AGRICULTURAL WATER DEMANDS IN THE SILISTRA REGION

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PREFACE

Interest in water resource systems has been a critical part of research at IIASA related to resources and the environment since the Institute's inception. As demands for water increase relative to supply, the intensity and efficiency of water resource management must be developed further. This in turn requires an increase in the degree of detail and sophistication of the analysis, including economic, social, and environmental evaluation of water resource development alternatives aided by application of mathematical modeling techniques, to generate inputs for planning, design, and operational decisions.

In 1977 IIASA initiated a concentrated research effort focusing on modeling and forecasting of water demands. Our interest in water demands derived from the generally accepted realization that these fundamental aspects of water resource management have not been given due consideration in the past.

This paper, the ninth in the IIASA water demand series, reports on the analysis of water demands of a large agroindustrial complex in the northeastern part of Bulgaria, covering a territory of about 2,700 km^2, with a population of some 175,000. With the aid of SWIM (*S*ilistra *W*ater for *I*rrigation *M*odel), which was developed at IIASA, several factors that influence both agricultural production and associated water demands have been analyzed. The major goal of the Silistra complex, i.e., to maximize the total crop and livestock production within the limited regional resources, has been taken into account in the analysis. (The user's guide to SWIM is available from IIASA on request.) The model allows analyses to be made of substitution possibilities in agricultural production (water for fertilizers, irrigated for nonirrigated crops, one subregion for another, and so on). The study, leading ultimately to the determination of an economically efficient level of irrigation development, may serve as an example for similar studies initiated elsewhere.

Janusz Kindler
Task Leader
Regional Water Demand and
Management Task

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1 INTRODUCTION

In most countries agriculture consumes more water than all other sectors of the economy combined. The US National Water Commission (1973) reported that globally 77 percent of all water withdrawals and 87 percent of all consumptive use occur in agriculture. The demand for water in agriculture can be expected to rise in the future as more irrigation is developed. The UN Food and Agriculture Organization (1977b) has estimated that a \$100 billion (US) (\$10 $\times$ 10^9) investment program in irrigation and drainage will be required to provide adequate food supplies to the world's population by 1990. In view of the very large investments required for developing water supplies to meet agricultural water demands, detailed studies of the nature of these demands are needed to ensure that the water is used productively and efficiently.

Research carried out at IIASA from 1976 to 1977 was aimed at improving the systems analysis methodology for studying water demands in a broad context of socioeconomic, engineering, and environmental issues. The application of this methodology at IIASA to a real-world agricultural problem was greatly facilitated by an agreement signed on 18 March 1977 between IIASA and the Bulgarian State Committee for Science and Technological Progress to promote technical cooperation in the development of the Silistra region of Bulgaria. Following the signing of this agreement, a case study of agricultural water demands in the Silistra region was begun at IIASA in collaboration with the Bulgarian Ministry of Agriculture and Food Industry. The goals of the case study were

- To provide the planners and decision makers of the Silistra region with detailed information about water demands and their impact on agricultural production in the region.
- To improve the systems analysis methodology for deriving and forecasting agricultural water demands by studying a real-world problem.

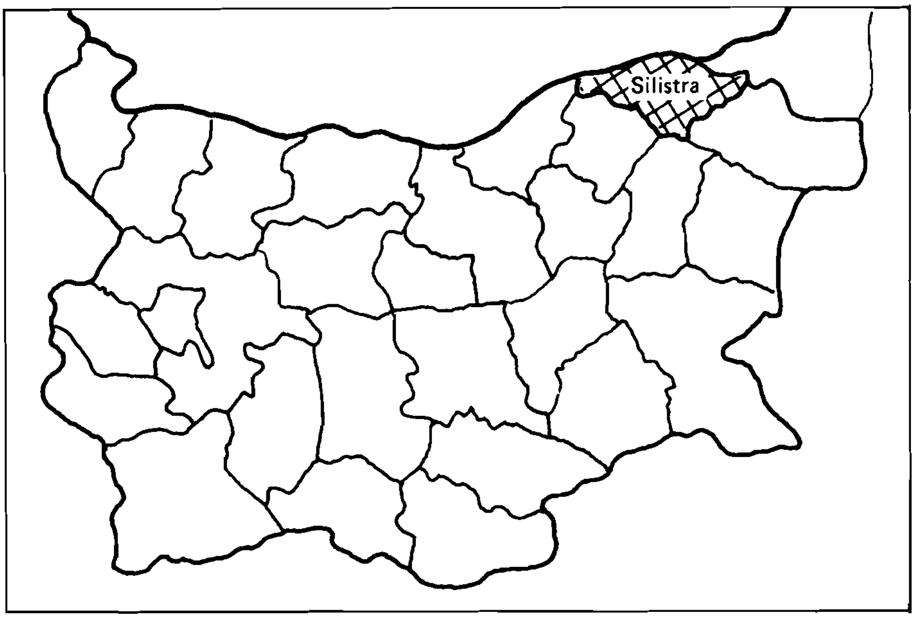


FIGURE 1a Location of the Silistra region in Bulgaria.

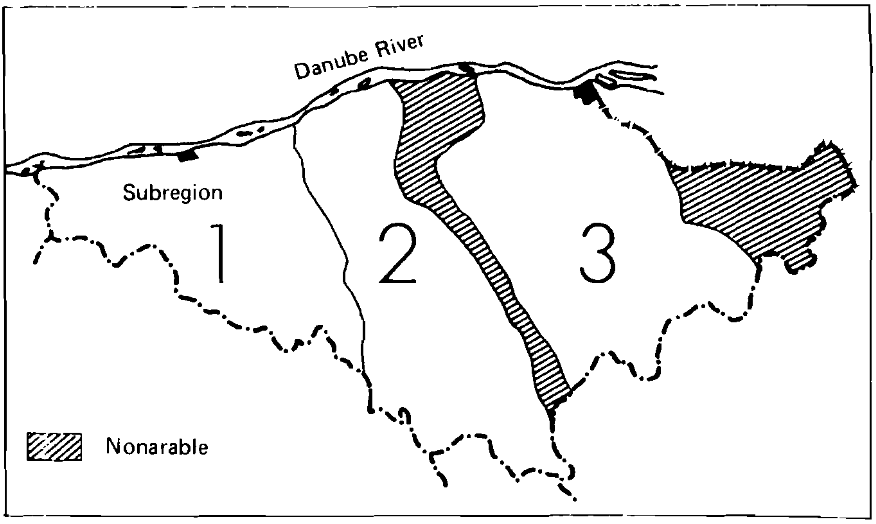


FIGURE 1b The Silistra region. There are 1,500 km^2 of arable land, which is 4.2 percent of the arable land in Bulgaria. The mean annual flow rate of the Danube River is 5,000 m^3/sec, and it is the only river in the region. Groundwater in the region is at a depth of 400 m.

The Silistra region has a population of 175,000, covers a territory of about 2,700 km^2, and is situated in the northeastern part of Bulgaria (Figure 1a). All agricultural activities in the region are organized into a large agroindustrial complex called Drustar. In the terminology that has been adopted in Bulgaria, an agroindustrial complex is an example of an aggregated agricultural system that consists of the following basic systems: crop production and processing, livestock production and processing, marketing, and environment. One administrative body is responsible for overall planning, development, and management of the complex.

The agroindustrial complex is a further development of the process of refining the management structure of agriculture in Bulgaria. There have been two turning points in this process. Until the early 1940s the agricultural activities in Bulgaria were spread over hundreds of thousands of small farms of a few hectares or less which had almost no mechanization. Following the socialist revolution in 1944, more cooperative farms were organized to better utilize the scarce resources available at that time. In the Silistra region cooperative farms were also organized which greatly improved the quantity and quality of the production as well as the living standards of the population. By the early 1970s it was recognized that further improvement of the existing 30 cooperative farms in the region required a new organization and management structure that could integrate all phases of the agricultural process, from the input resources to the final products. Thus all cooperative farms in the Silistra region were united in the present Drustar complex* which contains about 150,000 hectares (ha) of arable land.

Within the complex, crops are grown and harvested, stored, and fed to livestock, which are housed in concentrated feedlot areas. The Silistra region's planners consider self-sufficiency an important goal. As much as possible, they wish to supply all the region's needs from its own resources and export the surpluses. Because the management is integrated, it is reasonable to model the agricultural production system of the Silistra region as one unit. This is in contrast to modeling it as an assembly of separate units, as would be appropriate for regions with a different management structure and different goals.

Since rapid development is occurring, it is essential to choose the best way of directing future agricultural activities and investments. In the list of problems to be investigated in this respect, water resources appear to have a key role. There are two important reasons:

- Water resources within the region are limited to the bordering Danube River. No other rivers exist in the region. Groundwater is available only in small quantities or at depths exceeding 400 m, which makes it an unimportant resource as far as crop irrigation is concerned.

*The Drustar agricultural–industrial complex and the Silistra region are referred to interchangeably in the text.

- Vast irrigation development is to take place in the coming years to meet the feed requirements of meat- and milk-producing livestock – hence, to ensure stable agricultural production, a large reliable water supply has to be made available within the region.

The meteorological conditions in the region are favorable for crop and livestock production supported by irrigation. The average monthly rainfall in the irrigation season is 46 mm but extremes ranging from 0 mm to 137 mm have been recorded. The average monthly evapotranspiration for the same period is 171 mm, hence irrigation is necessary to ensure positive soil moisture balance over the vegetation season. The average water balance in the region under normal weather conditions is shown in Figure 2.

To overcome the difficulties associated with scarce water resources within the region and negative soil moisture balance, intensive investigations have been carried out over the past few years. As a result, a number of alternatives for

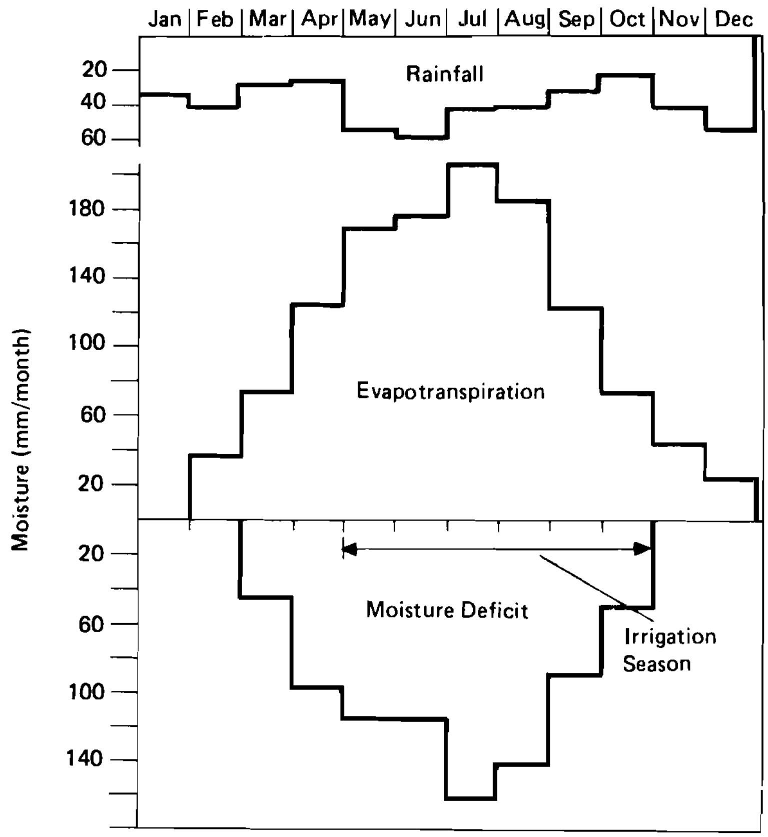


FIGURE 2 Average monthly water balance in the Silistra region.

augmenting the available water supply have been proposed. Some of them include the construction of reservoirs in various parts of the region; others combine the use of pumping stations and reservoirs, the construction of long-distance canals, and so on. The common characteristic of all alternatives is that, first, they rely on Danube River water and, secondly, all of the alternatives are rather costly. Obviously, one way of decreasing the supply cost would be to reduce agricultural water demands for irrigation, which constitute the major demand of the region, while keeping the production targets at the desired level. It is clear that keeping production at a certain level involves additional costs because other inputs must be substituted for water. The question is: Are these costs greater than the supply cost, and at what point is the water resource system in equilibrium, i.e., at what point is the incremental cost of additional supply equal to the incremental benefit that it produces?

Over the past 20 years there has been considerable interest in developing models that are able to answer one or both of these questions. Because of their great complexity and the planner's need to find "the best" solution in a set of feasible solutions, linear programming models have been employed from the very beginning. The models can be grouped into three categories: national, regional, and farm-level models. One of the first families of national models was developed at the Center for Agricultural and Rural Development (CARD) at Iowa State University in the United States beginning in 1954 (Heady and Agrawal 1972, Heady and Srivastava 1975, Nicol and Heady 1975). These models simultaneously consider (a) exogenous variables affecting food requirements, (b) government programs that control supply and increase food exports, (c) technological advances, and (d) the pricing of water through public investment in irrigation development. The models minimize total costs of crop and livestock production over a 25-yr time horizon. Duloy and Norton (1973) employed a similar concept for developing a model for the agriculture sector in Mexico. This model maximizes the sum of the producer and consumer surplus in national crop production. A similar model was developed by the UN Food and Agriculture Organization (1977a) in order to identify policy options for an optimal crop-mix pattern in long-term planning in Iraq.

