Irrigated_Land} * (\text{desired_growth_based_on_profitability_ \& _external_limitations})$$

When R/C is bigger than one, farmers interest to expand their business (“*max possible growth based on external limitations*” is considered 2%), but when it is losing they start to decrease the size of their business.

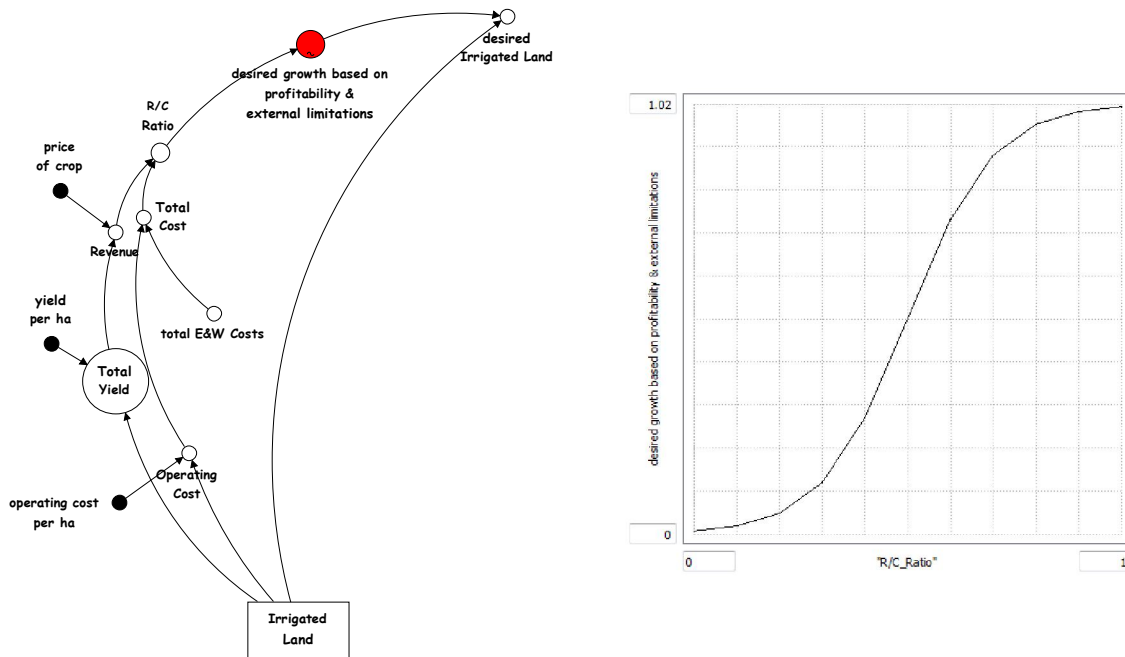


Figure 59: desired irrigated land

6. Operating Cost:

$$\text{Operating Cost} = (\text{operating_cost_per_ha}) * \text{SQRT}(\text{Irrigated_Land})$$

Please note two points regarding this formula:

- (1) The reason that we use SQRT function for calculating operating costs, is that we wanted to consider “economies of scale” effect.
- (2) applying this formula, we will face an error in unit consistency. To solve this problem, we used the variable of “unit regulator” which equals one and its units is “hectares”. Then we replaced above formula by the below one:

$$\text{Operating Cost} = (\text{operating_cost_per_ha}) * \text{SQRT}(\text{Irrigated_Land} * \text{Unit_Regulator})$$

