Innovative and Sustainable Groundwater Management in the Mediterranean

D4.3 Report on the Numeric Simulation Model Including Model Input Files

VERSION 1.0

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Executive Summary

The overall objective of the InTheMED project is to implement innovative and sustainable management tools and remediation strategies for MED aquifers (inland and coastal) in order to mitigate anthropogenic and climate-change threats by creating new long-lasting spaces of social learning among different interdependent stakeholders, NGOs, and scientific researchers in five field case studies, located at the two shores of the MED basin, namely in Spain, Greece, Portugal, Tunisia, and Turkey.

InTheMED will develop an inclusive process that will establish an ensemble of innovative assessment and management tools and methodologies including a high-resolution monitoring approach, smart modeling, a socio-economic assessment, web-based decision support systems (DSS) and new configurations for governance to establish efficient and sustainable integrated groundwater management in the MED considering both the quantitative and qualitative aspects.

The objective of Deliverable 4.3 is to document the progress in the dynamic system simulation model, which is developed based on the seed model created in modeling workshops in September 2021 and February 2022 and reported in Deliverable 4.2. To fulfill this objective, this document first summarizes the groundwater related issues in Konya, the problem description as it was set forth during the participatory modeling workshops, the adopted methodology and the research design; then focuses on the model description, validation, and analysis.

1. Introduction

This is the documentation of D4.3 of the "Innovative and Sustainable Groundwater Management in the Mediterranean" Grant Agreement Number 1923 project. In this deliverable we report the system dynamics model under development, and its preliminary analysis.

1.1. Groundwater Related Issues in Konya Closed Basin

The Konya Closed Basin (KCB) has semi-arid climate conditions with annual precipitation of 300-350 mm, which is less than half of the average yearly precipitation in Turkey (740 mm). According to the study carried out by Todaro et al. (2022), annual mean temperature towards the end of the century is expected to be 2.7 °C or 5 °C higher based on RCP 4.5 and RCP 8.5 scenarios, respectively. The study also estimates a 13-29% decrease in summer precipitation and a 3-10% increase in autumn precipitation. The basin holds 17% of groundwater sources and only 2% of the surface water sources of the country, therefore agriculture, which has been the prominent sector in the region, is mainly dependent on groundwater availability. A hydrogeologic model covering the entire basin and developed as part of WP3 indicates that the yearly groundwater deficit is about 55% over the past 2 decades. This figure is consistent with budget calculations presented in WWF (2014) which reports a yearly 50% budget exceedance in groundwater use.

It is evident that the groundwater in Konya-Çumra is over-extracted, i.e., the extractions are above recharge rates and the piezometric levels are declining. It is possible to foresee that if the current patterns in agricultural consumption rates, crop, and technology choices, as well as the water governance schemes prevail, water consumption will be restrained with its natural limits, manifested as drying wells and high investment and consumption costs. Indeed, there are various reports by farmers that wells are already drying, and water provision costs are increasing.

The crop pattern had an important role in shaping the rural development, industry, welfare and most importantly the water consumption levels in the KCB. Since the 1960s, the government has incentivized production of sugar beets. In the following years fruits, potato, corn, and trefoil production has increased in the basin. Corn and sunflower production have been supported via financial schemes since the 2000s (Figure 1). All these crops have higher water demand, compared to grains (wheat and barley) which were the dominant crop of the basin and did not require irrigation (WWF, 2014). With the change in crop patterns, the water demand consequently increased in the basin, resulting in significant groundwater level reduction.

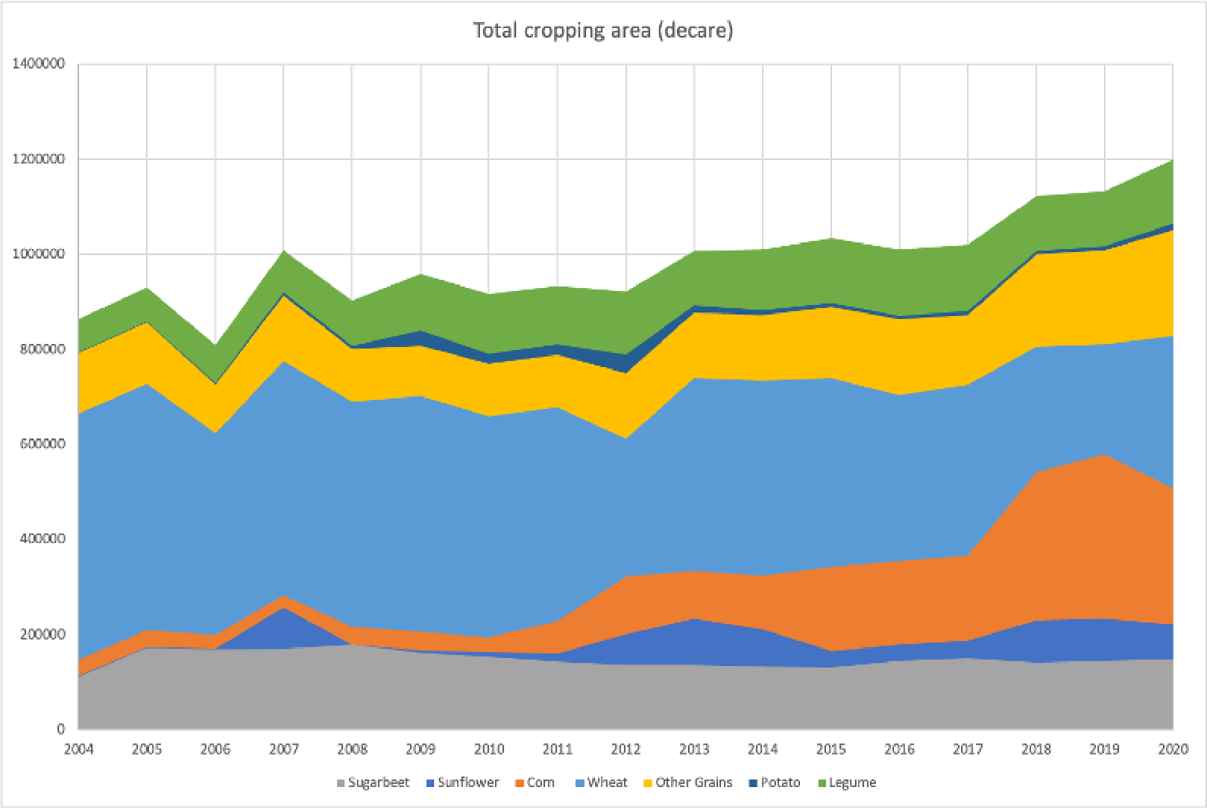

Figure 1. Temporal change in crop pattern in Çumra, Konya

1.2. Problem Description

In Konya-Çumra, reduction in agricultural water consumption is an imperative for the sustainability of agricultural communities and for the environment. However, although almost all the stakeholders involved in our analyses are aware that the resource is over-extracted, there is not a firm, well defined and commonly shared understanding on what exactly is the problem and its drivers, who are the responsible parties and what are the feasible, socially acceptable high leverage interventions that can alleviate the problem. With that regard, we argue that groundwater sustainability in Konya-Çumra is a "wicked problem" because of its complex interconnected characteristics, with multiple stakeholders with different perceptions and goals involved in decision making, sometimes with conflicting interests for the management of an inadequately observed, insufficiently characterized, commonly appropriated depletable natural resource.

To approach and articulate this wicked problem, and to move forward towards sustainable governance and management of groundwater resources in the region we started with two living labs (September 2021 and February 2022) to enhance learning amongst a large stakeholder base through scientific inquiry and experimentation. After that, we proceeded with dynamic simulation modeling and model analysis. As we work on this, our methodology is system dynamics, community-based approaches, and group model building. As a final step, our model will be presented and jointly tested at a stakeholder workshop planned for the Spring of 2023.

2. Methodology

2.1. System Dynamics

The goal of the system dynamics approach is to understand the source of a problematic dynamic behavior or trend within the system, discover the structure that generates such behavior, find and test leverage points in the system to end or reverse the undesired trend (Stave, 2010). Models built with this approach focus on the behavior of key variables over time and the feedback structure that creates the observed behavior, based on the defined problem and purpose of the model. Appropriate stock and flow structures are built to identify and capture important feedback loops, and the relationship between variables are mathematically formulated (Andersen et al., 2007a). Stocks are variables that accumulate or dissipate over time, and flows are the rate of change of stock variables. Figure 2 visualizes a stock-flow example to help readers better understand the concept.

2.2. Group Model Building

Involving stakeholders in practical sustainability research is often desirable. For stakeholder involvement in research with system dynamics, scholars in the field have developed an approach named Group Model Building (GMB) in the 1980s. Interested readers are referred to Vennix and Forrester (1999) which summarizes the process that led to the development of the GMB approach in more detail.

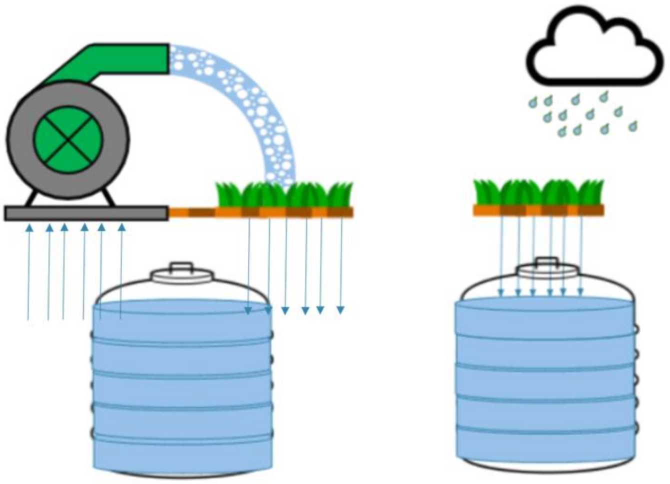

Figure 2. The barrel analogy: Water in a barrel is a stock variable that accumulates or dissipates in time; water extraction is an outflow and percolation from precipitation and/or irrigation return is an inflow

In the most general sense, GMB is the collection of a bunch of techniques to construct system dynamics models for decision making, with the involvement of those who have a stake in the outcome of the decision (Andersen et al., 2007). The purpose of GMB is to discover the potential leverage that stakeholder involvement adds to the models. It requires a deeper level of stakeholder engagement, by involving them directly in the model building process from the start with problem identification, to the end with policy analysis (Hovmand, 2014). Through a facilitated GMB study, researchers can elicit assumptions, ideas, knowledge, and mental models of the stakeholders, which creates an opportunity to develop a cumulative understanding of the connections between various components of the system at hand. By this way, proposed strategies to govern the system to improve (Richardson & Andersen, 2010; Sterling et al., 2019). Additionally, by bringing different knowledge systems together, GMB strives for reducing the gap between scientific and local communities and helps to combine formal analysis and empirical data with subjective knowledge and perceived dynamics of the system (Pahl-Wostl, 2008). Lastly, stakeholders possibly feel more empowered when their inputs (ideas, information, assumptions) are included in the resulting model and it creates a sense of ownership of the model among participants, especially for non-experts (Richardson & Andersen, 2010; Sterling et al., 2019), which in return contributes to achieving compliance with the shared decisions, after having experimented on the model with potential choices of action and familiarizing stakeholders with the outcomes of those (Pahl-Wostl, 2008).

GMB, by definition, is not a prescriptive methodology to be strictly followed; but is the collection of techniques to construct system dynamics models for decision making, with the involvement of those who have a stake in the outcome of the decision (Andersen et al., 2007b; Hovmand et al., 2012). The four main components of a GMB process are: the participants, the scripts, the team, and the boundary objects.

Readers are kindly referred to Deliverable 4.2, for more detailed information regarding both system dynamics approach, and group model building process.

3. Research Design

Our efforts to create a long-lasting learning space for sustainable groundwater management, augmented with system dynamics and group model building methodology which consists of several steps, including desktop literature review, field campaigns and three workshops, among which two of them are already conducted. In this deliverable, we focus on the system dynamics model under development and its preliminary analysis.

3.1. Field Process in Konya

Table 1 below illustrates the flow of conducted, and impending field activities. Detailed information regarding the previous field work is available in Deliverable 4.1. and 4.2. The next field campaign in winter 2023 will aim to discuss the system dynamics model specifics with prominent stakeholders prior to the third and final modeling workshop, to further test and validate the model. Then, during the last workshop in spring 2023, we will make a model-based analysis of the suggested interventions and policies from the previous workshops and discuss their implications together with a larger and more diverse group of stakeholders from Çumra region.

Table 1. Research design and flow of activities

Activity	Date	Purpose	Verification and synthesis
Desk research and literature review	Fall 2020	Identify sustainable groundwater management challenges, actors, and potential participants	D4.1 The Social-Economic System Characterization, Stakeholder Mapping and Water Governance for Selected Case Studies
First field campaign	Spring 2021	Approach institutional stakeholders for data and knowledge acquisition	D4.1
Second field campaign	Summer 2021	Approach individual stakeholders for data and knowledge acquisition	D4.1

First modeling workshop	Fall 2021	Building a living lab with key informants and forerunners, building consensus around the problem and suggested interventions	M4.1 First Living Lab Guiding Problem Identification and System Characterization
Second modeling workshop	Winter 2022	Slicing the problem into manageable units, conceptual modeling, and seed model development	M4.2 Second Living Lab Scrutinizing and Refining the Conceptual Model
Third field campaign	Winter 2023	Validating and testing the simulation model with the forerunners	
Third modeling workshop	Spring 2023	Model based analysis of suggested interventions with simulations in a workshop and larger conference setting	

3.2. System Dynamics Model Development

During the second modeling workshop, we created a seed model together with the participants as described in detail in Deliverable 4.2. We also discussed the limitations of that model in said document. Since then, we, as the modeling team, have been developing the seed model to eliminate those limitations.

The seed model assumed a single crop, and a constant target yield which drives the groundwater consumption. We added different crop types and relative attractiveness of crops, driven by their profitability, to incorporate the crop pattern change in the study area, and built a goal setting structure in the model to endogenize the potential changes in target yield.

We also developed the groundwater model to calibrate with the hydrogeological model developed for the basin. In the seed model, the groundwater stock had a volumetric unit; while in the model under development, we converted that to the hydraulic head, with a unit in length. The lateral movement of groundwater is formulated according to Darcy’s Law, and conversions from water volume to water head (and vice versa) are formulated accordingly when necessary.

The current version of the model is reported in detail in the following section.

4. Model Description

4.1. Model Overview

The model runs on a yearly basis, from 2000 to 2050. Figure 3 shows the model, as built on Stella Architect. It focuses on groundwater, wells (infrastructure for groundwater supply), crop choice, and factor consumption (irrigation) and yield dynamics.

Figure 4 shows the conceptual model. The groundwater demand side involves crop choice (land allocated for each crop), factor consumption (irrigation), yield goal setting, and crop production. Supply side involves groundwater and groundwater infrastructure, i.e., wells and pumps. While the demand for groundwater is driven by the land use (crop pattern) and targeted yield, its consumption is limited by the availability of groundwater, the cost of groundwater extraction, and the capacity of existing infrastructure.