Regional models receive the greatest attention in the literature. For example, Gisser (1970), Soltani-Mohammadi (1972), Voropaev (1973), and Dean *et al.* (1973) have developed regional agricultural models with heavy emphasis on crop production. Livestock production is considered as an exogenous variable. All of these models maximize net benefit difference between gross and production costs in the respective regions. The IIASA Food and Agriculture Program has also made a considerable effort to develop regional agricultural models (Carter *et al.* 1977).

Linear programming is a tool that can integrate the various production processes in agriculture, including water use, and hence can examine the major interrelationships between them. This is an attractive feature as far as the Drustar agroindustrial complex is concerned since this complex is a unified crop–

livestock agricultural system. Hence, linear programming was selected as the basic methodology for the study.

During the course of the study two versions of the *S*ilistra *W*ater for *I*rrigation *M*odel (SWIM) were developed, SWIM1 and SWIM2. SWIM1 derives agricultural water demands in the Silistra region taking into account only crop production, processing, and marketing (Gouevsky and Maidment 1977). It is a moderately sized linear program comprising 56 constraints and 68 decision variables. During July 1977, SWIM1 was developed and its results were reported in English and Bulgarian (see Figure 3).

After the results of SWIM1 were reviewed in Bulgaria, SWIM2 was developed. It takes into account three subregions within the Silistra region, livestock production and processing, and some environmental issues including different fertilizer application rates and manure disposal on the land. Some of the data were again revised in October 1977, and the model was run on the EC 1020 computer of the Central Computer and Management Center at the Ministry of Agriculture and Food Industry in Sofia.

The model and its results were presented during the second IIASA workshop on water demands, held in Laxenburg, Austria, from December 5 to 9, 1977. Following this workshop the final model was implemented on the ES1020 computer in Bulgaria where it is being further developed and refined.

This report is intended for the reader who wishes to familiarize himself with the modeling methodology and the type of results that can be produced. For the reader who also wishes to implement the SWIM2 model on his own computer, a users' guide has been prepared (Gouevsky *et al.* 1978). The users' guide illustrates all steps needed in computer implementation by means of a small linear programming model and then shows how to set up the input data

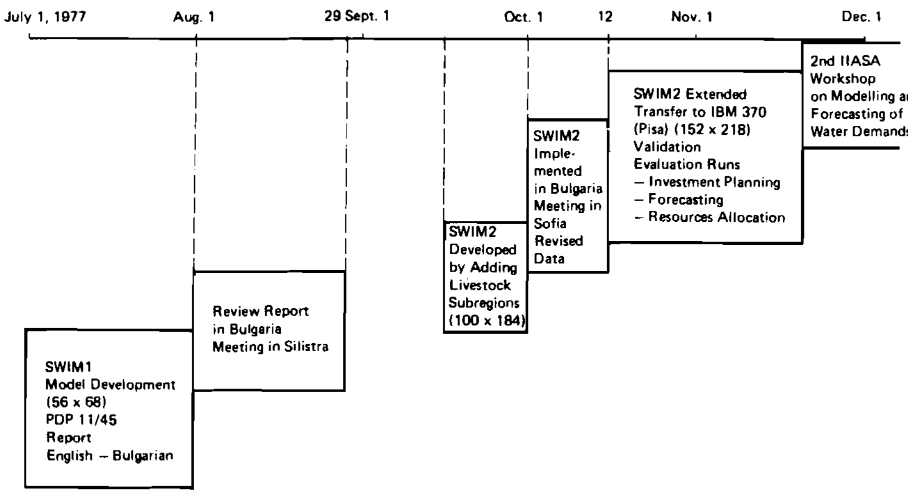


FIGURE 3 Progress of the Silistra case study.

to SWIM2 using a matrix generator. The full set of input data are given and also an example solution of SWIM2. These data are available on magnetic tape from the Resources and Environment Area of IIASA.

2 DESCRIPTION OF THE MODEL

2.1 The Agricultural Production System

There are about 1,500 km^2 (150,000 ha) of arable land in the Silistra region on which crops are grown to feed the livestock in the region and to meet the needs of the local population; 11,400 ha are irrigated, all with sprinklers. In the model, the region is divided into three main irrigation areas, all of which use Danube water.

The main objective of the model is to make a thorough analysis of factors that influence agricultural water demands and associated agricultural production in the three subregions, taking into account the major goal of the complex, which is to maximize the total net benefit from crop and livestock production with the limited regional resources. The model is intended to provide information for

- Estimating irrigation and livestock water demands and their distribution in space and time within a given year
- Forecasting the growth in these demands in response to different scenarios of growth in the numbers of livestock in the region
- Determining what proportion of the arable land within the complex should be developed for irrigation
- Evaluating the impact on water demands of various factors, including weather variability and the availability of other input resources (e.g., fertilizers)
- Estimating the demand function for water

For modeling purposes, agricultural production systems may be broken down into a number of subsystems as shown in Figure 4. Input resources such as land, water, and fertilizers go into producing crops whose output is processed for marketing or feeding to livestock. Crop production, supplemented by purchases from the market, is fed to livestock whose products are processed and sold. Livestock production may have substantial environmental impacts, such as those due to feedlot effluents, and these impacts may, in turn, affect crop production.

Those production processes modeled in detail for the Silistra region by SWIM2 are shown in Figure 5. The diagram indicates all processes that are involved in crop production and the uses of the crops. The input resources are land, water, seeds, fertilizers and chemicals, labor, machinery, fuel, and capital investments. Decision makers for the Silistra region consider that land is the only fixed input resource. All others are variable.

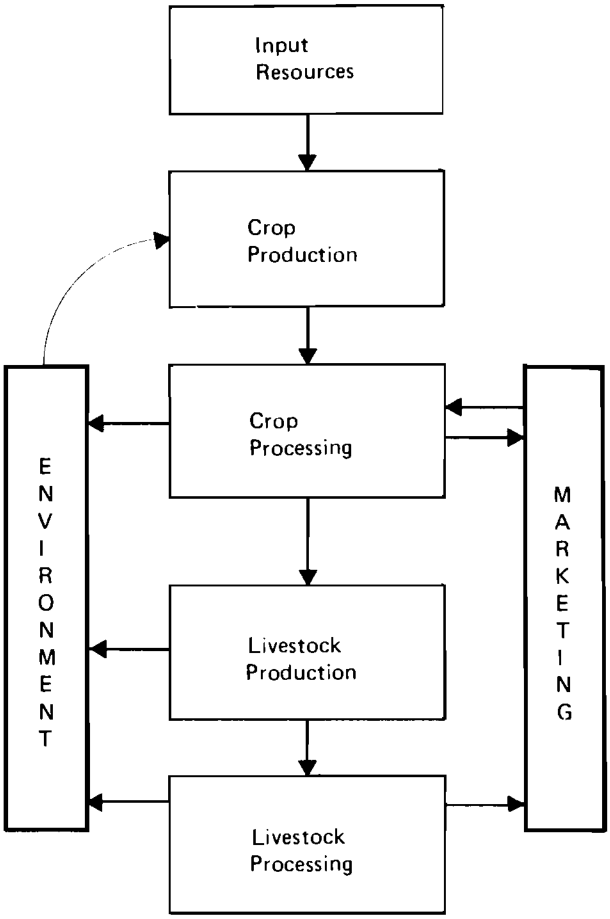


FIGURE 4 The agricultural production system.

Let us use wheat as an example. The input resources enter the crop production subsystem, which has various alternatives for producing wheat. It may be grown in any of the three subregions; it may or may not be irrigated; if it is irrigated, the usual amount of fertilizers may be supplied or these fertilizers may be reduced to 80 percent of their usual amounts. Thus, there are nine alternatives; no irrigation, irrigation with 80 percent fertilizers, and irrigation with 100 percent fertilizers, each of which can take place in any of the three subregions. In the next subsystem wheat undergoes processing to obtain grain, straw, flour, and bran.

The products are then distributed among different subsystems; grain goes to reserves and to livestock production, straw and bran go directly to livestock production, flour is sent to the market to meet the demands of the population.

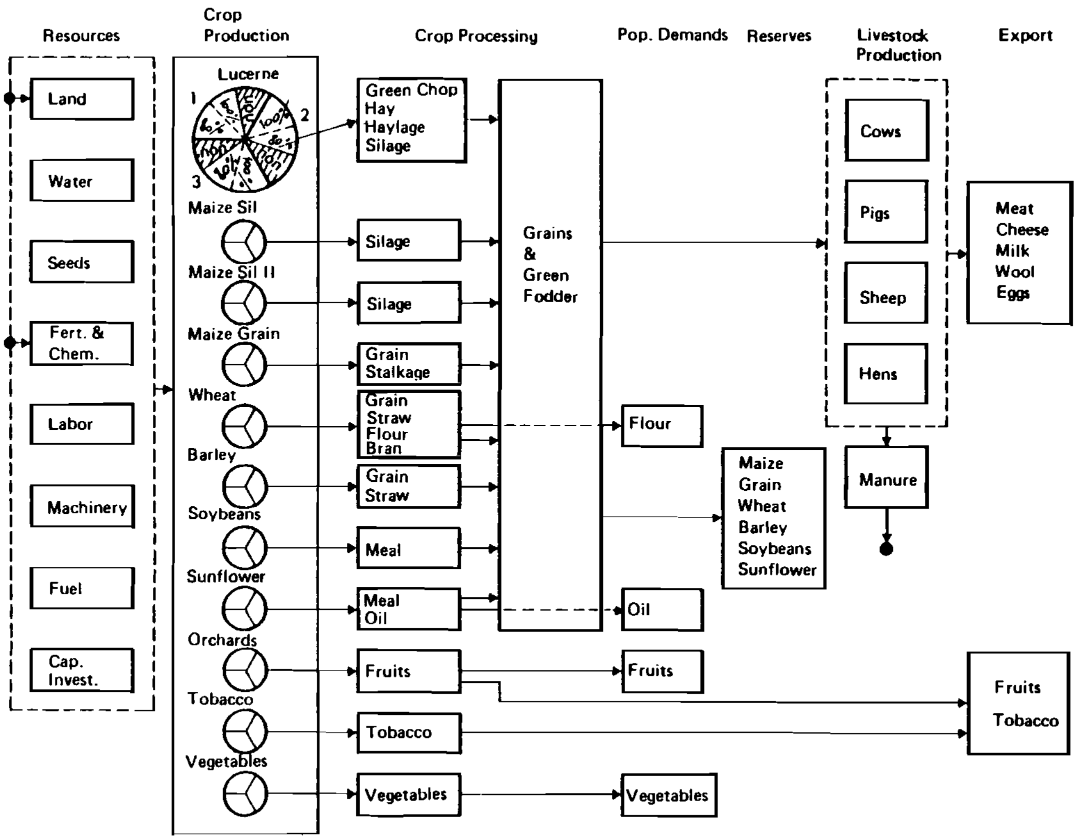


FIGURE 5 Agricultural production in the Silistra region.

Crop products feed four types of livestock – cows, pigs, sheep, and hens – all of which are housed in feedlots. Livestock products are exported from the Silistra region. The by-products of the livestock production subsystem, animal wastes from feedlots, are spread onto some of the land and partially substitute for fertilizers. These wastes may also have undesirable environmental impacts.

Water is one of the key parameters to be modeled in the system because it directly influences crop production, which in turn controls livestock production. The reverse also applies. If livestock numbers change, this will change the demands for crop production, and for irrigation and drinking water. These interrelationships are shown in Figure 6.

2.2 Modeling Assumptions

The decision makers for the Silistra region are considered to have a number of objectives in mind in planning the agroindustrial complex:

- *Maximum production*, so as to generate a high level of exports from the region and to meet the needs of the Silistra population for food and other agricultural products.
- *Efficient production*, i.e., minimum cost per unit of output. This implies that the flows of materials between the various processes in Figure 5 are in harmony with one another and that the least-cost combinations of inputs are used. It also involves an emphasis on using the most advanced technology (e.g., sprinkler rather than flooding systems are adopted for irrigation development).
- *Sustainable production*. Over the short term this involves minimizing the impact of weather variations by providing irrigation and production reserves. Over the long term, soil fertility must be maintained through

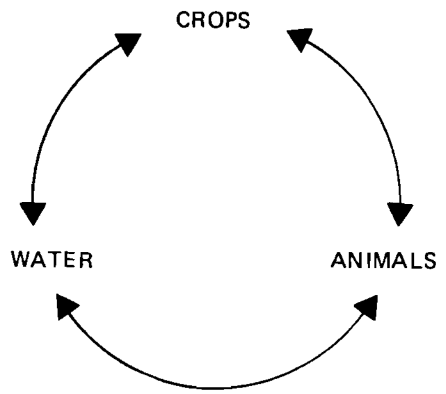


FIGURE 6 Relationship between water, crops, and livestock.

proper cultivation and crop rotation. A balance should also be maintained in the numbers of the different animals since if one animal becomes predominant the system is neither resilient to variations in market prices nor resistant to the spread of an animal disease.