Table 6: Equations

Equations
<p>Top-Level Model:</p> <p>Arable_Land(t) = Arable_Land(t - dt) + (- change_in_IL) * dt {NON-NEGATIVE}</p> <p>INIT Arable_Land = (20*1000*1000-Irrigated_Land)</p> <p>UNITS: Hectares</p> <p>OUTFLOWS:</p> <p>change_in_IL = gap_1/AT</p> <p>UNITS: Hectares/years</p> <p>Groundwater_Resources(t) = Groundwater_Resources(t - dt) + (recharge - withdrawal) * dt {NON-NEGATIVE}</p> <p>INIT Groundwater_Resources = (initial_GR-withdrawal*AT)</p> <p>UNITS: Liters</p> <p>INFLOWS:</p> <p>recharge = (MIN(Water_Table_Capacity-Groundwater_Resources, (Total_Consumed_Water+Rainwater_Penetration)*return_fraction))/AT {UNIFLOW}</p> <p>UNITS: Liters/years</p> <p>OUTFLOWS:</p> <p>withdrawal = (Number_of_Wells*withdrawal_per_well)/AT {UNIFLOW}</p> <p>UNITS: Liters/years</p> <p>Irrigated_Land(t) = Irrigated_Land(t - dt) + (change_in_IL) * dt {NON-NEGATIVE}</p> <p>INIT Irrigated_Land = 1.2*1000*1000</p> <p>UNITS: Hectares</p> <p>INFLOWS:</p> <p>change_in_IL = gap_1/AT</p> <p>UNITS: Hectares/years</p> <p>Irrigation_Efficiency(t) = Irrigation_Efficiency(t - dt) + (change_in_IE) * dt {NON-NEGATIVE}</p> <p>INIT Irrigation_Efficiency = 0.3</p> <p>UNITS: unitless</p> <p>INFLOWS:</p> <p>change_in_IE = ((MIN(Max_IE-Irrigation_Efficiency, IE_growth*Irrigation_Efficiency))/AT)</p> <p>UNITS: Per Year</p> <p>Number_of_Wells(t) = Number_of_Wells(t - dt) + (change_in_wells) * dt {NON-NEGATIVE}</p> <p>INIT Number_of_Wells = 6.58*1000</p> <p>UNITS: numbers</p> <p>INFLOWS:</p> <p>change_in_wells = gap_2/AT</p> <p>UNITS: numbers/years</p> <p>Water_Table_Capacity(t) = Water_Table_Capacity(t - dt) + (change_in_WTC) * dt {NON-NEGATIVE}</p> <p>INIT Water_Table_Capacity = initial_GR</p> <p>UNITS: Liters</p> <p>INFLOWS:</p> <p>change_in_WTC = ((-Water_Table_Capacity+MIN(Water_Table_Capacity, initial_GR*eff_of_water_level_on_WTC))/AT)</p> <p>UNITS: Liters/years</p> <p>AT = 1</p> <p>UNITS: Years</p>