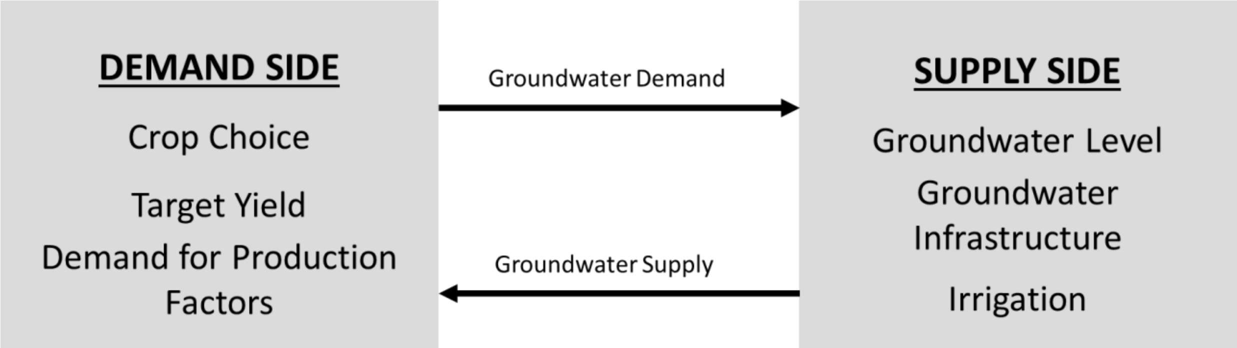

Figure 3. Conceptual model: demand vs supply

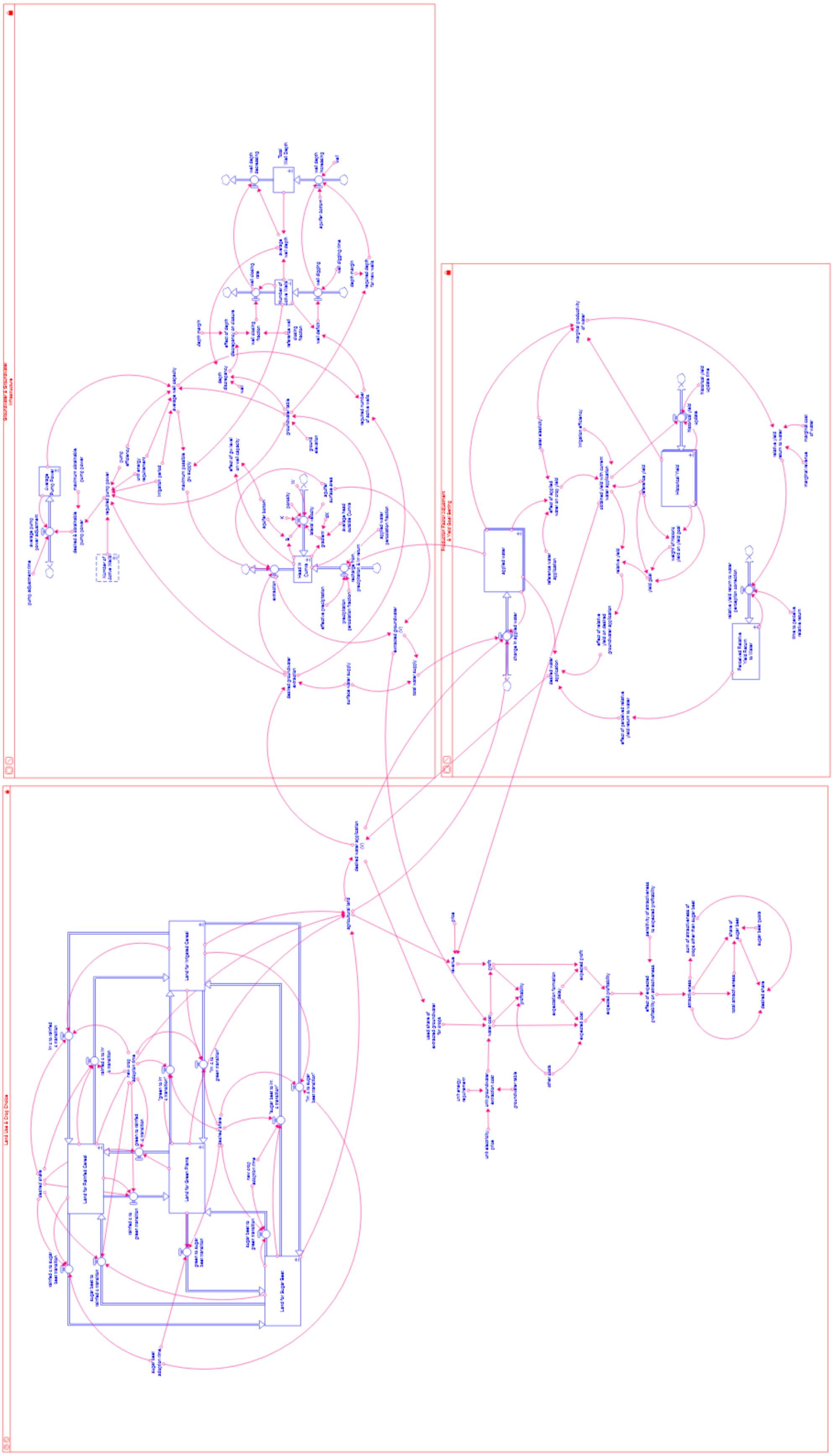

Figure 4. Model view in Stella Architect

Figure 5 is a schematic representation of the model sectors and shows the interaction (input/output relationships) between different parts of the model. Blue arrows introduce exogenous variables, which can be used to test different environmental scenarios (such as climate) and policy options (such as crop prices, quotas on crops, restrictions on groundwater extraction infrastructure etc.). Orange arrows show endogenous interactions between sectors of the model. Sectors' colors indicate their place in the conceptual model (Figure 4): grey sectors belong to the demand side and yellow sectors belong in the supply side. Production factor consumption and yield goal setting sector has both supply and demand side variables and contain feedback relationships between the two sides. Groundwater and groundwater infrastructure sector determines the water availability and accessibility, i.e., yearly groundwater extraction capacity. Factor adjustment and goal setting sector determines target yield for each crop type and adjusts the desired irrigation level accordingly. Desired irrigation water is determined from the desired irrigation level and how much land is allocated to each crop. Groundwater extraction depends both on the extraction capacity, and the demand for groundwater. Obtained (actual) yield for each crop type is calculated based on the realized irrigation level. Revenue from obtained yield and groundwater extraction cost determine the profitability and the attractiveness of crops. Farmers’ land use choice depends on relative attractiveness of crops; more land is allocated to a crop with relatively high attractiveness, and vice versa.

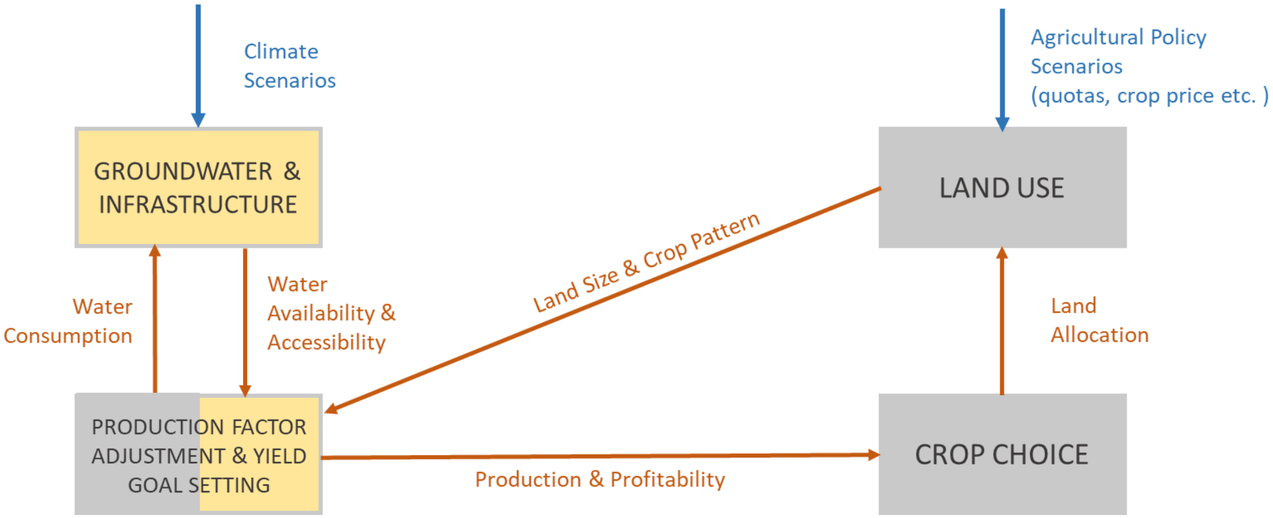

Figure 5. Sector overview

4.2. Model Sectors

4.2.1. Groundwater and Groundwater Infrastructure

Main Feedback Loops

Figure 6 shows the average well capacity, pump power, and well digging loops within the groundwater and groundwater infrastructure sector.

B1 is a simple loop that explains the relationship between the groundwater resource and extraction; an increase in extraction would reduce the available groundwater, and consequently – other conditions being equal – the extraction capacity decreases.

The well digging loop (R1) in Figure 6 is a reinforcing one. *Required number of active wells* is determined by how much water farmers wish to consume in a season (*desired water application*) and *average well capacity*. *Well deficit* is the difference between the *required number of active wells* and the actual *number of active wells*. If *well deficit* increases, *well digging* rate becomes higher, therefore farmers have more active wells, decreasing the *well deficit*.

In B2 average well capacity balancing loop, a decrease in *groundwater table*, when the *average pump power* is constant, decreases the *average well capacity* due to increased energy requirement. Therefore, the *maximum possible groundwater supply* is reduced as well. *Extraction* also reduces due to the decreased capacity, therefore, the fall in groundwater *head in Çumra* is slowed down and the drop in the *groundwater table* is balanced.

Lastly, R2 is the reinforcing pump power loop. If the *groundwater table* drops, farmers will require more power to extract water from a deeper level. Therefore, the *desired pump power* will increase, and in time farmers will invest in more powerful pumps. With a certain amount of delay, the *average pump power* will increase, thus the *average well capacity* will also increase. The *maximum possible groundwater supply* will be higher due to the increased well capacity, and farmers will be able to use more water, decreasing the *groundwater table* further. This is a reinforcing loop because the change in *groundwater table* is fortified when the loop operates.

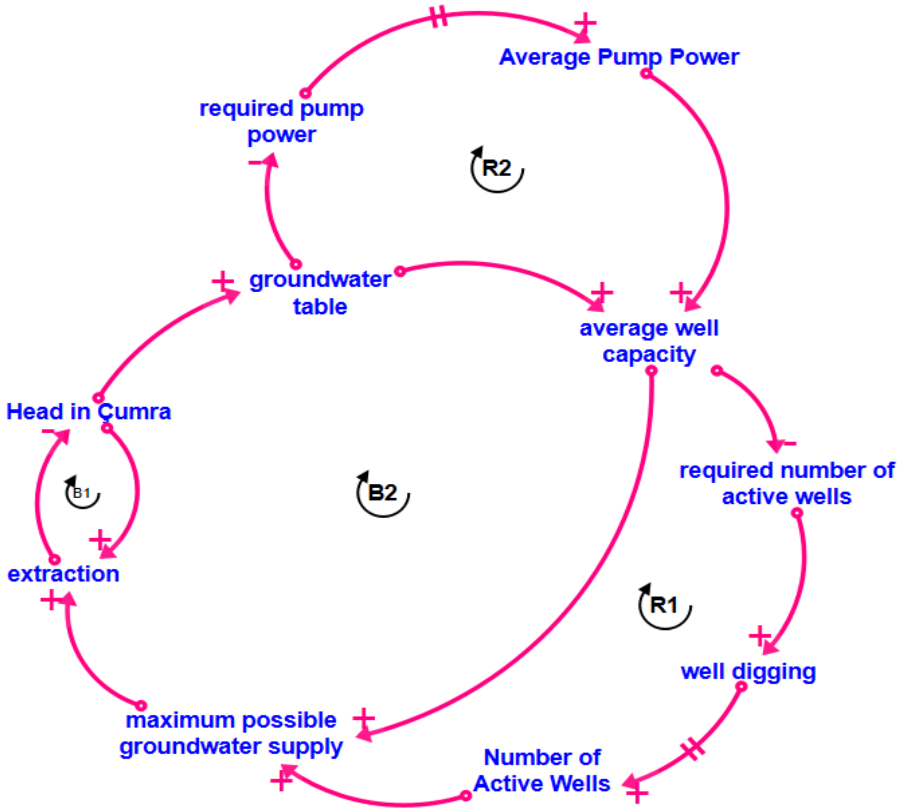

Figure 6. Average well capacity, pump power, well digging loops

Figure 7 shows two loops: one balancing and one reinforcing. If the *number of active wells* increases, the *maximum possible groundwater supply* increases. Therefore, farmers can use more water. Higher realized water consumption leads to a decrease in *groundwater table*. *Depth discrepancy* is defined as the difference between *groundwater table* and *average well depth*. Therefore, drops in *groundwater table* decrease the *depth discrepancy*, while decrease in *average well depth* increases it. When we look at the balancing loop, we see that the drop in *groundwater table* caused by increased water consumption decreases the *depth discrepancy*, therefore, *the well closing rate* is higher. At the end of the loop, we see that the initial increase in the *number of active wells* is balanced. On the other hand, when we look at the reinforcing loop, we see that drop in *groundwater table* also leads to a decrease in *average well depth*, because farmers dig deeper wells as the *groundwater table* falls. Therefore, the *depth discrepancy* increases, lowering the rate of well closing.

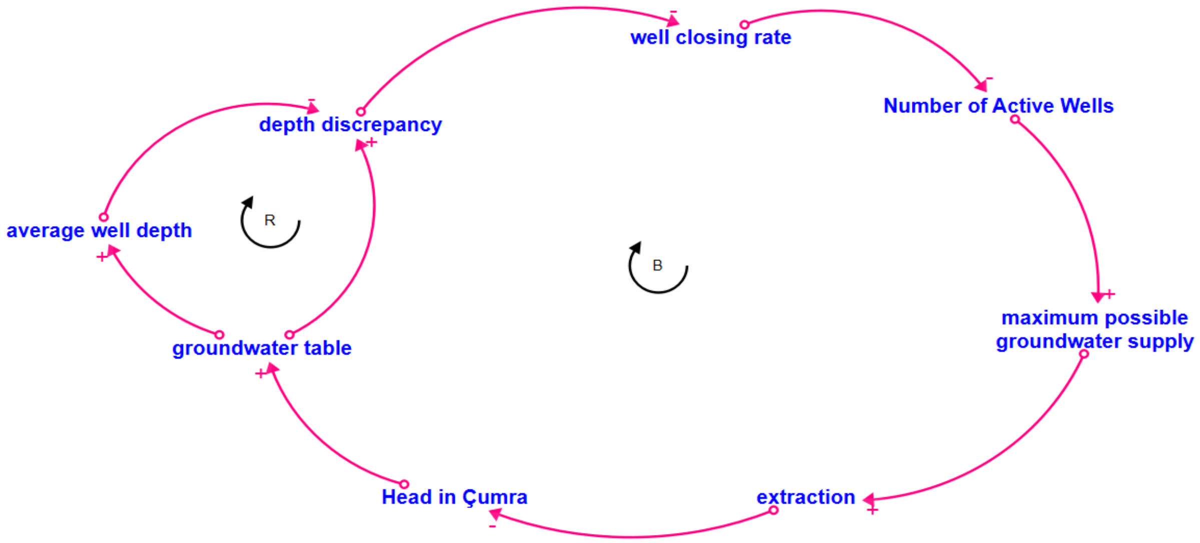

Figure 7. Well closing loops

Stock - Flow Description and Main Formulations

Figure 8 shows the simplified stock - flow structure of the groundwater and groundwater infrastructure sector.

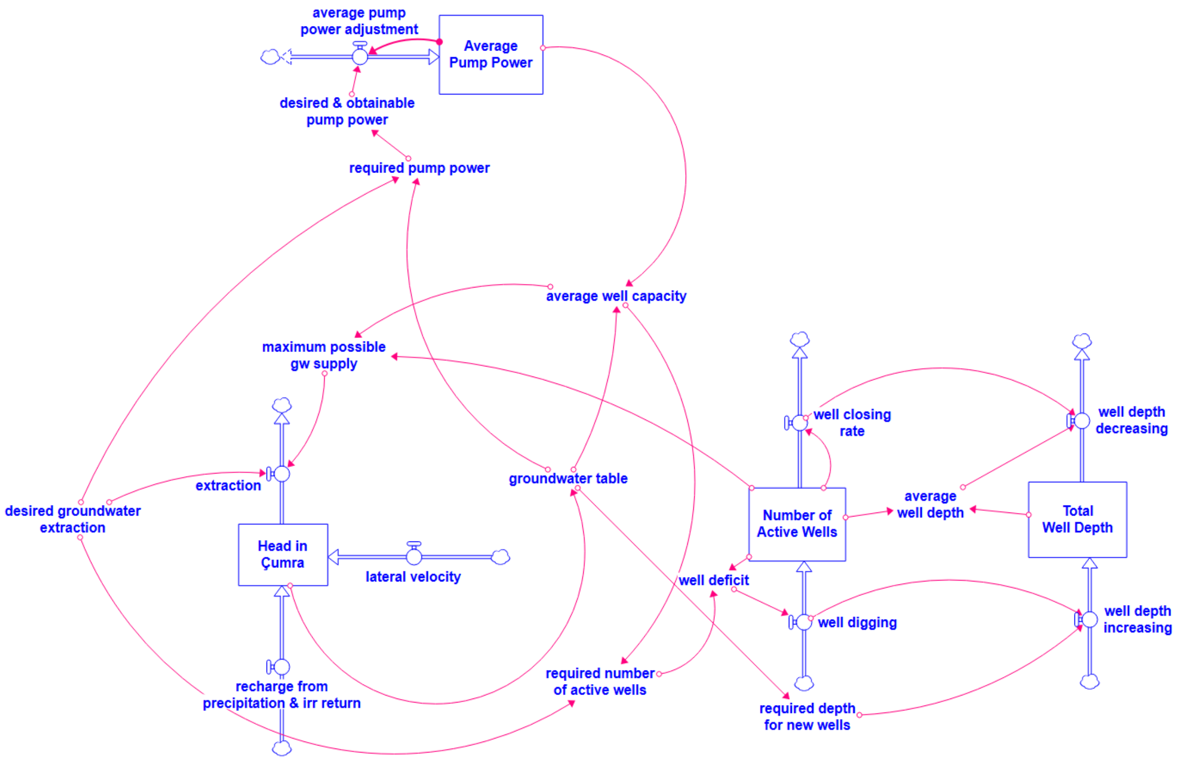

Figure 8. Groundwater and groundwater infrastructure sector stock - flow structure

Below are some of the main formulations of this sector:

The main stock in this sector is the *head in Çumra*. The change in the groundwater head is driven by *recharge from precipitation and irrigation return* (vertical recharge), *lateral velocity*, and *extraction*. *Lateral velocity* is formulated according to Darcy's Law, and the values of the variables in the formula are taken from the hydrogeological model built for the Konya Closed Basin by our research team. When the *desired groundwater extraction* is less than the *maximum possible groundwater supply*, the demand is met. Otherwise, *extraction* is limited by the capacity imposed by groundwater infrastructure (*number of active wells* and *average pump power*).

