IRRIGATION PROJECTS, AGRICULTURAL DYNAMICS AND THE ENVIRONMENT

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Contents

Summary

Problems of large-scale irrigation systems and their interactions with agricultural environment are analyzed with system dynamics approach. The presented simulation model is a simplified and generalized version of a large model built for the analysis of long term environmental problems in land and water resources development in Southeast Turkey (Southeast Anatolian Project – GAP). The model consists of four components representing *farmlands*, *land-water development*, *irrigation-salinization*, and *pest* dynamics and contains 17 state (stock) variables in total. Model components include formulations of irrigation authorities' water release decisions and farmers' land transformation, crop selection, water consumption, and pesticide application decisions. Interactions among these decisions create a complex system with nontrivial long-term effects on irrigation system performance, agricultural production and the environment. Model analysis shows that, irrigation development projects are prone to problems of shortfall in energy, irrigation and agricultural production targets. It reveals the systemic nature of these problems and the limitations of traditional piecemeal policies to overcome the problems involved in many mid-latitude semi-arid agricultural systems. The model can be used as an experimental platform for the long-term policy analysis of

irrigation development in similar technological and environmental contexts, among students, professionals and decision makers in related organizations and it can serve as a foundation for studies involving stakeholder participation.

1. Introduction

On fertile lands in semiarid environments, large-scale surface irrigation facilitated by dam building has been a prominent regional and national development policy. According to the World Commission on Dams, in the past century at global scale, more than 45000 big dams have been built to provide water for irrigated agriculture, domestic or industrial use, to generate hydropower or help control floods. Expected benefits of hydropower and irrigation dams were high crop yields and increased varieties, agricultural modernization, improved rural welfare and regional development. However, the record of existing dams has been rather appalling with many adverse social and environmental impacts (Goldsmith and Hilyard, 1984). A global review of 52 large dams by World Commission on Dams reveals that many hydropower dams show an overall tendency to fall short of power generation goals; large dams designed to deliver irrigation services have typically fallen short of physical targets; and one-fifth of irrigated land worldwide is affected by water-logging and salinity due to dam-fed irrigation, which often means severe, long-term and often permanent impacts on land, agriculture and livelihoods (WCD, 2000).

The model presented in this paper aims to analyze the systemic causes of these observations and the limitations of piecemeal management, focusing on the integrity of irrigation, land use, environment and production at regional level. It is a simplified version of an original model built and validated for an irrigation development project in Southeast Turkey (Saysel, 1999). The original model contained 62 state variables and 11 model components representing various sectors of the agricultural economy and the environment including wine yards, rangelands and forests; soil nutrients and erosion; population, urban development and the regional market. The current version is simplified from and validated against the original and it contains 17 state variables and 4 model components only. The physical processes and decision rules have a higher level of aggregation. The purpose of this simpler version is to disseminate the systemic causes of underperformance in large-scale irrigation with a clear representation of fundamental accumulation processes and feedback loops that identify the system structure. Moreover, departing from a large case specific model, this simple version aims to be a step towards a more general/generic representation of identical problems observed in similar agro-environmental contexts. Therefore, the irrigation development in Southeast Turkey (GAP) provides an empirical basis, but the presented model structure aims to be a general systemic representation of similar phenomena that can be observed in similar agro-ecological contexts.

Section 2 in this paper introduces the model structure. In Sections 3 and 4, the model validation and reference behavior are illustrated respectively. Section 5 illustrates model behavior response to well known management strategies and their limitations, gradually integrating the *irrigation*, *salinization* and *pest* model components. In this section, a causal loop (feedback) analysis of the model structure is developed to support understanding of model behavior (For the nature of feedback problems and feedback analysis, see *System Dynamics: Systemic Feedback Modeling for Policy Analysis*). Section 6 is a discussion on the use and benefits of system dynamics modeling for policy analysis on land and water development problems.

2. Model Description

This is a descriptive model, which represents a low technology and low agro-input agricultural system in mid-latitudes where annual precipitation concentrates in winter seasons and a large water deficit occurs during summer. Winter cereals such as wheat and barley, and pulses such as lentil, bean and chickpea benefiting from the winter water surplus are the traditional crops, which sustain regional population. Although mechanization is low and primary inputs such as fertilizers, crop protecting chemicals and irrigation are rare and scarce, lands are fertile and traditional yields are sufficient to sustain the population and the national market. By introducing irrigation through canal structures, central authority enables the receivers to enhance their yields, switch from traditional crops to industrial cash crops, and increase their income by secure water supply like in Southeast Turkey and in similar systems in Mesopotamia and North East Africa.