These objectives have been substantially incorporated into SWIM2 either in its objective function or in its constraints. It may be noted that there could be other important objectives in the region that are not explicitly included in the model, such as increasing the efficiency of agricultural labor.

In the process of modeling agricultural production and deriving water demands, four basic assumptions have been made. (a) The agricultural system is modeled for 1 year. Depending on the coefficients included in SWIM2, this 1 year can represent the conditions of any specified year. SWIM2 does not contain year-to-year variations in its model structure, however. (b) The inputs and outputs of each of the seven subsystems shown in Figure 5 represent the decision variables in the model. It is further assumed that there are three types of relationships between decision variables:

- A linear-by-nature relationship; for example, the amount of seeds for planting a given crop is a linear function of the area to be planted. (See Figure 7(a)).
- A nonlinear relationship; for example, crop yield vs. fertilizer application. In this case the nonlinear function is linearized and the linear segments obtained are introduced as separate decision variables in the model (Figure 7(b)).
- A relationship where the decision maker is indifferent over a certain interval of variation of the dependent variable, or where the dependent variable is constant over a specified range of the independent variable (Figure 7(c)).

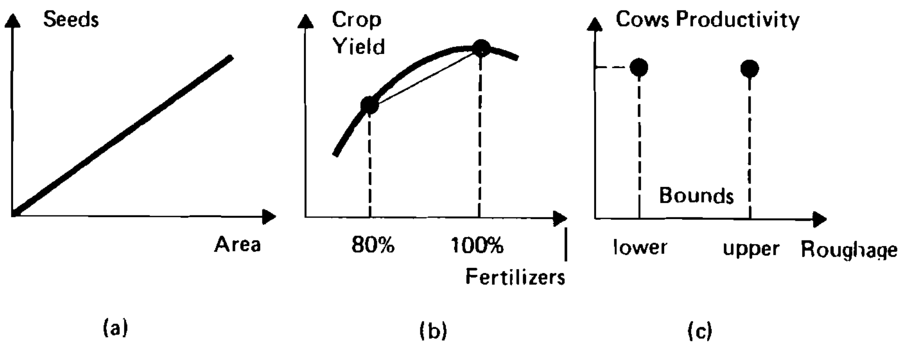


FIGURE 7 Relationships between decision variables.

(c) All costs, prices, and technological coefficients are known; economies of scale are not explicitly included. For example, in a given subregion the cost per hectare of bringing irrigation water to the field does not depend on the number of hectares irrigated. (d) No interest rate or investment is included in SWIM2 because, at present, interest rates are not considered to be the only and most important indicator of the socioeconomic value of investment in Bulgaria. For each piece of equipment purchased or facility developed by means of investment, the fixed cost is included in SWIM2 as an annual cost found from straightline depreciation of the investment over the useful working life of the facility. There are also other assumptions that relate to each of the subsystems described below.

2.3 Description of the Subsystems

2.3.1 INPUT RESOURCES

All input resources are introduced into SWIM2 as rates of use of resources per hectare of land or per animal. These rates may be taken directly from crop and livestock production manuals (e.g., Lidgi *et al.* 1976) and adapted to the region's conditions, or they may involve more sophisticated computations like those for irrigation water in this study.

Land. The main soil type of the region is chernozem (black earth). It is assumed that soil structure and productivity are uniform over the region. SWIM2 allows for different soil types in the three subregions shown in Figure 1b but there were no relevant data available concerning different soil types at the time of modeling. Out of 150,000 ha of arable land about 4,500 ha are reserved for seed production. The seed area is determined internally in the model solution. To allow for better land utilization SWIM2 takes into account the possibility of having maize silage as a second crop (maize silage II) after the midsummer harvest of wheat and barley. The model also computes the amount of irrigated or nonirrigated land planted with orchards and tobacco, as well as the irrigated area of vegetables. The areas of land planted in these three crops are fixed exogenous variables.

SWIM2 computes the cost of developing land for irrigation in two parts, the cost of bringing water to the fields and the cost of the sprinkler application equipment. The cost of all structures and equipment needed to bring water to the fields is expressed as a lumped cost in Lv/ha (1 leva (Lv) ≐ $1 (US)). This cost is 2,850 Lv/ha, 3,170 Lv/ha, and 2,750 Lv/ha in subregions 1, 2, and 3, respectively. These lumped costs are based on detailed engineering designs, using 1-in-4 dry year conditions, for developing more irrigation in these subregions that were already carried out. (A 1-in-4 dry year is one whose rainfall is exceeded on average in 3 years out of 4.) SWIM2 depreciates these costs over 25 years. Although SWIM2 computes the peak water demand rates in the irrigation season needed for engineering design and costing, there is no feedback in the model that changes the development cost per hectare as the peak demand rate changes. The costs of the sprinkler application equipment are described below.

SWIM2 assumes that the natural drainage of the soil in the Silistra region is sufficiently good that problems of waterlogging and soil salinization will not occur as irrigation is developed. In discussions with local officials it was confirmed that such problems have not been observed in irrigation areas.

Water. It was assumed that the Danube River is the only source of irrigation water and because of the rolling hills and potential for erosion, sprinkler irrigation is the only application method considered. The model computes the total amount of irrigation water as well as its distribution among subregions and various crops using 10-day intervals during the irrigation season from May to September. Unit crop demands are calculated by means of a soil moisture balance model.

This model uses the rainfall and evapotranspiration in each 10-day period from March to September as input data. Calculating forward in time, 60-mm irrigation is applied when soil moisture falls more than 60 mm below its capacity. Drainage occurs if excess rainfall fills soil moisture beyond its capacity.

Both normal weather conditions and 1-in-4 dry year conditions are analyzed. Using mean monthly data recorded at Silistra for each of the years 1961–70, normal weather conditions are defined for each month by averaging the 10 years of data. The conditions of 1961 are adopted as representing the 1-in-4 dry year by means of the probability analysis shown in Figure 8. Evapotranspiration

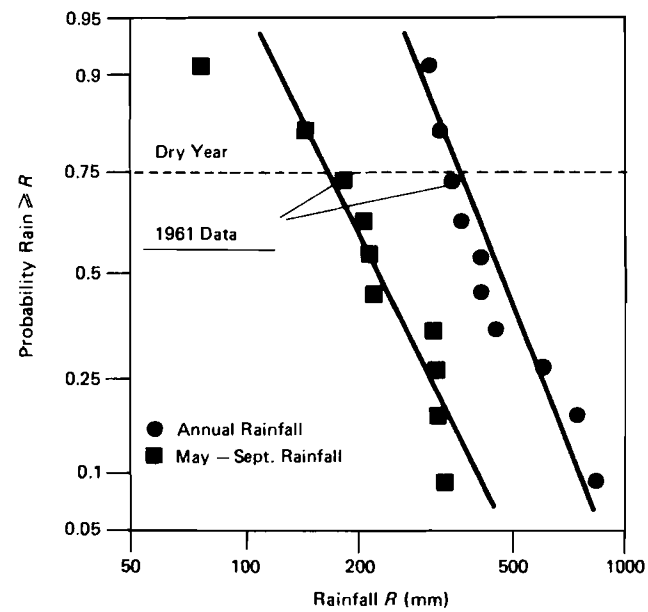


FIGURE 8 Probability analysis of rainfall. Source: Agrocomplect Silistra.

is computed from data on mean monthly temperature, humidity, windspeed, and cloudiness by the Penman method (Doorenbos and Pruitt 1977). An example of the soil moisture balance calculations for maize grain is shown in Figure 9. The procedure is described in detail in Appendix D.

A total water use efficiency of 50 percent is estimated on the basis of conveyance losses (5 percent), application losses (30 percent), and leaching requirements (15 percent). SWIM2 calculates the water use of each crop as the product of its unit crop water demand and the crop area. Then, to get the volume of water withdrawn from the Danube River, SWIM2 sums all crop water uses and divides the total by the efficiency. As in most irrigation systems, the price of irrigation water is subsidized and does not reflect the actual unit cost of supplying water. For this reason, a sensitivity analysis of water price, which is described in the analysis of the results (Section 3), has been performed. SWIM2 also computes livestock drinking water demands as the product of the unit water demand (liters/animal) for each type of animal, and the number of animals. This water is supplied from wells located near the Danube and subsequently transferred to the animal farms. The model does not consider treatment of wastewaters from the livestock feedlots.

Seeds. All seeds required for lucerne, maize, wheat, barley, soybeans, and sunflowers are assumed to be grown within the complex on nonirrigated land. SWIM2 computes the area of land needed for seed growing per hectare of field crop production by dividing the seed-planting rate for each crop by its seed crop yield rate and summing the resulting seed crop areas. The data used for seed-planting rates, seed crop yields, and the cost of seeds are given in Table A.1 in Appendix A.

Fertilizers and chemicals. Three nutrients must be supplied by artificial fertilizers: nitrogen, phosphorus, and potassium. The corresponding fertilizers are ammonium sulfate (34 percent active nitrogen), superphosphate (20 percent active phosphorus), and potassium sulfate (44.5 percent active potassium). The amount of each fertilizer needed per hectare is calculated so as to replace the nutrients removed by crop production with allowance for the natural ability of the soil to absorb or release nutrients. To estimate the effect on crop production of shortages in the supply of fertilizers, SWIM2 has an alternative for each crop that allows an application rate of only 80 percent of the fertilizer needed per hectare, with an associated loss in crop yield. The data on fertilizer application rates for all crops are given in Table A.2 in Appendix A. Their costs are given in Appendix C.

SWIM2 also allows for partial substitution of fertilizers by the nutrients in animal wastes from feedlots. The amount of nutrients in the animal wastes is given in Table A.3 in Appendix A. Although manure is generated throughout the year, the spreading of manure is limited by weather and transportation costs, so SWIM2 assumes that only 50 percent of the nutrients in the manure coming from the feedlots can substitute for the nutrients supplied by artificial fertilizers. As far as pesticides are concerned, there are too many individual chemicals involved to account for each one separately, as is done for fertilizers. Instead, a

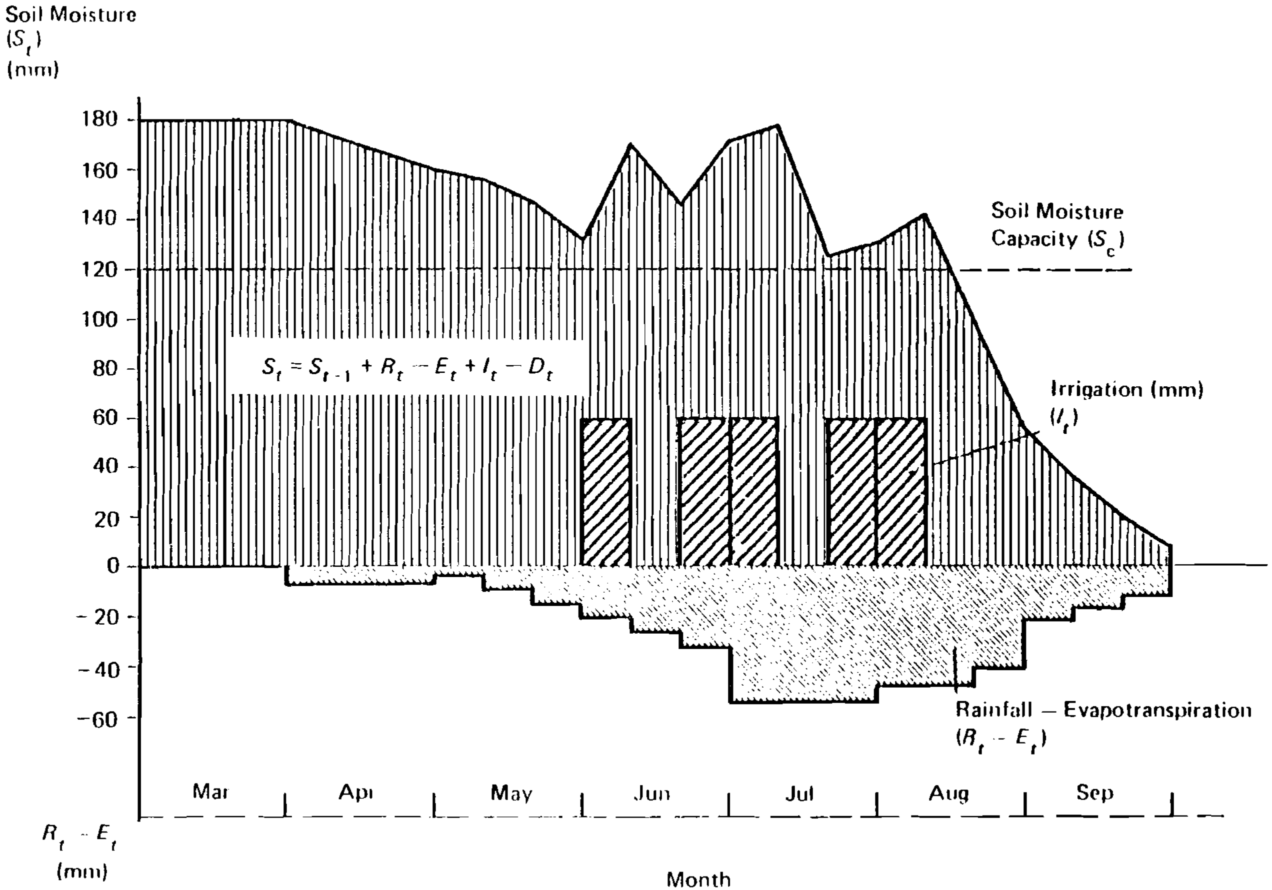


FIGURE 9 Soil moisture balance with irrigation.

lumped cost per hectare is specified for each crop and included as a cost per hectare in the production cost tables in Appendix C.