(I) $$d(\mathit{Head\ in\ Çumra})/dt = \mathit{recharge\ from\ precipitation\ and\ irrigation\ return} + \mathit{lateral\ velocity} - \mathit{extraction}$$

(II) $$\mathit{recharge\ from\ precipitation\ and\ irrigation\ return} = \mathit{effective\ precipitation} \times \mathit{precipitation\ percolation\ fraction} + \mathit{SUM}(\mathit{Applied\ Water} \times \mathit{agricultural\ land}) \times \mathit{applied\ water\ percolation\ fraction} \div \mathit{aquifer\ surface\ area}$$

(III) $$\mathit{lateral\ velocity} = (K \times B \times W \times \mathit{gradient}) \div (\mathit{aquifer\ surface\ area} \times \mathit{porosity})$$

(IV) $$\mathit{extraction} = \mathit{MIN}\ (\mathit{maximum\ possible\ groundwater\ supply}\ ; \mathit{desired\ groundwater\ extraction} \div \mathit{aquifer\ surface\ area})$$

Although the model is not yet fully calibrated, we did some partial model calibration while building the model, which can be mentioned here as a side note. Figure 9 shows the partial model calibration results for lateral velocity flow; it is calibrated against the hydrogeological model, based on the results of a run under the following assumptions: zero extraction, zero precipitation, constant and equal head outside Çumra, homogenous head inside Çumra.

The equation of the flow in the SD model is Darcy's Law, as mentioned above. The aquifer thickness (B) is calculated as the difference between the average Head in Çumra and the aquifer bottom, which is the most uncertain parameter within those included in the formulation because many of the existing wells in the region were not drilled to the bottom of the aquifer. The other parameters in the formulation are taken from the hydrogeological model, then the outcome is calibrated for the aquifer bottom.

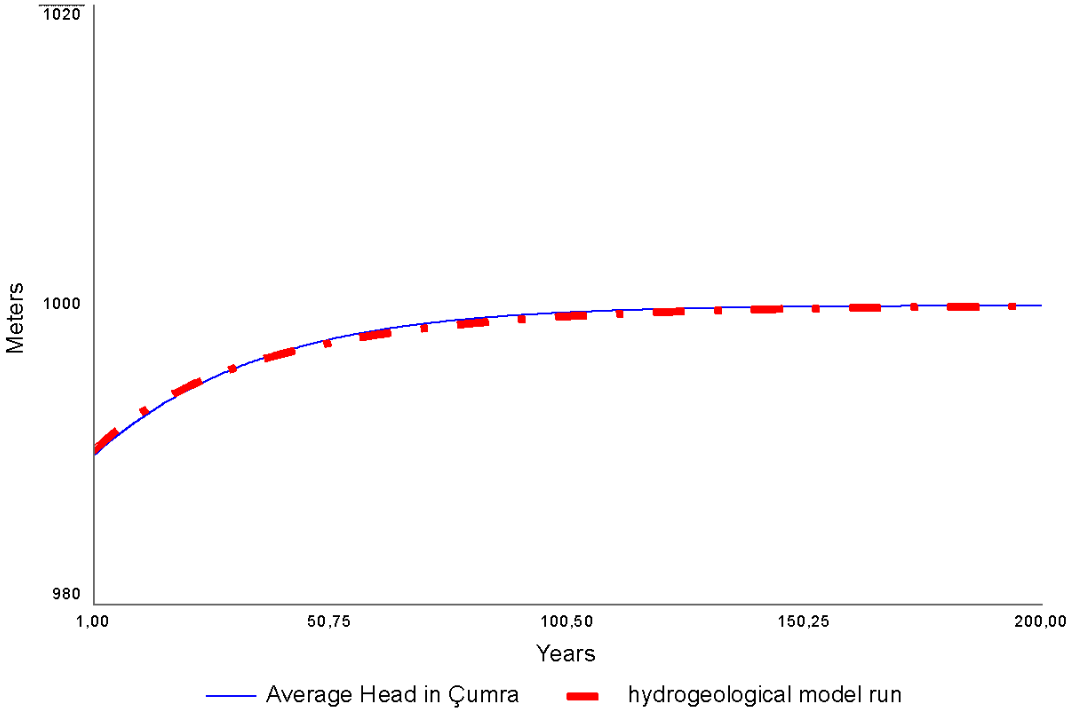

Figure 9. Partial model calibration for lateral velocity

Number of active wells changes with well digging and well closing dynamics. Well digging is driven by the well deficit, which is simply the difference between the required number of active wells and Number of Active Wells. Well closing rate depends on the stock, Number of Active Wells, and well closing fraction, which is a variable itself. The fraction increases when the groundwater table and average well depth values are close to one another; as average well depth decreases more than the groundwater table, well closing rate reduces.

(V) $d(Number\ of\ Active\ Wells)/dt = well\ digging - well\ closing$

(VI) $well\ digging = \ well\ deficit\ \div well\ digging\ time$

(VII) $well\ closing\ rate = \ Number\ of\ Active\ Wells \times well\ closing\ fraction$

Average pump power is continuously updated by *average pump power adjustment*. The *desired and obtainable pump power* indicates the desired level of pump power but capped by a technological capacity constraint.

(VIII) $$d(Average\ Pump\ Power)/dt = average\ pump\ power\ adjustment$$

(IX) $$average\ pump\ power\ adjustment = \ (desired\ \&\ obtainable\ pump\ power - Average\ Pump\ Power) \div pump\ adjustment\ time$$

4.2.2. Land Use and Crop Choice

Main Feedback Relationships

The allocated land for each crop in the land use sector is updated according to the desired share of crops, which is driven by the attractiveness of crops, depending on their profitability.

Land allocation determines the desired water level, and groundwater and groundwater infrastructure sector determine the irrigation capacity. Based on these, applied irrigation is calculated, which provides both the obtained yield (and revenue), and water cost. Revenue and cost are used to calculate the profitability of crops in the land use and crop choice sector, and the desired share of crops for land allocation is continuously updated as such.

Stock - Flow Description and Main Formulations

Figure 10 shows the stock-flow representation of the feedback relationships in the land use sector. There exist four land stocks for four crop types, and each crop type can be converted into one another continuously.

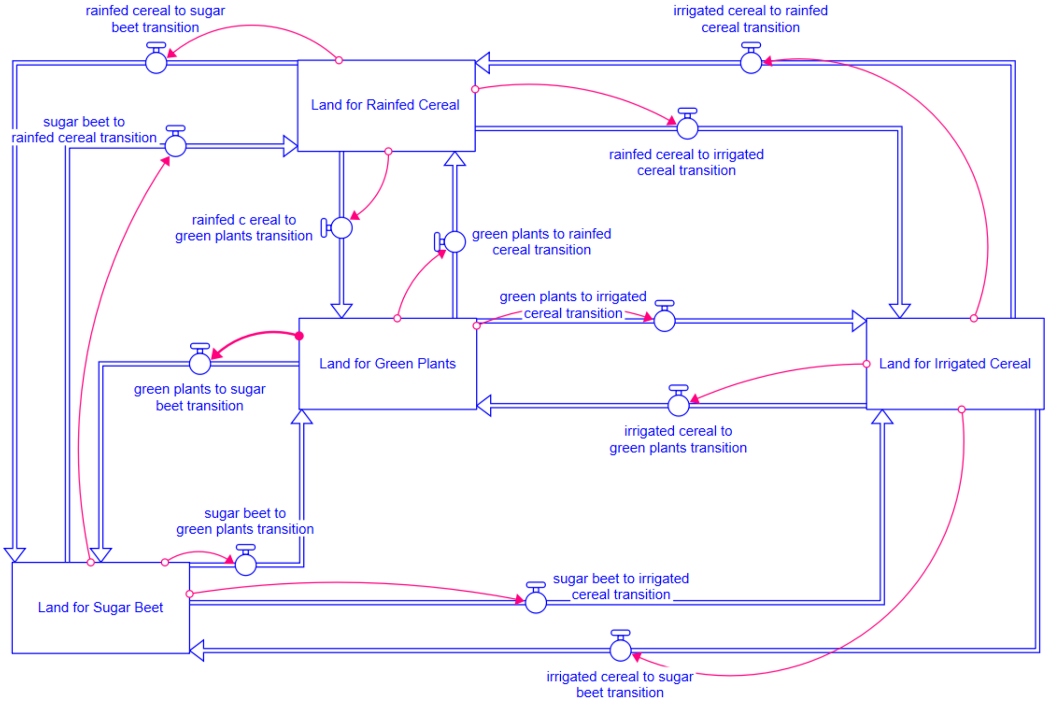

Figure 10. Land use and crop choice sector stock - flow structure

Below are some exemplary formulations:

(X)

$$\begin{aligned}
&d(\mathit{Land\ for\ Sugar\ Beet})/dt = \mathit{green\ plants\ to\ sugar\ beet\ transition} - \\
&\mathit{sugar\ beet\ to\ green\ plants\ transition} + \\
&\mathit{rainfed\ cereal\ to\ sugar\ beet\ transition} - \mathit{sugar\ beet\ to\ rainfed\ transition} + \\
&\mathit{irrigated\ cereal\ to\ sugar\ beet\ transition} - \\
&\mathit{sugar\ beet\ to\ irrigated\ cereal\ transition}
\end{aligned}$$

(XI)

$$\begin{aligned}
&\mathit{sugar\ beet\ to\ green\ plants\ transition} = \mathit{Land\ for\ Sugar\ Beet} \times \\
&\ \mathit{desired\ share\ of\ green\ plants} \div \mathit{new\ crop\ adoption\ time}
\end{aligned}$$

Rate of change in land stocks is equal to the sum of all inflows subtracted by the sum of all outflows. The change is integrated over time. Flow variables are calculated as multiplication of the land stock they originate from and the desired share of the crop they attain to, over *new crop adoption time*. While the other three crops have a crop adoption time of one year, meaning that farmers can switch from one crop to another every year, the only exception for the crop adoption time is sugar beet because it can only be cultivated once every four years.

It should be noted here that, variables in this sector, besides stocks and flows, are calculated and updated separately for each crop type through arrayed structures.

There has been a quota on sugar beet production in Turkey since 1998; therefore, when allocating the available land to the four crop types, we need to take this into account. The share of sugar beet is calculated as the minimum of the quota and the desired share of sugar beet; unless the desired share is larger than the quota, as much land as desired is allocated to sugar beet. Otherwise, the quota is imposed. Consequently, the share for other three land use options are calculated based on the land allocated to sugar beet, as exemplified in Equation XIII, and the formulas for the remaining two land use options are analogous to it.

(XII) $share\ of\ sugar\ beet = MIN(sugar\ beet\ quota; attractiveness[Sugar\ Beet] \div total\ attractiveness)$

(XIII) $desired\ share\ of\ greens = (1 - share\ of\ sugar\ beet) \times attractiveness[Greens] \div SUM(attractiveness\ of\ crops\ other\ than\ sugar\ beet)$

Expectation formation in the model is based on the past values of variables; in the case of expected profit (Equation XIV) and expected cost, the variables are smoothed over a certain period, i.e., expectation formation delay. Logit model is used for the allocation of land to the four land use options. Attractiveness of crops are calculated as an exponential function of expected profitability, and sensitivity to expected profitability.

(XIV) $expected\ profit = SMTH1(profit, expectation\ formation\ delay)$

(XV) $expected\ profitability\ = expected\ profit \div expected\ cost$

(XVI) $attractiveness = EXP(sensitivity\ of\ attractiveness\ to\ expected\ profitabiliy \times expected\ profitability \div reference\ profitability)$

4.2.3. Production Factor Adjustment and Yields Goal Setting Sector

Main Feedback Loops

Figure 11 shows the causal loop diagram of the factor adjustment and goal setting sector.

The R1 reinforcing loop is rather straightforward; *desired water application* is anchored on *Applied Water*; therefore, they have a positive relationship. Also, if more water is desired, more water is used for irrigation (if available), indicating another positive relationship between these two variables. Simply, if more water is consumed, more water is desired; and vice versa.

Desired water application increases if there is an increase in *relative yield,* which is dependent on *obtained yield with current water application* and *yield goal*. The – respectively – negative and positive impact of those two variables result in B1 balancing and R2 reinforcing loops. If the *applied water* increases, so does the *obtained yield*. Therefore, *relative yield* decreases, and the *desired water application* is also lower than it would otherwise be, which is reflected in *applied water*. On the other hand, the change in *obtained yield* is reflected in *Historical Yield* with an information delay. It should be noted here that the R2 reinforcing loop involves the goal setting structure for the *yield goal*; historic performance of the obtained yield is stored in the *Historical Yield* variable with a certain information delay, and the *yield goal* is driven by this past performance. Therefore, considering the same case starting with an increase in *applied water* and *obtained yield* for the R2 loop, we would also observe an increase in *Historical Yield* and *yield goal*, which has a positive relationship with *relative yield*. In short, in case of a change in applied water, while the B1 loop tries to damp the change, the R2 loop amplifies it. At the end, whether the change is damped or amplified depends on the relative strength of the two loops and can be simulated and tested numerically.

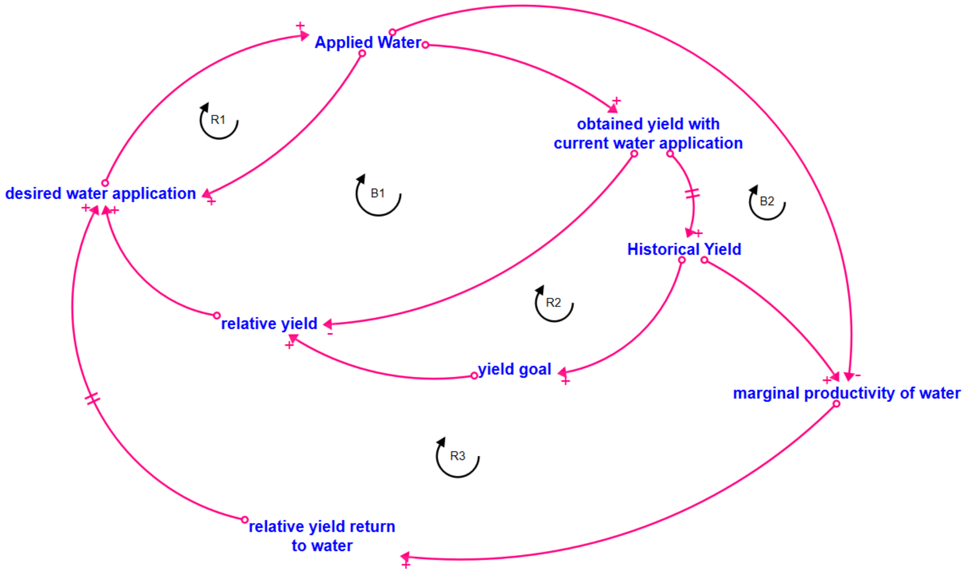

Figure 11. Causal Loop Diagram (CLD) of factor adjustment and goal setting sector

A similar loop dominance conundrum exists between the B2 and R3 loops. In this case, *marginal productivity of water* is the variable analogous to *relative yield* in the previous paragraph. While *marginal productivity of water* increases when *applied water* is increased, it decreases when there is a rise in *Historical Yield*.

The same structure applies to all four crop types; all variables shown in Figure 11 are calculated separately for each crop.

Stock – Flow Description and Main Formulations

Figure 12 shows the stock – flow structure in production factor adjustment and yield goal setting sector.