As the hydropower and irrigation structures are constructed, the water release capacity increases and farms begin to receive water. Authorities release water in response to the water requirements of farmers. Water consumption on farmlands depends on water requirements of crops and the amount of water available to individual farmlands. Irrigation elevates the water-tables and evapo-transpiration of irrigation water releases salt on farmlands that inhibit plant growth in the long term. Pesticide requirements may also increase as pests develop resistance when monocultures prevail and when integrated pest management is not a viable option because of several institutional and technological constraints.

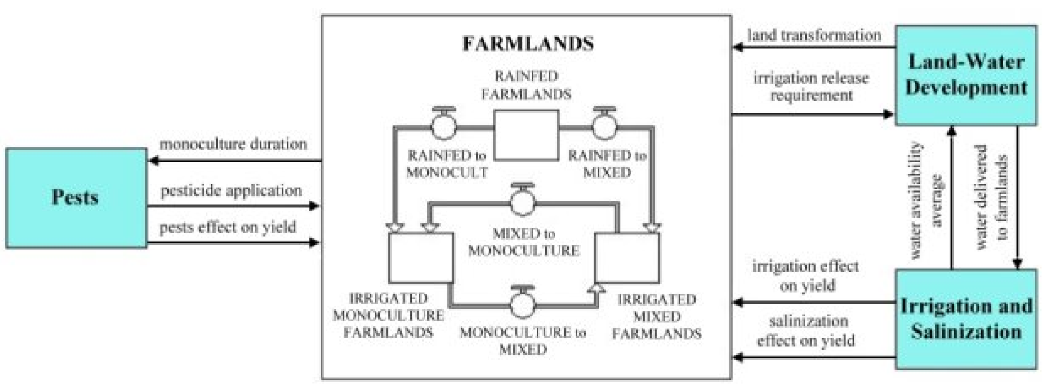

Figure 1. Model overview.

The model represents these dynamics with four model components (sectors), *farmlands*, *land-water development*, *irrigation-salinization*, and *pests*. This selection of model components is not by coincidence. Extensive analysis with the previous version proved other components to be ineffective on this current policy analysis. The farmlands component consists of three stock (state) variables, and the other components include two stock variables each. Figure 1 is the model overview illustrating model components and information flows. The *farmlands* model calculates irrigation release requirement. Then, based on this requirement and water availability, the *land-water development* calculates water delivered to farmlands and land transformation rate. The *irrigation-salinization* model receives water delivered to farmlands, irrigates farmlands and feeds back the average water availability in the system to the *land-water development*. It also informs the farmlands on the effect of irrigation and the effect of salinization on yields. The *pests* model calculates pest population and pesticide application rates. The duration of monocultures is an input from the *farmlands* for these calculations. All physical processes and decisions are represented on annual basis since the model is designed for long-term strategic analysis. Uncertainty in weather conditions and stream flows are not considered. Next, we introduce the individual model components. Complete model equations are available from the author.

2.1. Farmlands

The farmlands sub-model represents rainfed and irrigated farmlands aggregated under three stock variables. The first stock variable *Rainfed Farmlands* stands for the traditional farms producing winter crops such as winter cereals and pulses either based on monocultures or rotations. The input of the production factors is low, crops depend on precipitation, and yields are less reliable and are at moderate levels. Tillage is not intensive and in certain periods, fields are left on fallow to recover the soil moisture and nutrition contents.

Monoculture Farmlands stand for the irrigated cotton monocultures. Cotton represents the new prominent crop for the agricultural system after water development. Research in agricultural extension practices show, the ease of implementing monoculture practices and market incentives can make monoculture more attractive compared to its alternatives. *Mixed Farmlands* represent irrigated farmlands with a balanced allocation of land resources among cotton, winter crops and several summer crops such as summer cereals, oil seeds and vegetables. The stock-flow structure of the farmlands model can be seen in Figure 1. The rectangles are the stock variables (land accumulations) and the pipes with valves are the flow variables (associated land flows).

The farmlands model calculates the profitability for each farmland stock under changing yield and input conditions. The model hypothesis is that, in aggregate terms, yields change under varying environmental conditions of soil salinity, soil moisture content and pest abundance on farmlands. Input application rates change based on factors of water availability and pest abundance. The equation below shows the calculation of yields for example for the *Monoculture Farmlands*:

Yield cotton Monoculture = potential yield cotton x irrigation multiplier x salinization multiplier x pest multiplier; *(kg/ha/year)* (1)

The hypotheses and formulations representing the change in input rates and individual effects of those inputs on yields (the multipliers) are described in the respective model components *irrigation-salinization* and *pests*. Annual income minus annual cost divided by the size of farmland is unit farmland profit.

The rate of change between monocultures and mixed farmlands is a function of their relative profitability and other exogenous factors representing the ease of adopting cropping methods. Below is the formulation of flow from monoculture to mixed farming:

Monoculture to Mixed = Monoculture Farmlands x fractional farm change normal x farm transformation indicator effect Mono to Mixed; (ha/year) (2)

farm transformation indicator effect Mono to Mixed = f(farm transformation indicator); where 0<f<2; f(1)=1; f′<0;
(dimensionless) (3)
as shown below in Figure 2.