Labor, machinery, and fuel. These three inputs are interrelated in the sense that labor and fuel depend on the number of machines (the complex is considered to be fully mechanized).

Only one type of sprinkler irrigation system, called "Blue Arrow," is considered by SWIM2. "Blue Arrow" has fixed pipes that are towed from place to place by tractor. Other sprinkler systems, including side-roll and center-pivot systems, were considered when SWIM2 was being formulated, but data on their labor requirements, capital costs, and watering capacities were insufficient at that time to include them in the model as alternatives.

One "Blue Arrow" system consisting of eight lines of pipes can irrigate 10 ha/day. The purchase cost of 48,000 Lv is depreciated over a useful working life of 15 years. The number of "Blue Arrow" systems that are needed is computed by taking into account the area irrigated and the complementary relationships owing to the fact that not all crops are irrigated at the same time. As can be seen in Table A.6 in Appendix A, wheat and barley are irrigated only at the beginning of May when no other crops are irrigated. Hence, they can be irrigated by the equipment used for the other crops, provided that enough equipment is available. The same also applies to sunflowers and maize silage II, because the irrigation schedules of these two crops never coincide.

To determine the number of the other machines, such as tractors, that will be needed in the complex, the critical period in the schedule of field operations must be known when all of the available machines are being used. This schedule is shown in Table A.7 in Appendix A. SWIM2 finds the number of tractors, combine harvesters, and silage choppers in the following way. Assuming that there is some time lost due to bad weather during the critical period and that the working day has 10 hours, we calculated the number of working hours in the critical period. The area per hour that a machine can cover is known; hence, the area that can be covered by one machine during the critical period can be computed, and once the crop areas are fixed as a result of the model, the number of machines may be calculated.

For tractors the critical period is during spring cultivation from 20 March to 20 April; for combine harvesters it is during the wheat/barley harvest from 20 June to 20 July; and for silage choppers it is during the maize silage harvest in July.

The fuel needed by the field machinery is computed on the basis of the fuel used for individual field operations: plowing, cultivation, planting, and harvesting. The data on fuel use rates are presented in Table A.5 in Appendix A. For irrigated crops, the fuel use for harvesting is higher than for nonirrigated crops because of the higher yield.

For all machines and equipment two kinds of annual costs are considered: the fixed costs of depreciated capital investment over the machine life, and the variable costs of operation and maintenance.

The labor needed for field operations is calculated on the basis of the number of hours each machine is in the field with one operator per machine (Table A.4 in Appendix A). The additional labor required for administration and support services is not directly computed but is assigned a cost per hectare of land. Labor costs for irrigation are included in the total cost of irrigation.

Capital investments. SWIM2 accounts explicitly for the capital investments required for development of the complex. There are two types of capital investments distinguished in the model: irrigation capital investments and investments for machinery, feedlots, and perennial crops (orchards). The only cost of capital investments included in SWIM2 is their depreciation over the lifetime of the equipment. The lifetime is taken from the existing standards for Bulgarian conditions. For example, if a piece of equipment costs 10,000 Lv and its lifetime is 10 years, then the depreciated cost of capital is 10,000/10 = 1,000 Lv/yr. This coefficient is assigned as an annual cost in the objective function coefficient of the decision variable for this kind of equipment.

It should be noted that since SWIM2 is a static model of one year's conditions, the model shows the results of investments as if they were instantly in effect. It does not show the economic effect of staged investments over time.

In economic analysis involving the discounting of time streams of benefits and costs, the discount or interest rate employed plays a central role. This interest rate reflects the value of capital investment in alternative uses. Since SWIM2 does not contain discounting over time internally, it is not necessary to include an interest rate in the model. As is demonstrated in the analysis of the results, SWIM2 can be optimized for specified conditions in a sequence of future years linked by forecast growth in the numbers of livestock. In this case discounted time streams of benefits and costs could be obtained from the model's results.

2.3.2 CROP PRODUCTION AND PROCESSING

The key problems in modeling crop production are determining the crop production alternatives and the crop yields. There are nine alternatives introduced in SWIM2 for each crop. The crop may be grown in any of the three subregions using any of the three technologies (no irrigation, irrigation with 80-percent fertilizers, and irrigation with 100-percent fertilizers). The crop production costs for each crop, both irrigated and nonirrigated, are tabulated in Appendix C. The fertilizer use rates shown in these tables are for 100 percent of the requirements. In the model, lucerne is replanted every 3 and orchards every 15 years. Accordingly, the costs associated with their planting have been depreciated in a straight-line fashion over this period.

The crop yields are one of the most sensitive parameters of SWIM2. The relationships between crop yield, weather, fertilizer application, and irrigation are central to any analysis of irrigation. The yields used in SWIM2 under normal

TABLE 1 Crop yields (tons/ha).

	Irrigated		Nonirrigated	
CROP	100% fertilizer	80% fertilizer	Normal weather	Dry weather
Lucerne	11.0	9.5	5.5	5.1
Maize silage	48.0	42.0	28.0	14.0
Maize silage II	22.0	17.0		
Maize grain	9.0	7.5	4.3	2.4
Wheat	4.1	4.0	3.8	2.7
Barley	3.9	3.8	3.5	2.8
Soybeans	2.7	2.4	1.5	1.2
Sunflowers	2.2	2.15	2.0	1.5
Orchards	24.0	22.0	21.0	17.0
Tobacco	2.2	2.1	1.8	1.4
Vegetables	41.3			

NOTE: Maize silage II and vegetables are grown only with irrigation. Vegetables are grown only with 100-percent fertilizers.

weather conditions are based on average yields obtained in the Silistra region (Table 1). Because of lack of data, the yields are assumed to be the same regardless of the subregion in which the crops have been planted. However, the structure of SWIM2 permits the introduction of different yields in the subregions if this is justified.

At present, some crops are not grown with irrigation in the region. For these crops the increase in yield due to irrigation can only be based on experience gained in other regions with similar conditions. The decrease in yield in response to drought as well as the yield change in response to fertilizer application must be similarly estimated. In general, wheat, barley, and lucerne are more drought-resistant than the other crops because they are in the ground over the winter and the moisture absorbed by the soil during that time is not lost through cultivation in the spring. Maize is much affected by drought because it has a large amount of vegetative growth and small roots. The yield of irrigated crops during drought is assumed not to change because the loss in rainfall is made up by irrigation water.

Crop rotation to keep the natural productivity of the soil is explicitly introduced in SWIM2. Since SWIM2 is a static (1-year) model, the crop rotation is taken into account by constraining the ratio between the areas of field crops (lucerne, wheat, and barley) and interrow-cultivated crops (maize, soybeans, and sunflowers). This ratio can vary between 0.95 and 1.3.

The crops harvested from the field can be processed into a number of outputs (see Figure 5). Since the requirements for feeding livestock are expressed in terms of processed outputs, SWIM2 has some processing activities included in it.

Lucerne is grown for fodder, which can be green forage, hay, haylage, or silage. Silage can also be produced from maize. If maize is grown for grain, it is assumed that the stalks are harvested to be used as roughage. The processing of wheat includes milling for flour, in which case 78 percent of the grain becomes flour and 14 percent becomes wheat bran, which is fed to livestock. Maize and barley must be milled before being fed to animals but there are no significant weight losses in this process. Both wheat and barley straw are also harvested and processed for roughage. Soybeans and sunflowers are crushed and the oil is extracted, leaving a residual meal for livestock which amounts to 75 percent by weight of the soybean grain and 71 percent of the sunflower seeds. All the grain crops are assumed to undergo drying before being further processed or used. No cannery processing is assumed for fruits and vegetables. Drying is the only processing activity for tobacco considered in SWIM2.

2.3.3 USE OF CROP PRODUCTS

Crop products can be exported, set aside as reserves for the region, fed to livestock in the region, or used by the Silistra population. All estimates of product benefits used in SWIM2 are based on internal Bulgarian prices taken from Lidgi *et al.* (1976).

In the model, the requirements of the population for cooking oil and fruits are fixed. Vegetables are grown only for internal consumption in the region and their total production is constrained by the area planted.

The simplest way to account for the impact of dry weather on crop production is to build up reserves that can partially make up for crops lost because of bad weather. Reserves of grain crops only are considered. SWIM2 is based on normal weather conditions, but it also accounts for the additional amount of grain needed for feeding livestock if the year turns out to be a dry one. If a certain crop is grown without irrigation, the difference between the yield obtained in a normal year and that obtained in a dry year (shown in Table 1) is multiplied by the crop area to give the potential amount of the crop that goes to reserves. This potential amount is further multiplied by a coefficient, which takes into account that not every year in a given sequence is dry, to give the actual amount of reserves set aside. The reserves are assigned a benefit equivalent to the cost of purchasing an equivalent amount of grain from outside the region.

Since the agroindustrial complex is supposed to be a self-contained crop–livestock enterprise, the export of crops is limited only to fruits and tobacco. All excess feedstuff production is assumed to support the increase in the number of animals that provide the main export goods. The market for livestock production is assumed to be perfectly elastic. Imports of crop production are not allowed in SWIM2 (they were allowed in SWIM1).

The ultimate goal of the complex is to export livestock products from the region. Four types of animals are assumed to be raised in the complex: cows with associated calves and heifers, sheep, pigs (breeding sows and pigs raised for slaughter), and hens. For ease in the subsequent analysis of diets, "structural" animals have been defined on the basis of the population structure of each type of animal.

1 structural cow	=	1 cow + 0.41 calves + 0.23 heifers
1 structural pig	=	1 fattening pig + 0.06 sow + 0.02 boar
1 structural sheep	=	0.5 milk ewe + 0.5 meat and wool ewe
1 structural hen	=	1 hen

The animals are in feedlots so their diets are controlled. These diets are made up of five feedstuffs: concentrated forage from grains, green forage freshly cut from the fields, silage, hay, and roughage from the harvest residuals of grain crops. Each animal must receive certain minimum amounts of energy and protein in a balanced diet of the five feedstuffs. To do this the weights of feedstuffs are converted into their energy equivalent in feed units, where one feed unit is the energy contained in 1 kg of oats. SWIM2 ensures that each animal receives a certain number of feed units and also keeps the number of feed units supplied by each of the feedstuffs within a specified range to maintain a balanced diet. Tables B.1 to B.3 in Appendix B contain the details. To maintain adequate levels of protein in the diets, SWIM2 does not permit the weight of high-protein feeds (soybeans and sunflowers) to be less than one-fourth of the weight of low-protein feeds (maize grain, wheat, and barley).

Animal products are calculated on an annual basis taking into account the population structure of each animal. In certain cases where improvements in productivity beyond 1975 levels can be expected as the complex develops, perspective productivities achievable by 1985 are used. One structural cow is assumed to produce annually 0.6 calves for slaughter at 6 months and 4,000 liters of milk and to have a milking life of 5 years. Pigs are raised to 120 kg live weight yielding a 75-kg slaughtered carcass. Sheep are milked for 180 days to produce 135 liters of milk, from which 13.5 kg of cheese are made. Hens lay 200 eggs over a 10-month laying season. The market prices for these products are taken from Lidgi *et al.* (1976).

2.4 General Mathematical Representation

The description that follows formalizes the relationships among the various subsystems in the complex into an aggregated linear programming format. Appendix E contains a complete mathematical description of the model and should be referred to if details are desired.

For ease in the explanation, all decision variables and constraints in the model are aggregated into 15 decision vectors and 18 sets of constraints, as shown in Table 2. The objective function OB, which has been adopted for the agricultural production in the region, maximizes the annual net benefits, i.e., the

TABLE 2 General structure of SWIM2, including decision vectors y, w^i, v^i, q^i, and x^i.