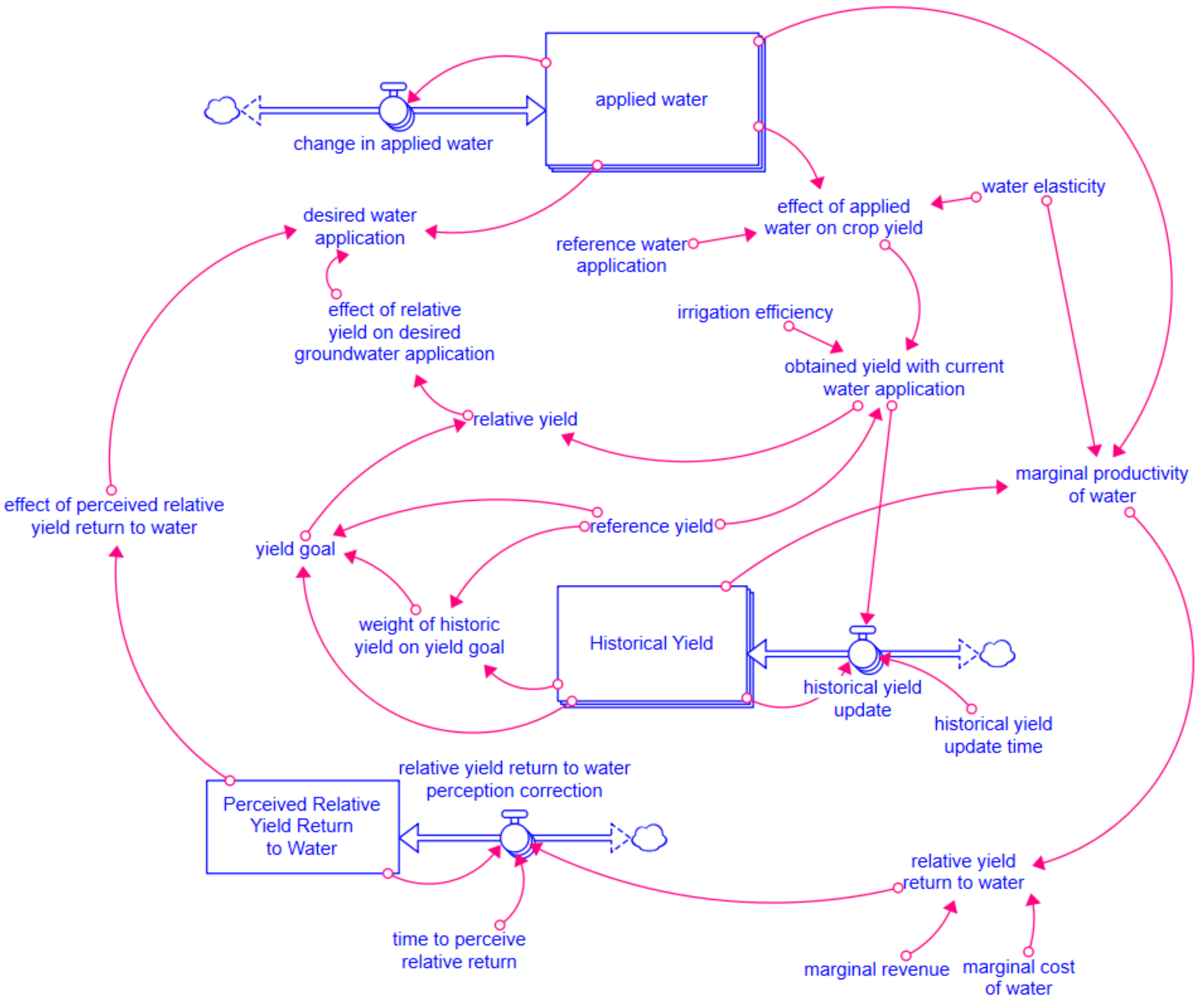

Figure 12. Production factor adjustment and yield goal setting sector stock - flow structure

The main formulations of this sector are as follows:

Change in applied water is calculated for each crop separately (Equation XVII), as mentioned above. The total water supply is distributed among different crops according to their relative *desired water application*. Then, it is divided by the land of the given crop to convert volume into length units. *Applied Water* is subtracted from the obtained value and the result is divided by *dt* for instantaneous update in *Applied Water.*

(XVII) $d(Applied\ Water)/dt = change\ in\ applied\ water$

(XVIII) $change\ in\ applied\ water = [desired\ water\ application \div SUM(desired\ water\ application)\ \times total\ water\ supply \div agricultural\ land - Applied\ Water] \div DT$

We use a Cobb-Douglas production function to calculate obtained yield (Equations XIX and XX), and the marginal productivity of water is calculated as the partial derivative of yield over water use, yielding Equation XXI.

(XIX) $obtained\ yield = MIN(reference\ yield\ ;\ reference\ yield \times effect\ of\ applied\ water\ on\ crop\ yield$

(XX) $effect\ of\ applied\ water\ on\ crop\ yield = (Applied\ Water \times irrigation\ efficiency \div reference\ water\ application){}^\wedge(water\ elasticity)$

(XXI) $marginal\ productivity\ of\ water = water\ elasticity \times Historical\ Yield \div Applied\ Water$

Yield goal is a function of both *reference yield* and *Historical Yield*. *Weight of historical yield on yield goal* is a function of the difference between reference and Historical Yields; when *Historical Yield* is close to the reference yield, the yield goal approaches the reference yield. However, as Historical Yield diverges from the reference yield, it means that there have been factor(s) which hamper the obtained yield, therefore the yield goal erodes in time (Barlas & Yaşarcan, 2005).

(XXII) $d(Historical\ Yield)/dt = historical\ yield\ update$

(XXIII) $historical\ yield\ update = (obtained\ yield\ with\ current\ water\ application - Historical\ Yield) \div historical\ yield\ update\ time$

(XXIV) $yield\ goal = Historical\ Yield \times weight\ of\ historical\ yield\ on\ yield\ goal + reference\ yield \times (1 - weight\ of\ historical\ yield\ on\ yield\ goal)$

(XXV) $relative\ yield\ return\ to\ water = marginal\ revenue \times$
$marginal\ productivity\ of\ water \div marginal\ cost$

(XXVI) $desired\ water\ application = Applied\ Water \times$
$effect\ of\ relative\ yield\ on\ desired\ water\ application \times$
$effect\ of\ perceived\ relative\ yield\ return\ to\ water$

5. Model Validation

In system dynamics methodology, both structural and behavioral validation is important. In system dynamics, model validation consists of sequential steps of structure and then behavior validation. Structure validity focuses on the consistency and sufficiency of model structure with respect to its purpose. Behavior validity focuses on behavior pattern match between real life and simulated data. To get the right behavior for the right reasons, it is crucial to test structural validity first. Therefore, we first perform structural validation tests, and then behavioral validation tests.

5.1. Structural Validation

There are several options to test the structural validity of a system dynamics model (Sterman, 2000); namely,

Boundary adequacy tests check whether the boundary assumptions are suitable for the problem and important concepts to the problem are endogenized in the model structure.

Structure assessment tests relate to the consistency of the model with the relevant descriptive knowledge of the system at hand, and to the level of aggregation. These tests check whether the model conforms to the physical laws and the behavior modes of the actors in the system.

Dimensional consistency tests check whether the equations in the model are dimensionally consistent without dummy variables that do not have any real world meaning.

Parameter assessment tests control whether the values of the parameters in the model are consistent with the reality and all parameters have real world counterparts.

Extreme condition tests check whether the model behaves in a meaningful way when the parameters are given extreme values.

5.1.1. Direct Structure Tests

Boundary adequacy, structure assessment, dimensional consistency, and parameter assessment tests are direct structure tests that do not necessarily require numerical simulation.

Boundary Adequacy & Structure Assessment

We benefited from the participation of the local groundwater users and experts to the group model building workshops for boundary adequacy and structure assessment tests. As described in D4.2 and M4.2, the first modeling workshop helped us identify the problems and the related parts of the system that should be included in the model. In other words, a general framework for the model boundaries was shaped in the first workshop. We also took advantage of several causal loop diagrams, conceptual model diagrams, and simple stock - flow maps.

In the second workshop, we built a seed model together with the participants (please see M4.2 for details) which constituted the base of the model described in this document. Thus, the basic structures of the model rely on stakeholder knowledge and experience; then, those are developed based on information obtained in semi-structured interviews and through intense qualitative work (causal loop diagrams, conceptual model maps, etc.).

Prior to the first workshop, we intend to organize another field trip to meet with prominent stakeholders one by one and further validate the model structure.

Dimensional Consistency and Parameter Assessment

Each of the mathematical equations in the model is checked one by one, to find if there are unit errors. An example is provided below.

$$\begin{aligned} &average\ well\ capacity \\ &\qquad = Average\ Pump\ Power\ x\ pump\ efficiency\ x\ irrigation\ period \\ &\qquad / \, (-1) x\ groundwater\ table\ x\ unit\ energy\ requirement \end{aligned}$$

Average well capacity indicates the amount of water a single well can produce in one year; therefore, it has a unit of volume per well per year. The right-hand side of the equation must obviously produce the same unit. Average pump power has a unit of kW per well. Pump efficiency is dimensionless parameter. Irrigation period indicates the portion of time in which farmers irrigate the crops each year, therefore it has a unit of hours per year. Groundwater table represents the depth, and it has a length unit. The (-1) in the formula is to avert calculation flaws, as groundwater table depth is below 0. Lastly, unit energy requirement is the energy required to lift one cubic meter of water, one meter. Therefore, it has a unit of kilowatt hours per cubic meters per meter. The unit consistency of the equation is as follows:

$$〖(m〗\ \hat{}(3\ )/Year/Well) = (kW\ x\ Hours/Year)/(Metres\ x\ kW\ x\ Hours\ /\ Metres\hat{}4)$$

For parameter assessment, we have been doing partial model tests and partial model calibration with the datasets that we have from various state institutions and the hydrogeological model (for the groundwater and infrastructure sector). However, it needs further work and may also require statistical methods for parameter estimation.

5.1.2. Indirect Structure Tests

Extreme Condition Tests

Groundwater and Groundwater Infrastructure Sector

Extreme condition tests are performed for four variables in this sector: namely, *desired groundwater extraction, well digging time, pump adjustment time, average head outside Çumra*. The results are as follows:

1. Extremely low desired groundwater extraction

In the first experiment, we set the desired groundwater extraction to 0. Given that there is no demand, we expect groundwater extraction to be zero as well, which means that the resource would not be depleted but fed by vertical and lateral recharge. Therefore, we would expect to see an increase in the groundwater table.

As can be seen in Figure 13, the extraction rate is 0 due to lack of demand. Therefore, the resource is not extracted, only fed by lateral and vertical recharge, which is reflected in the slight increase in the groundwater table. Also due to lack of extraction, no new wells or power are required, therefore, the initially existing infrastructure decay in time, as they complete their useful lifetime.

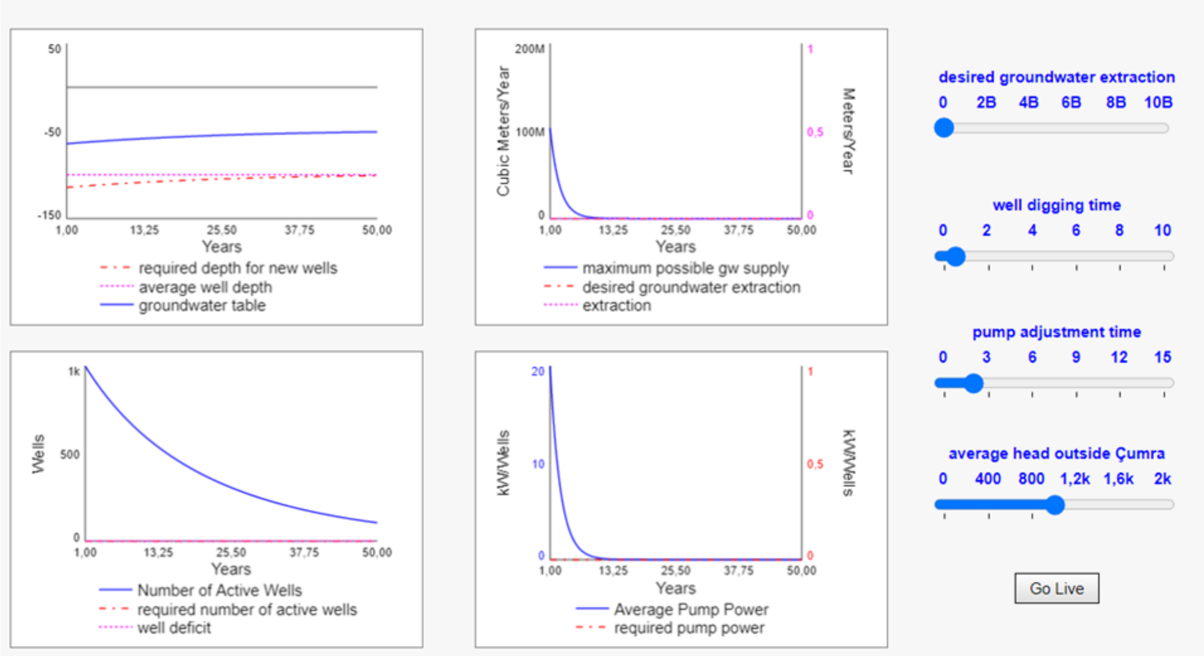

Figure 13. Extremely low desired groundwater extraction

Figure 14 shows the results. As expected, we see a fast and steep decrease in the groundwater table, even though the existing groundwater extraction infrastructure is unable to fully meet the demand (maximum possible groundwater supply < desired groundwater extraction). To increase the maximum possible groundwater supply, average pump power in the wells is increased, so that more water is procured from each well. However, as the average pump power reaches its technological upper limit, since the groundwater supply capacity is still below the desired amount, we observe a steep growth in the number of wells; well digging rate increases substantially. In the meantime, as groundwater table goes deeper and since the average pump power can no longer be increased, average well capacity shrinks, in return to the increased rate of well digging. Therefore, in contrast with the initial intuition, the overall groundwater supply capacity decreases close to the end of the simulation period, despite the increase in the number of wells.

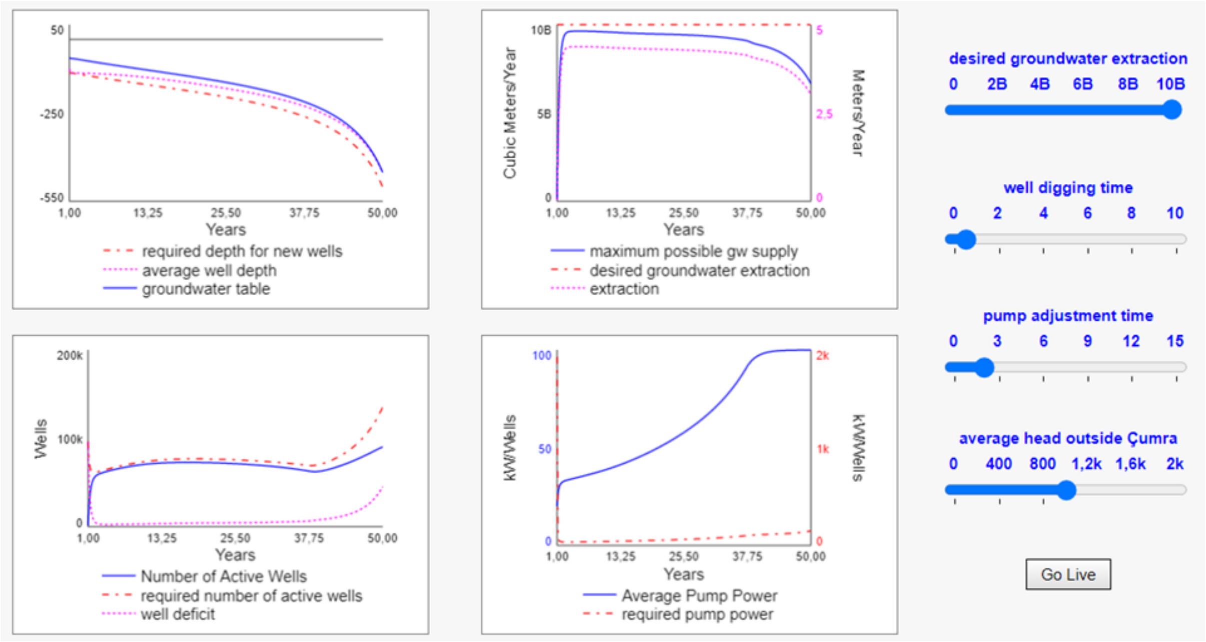

Figure 14. Extremely high desired groundwater extraction

3. Extremely high *well digging time*

Figure 15 shows the results of the test in which we set the well digging time to 10 years. In other words, it takes 10 years to drill one well. Under this assumption, we anticipate a large well deficit and a gap between the maximum groundwater supply and desired groundwater extraction; the infrastructure would be insufficient to meet the demand.