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```

Available_Surface_Water = 20*1000*1000*1000
UNITS: Liters
Available_Water = withdrawal*AT+Available_Surface_Water
UNITS: Liters
Crop_Water_Requirements_per_ha = 5000
UNITS: Liters/hectares
desired_growth_based_on_profitability_&_external_limitations = GRAPH("R/C_Ratio")
(0.000, 0.00682670794277), (0.100, 0.0183459341613), (0.200, 0.0483743906411), (0.300,
0.121586980463), (0.400, 0.274320249797), (0.500, 0.510), (0.600, 0.745679750203), (0.700,
0.898413019537), (0.800, 0.971625609359), (0.900, 1.00165406584), (1.000, 1.01317329206)
UNITS: unitless
desired_IL_based_on_all_limitations = (Max_Possible_Irrigated_Land_based_on_Water_Availability)
UNITS: Hectares
desired_Irrigated_Land =
Irrigated_Land*desired_growth_based_on_profitability_&_external_limitations
UNITS: Hectares
desired_number_of_wells = IF (Groundwater_Resources>0) THEN ((desired_water-
Available_Surface_Water)/withdrawal_per_well) ELSE (0)
UNITS: numbers
desired_water = (desired_Irrigated_Land*Crop_Water_Requirements_per_ha)/Irrigation_Efficiency
UNITS: Liters
EC_per_liter_water = Normal_EC_per_Liter*eff_of_water_level_on_EC
UNITS: kilowatts/liters
"eff_of_R/C_Ratio_on_IE_growth" = GRAPH("R/C_Ratio")
(0.000, 3.97992144723), (0.200, 3.85772238047), (0.400, 3.19317573589), (0.600, 1.80682426411),
(0.800, 1.14227761953), (1.000, 1.02007855277)
UNITS: unitless
eff_of_water_level_on_EC = GRAPH((1-Normalized_Level_of_Water))
(0.000, 1.00), (0.100, 2.74345830469), (0.200, 5.11104383467), (0.300, 8.32618309361), (0.400,
12.6922853204), (0.500, 18.6213748928), (0.600, 26.6729736262), (0.700, 37.6069022456), (0.800,
52.4549838517), (0.900, 72.618415959), (1.000, 100.00)
UNITS: unitless
eff_of_water_level_on_return_fraction = GRAPH((Normalized_Level_of_Water))
(0.000, 0.000), (0.125, 0.406375195854), (0.250, 0.650401704303), (0.375, 0.79693854374), (0.500,
0.884933267954), (0.625, 0.937773710804), (0.750, 0.969504163118), (0.875, 0.988558159446),
(1.000, 1.000)
UNITS: unitless
eff_of_water_level_on_WTC = GRAPH(Normalized_Level_of_Water)
(0.000, 0.00449627316094), (0.100, 0.0131253183371), (0.200, 0.0376878905086), (0.300,
0.103400451458), (0.400, 0.253506016662), (0.500, 0.500), (0.600, 0.746493983338), (0.700,
0.896599548542), (0.800, 0.962312109491), (0.900, 0.986874681663), (1.000, 0.995503726839)
UNITS: unitless
Electricity_Cost = Total_EC*Electricity_Price
UNITS: dollars
Electricity_Price = 0.002
UNITS: dollars/kilowatts
gap_1 = desired_IL_based_on_all_limitations-Irrigated_Land
UNITS: Hectares
gap_2 = desired_number_of_wells-Number_of_Wells
UNITS: numbers
IE_growth = Normal_IE_growth*"eff_of_R/C_Ratio_on_IE_growth"

```

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UNITS: unitless
 initial_GR = 300*1000*1000*1000
 UNITS: Liters
 Lifetime = 20
 UNITS: Years
 max_growth_based_on_external_limitations = 1.01
 UNITS: unitless
 Max_IE = 0.65
 UNITS: unitless
 Max_Possible_Irrigated_Land_based_on_Water_Availability =
 (Available_Water*Irrigation_Efficiency)/Crop_Water_Requirements_per_ha
 UNITS: Hectares
 min_acceptable_withdrawal_per_well = 0.001
 UNITS: unitless
 netflow = recharge-withdrawal
 UNITS: Liters/years
 Normal_EC_per_Liter = 6
 UNITS: kilowatts/liters
 Normal_IE_growth = 0.001
 UNITS: unitless
 normal_return_fraction = 0.3
 UNITS: unitless
 Normalized_Level_of_Water = Groundwater_Resources/initial_GR
 UNITS: unitless
 Operating_Cost = (operating_cost_per_ha)*SQRT(Irrigated_Land*Unit_Regulator)
 UNITS: dollars
 operating_cost_per_ha = 300
 UNITS: dollars/hectares
 price_of_crop = 0.5
 UNITS: dollars/ kilograms
 "R/C_Ratio" = Revenue/Total_Cost
 UNITS: unitless
 Rainwater_Penetration = 33*1000*1000*1000
 UNITS: Liters
 return_fraction = normal_return_fraction*eff_of_water_level_on_return_fraction
 UNITS: unitless
 Revenue = Total_Yield*price_of_crop
 UNITS: dollars
 Total_Consumed_Water = Irrigated_Land*Crop_Water_Requirements_per_ha/Irrigation_Efficiency
 UNITS: Liters
 Total_Cost = total_E&W_costs+Operating_Cost
 UNITS: dollars
 total_E&W_costs = Electricity_Cost+Water_Cost
 UNITS: dollars
 Total_EC = (withdrawal*AT)*EC_per_liter_water
 UNITS: kilowatts
 Total_Yield = Irrigated_Land*yield_per_ha
 UNITS: Kilograms
 Unit_Regulator = 1
 UNITS: Hectares
 Water_Cost = Available_Water*Water_Price

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```
UNITS: dollars
Water_Price = 0.0025
UNITS: dollars/liters
withdrawal_per_well = 40*1000
UNITS: Liters/numbers
yield_per_ha = 2700
UNITS: Kilograms/ hectares
{ The model has 59 (59) variables (array expansion in parens).
In root model and 0 additional modules with 4 sectors.
Stocks: 6 (6) Flows: 6 (6) Converters: 47 (47)
Constants: 19 (19) Equations: 34 (34) Graphicals: 5 (5)
}
```