CONSTRAINTS	Crop production alternatives (y)	Fodder products (w^1)	Grain products (w^2)	Population crop products: Grain (v^1)	Population crop products: Other (v^2)	Grain reserves (v^3)	Export of other crop products (v^4)	Grain products for livestock (v^5)	Livestock: Numbers (q^1)	Livestock: Products (q^2)	Irrigation & drinking water demands (x^1)	Irrigation equipment (x^2)	Fertilizers (x^3)	Machinery (x^4)	Capital investments (x^5)	Right-hand side
Objective function	c^1	c^2	c^3	b^1	b^2	b^3	b^4		c^4	b^5	p^1	p^2	p^3	p^4	p^5	
Land balance	$A_{1,1}$															$\leq l$
Irrigation & livestock drinking water	$A_{1,2}$								$A_{9,2}$		$-I$					$= 0$
Irrigation equipment	$A_{1,3}$											$-I$				$= 0$
Fodder production	$A_{1,4}$	$-I$														$= 0$
Grain production	$A_{1,5}$		$-I$													$= 0$
Grain production balance			$A_{3,6}$	$-A_{4,6}$		$-A_{6,6}$		$-A_{8,6}$								$= 0$
Other crop production balance	$A_{1,7}$				$-A_{5,7}$		$-A_{7,7}$									$= 0$
Livestock feedstuff requirements		$A_{2,8}$						$A_{8,8}$	$-A_{9,8}$							≥ 0
Livestock products									$A_{9,9}$	$-I$						$= 0$
Fertilizers	$A_{1,10}$								$-A_{9,10}$				$-I$			$= 0$
Machinery	$A_{1,11}$													$-I$		$= 0$
Capital investments	$A_{1,12}$								$A_{9,12}$			$A_{12,14}$		$A_{14,12}$	$-I$	$= 0$
Constrained irrigation water											I					$\leq w$
Constrained fertilizers													I			$\leq f$
Constrained capital investments															I	$\leq k$
Grain products for population				I												$\geq g$
Other products for population					I											$\geq r$
Livestock numbers									I							$\geq n$

difference between the value of marketed livestock and crop products, and their production cost. Vectors are in boldface.

$$OB = \max\Big[\mathbf{b}^1\mathbf{v}^1 + \mathbf{b}^2\mathbf{v}^2 + \mathbf{b}^3\mathbf{v}^3 + \mathbf{b}^4\mathbf{v}^4 + \mathbf{b}^5\mathbf{q}^2$$

crop and livestock production benefits

$$-\mathbf{c}^1\mathbf{y} \quad - \quad \mathbf{c}^2\mathbf{w}^1 - \mathbf{c}^3\mathbf{w}^2 \quad - \quad \mathbf{c}^4\mathbf{q}^1$$

crop production cost	crop processing cost	livestock production cost

$$-\mathbf{p}^1\mathbf{x}^1 - \mathbf{p}^2\mathbf{x}^2 - \mathbf{p}^3\mathbf{x}^3 - \mathbf{p}^4\mathbf{x}^4 - \mathbf{p}^5\mathbf{x}^5\Big]$$

input resources cost

where

$\mathbf{b}^1$ and $\mathbf{b}^2$ are the benefits form crop products sold to meet the requirements of the population in Silistra

$\mathbf{v}^1$ and $\mathbf{v}^2$ are the amounts of these crop products

$\mathbf{b}^3$ and $\mathbf{v}^3$ are the benefits per unit of grain reserves and the quantities of grain reserves, respectively

$\mathbf{b}^4$ and $\mathbf{v}^4$ are the benefits per unit of crop products exported and the quantities of crop products exported, respectively

$\mathbf{b}^5$ and $\mathbf{q}^2$ are the benefits per unit of livestock products and the quantities of livestock products, respectively

$\mathbf{c}^1$ and $\mathbf{y}$ are the crop production costs per hectare and the areas of crop alternatives, respectively

$\mathbf{c}^2$ and $\mathbf{w}^1$ are the unit costs of processing fodder products and the amounts of these products, respectively

$\mathbf{c}^3$ and $\mathbf{w}^2$ are the unit costs of processing grain products and the amounts of these products, respectively

$\mathbf{c}^4$ and $\mathbf{q}^1$ are the production costs per animal and the number of animals, respectively

$\mathbf{p}^1, \mathbf{p}^2, \ldots, \mathbf{p}^5$ are the prices of input resources

$\mathbf{x}^1, \mathbf{x}^2, \ldots, \mathbf{x}^5$ are the quantities of input resources

It may be noted that grain products for livestock $\mathbf{v}^5$ do not have a coefficient in the objective function because they are an intermediate product transferred straight into feeding livestock.

The objective function is maximized subject to the following set of constraints. Matrices denoted by $A_{i,j}$ are located in column i and row j of the linear programming tableau, Table 2.

2.4.1 LAND BALANCE

The area planted cannot exceed the available land area, both irrigated and non-irrigated:

$$A_{1,1}\mathbf{y} \leqslant \mathbf{l}$$

where

$A_{1,1}$ is a matrix that sums up the land used in each subregion
$\mathbf{l}$ comprises the areas of available land in the three subregions and the available irrigated land

2.4.2 DEMANDS FOR IRRIGATION WATER AND LIVESTOCK DRINKING WATER

$$A_{1,2}\mathbf{y} + A_{9,2}\mathbf{q}^1 - I\mathbf{x}^1 = 0$$

where

$A_{1,2}$ are the coefficients for irrigation crop water use per hectare
$A_{9,2}$ are the coefficients for livestock drinking water use per animal
I is the identity matrix that is introduced because the linear programming format does not allow variables on the right side of the constraint equations
$\mathbf{x}^1$ are the volumes of irrigation and livestock water demands

2.4.3 IRRIGATION EQUIPMENT

$$A_{1,3}\mathbf{y} - I\mathbf{x}^2 = 0$$

where

$A_{1,3}$ are the irrigation equipment requirements per hectare
$\mathbf{x}^2$ is the number of sets of irrigation equipment required

2.4.4 FODDER AND GRAIN PRODUCTION

$$A_{1,4}\mathbf{y} - I\mathbf{w}^1 = 0$$

$$A_{1,5}\mathbf{y} - I\mathbf{w}^2 = 0$$

where

$A_{1,4}$ and $A_{1,5}$ are the yields of fodder and grain crops, respectively
$\mathbf{w}^1$ and $\mathbf{w}^2$ are the quantities of fodder and grain products, respectively

2.4.5 GRAIN PRODUCTION BALANCE

The grain produced must equal the grain used.

$$A_{3,6}\mathbf{w}^2 - A_{4,6}\mathbf{v}^1 - A_{6,6}\mathbf{v}^3 - A_{8,6}\mathbf{v}^5 = 0$$

where

$A_{3,6}$, $A_{4,6}$, $A_{6,6}$, and $A_{8,6}$ are matrices that sum up, respectively, total grain production, population requirements of grains, reserves, and grain products for livestock

$\mathbf{v}^1$ are the quantities of population crop products

$\mathbf{v}^3$ are the amounts of grain reserves

$\mathbf{v}^5$ are the amounts of grain products for livestock

2.4.6 PRODUCTION BALANCE OF OTHER CROPS

$$A_{1,7}\mathbf{y} - A_{5,7}\mathbf{v}^2 - A_{7,7}\mathbf{v}^4 = 0$$

where

$A_{1,7}$, $A_{5,7}$, and $A_{7,7}$ are matrices that sum up the production of other crop (vegetables, tobacco, and orchards), their population requirements, and their exports, respectively

$\mathbf{v}^2$ are the amounts of other crops that go to the Silistra population

$\mathbf{v}^4$ are the amounts of exports of these other crops

2.4.7 LIVESTOCK FEEDSTUFF REQUIREMENTS

Livestock feed must at least meet minimum requirements.

$$A_{2,8}\mathbf{w}^1 + A_{8,8}\mathbf{v}^5 - A_{9,8}\mathbf{q}^1 \geqslant 0$$

where

$A_{2,8}$, $A_{8,8}$, and $A_{9,8}$ are matrices that sum up fodder products, grain livestock products, and animal diet requirements for these products, respectively

2.4.8 LIVESTOCK PRODUCTS

$$A_{9,9}\mathbf{q}^1 - I\mathbf{q}^2 = 0$$

where

$A_{9,9}$ are the amounts of livestock products generated per animal

2.4.9 FERTILIZERS, MACHINERY, AND CAPITAL INVESTMENTS

The nutrients that are needed must be supplied by fertilizer or manure.

$$A_{1,10}\mathbf{y} - A_{9,10}\mathbf{q}^1 - I\mathbf{x}^3 = 0$$

where

$A_{1,10}$ and $A_{9,10}$ are matrices of crop fertilizer requirements and manure generation, respectively

$\mathbf{x}^3$ are total requirements for each fertilizer

The machines that are needed must be available.

$$A_{1,11}\mathbf{y} - I\mathbf{x}^4 = 0$$

where

$A_{1,11}$ are the numbers of each type of machine needed per hectare of crop production

$\mathbf{x}^4$ are the total numbers of each type of machine needed in the complex

The capital investment used is summed up.

$$A_{1,12}\mathbf{y} + A_{9,12}\mathbf{q}^1 + A_{12,12}\mathbf{x}^2 + A_{14,12}\mathbf{x}^4 - I\mathbf{x}^5 = 0$$

where

$A_{1,12}$, $A_{9,12}$, $A_{12,12}$, and $A_{14,12}$ are matrices of capital investments for developing irrigated land, livestock farming houses, irrigation equipment, and machinery, respectively

$\mathbf{x}^5$ are amounts of capital investments for different purposes

It should be noted that the cost of capital $\mathbf{p}^5$ is actually zero in SWIM2 because no interest rate is used. The depreciated cost of capital is contained in the costs of the decision vectors requiring capital investment.

The last six constraints reflect direct limits on decision vectors and have been isolated to facilitate variations in these limits.

2.4.10 CONSTRAINED INPUT RESOURCES

The input resources used cannot exceed those available.

$$\mathbf{x}^1 \leqslant \mathbf{w} \qquad \mathbf{x}^3 \leqslant \mathbf{f} \qquad \mathbf{x}^5 \leqslant \mathbf{k}$$

where

w, **f**, and **k** are the amounts of available water, fertilizers, and capital investments, respectively

2.4.11 CONSTRAINED OUTPUTS

Some production outputs must meet target levels.

$$\mathbf{v}^1 \geqslant \mathbf{g} \qquad \mathbf{v}^2 \geqslant \mathbf{r} \qquad \mathbf{q}^1 \geqslant \mathbf{n}$$

where

g, **r**, and **n** are target levels of grain products for the Silistra population (flour and cooking oil), other products for the Silistra population (vegetables, peaches and tobacco), and numbers of livestock (cows, sheep, pigs, and hens).

The total dimension of the decision vectors **y**, $\mathbf{w}^i$, $\mathbf{v}^i$, $\mathbf{q}^i$, and $\mathbf{x}^i$ is 218 decision variables interrelated by 152 constraints. The linear program for SWIM2 contains 2,050 data, which is about 6 percent data density in the tableau.

3 ANALYSIS OF THE RESULTS

To obtain the results of SWIM2, the IBM 370/168 computer at the CNUCE Institute of the National Research Council in Pisa, Italy, was used through the IIASA computer network. The linear programming package there is contained in the SESAME mathematical programming system (National Bureau of Economic Research 1972). An optimal solution is obtained in about 280 iterations.

About 70 solutions of SWIM2 were obtained. Each of the questions addressed has associated with it a few key variables in the model. To formulate a set of computer runs these variables are assumed to take a number of values within a certain range and the model is optimized for each of these values to obtain the required results.

First, the validity of the model's representation of the conditions in the Silistra region is examined by comparing its outputs with production statistics recorded in the region in 1975. Next, the consequences of investing capital in irrigation development are analyzed and the impact of restricting the input resources is investigated. Finally, various scenarios of future growth in water demands are determined on the basis of forecasts of the numbers of livestock in the region.

3.1 Validation of the Model

In general, validation is the process of ascertaining the agreement between the model's behavior and points of interest in a real situation (Thesen 1974). The goal of validation in the case of SWIM2 is to ensure that the model adequately reflects the overall realities of the Silistra agricultural production system. This would mean, for example, that its crop yields and animal diets are reasonably correct. The model can then be used with confidence to suggest policies for situations different from those currently practiced.

It should be noted that SWIM2 is an optimization and not a simulation model. As such, SWIM2 possesses internal decision-making capability to maximize net benefits subject to the set of constraints. A simulation model, by contrast, usually possesses no internal decision-making capability; it is intended only to mirror the actual conditions so that the effects of externally specified decisions can be evaluated.

Data on actual production outputs (e.g., tons of wheat and numbers of animals) from the Silistra region in 1975 are available in the *Bulgarian Statistical Yearbook* (Ministry of Information and Communications 1976). Unfortunately, these data do not include water withdrawals from the Danube River so it was not possible to check the model's computation of water withdrawals. For the validation, SWIM2 was run with an irrigated area of 11,400 ha, the amount of irrigated land in the region in 1975.

Aggregated production outputs recorded in the region are compared with the model's results in Figure 10. The model result shown is the sum of the optimized values of all relevant decision variables; for example, each crop has nine decision variables so the total grain production shown for five crops is the sum of 45 values. In order to avoid drawing a pair of bars for each of the animals, they have all been lumped together by defining a composite livestock unit based on the ratios of the numbers of pigs, sheep, and hens, to the number of cows in the region in 1975. These ratios are for pigs 8.4:1; for sheep 9.7:1; and for hens 27.8:1. One livestock unit = 1 cow + 8.4 pigs + 9.7 sheep + 27.8 hens. The ratios are preserved in this solution of SWIM2.