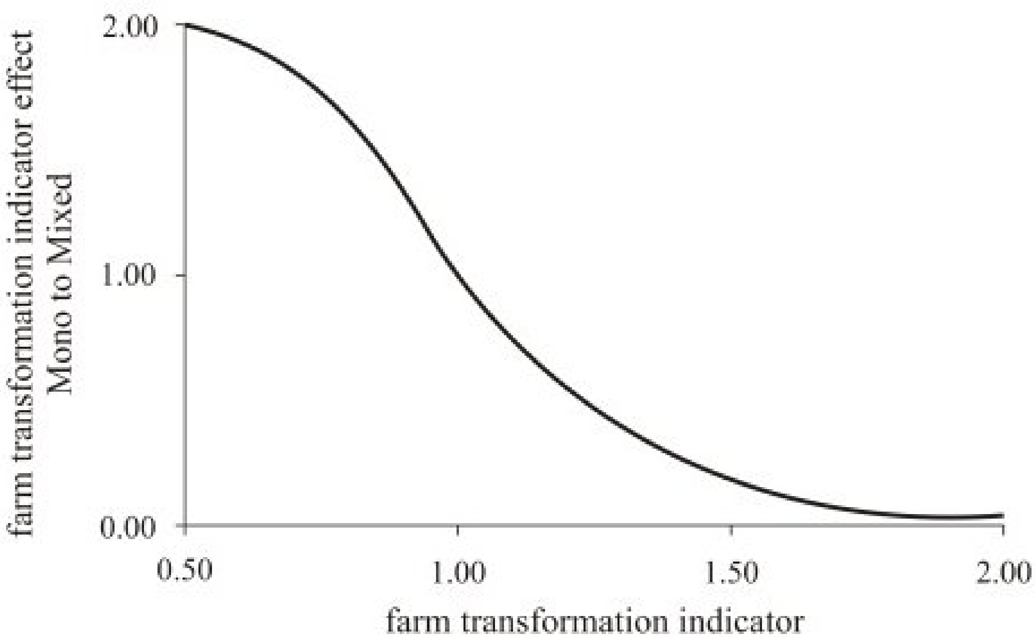

Figure 2. Farm transformation indicator effect Mono to Mixed.

farm transformation indicator = profit ratio Mono to Mixed x farm constant ratio; (dimensionless) (4)

profit ratio Mono to Fixed = unit profit Monoculture / unit profit Mixed; (dimensionless) (5)

farm constant ratio = Mixed farm constant / Monoculture farm constant; (dimensionless) (6)

According to this formulation, if neither monoculture nor mixed farmland is superior to the other, i.e. *farm transformation indicator effect* is 1, the flows in both directions are determined by the constant, *fractional farm change normal (fraction/year)*. Parameters *Mixed farm constant* and *Monoculture farm constant* represent the ease of adoption of the alternative cropping methods and captures the factors in land transformation exogenous to the model. Model behavior can be experimented with respect to different values of these parameters as well as with several non-linear forms of *farm transformation indicator effect* (illustrated in the Appendix).

Rate of change from rainfed to irrigated farmlands (*Rainfed to Monoculture* and *Rainfed to Mixed*) depend on the availability of irrigation water. As new irrigation canals are constructed and as irrigation becomes available for more farmlands, more farmers switch to irrigation. This process is described in the respective model component, *land-water development*.

2.2. Land - Water Development

Hydropower and irrigation structures develop based on exogenous construction scenarios representing project targets according to a master plan study. However, worldwide evidence on irrigation development projects show that, projects may fall short of these target values. The model develops a dynamic hypothesis and creates an endogenous, systemic explanation to the causes of this underperformance.

Irrigation release capacity increases as the irrigation structures develop. The construction of irrigation structures accumulates in *Irrigated Farmlands Potential* (ha) and in *Irrigation Release Capacity* (m^3/year) (Figure 3). Since land transformation from rainfed to irrigated farmlands is the farmers' decision, *Irrigated Farmlands Potential* is not irrigated unless the farmers decide to do so. This is formulated by the flow variable *land transformation*, which drains the potentially irrigated farmlands and accumulates in the *Monoculture Farmlands* and *Mixed Farmlands* in the *farmlands model*.