As expected, the change in the number of wells is much slower. Average pump power increases to its upper limit much faster, to make up for the lack of groundwater extraction capacity increase. However, we observe that it is still insufficient to fulfill the demand for groundwater, thus extraction is much lower than the desired amount. As a result, the fall in groundwater table is rather slow.

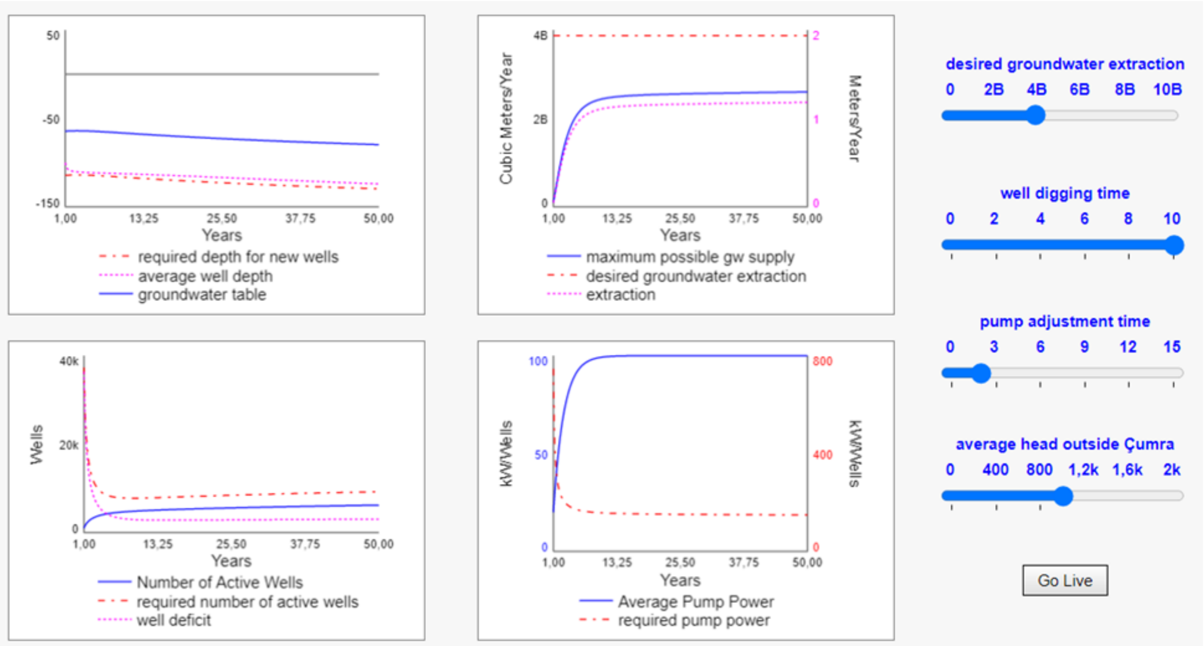

Figure 15. Extremely high well digging time

4. Extremely high pump adjustment time

In this experiment, similar to the previous one, we increase the pump adjustment time to 15 years. Since there are no constraints on well drilling, we would expect to see a steep increase in the number of wells to increase the groundwater supply capacity, to meet the existing demand.

The results of this test are shown in Figure 16. We initially see a jump in the number of wells, and then a continuous increase, because the time required to adjust the pump power and increase average well capacity is too long. The initial jump in the number of wells is reflected in the maximum possible groundwater supply, which is quite close to the desired groundwater extraction amount. By slowly increasing the average pump power and the number of active wells, the groundwater supply capacity is kept constant throughout the rest of the simulation and due to the moderately high extraction, we observe a decrease in the groundwater table.

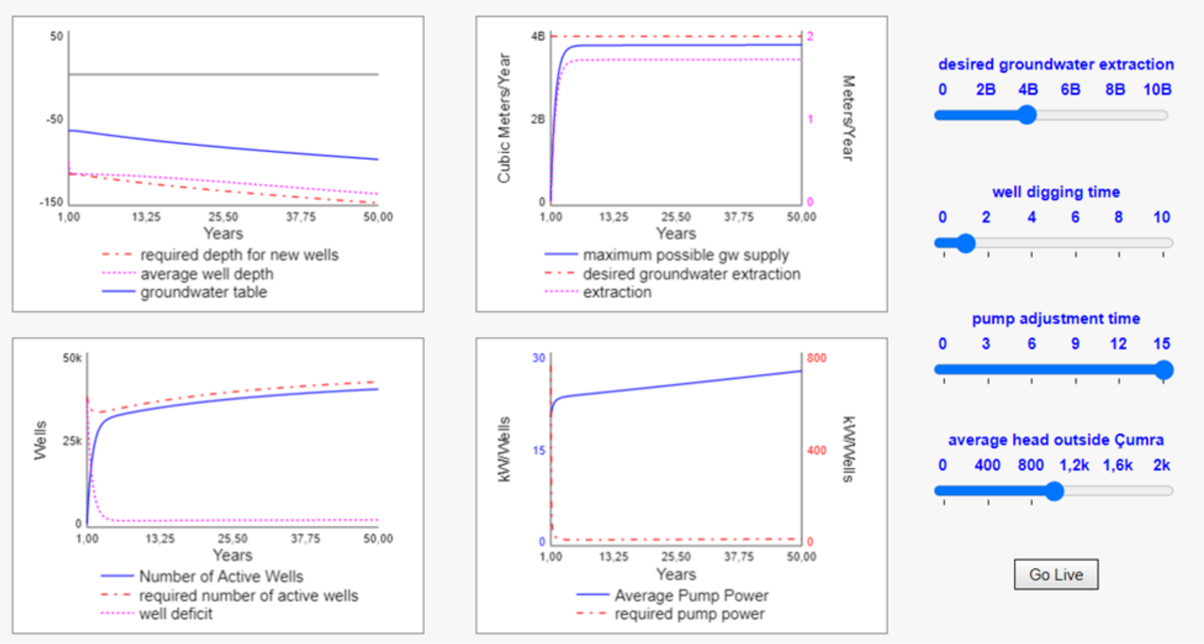

Figure 16. Extremely high pump adjustment time

5. Extremely high average head outside Çumra

In this experiment, we test the situation when the average head outside Çumra is close to the ground elevation outside, i.e., the head difference between inside and outside Çumra is very high. When the head difference is very high, we expect substantial lateral flow into Çumra, which might even offset the depletion effect of extraction.

As can be seen in Figure 17, despite the moderately high groundwater extraction, the groundwater table rises, which is due to the lateral flow of water into Çumra resulting from the head difference inside and out. The rise in groundwater table increases the average well capacity, therefore the demand for groundwater can be met with existing wells; there isn't a need to drill new wells, therefore the number of active wells slowly decreases as they complete their lifetime. However, the groundwater supply capacity is held constant by increasing the average pump power in the remaining wells.

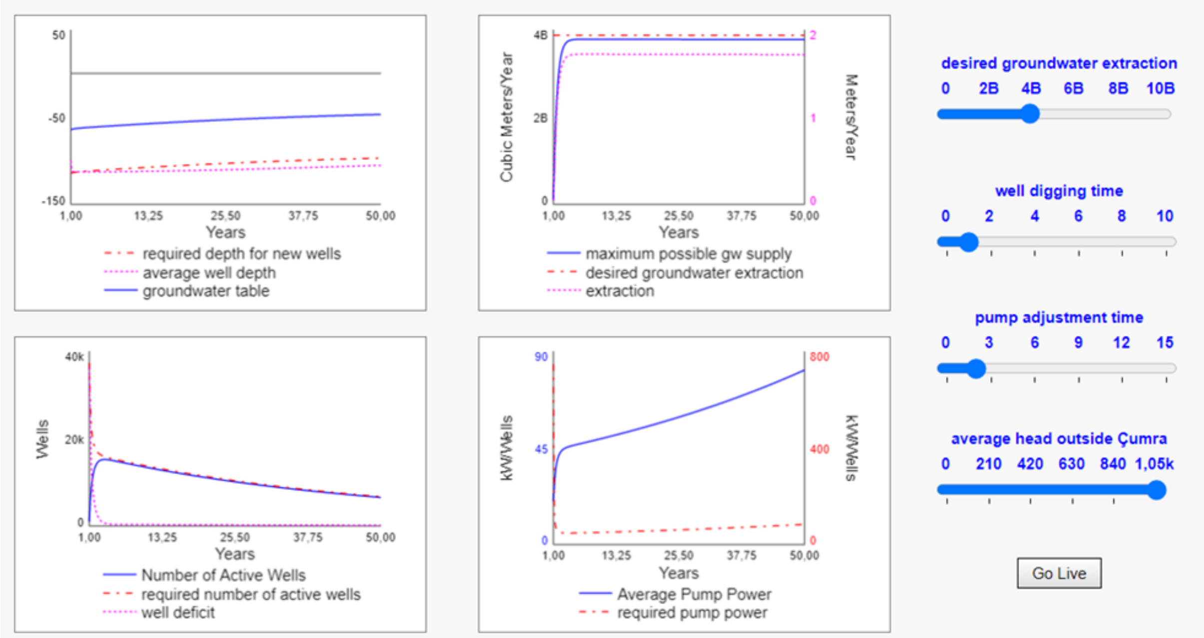

Figure 17. Extremely high average head outside Çumra

6. Extremely low average head outside Çumra

Figure 18 shows the results of the experiment in which we set the average head outside Çumra to an extremely low value. Given that the head cannot be lower than the aquifer bottom, the extremely low value is chosen according to the average aquifer bottom outside Çumra, which is not a parameter in the model, but taken from the hydrogeological model built by our research team. We expect a high level of lateral outflow, which is reflected in the steeper decline of the groundwater table under a moderately high extraction condition.

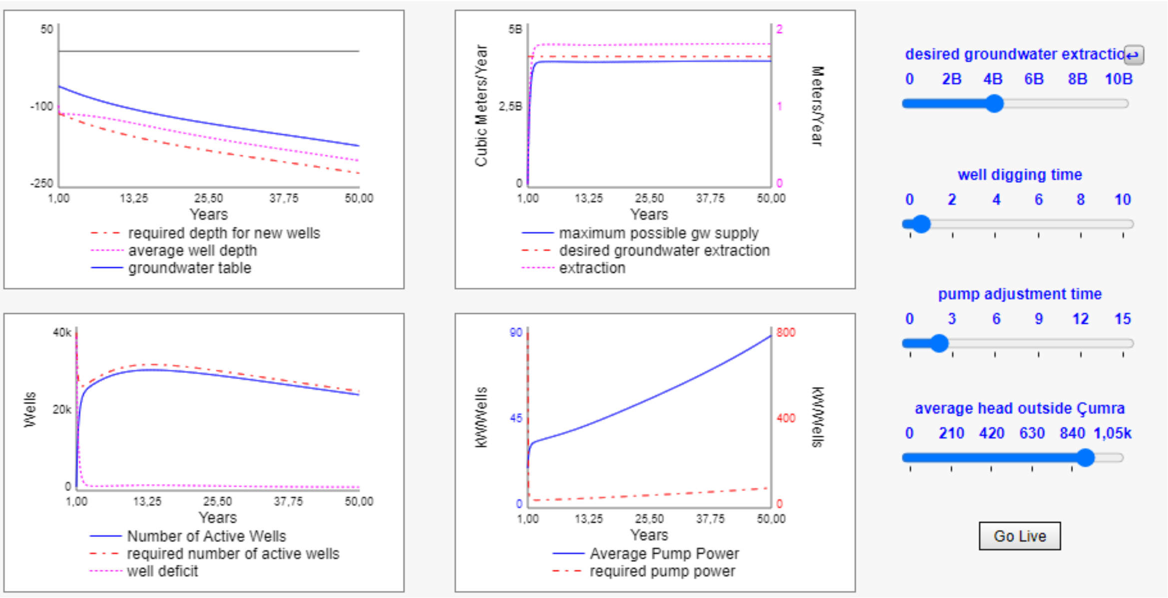

Figure 18. Extremely low average head outside Çumra

Production Factor Adjustment and Yields Goal Setting Sector

Extreme condition tests are performed for the following variables in this sector: water elasticity, marginal revenue, and marginal cost. It should be noted that the groundwater and groundwater infrastructure sector is also active in the test runs for this sector, in order not to cut the feedback connection between desired water application and Applied Water. Additionally, for the sake of simplicity, a single crop variety is assumed in the tests. The results are presented below.

1. Extremely low water elasticity

Water elasticity is set to 0 for this experiment, which means that the crop is completely inelastic to water; the level of irrigation has no impact on the crop yield. Under these conditions, there is no need to irrigate the crop. Therefore, under this assumption we expect that farmers' water demand becomes zero, yet still they obtain the reference yield. As we observe in Figure 19, the results completely match our expectations.

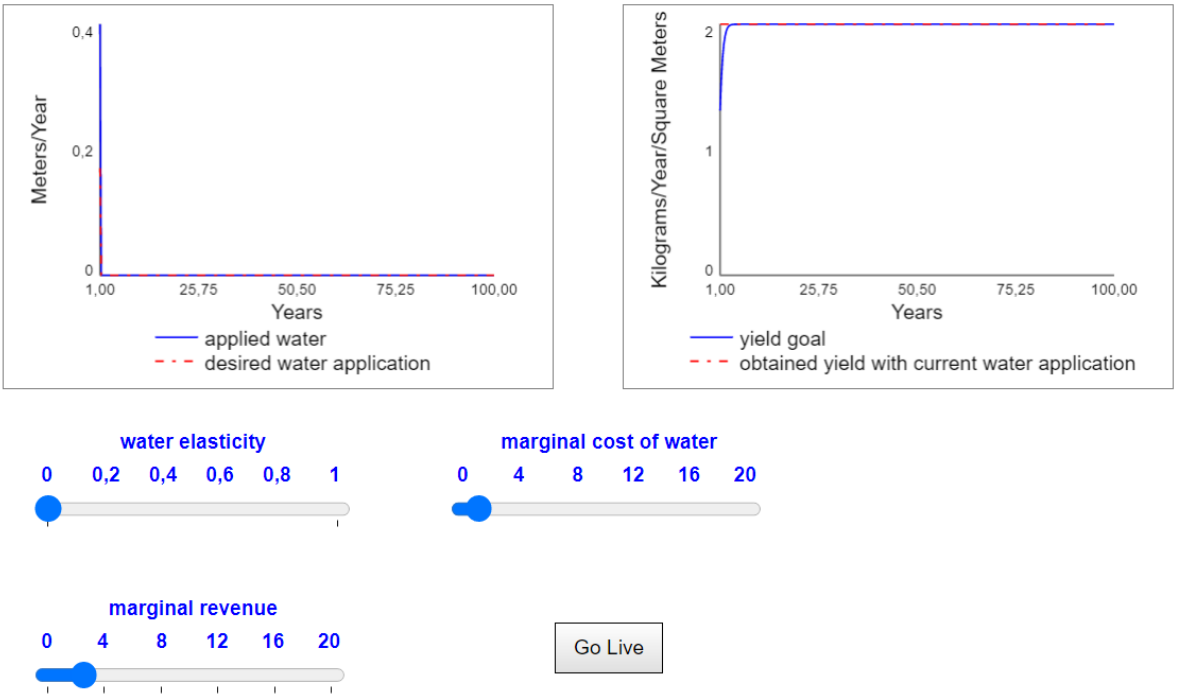

Figure 19. Extremely low water elasticity

2. Extremely high water elasticity

Figure 20 shows the results when the water elasticity is set to 1; the crop yield is highly sensitive to irrigation. We observe a search for the optimal water use in the results; desired water application and applied water, following the former with a small delay, have a fading oscillatory behavior with initial overshoots and drops. Once an ideal irrigation level is achieved, applied water stays constant throughout the rest of the simulation. The oscillation is due to the very small delay value in the formulation of the change in applied water; when the delay value is larger, a smooth adaptation is observed instead of oscillation. In practice there should not be a long-time delay between groundwater extraction and irrigation.