Compared with the 1975 data, SWIM2 gives 0.6 percent less grain, 24 percent less green fodder, and 20 percent more livestock. This is a fairly good agreement, because some of the 1975 production may have been exported from the region and not fed to animals, as SWIM2 assumes. It may be concluded that the model is reasonably valid at this level of aggregated production quantities.

The comparison begins to diverge, however, when details are considered. For example, Figure 11 compares the proportion of total grain production contributed by each crop. The model-optimal solution indicates that 13.1 percent of the grains should be soybeans, but soybeans were only 0.9 percent of production in 1975. Decision makers for Silistra have recognized the value of soybeans and progressively larger areas of it are being grown; however, no production of soybeans was recorded for 1974 (Ministry of Information and Communications

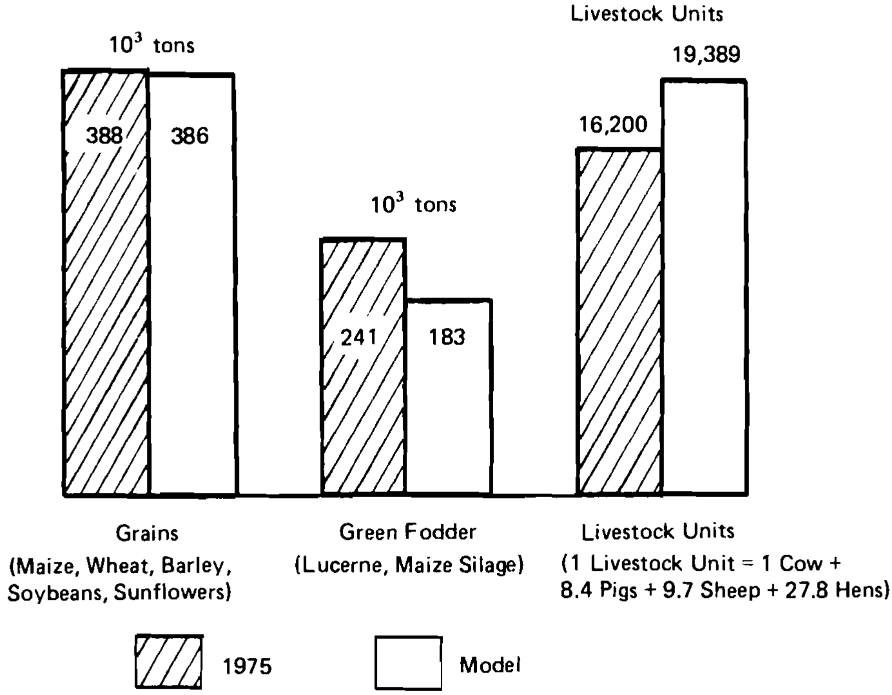


FIGURE 10 Comparison of aggregated production quantities.

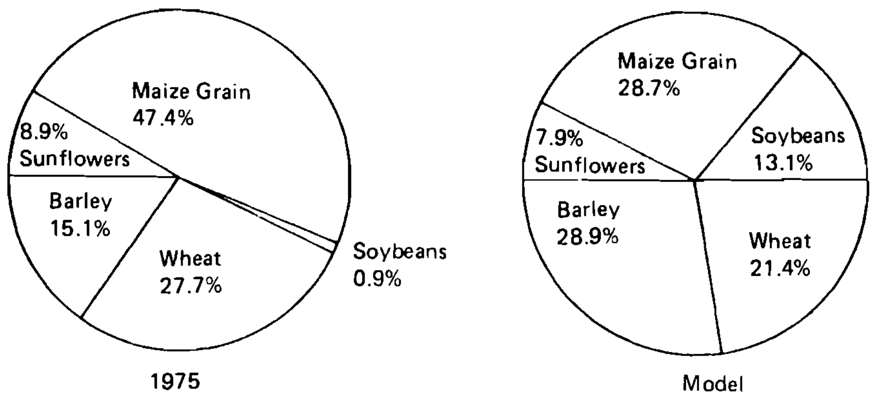


FIGURE 11 Distribution of grain production. SOURCE for 1975 statistics: Ministry of Information and Communications 1976.

1975). Therefore, this discrepancy between the model and the actual conditions may be attributed to the time required to introduce a new crop on a wide scale.

The model calls for more barley and less wheat than were grown in 1975. This may be due to the similar production technologies and costs of these two crops, which make it difficult for the model to choose between them. Small changes in the data can produce dramatic shifts in the balance between SWIM 2's optimal areas of wheat and barley.

The results obtained from the validation run showed that the model is relatively realistic at an aggregated level. Individual crop areas, however, should not be taken too literally – other considerations, such as habit and methods of crop rotation, probably affect production in ways not included in the model.

3.2 Development of Irrigated Land

The most important factor in determining agricultural water demands is the area of land that is developed for irrigation. This development requires extensive capital investment to provide supply facilities at the water source, canals or pipes to bring the water to the field, and equipment to apply the water to the crops. Economic evaluation of this investment plays a central role in determining the area that will be developed.

3.2.1 INVESTMENT PLANNING

Developing irrigation increases both the benefits and the costs of an agricultural enterprise because production is intensified. The net benefits (benefits minus costs) of irrigation development are usually positive, but normally, as additional increments of land in a region are converted from dry land to irrigation, each additional increment in the irrigated area generates a smaller increase in the net benefits over the whole region, i.e., there are diminishing marginal returns on the investment. Before all the arable land is irrigated, a point can be reached at which the marginal cost of additional irrigation equals its marginal benefit. This point can be considered as the ultimate economical level of irrigation development.

In SWIM2, net benefits are found by subtracting from the benefits obtained by selling crop and livestock products the annual costs of production and depreciated capital investments. In the investment analyses the ratios between the numbers of animals were kept fixed at their 1975 values (1 cow: 8.4 pigs: 9.7 sheep: 27.8 hens) so that one type of livestock does not dominate the others in the complex.

In 1975, 11,400 ha of land were developed for irrigation in the Silistra region. Of the 150,000 ha of arable land included in SWIM2, only 139,700 ha are considered to be potentially irrigable for physical reasons, i.e., limitations of topography, slope, and soil type. With 11,400 ha irrigated, SWIM2 estimates the average annual net benefits as 105.6 million Lv/yr. The additional net benefits generated by investment to develop more irrigated area are shown in Figure 12.

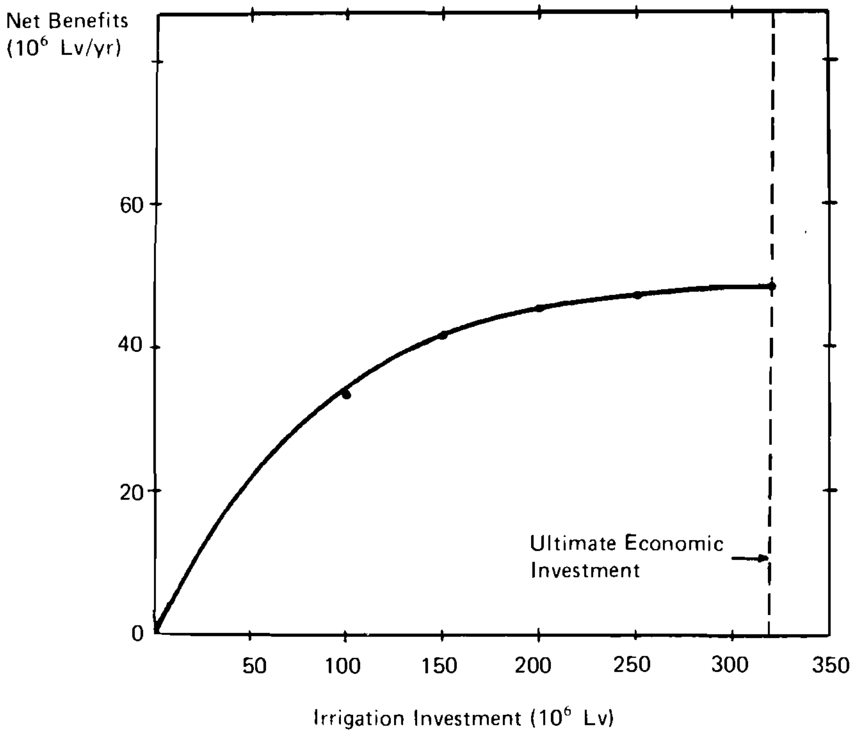


FIGURE 12 Net benefits of irrigation investment in the Silistra region.

This figure illustrates the principle of diminishing marginal returns on investment and identifies the ultimate economical investment as approximately 320 million Lv. This is the point of maximum additional net benefits and SWIM2 does not utilize any further investment funds made available. It should be noted that the investment shown in Figure 12 is just a total; it has no time dimension and could actually be provided in increments over many years. The additional net benefits shown in the figure are those that would occur on average each year after such an investment program had been completed.

The spatial distribution of future water demands depends on which subregion is chosen first for the development in irrigation. The investment to bring water to the field, expressed in Lv per hectare irrigated, is different for each of the three subregions. It is to be expected that as more investment funds are provided the subregions in which irrigation is relatively cheap will be developed first. This is demonstrated in Figure 13. Subregion 3 (2,750 Lv/ha) is developed first to the limit of its potentially irrigable area, followed by subregions 1 (2,850 Lv/ha) and 2 (3,170 Lv/ha). The ultimate economical investment is reached before subregion 2 is developed to its limit. The corresponding ultimate economical irrigation area is 105,500 ha, which is 70 percent of the arable land or 75 percent of the land considered to be potentially irrigable.

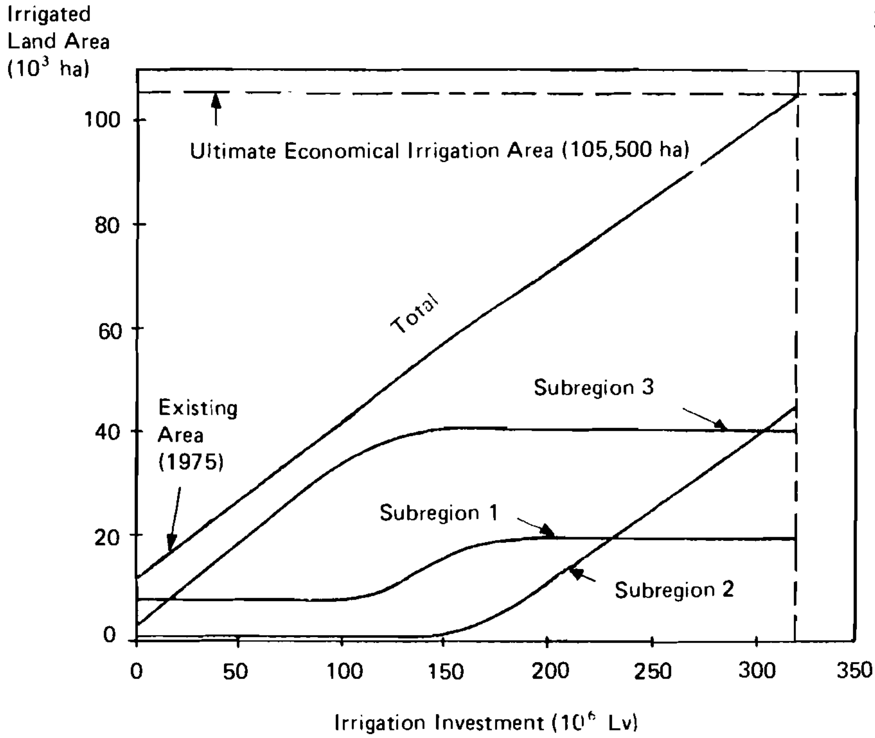


FIGURE 13 Irrigated area and investment.

The demands for Danube River water that result from developing the irrigated area are shown in Figure 14 for average weather and dry weather. (The dry weather condition is representative of a 1-in-4 year, as explained previously.) The extra water demanded during dry weather is that needed for a fixed irrigation area, i.e., SWIM2 assumes that in dry weather extra water is applied by longer sprinkling times to the area that would normally be irrigated under average weather conditions.

Under these assumptions, water demands for the 11,400-ha irrigated area are 78×10^6 m^3/yr and 103×10^6 m^3/yr for normal weather and dry weather. These demands increase approximately linearly with increasing irrigated area to ultimate economical levels of 585×10^6 m^3/yr (normal) and 820×10^6 m^3/yr (dry). The corresponding water withdrawal coefficients are 5,500 m^3/ha (550 mm) for normal weather and 7,750 m^3/ha (775 mm) for dry weather. Since an irrigation efficiency of 50 percent is assumed, these coefficients correspond respectively to 275 mm and 387 mm of consumptive use of irrigation water by the crops over the irrigation season.