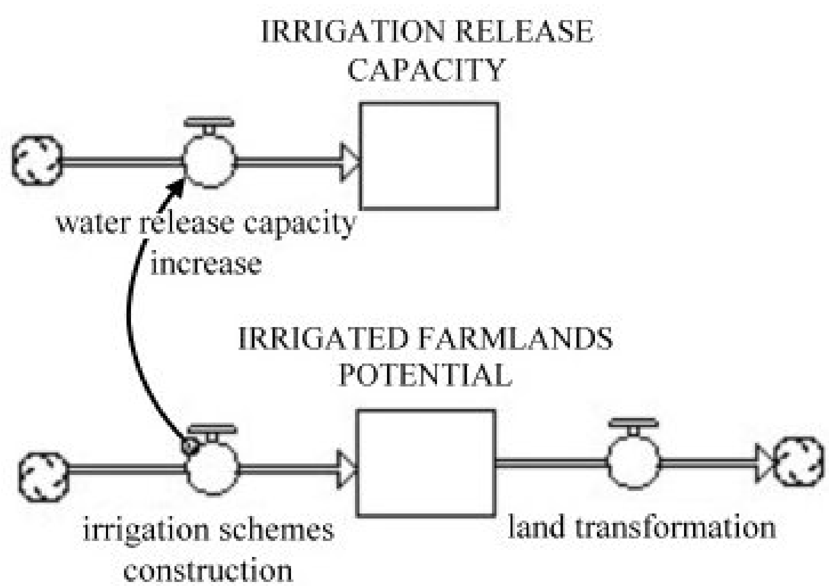

Figure 3. Stock flow structure of the land–water development component.

Farmers switch to irrigation to be able to have control over their water supply and to secure their yields. As irrigation systems develop, if water becomes abundant, this creates greater incentive for the farmers to transform their lands and switch to irrigation. However, if the water in the irrigation system is scarce, there will be less incentive to do so. The model hypothesis is that, the water availability in the irrigation system affects the rate of land transformation from rain-fed to irrigated systems. Research on farmers' response to insecure water supplies supports this hypothesis. Land transformation process is formulated as:

land transformation = Irrigated Farmlands Potential x land transformation fraction normal x water availability effect land transformation;(ha/year) (7)

water availability effect on land transformation = f (water availability average); (8)

where *f* denotes a dimensionless function such that $0<f<1;\ f(1)=1;\ f'>0$, as was illustrated above, in Eq.3;

The constant, *land transformation fraction normal (1/year)* stands for the fractional change when there is no water scarcity, i.e. *water availability effect land transformation* is 1. The *water availability average* is calculated in the *irrigation-salinization* model. *Water availability effect land transformation* is an increasing function of *water availability average*. Different non-linear formulations of this function would represent different farmers' response to water availability. Farmers can be sensitive or insensitive to average water availability in their land transformation response. Model can be experimented with alternative non-linear formulations. The two non-linear formulations used in this analysis are given in the Appendix.

Irrigation authorities' water release policy is also represented. Irrigation release decision is endogenous and based on *farm irrigation requirements* and *Irrigation Release Capacity*. It is assumed that as water demanded by the irrigated fields increase, this creates increasing pressure to utilize installed irrigation release capacity. *Irrigation release* formulation is:

irrigation release = Irrigation Release Capacity x irrigation release capacity utilization; *(m^3/year)* (9)

irrigation release capacity utilization = f (irrigation release pressure); $0<f<1;\ f(0)=0;\ f'>0;$ *(dimensionless)* (10)

irrigation release pressure = irrigation release requirement / Irrigation Release Capacity; *(dimensionless)* (11)

Formulation of authorities' water release decision allows experimenting with loose and tight water release policies by *irrigation release capacity utilization*. Authorities can try to deliver whatever is demanded or can try to conserve water. The two alternative non-linear formulations used in this analysis are provided in the Appendix.

Finally, hydropower production is calculated. The model does not represent seasonal fluctuations in stream flows; construction delays are exogenous. In the long term, hydropower production can fall short of its installed capacity because of reduced in-stream flow and decreased water storage levels in artificial ponds. The endogenous factor of water scarcity is the irrigation release as observed in many case studies reported by World Commission on Dams. As upstream irrigation release increases and less water becomes available for hydropower, the energy production levels decrease. In this calculation, the function *water availability effect on hydropower* is estimated from the data for Southeast Anatolian Project in Turkey.

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Biographical Sketch

Dr. Ali Kerem Saysel is an assistant professor at the Institute of Environmental Sciences in Boğaziçi University, İstanbul, Turkey. During his Ph.D studies in the same institute, he extensively worked on the problems of irrigation development and agricultural modernization in Southeastern Anatolian Project (GAP is the acronym) in system dynamics perspective. After his Ph.D, he joined the System Dynamics Group in the University of Bergen in Norway as a tenured faculty member and thought several courses on system dynamics research method. Dr. Saysel's research and teaching interests focus on dynamic modeling for environmental and ecological management and simulation as an experimental platform for decision analysis. Dr. Saysel is a good standing member of the International System Dynamics Society and the International Society for Ecological Economics.