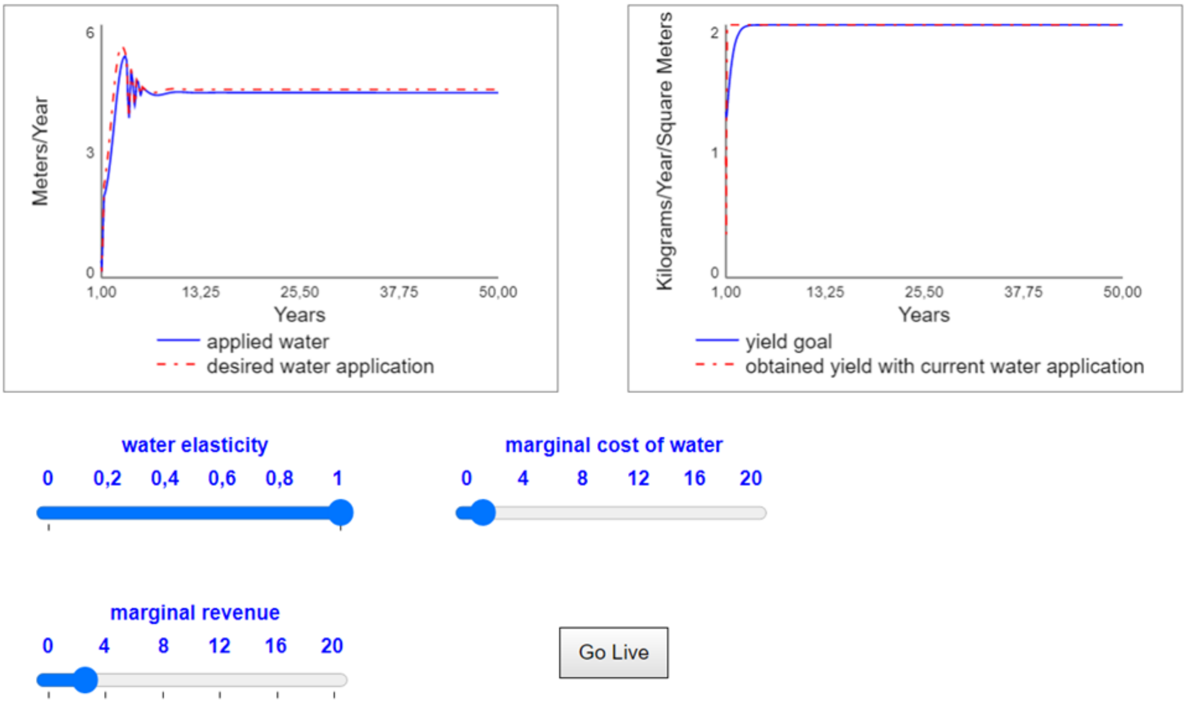

Figure 20. Extremely high water elasticity

3. Extremely low marginal revenue

In this experiment, we set the marginal revenue to zero, which means that producing the crop does not bring any income. Therefore, from the farmers' point of view, it doesn't make financial sense to continue production; we expect farmers to quit agriculture. The result we observe in Figure 21 is in line with this anticipation; the yield goal and the obtained yield are zero, which means that there is no production, and accordingly the desired and applied water are also zero.

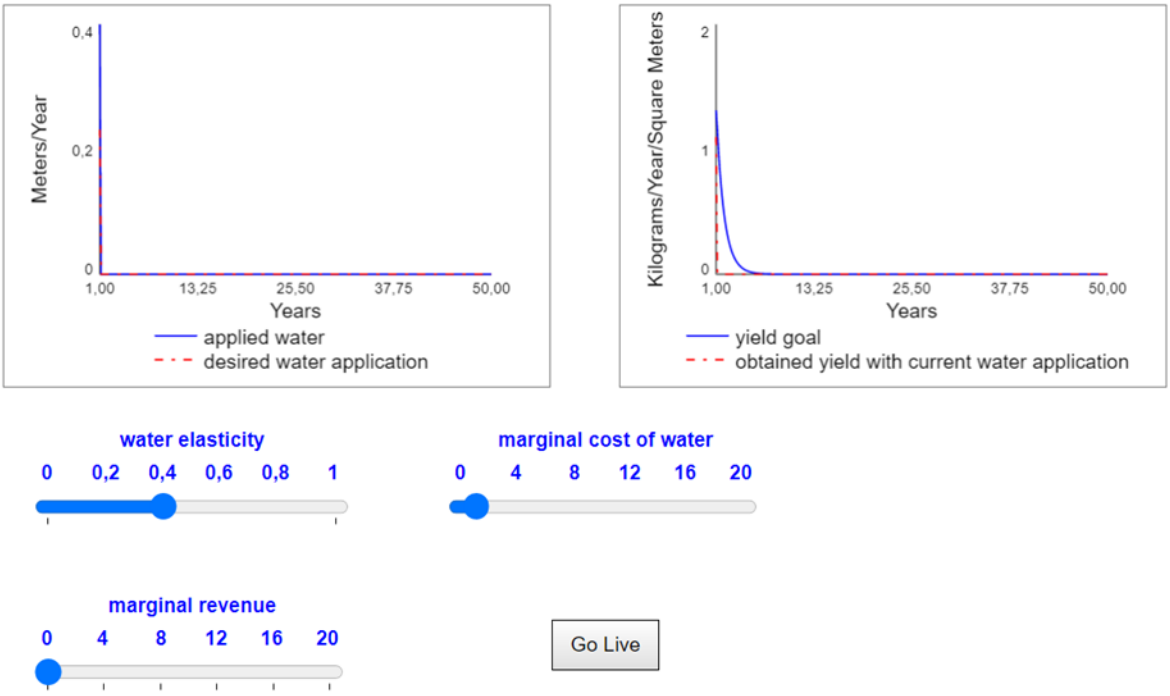

Figure 21. Extremely low marginal revenue

4. Extremely high marginal revenue

When the marginal revenue is extremely high and marginal cost of water is relatively low, the logical behavior would be to obtain an irrigation level such that it maximizes the crop yield as the revenue earned from the increased yield would exceed the additional cost. In Figure 22, we observe such behavior. Like the high water elasticity experiment, there is a fading oscillation in desired water application and applied water. The difference is that the amplitude of the oscillation is much bigger and the applied water balances at a higher level compared to the high water elasticity case, meaning that the structure is highly sensitive to the marginal revenue.

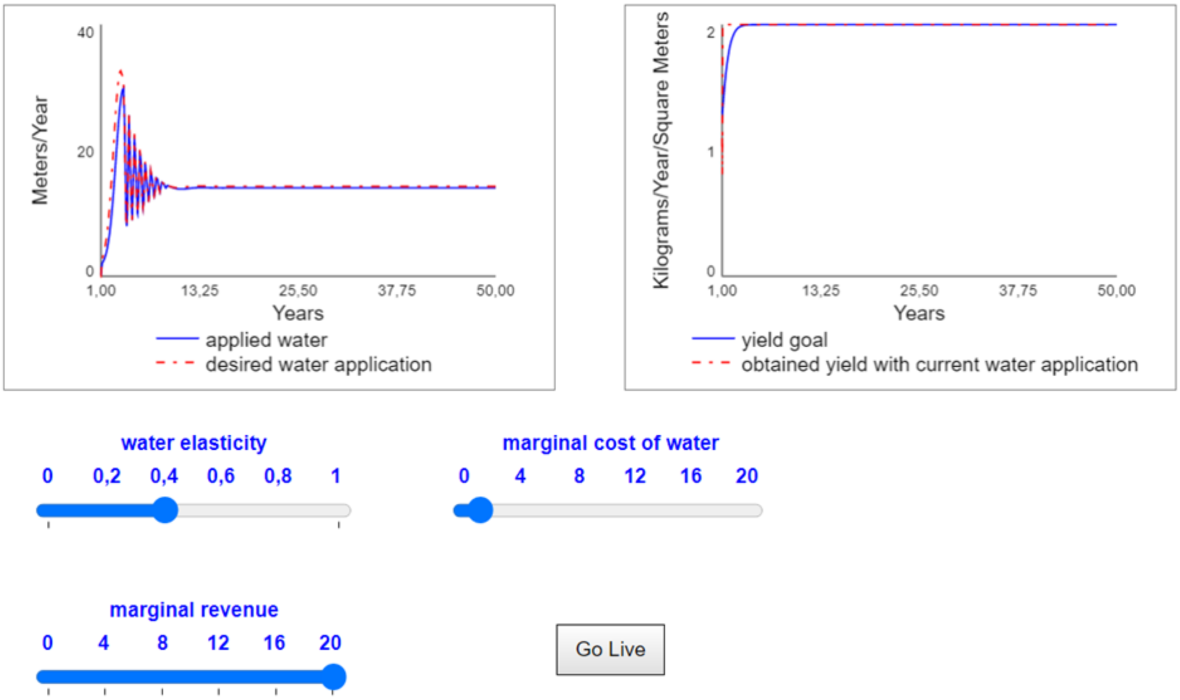

Figure 22. Extremely high marginal revenue

5. Extremely low marginal cost

An extremely low -zero- marginal cost implies that one does not need to pay extra for an additional unit of resource consumption; there is no financial constraint limiting the irrigation level. Therefore, we expect a higher applied water value, such that the reference yield is obtained, as observed in the results in Figure 23. Similar to the high water elasticity and high marginal revenue cases, a fading oscillatory search behavior is seen in desired water application and applied water variables.

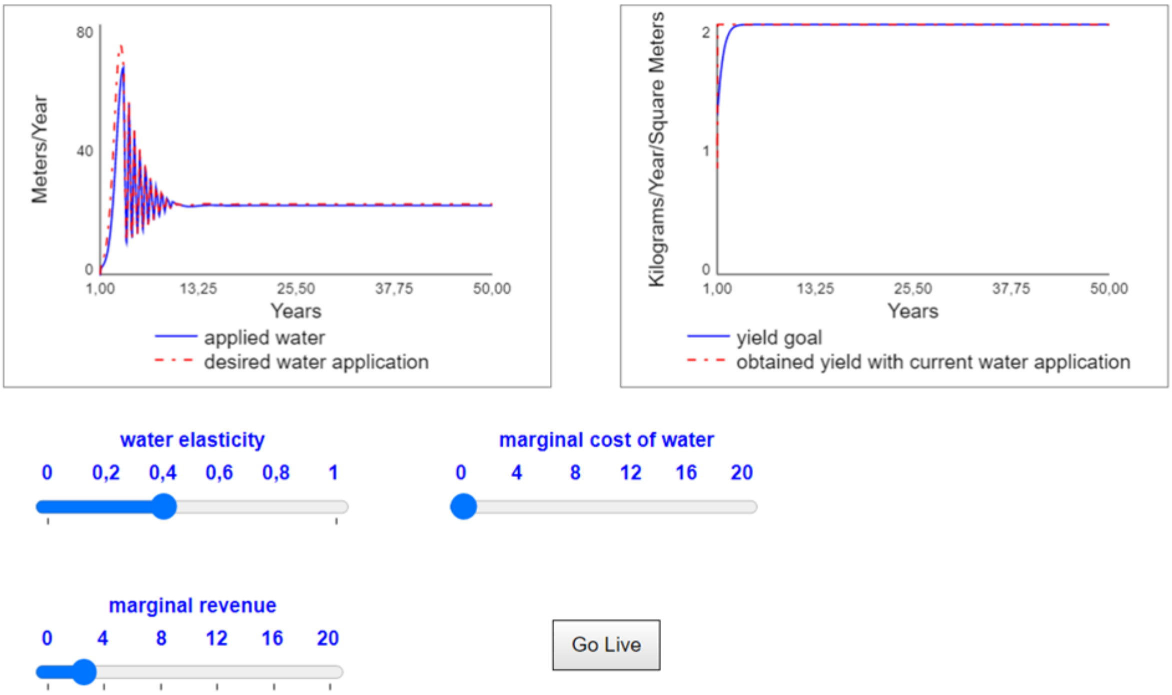

Figure 23. Extremely low marginal cost

6. Extremely high marginal cost of water

When the marginal cost of water is extremely high, irrigation hampers profitability, which is the main driver of production. Therefore, as seen in Figure 24, the level of desired water application and applied water steeply and substantially falls, considerably decreasing the obtained yield. In this case, more irrigation would be reflected in the crop yield, which would increase the revenue, however, it cannot pay off the high cost of water extraction.

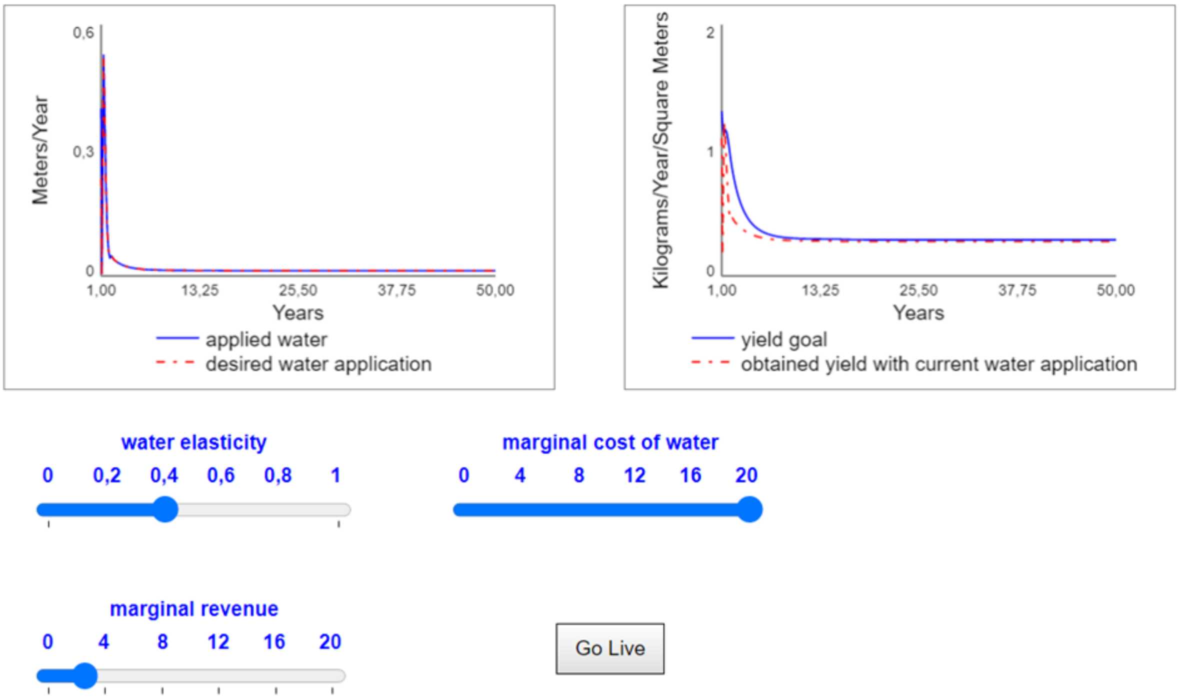

Figure 24. Extremely high marginal cost

Land Use and Crop Choice Sector

Extreme condition tests are performed for the following variables in this sector: crop prices, sensitivity of attractiveness to profitability, unit electricity price, and sugar beet quota. The results are as follows:

1. Extremely high crop prices

In this experiment, first, the price of green plants is set to 15 TRY. Such radical increases in crop prices are expected to result in substantial changes in crop attractiveness values. Figure 24 shows the results. In the next test run, the price of cereals is incremented to the same value, as shown in Figure 25. As expected, the desired share of crops within the total agricultural land becomes higher and it is reflected in the first graph in both Figures 25 and 26.