If the results obtained from SWIM2 are extrapolated linearly to estimate water demands for the potentially irrigable area (139,700 ha), total withdrawals of 770×10^6 m^3/yr and 1,080 m^3/yr are found. These demands are 32 percent higher than those for the ultimate economical area. From this it may be con-

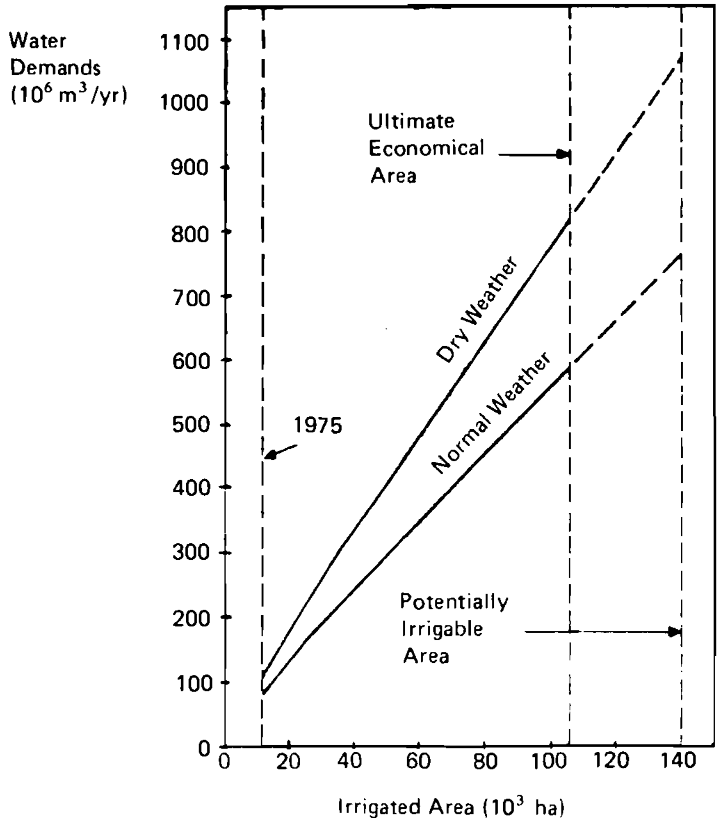


FIGURE 14 Water demands and irrigated area.

cluded that irrigation water demands in the Silistra region could be significantly overestimated if they are calculated from the potentially irrigable area.

3.2.2 DEMAND FUNCTION

The ultimate economical level of irrigation development identified previously is actually the point where the unit cost, or price, of water is equal to its marginal benefit. This is the point where the water resource system is in equilibrium. The sensitivity of this equilibrium point is an important criterion in determining how much investment should be made in irrigation. The variation in the amount of water demanded with its unit cost is expressed in the demand function shown in Figure 15.

The demand function for water in Figure 15 can be derived by differentiating net benefits from Figure 12 with respect to water demands, Figure 14. Using SWIM2, the demand function is obtained as the dual value (or shadow price) of the constraint on water when all other input resources, except land, are

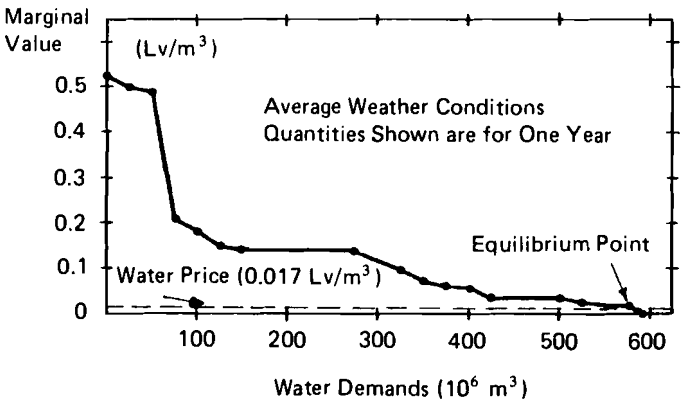


FIGURE 15 Demand function for irrigation water in Silistra region.

unconstrained. For a given level of demand the marginal value shown in this figure is the increase in average annual net benefits in the complex if one more cubic meter of water is supplied. This value is what the complex could afford to pay for that one extra cubic meter; hence, conceptually, the demand function is the locus of the points of equilibrium of the water system as the unit cost of water is raised.

As the limit on available water in SWIM2 is progressively decreased, a chain of impacts passes through the crop and livestock production systems. Reducing available water means that less area can be irrigated. Although the desirability of having production alternatives for reducing the amount of water per hectare was recognized, data on the consequent losses in crop yields were not available; hence SWIM2 does not allow for reducing the number of times a crop is irrigated or the amount of water applied in an irrigation. Reducing irrigated areas means that crop production falls; less crop products are then available for feeding livestock so the number of livestock that the complex can support is reduced. However, this does not mean that livestock will be slaughtered since the model is being used to look to the future to try to determine what the proper level of development of the complex should be.

The water price charged in the Silistra region (0.017 Lv/m^3) is small compared with its marginal value. The actual unit cost of water, based on the costs of the supply facilities, is estimated to be approximately 0.13 Lv/m^3 in the Silistra region. If this were charged as the water price, the demands at SWIM2's equilibrium point would fall to 275×10^6 m^3, which corresponds to 51,000 ha of irrigated land. The water demands of the 11,400 ha irrigated in 1975 lie in the range of very high marginal values, however, and would be unaffected even if such a price were charged.

There are 17 data points shown on the demand function. At each point something changes in the SWIM2 solution; for example, a different crop is irrigated or the livestock diets are changed. The relatively smooth nature of the demand function and the large number of solution changes on it reflect the considerable ability of SWIM2 to substitute one input for another or one production process for another as external circumstances change.

The demand function shown in Figure 15 is for normal weather conditions. It could be expected that in dry weather conditions the demand for water would be larger and the price would be higher. Thus, the derived demand function for water in agriculture must be associated with a specific set of weather conditions. This is demonstrated for the Silistra region by Gouevsky and Maidment (1977).

It may be noted that most of the results presented from SWIM2 are based on maximizing net benefits from a fixed area of land, i.e., land is considered as the constraining resource rather than water. This is realistic since the Danube provides an abundant water supply. However, the demand function provides a mechanism by which the effect of water as the constraining resource can be explored, and this could be very useful in regions where the available water resources are limits to development.

3.2.3 RISK ANALYSIS

The risks in an agricultural enterprise are associated with fluctuating market prices, animal or crop diseases, and adverse weather conditions. A number of features of SWIM2 are designed to minimize those risks.

For products sold within Bulgaria there are few difficulties with fluctuating markets since internal prices and product flows are centrally planned. However, for products sold on international markets, less control is possible. Future international prices are uncertain. This is one of the reasons why the proportions of animals in the livestock population are kept fixed in the economic analyses made using SWIM2. With set international prices it would be possible to compute proportions that would maximize foreign exchange earnings; these new proportions could then be substituted for the old ones for the purpose of economic analysis. There was insufficient time during the study to pursue this point further.

Another reason for maintaining fixed proportions of the different types of livestock is to minimize the risk of animal disease. If one animal is allowed to dominate all others in the complex, the spread of a contagious disease could cripple livestock production. Likewise for crop production; SWIM2 follows certain crop rotations that prevent solutions in which one crop, such as maize, is grown everywhere in the region.

To allow for adverse weather conditions, SWIM2 sets aside reserves of each grain crop in proportion to the crop area and yield loss expected in dry weather. Developing irrigation also insures against production losses due to dry weather. Intuitively it seems clear that as a greater proportion of grain crops are irrigated there is less need to store reserves of them. This is demonstrated in Figure 16, which shows that about 12 percent of grain production is stored as reserves when a tenth of the grain crop area is irrigated, but only 5 percent goes to reserves when half the grain crop area is irrigated.

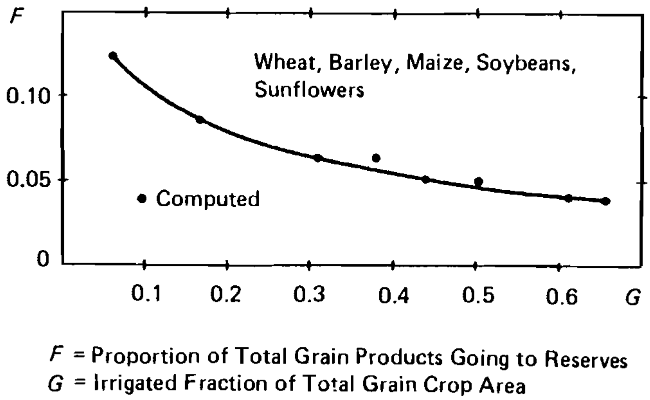


FIGURE 16 Grain reserves and irrigation.

3.2.4 FERTILIZER RESTRICTIONS

As can be seen from the cost tables in Appendix C, fertilizers are one of the most expensive inputs in crop production. In addition, fertilizers contained in agricultural drainage can promote eutrophication in the receiving waters, although this is unlikely in the Silistra region since the Danube has such a large flow rate. Fertilizer applications may be restricted for either of these reasons. Highly productive crops usually require large amounts of fertilizers; SWIM2 has alternatives where crops can be grown with only 80 percent of their optimal requirements for fertilizers, with a consequential drop in crop yields.

Other methods that the complex can employ in adjusting to fertilizer restrictions are to switch to less productive crops, which will mean that crop and livestock production are reduced, or to attempt to maintain crop production by developing more irrigation, i.e., by substituting water for fertilizers.

The amount of irrigation water used, as ammonium sulfate fertilizer is restricted, is shown in Figure 17. From the model results it can be seen that less productive crops are used on the right portion of the figure until the number of livestock supported is reduced to 1975 levels. At this minimum point on the curve SWIM2 substitutes water for fertilizers. The substitution possibilities are limited, however, and the solution rapidly becomes infeasible.

3.3 Forecasting Water Demands

Forecasts of water demands are the basis for the design of supply facilities. Two types of information are needed: the *volume* that will be demanded in future years, and the distribution of the volume within a given year to produce *flow rates*. In the Silistra region the growth in water demands over time is linked to the overall agricultural development of the region; the numbers of livestock are the primary decision variables. The path of agricultural development of the

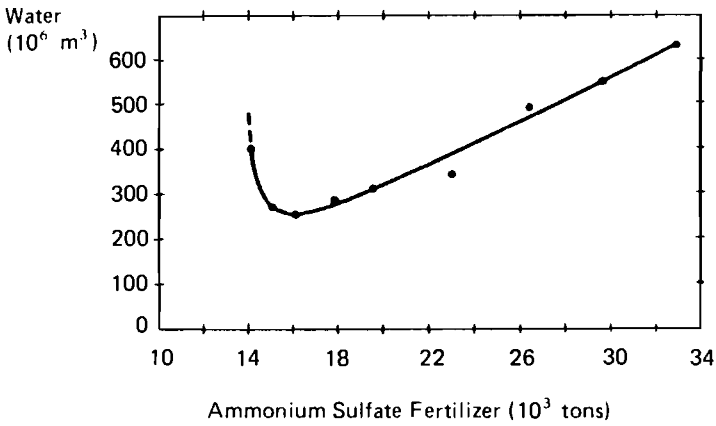


FIGURE 17 Water and fertilizers in the Silistra region.

Silistra region will be different depending on which of the animals (cows, pigs, sheep, or hens) predominates in the future. Cows and pigs may be more productive than milking sheep but Bulgarian sheep's cheese has an established image in international markets. The issue of which animals to concentrate on in the development of agricultural production is clearly a very complex one, involving many factors outside the scope of this study.

In order to illustrate the effect on water demands of various assumptions about the future growth in livestock, a set of scenarios has been developed. Each scenario corresponds to specified growth rates in the numbers of each type of livestock in the complex. These growth rates are all assumed to be linear from the base year 1975, i.e., a 2-percent growth rate means that in each subsequent year 2 percent of the number of livestock in 1975 are added to the total.

Four scenarios have been formulated with equal annual growth rates for each animal of 2, 4, 5, and 10 percent. Two additional scenarios favoring cows have also been formulated, one in which cows grow at 5 percent/yr and the other animals at 2 percent/yr, and another in which cows grow at 10 percent/yr and the others at 5 percent/yr.

For all the scenarios the numbers of livestock in the complex in 1980, 1985, 1990, 1995, and 2000 are computed and fed into SWIM2 as fixed variables. SWIM2 computes the most efficient production system needed to support these numbers of livestock.

The results for normal weather conditions are shown in Figure 18. For the faster-growth scenarios the ultimate economical level of development is reached before the year 2000 so the forecast was terminated at that level. It is striking that water demands grow about four to five times faster than the number of livestock. For example, in the scenario with a 5-percent livestock growth rate, water demands increase from 78.1×10^6 m^3/yr in 1975 to 340×10^6 m^3/yr in 1990, an increase of 335 percent or 22 percent/yr.