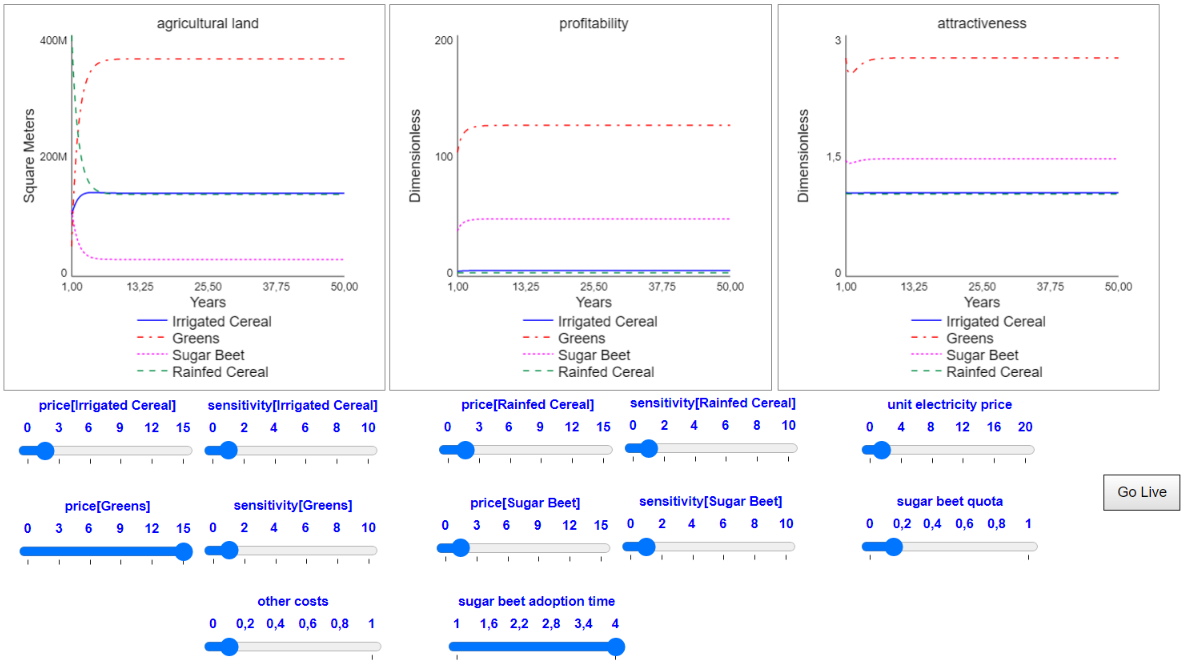

Figure 25. Extremely high green plant price

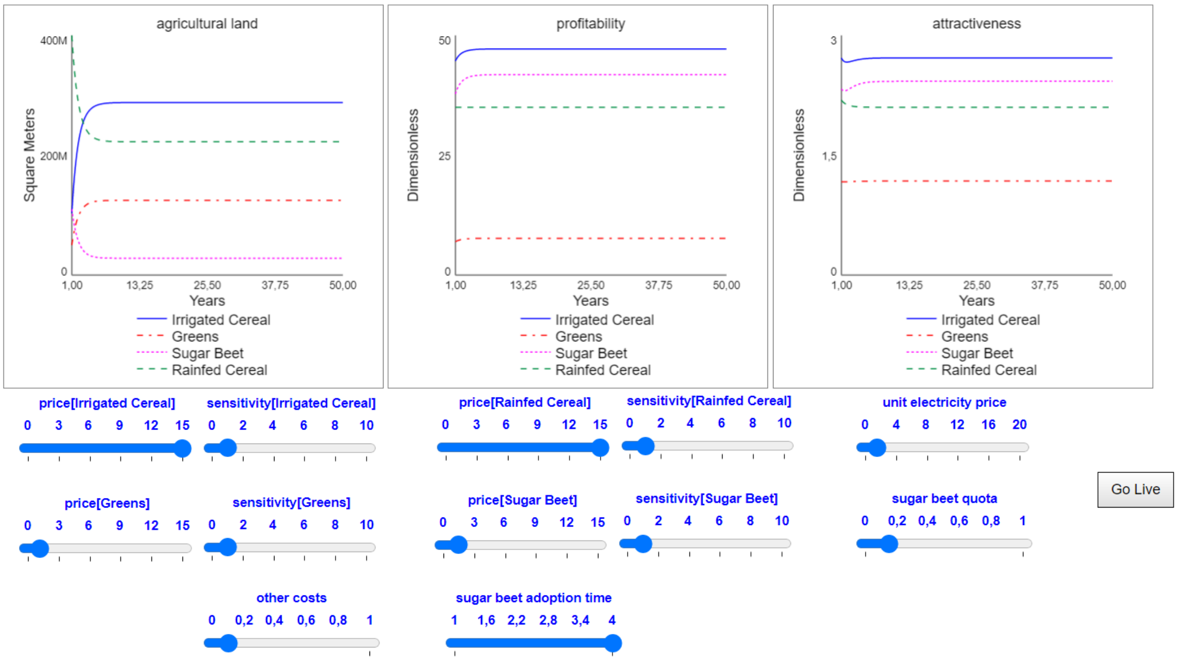

Figure 26. Extremely high cereal price

2. Extremely low crop prices

Figures 27 and 28 show the results when the prices of green plants and cereal are respectively set to zero, which indicates zero revenue and production at a loss. In both cases, we observe that the profitability is below zero, as anticipated, and the attractiveness of the crop with zero price has the lowest attractiveness. However, the agricultural land graph exhibits that the production unexpectedly continues. That is due to the exponential function used in the logit model in this sector; exponential function is not very robust under some extreme conditions (Sterman, 2000). On the other hand, in an extreme condition where both cereals and green plants have prices set to zero, the production of these crops would need to continue regardless of the negative profitability, given the model assumptions that there is no opt out option, i.e., an option to quit agricultural production, and sugar beet has a quota (Figure 29).

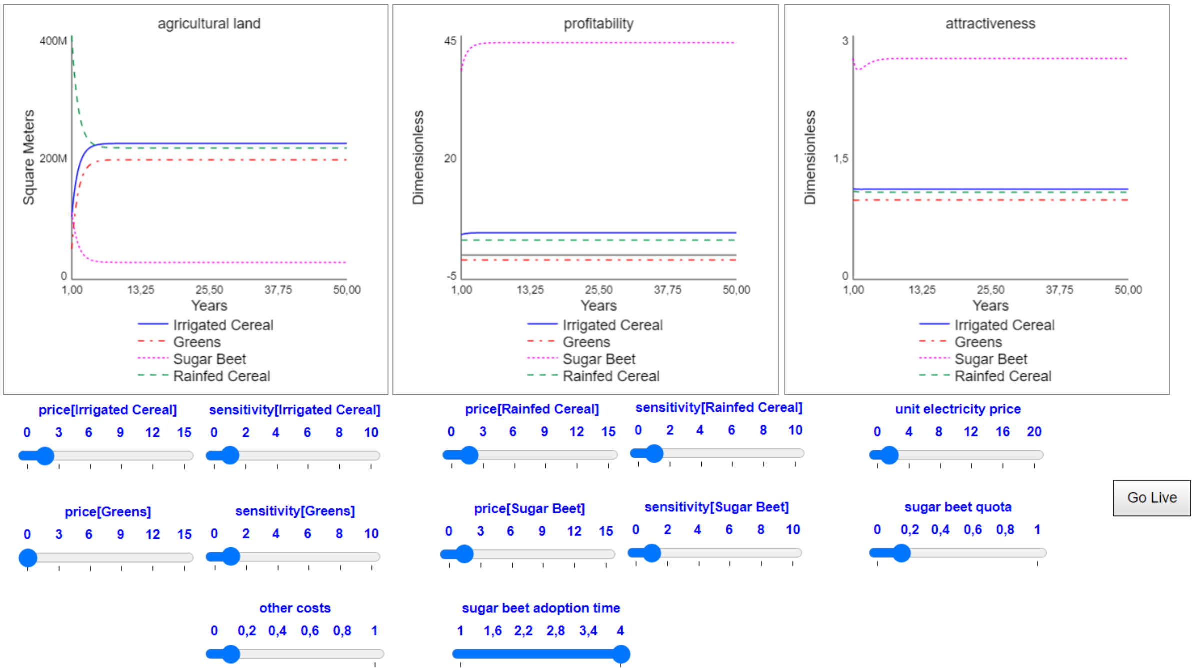

Figure 27. Extremely low green plant price

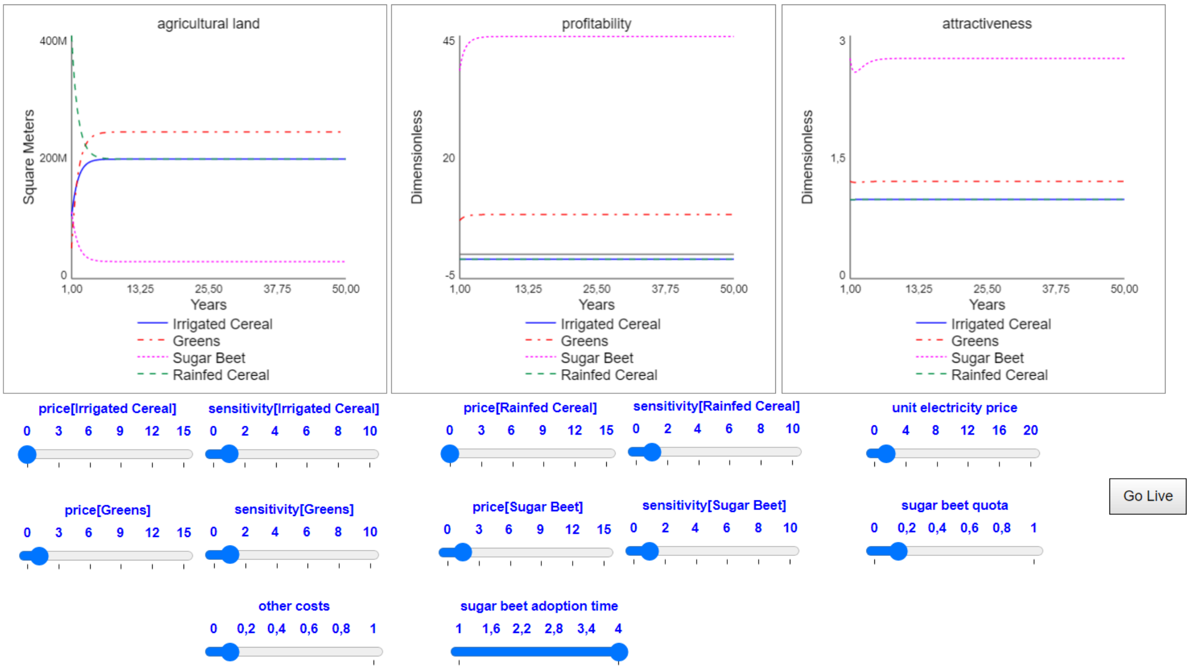

Figure 28. Extremely low cereal price

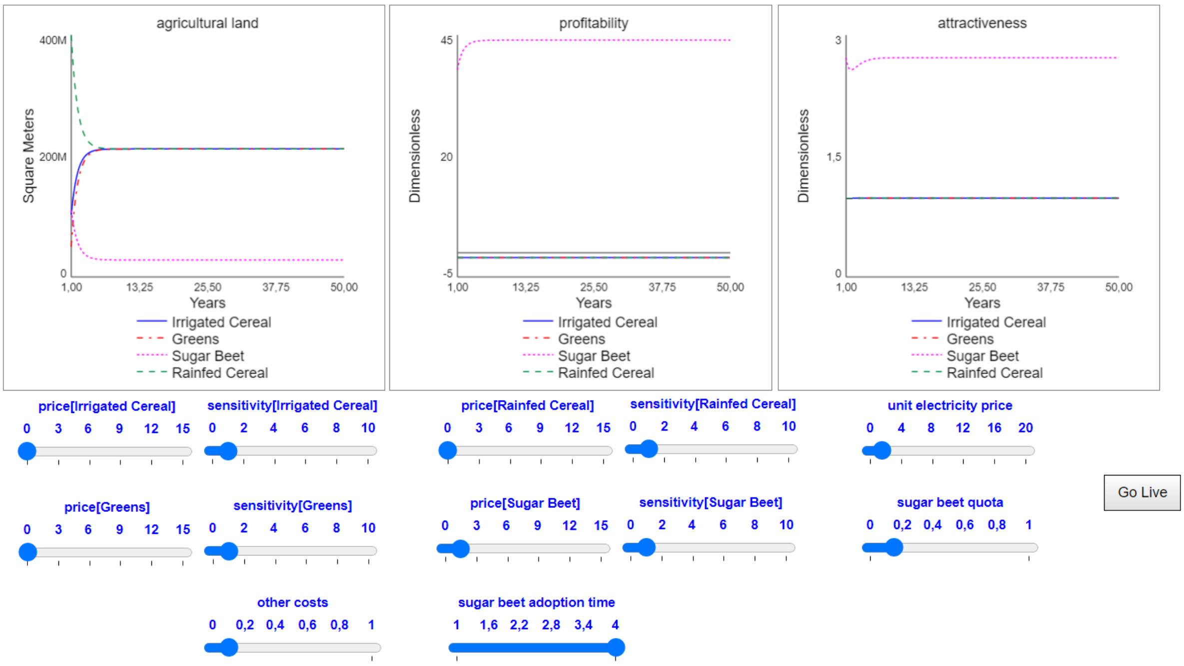

Figure 29. Extremely low cereal and green plant price

3. Extremely high sensitivity to profitability

In this experiment, sensitivity of green plants' attractiveness to their price is substantially increased. As shown in Figure 30, even though the green plants are not as profitable as sugar beet, due to the very high sensitivity to profitability, they are more attractive to farmers, thus the biggest share goes to green plants in the total agricultural land.

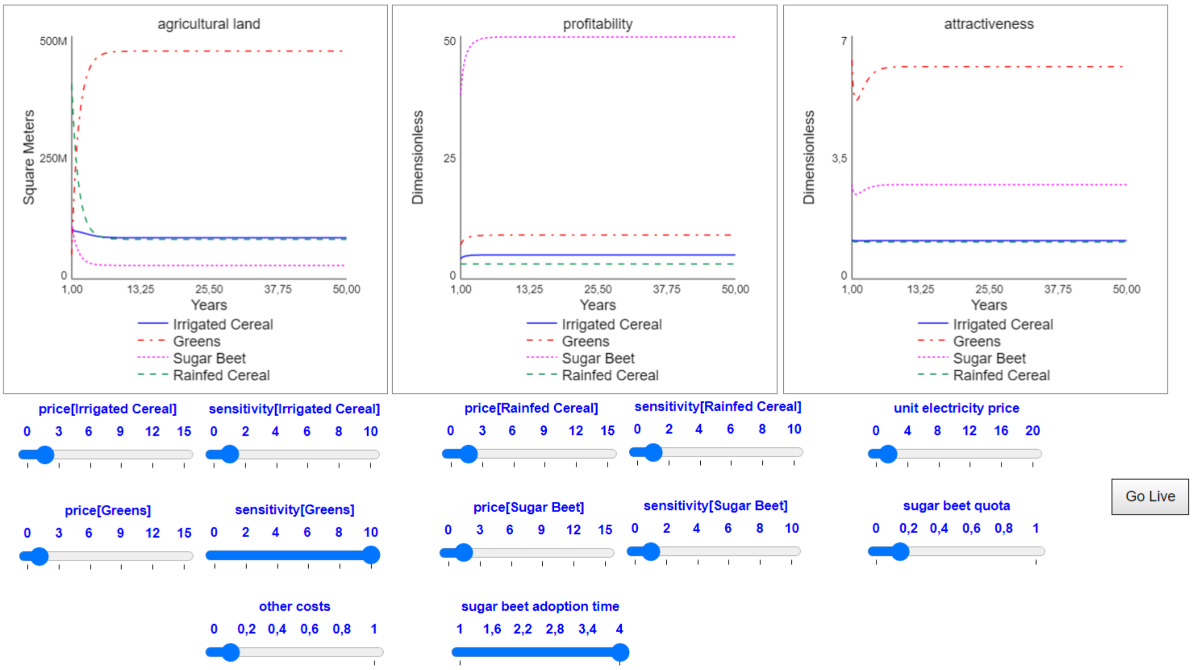

Figure 30. Extremely high sensitivity to profitability for green plants

4. Extremely low sensitivity to profitability

Figure 31 shows the results when the sensitivity of both green plants' and cereals' attractiveness to their profitability are set to zero; in other words, the attractiveness of those crops are completely insensitive to their profitability. Therefore, both crop types are equally attractive regardless of their profitability and are allocated the same amount of land.

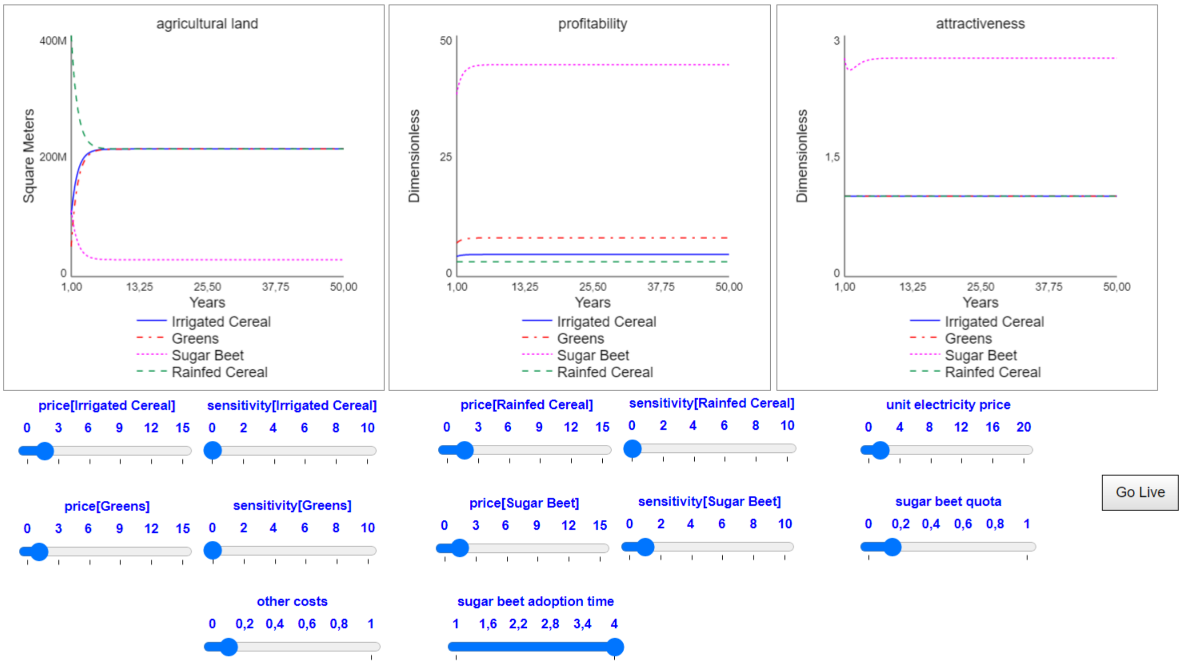

Figure 31. Extremely low sensitivity to profitability for green plants and cereals

5. Extremely high sugar beet quota

Sugar beet quota value is set to one, which indicates that there is no quota and farmers are free to allocate as much land as they want to this crop. Figures 32 and 33 demonstrate the results when the mandatory crop rotation practice is applied and ended, respectively. Briefly, crop rotation means that sugar beet can be cultivated on the same land once every four years.

If there is no crop rotation (Figure 33) we observe that sugar beet is allocated the most land, due to its higher profitability and attractiveness, as expected. When we compare these results with those in Figure 32, we clearly see the difference that the crop rotation practice makes; the land allocated to sugar beet is much lower, even though the profitability and attractiveness of sugar beet is the same and highest above all land use options.

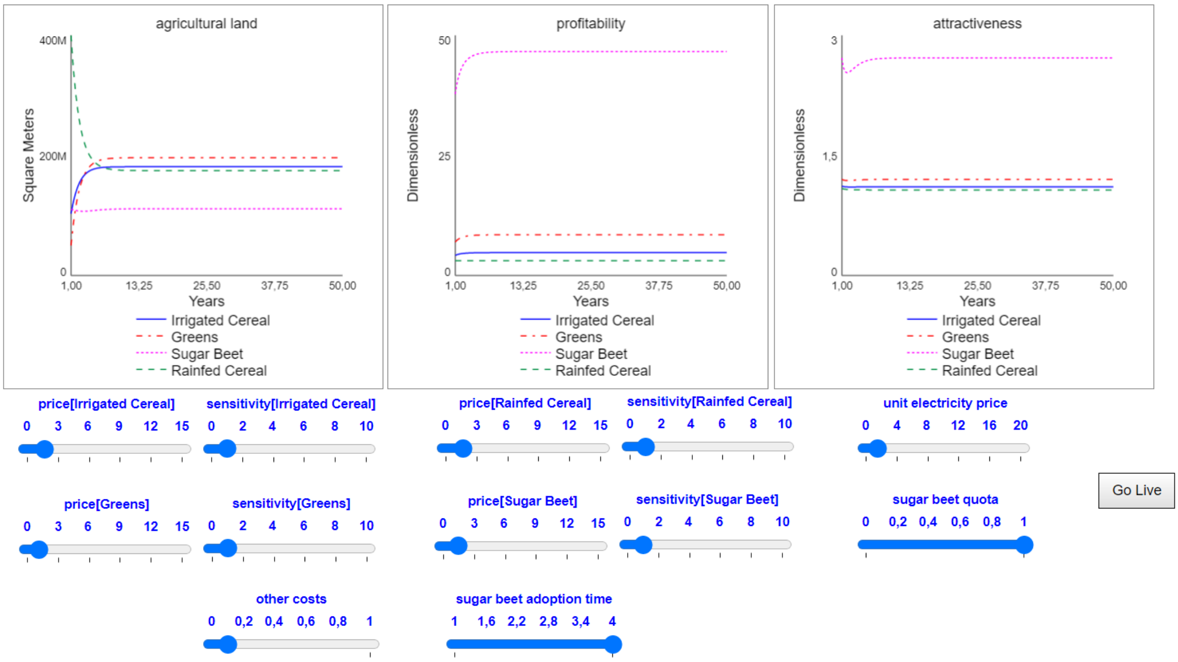

Figure 32. Extremely high sugar beet quota with mandatory crop rotation

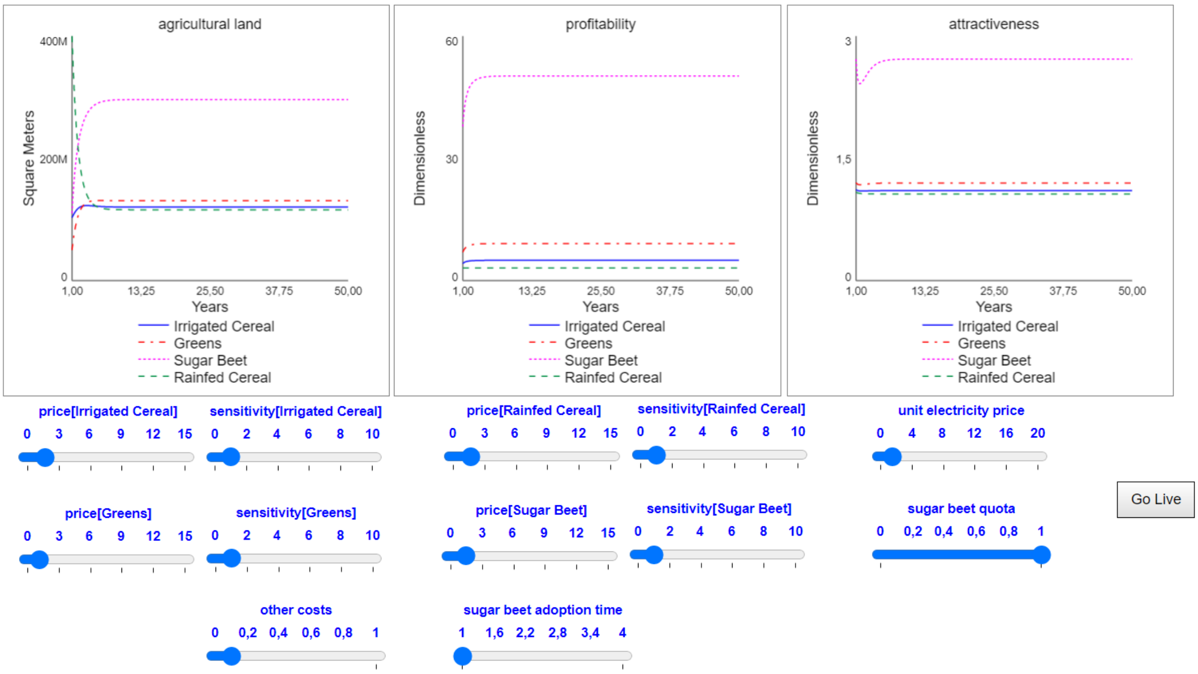

Figure 33. Extremely high sugar beet quota without mandatory crop rotation

6. Extremely low sugar beet quota

The result of this experiment is rather straightforward; the sugar beet quota is set to zero, which implies that its production is prohibited. Therefore, as can be seen in Figure 34, the land allocated to sugar beet is 0.

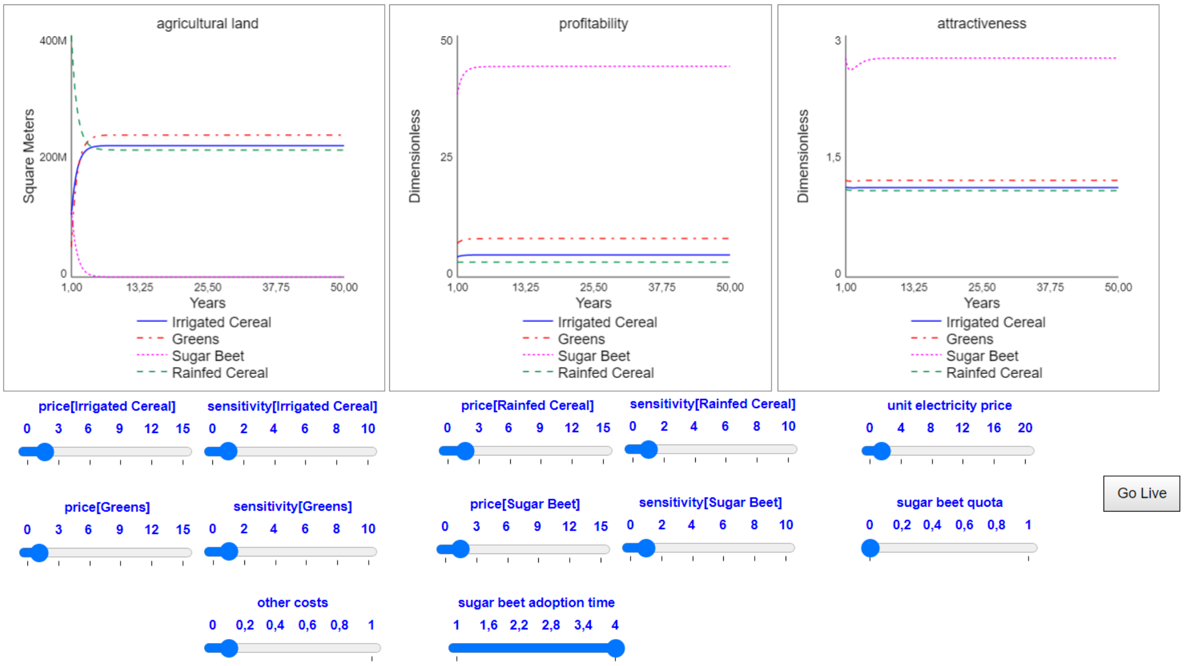

Figure 34. Extremely low sugar beet quota

7. Extremely high unit electricity price

When the unit electricity price is at an extremely high value, the irrigated crops are expected, become less profitable. Therefore, as observed in Figure 35, the attractiveness of rainfed cereals is higher (sugar beet being the exception due to its high revenue but its production is limited by the quota) and the most land is allocated to rainfed cereal production.

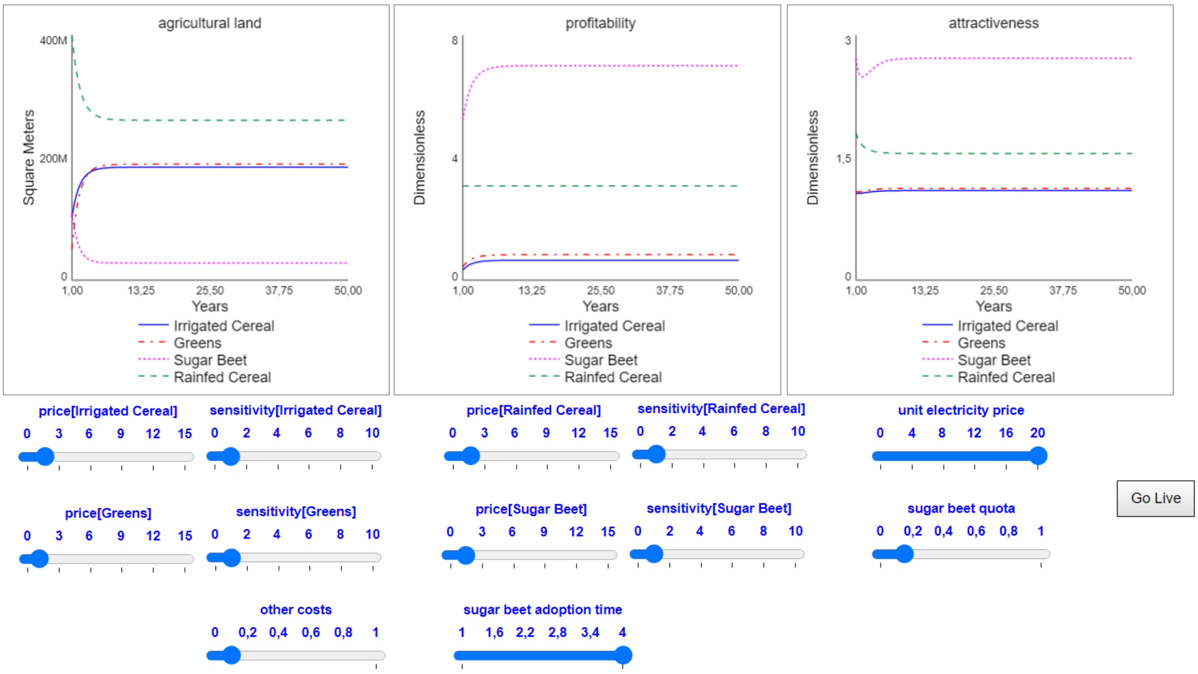

Figure 35. Extremely high unit electricity price

8. Extremely low unit electricity price

In this experiment we set the unit electricity price to zero; it implies that groundwater extraction is free of charge. Therefore, we observe in Figure 36 that the attractiveness of irrigated crops is higher as expected, due to their higher revenues. However, in these tests, the water cost is not very high because only land use and crop choice sectors are run, which implies that the groundwater table is constant at a shallow level. Therefore, the water cost in these runs is rather low and insignificant, as it increases with groundwater table depth.

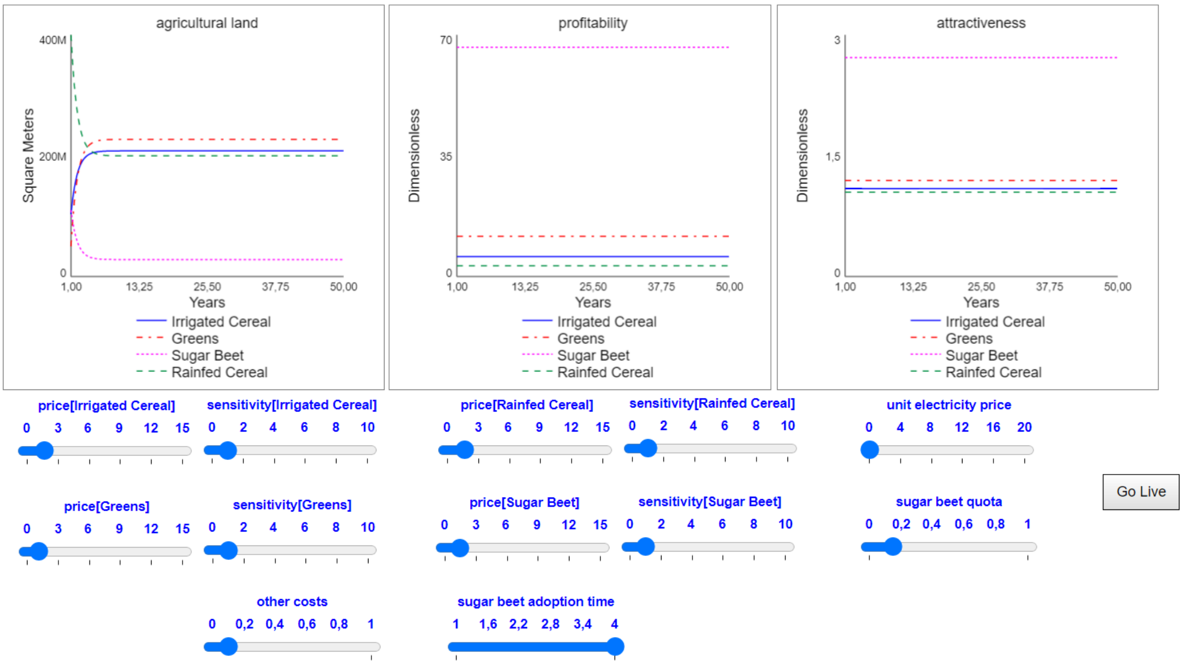

Figure 36. Extremely low unit electricity price

Sensitivity Analysis

The results of the sensitivity tests are consistent with the extreme condition tests; the model is highly sensitive to crop prices, crop water elasticities, sensitivity of crop attractiveness to profitability, production costs, and average groundwater head outside Çumra.

6. Future Work

Major limitations of the seed model are eliminated with developments in the model since the documentation of M4.2. However, the model may be further developed in the following aspects. First, we know from the field work that the transformation in irrigation technology played an important role in land use choices and the change in water use for irrigation, in the last 20 years. Therefore, it is very relevant to the problem at hand and should be an endogenous dynamic in the model. Second, well drilling, change in the pump power, and changes in the irrigation technologies are all investment decisions; a financial aspect is lacking from the current version of the model. Thus, a simple farm accounting sector would be relevant to the model; not only to improve the decision-making structure in the model but also to include economic performance indicators as well as environmental ones.

Upon completion of the above steps, validating the model further (structurally and behaviorally), and calibration, we will move on to the scenario analysis and policy design step. We will organize the third and final living lab, and invite a larger number of stakeholders this time to present the model and its outputs. The goal will be to have an interactive scenario analysis and participatory policy design session with a larger stakeholder group. In the third living lab, the participants will be able to interactively ask their policy related questions to the model itself, and the model will reveal the long-term outcomes of proposed policy scenarios.

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