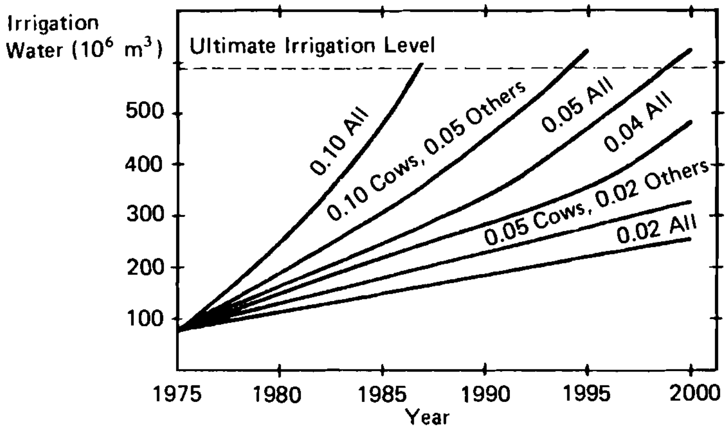


FIGURE 18 Comparison of water demand forecasts.

There is such a difference in the growth rates of water demands and livestock because the 1975 livestock numbers are almost entirely supported by nonirrigated crop production. To increase the livestock numbers, some of this land must be irrigated. It turns out that over a considerable range of livestock development, increases in irrigated area and water demands are linearly related to the number of livestock units (1 livestock unit = 1 cow + 8.4 pigs + 9.7 sheep + 27.8 hens), as shown in Figure 19. In this range each additional livestock unit requires the conversion of about 4 ha of nonirrigated land into irrigated land, 22,000 m^3/yr more irrigation water, and 175 m^3/yr more livestock drinking water, i.e., a 1-percent increase in the numbers of livestock in 1975 would require increases of 650 ha in irrigated land, 3.5 $\times$ 10^6 m^3/yr in irrigation water, and 2.8 $\times$ 10^6 m^3/yr more livestock drinking water. Future increases of livestock drinking water demands would, therefore, be less than 1 percent of the increases in irrigation water demands but livestock drinking water demands may still cause difficulties since these must be met by pumping groundwater.

As livestock development approaches twice the 1975 levels, more irrigation is needed per additional livestock unit because less productive crops begin to be irrigated. At this level of water demand, approximately 350 $\times$ 10^6 m^3/yr, the demand function for water (Figure 19) falls rapidly, also reflecting the decreasing productivity of irrigation.

Consider the "5 percent all" scenario in more detail. Irrigated land must be developed at the rate of about 3,000 ha/yr until 1995; this requires an investment of 10 million Lv/yr in irrigation. SWIM2 also computes the distribution of water demands over the irrigation season to enable the identification of the peak demand rate. For this scenario the growth in the peak demand rate can be seen in Figure 20. The peak demand rate rises from 19.7 $\times$ 10^6 m^3/10 days in 1975 to 79.2 $\times$ 10^6 m^3/10 days in 1995.

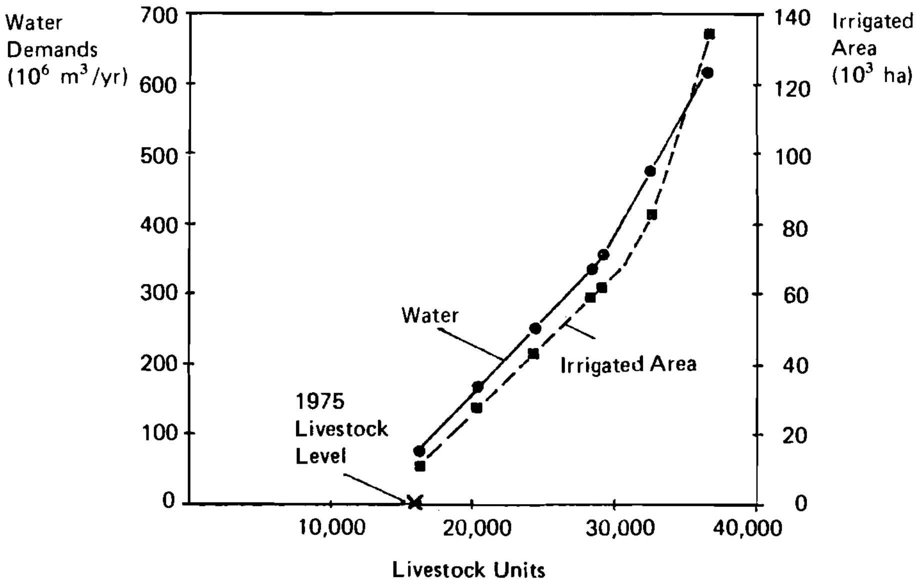


FIGURE 19 Livestock and irrigation.

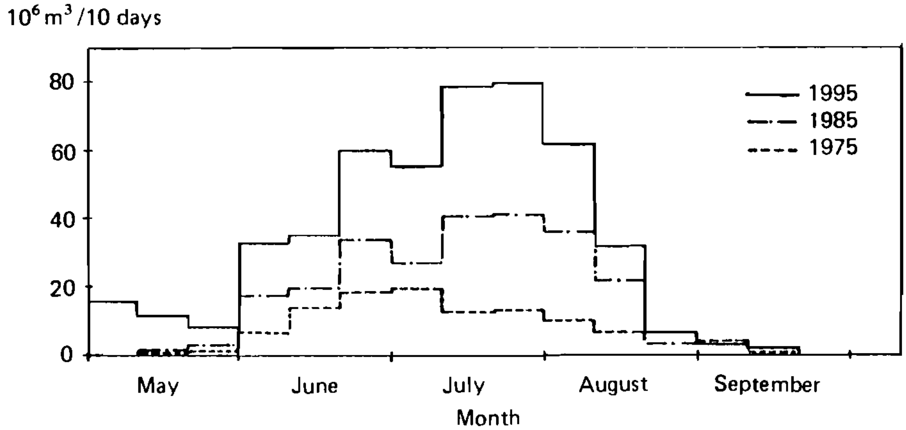


FIGURE 20 Water demands over the irrigation season.

It may be noted that the solutions of SWIM2 contain other data that may be of interest to regional planners, including the numbers of tractors and combine harvesters needed in the complex, annual requirements for fertilizers and fuel, and total quantities of the various types of crop production.

3.4 Sensitivity of the Results

In formulating a model, the relative importance of the parameters in the real system must be assessed. The more important parameters require detailed treatment in the model structure and more accurate input data. An assessment of the sensitivity of the model's output to changes in the parameters can show where improvements in the model structure or input data are needed and can give some indication as to how reliable the results are.

The experience accumulated during the study while performing more than 70 runs of SWIM2 demonstrates that there are five parameters that have a substantial influence on the results: animal benefits (value of animal products), crop production costs, crop yields, animal diets, and coefficients of irrigation water use. The main results described previously are sensitive to some parameters more than others (Table 3).

As far as the economic results from the model are concerned, the least reliable input data are those for animal benefits since these data involve assumptions about future market prices. In order to evalutate the effect of variations in the animal benefits on the net benefits of the system, SWIM2 was run for several values of animal benefits around the value adopted in the results previously described. From these runs it was found that a 1-percent change in the animal benefits produces a 0.9-percent change in the net benefits of the system. This indicates that there is little damping effect of the model itself on variations in these input data.

Since SWIM2 is available at IIASA and on the computer of the Ministry of Agriculture and Food Industry in Sofia, its input data and model structure can be improved where necessary and further results can be produced.

TABLE 3 Sensitivity of the model.

	Parameters				
Result	Animal benefits	Crop costs	Crop yields	Animal diets	Water coefficients
Validation		*	*	+	
Ultimate economic investment	*	*	+	+	
Demand function	*	+	*	+	*
Forecasting		+	*	*	*

NOTE: The symbols show how the main results from the model are sensitive to its input parameters: Blank – not sensitive, + – moderately sensitive, * – very sensitive.

4 CONCLUSIONS

A number of conclusions may be drawn from the results of the SWIM2 model. At the level of aggregated production quantities the model compares reasonably well with data recorded in the region in 1975. When more detailed comparisons are made there are some discrepancies between the model's results and the regional data, which is to be expected since the model optimizes rather than simulates the actual system.

An ultimate economical level of irrigation development, the level of maximum net benefit, is identified as the point where 70 percent of the arable land is irrigated. This area of irrigation corresponds to complete development of the potentially irrigable land in two of the three subregions within the Silistra region, and to partial development of the third subregion.

Water demands increase approximately linearly with increasing irrigated area to ultimate economical levels of 585 $\times$ 10^6 m^3/yr (under normal weather conditions) and 820 $\times$ 10^6 m^3/yr (under dry weather conditions). The corresponding water withdrawal coefficients are 5,500 m^3/ha (550 mm) under normal weather conditions and 7,750 m^3/ha (775 mm) under dry weather conditions. Since an irrigation efficiency of 50 percent is assumed, these coefficients correspond respectively to 275 mm and 387 mm of consumptive use of irrigation water by the crops. At these levels of development, water demands are quite sensitive to the price of water. Removing the existing price subsidy on water would reduce the ultimate economical irrigation area to about 35 percent of the arable land.

Further development of livestock production in the region beyond 1975 levels would require substantial investments in irrigation because the existing livestock are almost entirely supported by nonirrigated crop production. Over a substantial range of livestock development the associated demand for water and irrigated area varies linearly with the number of livestock. Each 1-percent increase in livestock from the 1975 levels requires about 650 ha of new irrigated land, or an increase of 4.5 percent in irrigated area. The corresponding increase in water demands amounts to 3.5 $\times$ 10^6 m^3/yr.

What are the advantages of using SWIM2 rather than the conventional methods of estimating agricultural water demands? The major advantage of SWIM2 is that it integrates the regional water demands with the crop and livestock production processes that determine these demands. This allows for various substitutions to be made among the inputs to these production processes (e.g., changing the composition of animals' diets) and among the production processes themselves (e.g., exchanging crops, converting land to irrigation). The integrated nature of the model is particularly important in the Silistra region because it corresponds to the centralized management structure controlling all aspects of agricultural production.

Although SWIM2 covers only a 1-year time period in each solution, it can be used to look at longer time horizons by forecasting various scenarios of the growth in livestock numbers and by running SWIM2 for several future years to derive the corresponding forecasts of water demands. Since the numbers of livestock are the primary variables of interest to Silistra decision makers, SWIM2 provides a means for evaluating the impact of various livestock development strategies. However, these results should be interpreted carefully because SWIM2 does not discount benefits or costs over time, only one set of production coefficients has been used, and no economies of scale are included.

A number of limitations of SWIM2 may also be noted. The model is not truly dynamic since it does not contain internally the linkages of year-to-year evolution. Another limitation is that livestock processing is treated only in a very aggregated way. As with most models, improvement of the data on the more sensitive variables would improve the accuracy of the results. Better data on crop yields, crop production costs, prices for outputs, and water use coefficients would be especially useful.

APPENDIXES

Appendix A

TABLES OF INPUT RESOURCES

The following tables show the rates of application of various resources (seeds, fertilizers, machinery, and fuel) for each of the crops considered in the model. Also shown are time schedules for crop production activities and irrigation. The data given in this appendix are used to calculate tables of production costs in Appendix C.

TABLE A.1 Seed requirements.

Crop	Seeding rate (ton/ha)	Seed crop yield (ton/ha)	Cost of seeds (Lv/ton)	a_i
Lucerne				
irr[a]	0.020	0.3	5,504	0.0667
non[b]	0.020	0.3	5,504	0.0667
Maize silage				
irr	0.040	4.3	660	0.0093
non	0.030	4.3	660	0.0093
Maize silage II				
irr	0.019	4.3	660	0.0044
Maize grain				
irr	0.020	4.3	660	0.0046
non	0.015	4.3	660	0.0035
Wheat				
irr	0.308	3.8	130	0.0810
non	0.280	3.8	130	0.0740
Barley				
irr	0.209	3.5	120	0.0597
non	0.190	3.5	120	0.0543
Soybeans				
irr	0.100	1.5	700	0.0667
non	0.100	1.5	700	0.0667
Sunflowers				
irr	0.066	2.0	307	0.0330
non	0.060	2.0	307	0.0300

NOTE: a_i = Seeding rate ÷ seed crop yield.
[a]Irrigated.
[b]Nonirrigated.

TABLE A.2 Fertilizer requirements (ton/ha).

Crop	Ammonium sulfate	Superphosphate	Potassium sulfate
Lucerne			
irr, 80[a]	0.152	0.36	0.10
irr, 100[b]	0.190	0.44	0.13
non[c]	0.100	0.30	0.09
Maize silage			
irr, 80	0.640	0.72	0.22
irr,100	0.800	0.90	0.27
non	0.360	0.55	
Maize silage II			
irr, 80	0.640	0.42	0.22
irr, 100	0.800	0.53	0.27
Maize grain			
irr, 80	0.420	0.48	0.16
irr, 100	0.530	0.60	0.20
non	0.240	0.30	
Wheat			
irr, 80	0.260	0.29	0.18
irr, 100	0.325	0.36	0.22
non	0.250	0.28	
Barley			
irr, 80	0.168	0.19	0.10
irr, 100	0.210	0.24	0.14
non	0.167	0.15	0.07
Soybeans			
irr, 80	0.130	0.25	0.09
irr, 100	0.170	0.32	0.11
non	0.120	0.23	0.07
Sunflowers			
irr, 80	0.416	0.33	0.02
irr, 100	0.520	0.42	0.03
non	0.400	0.32	0.02
Orchards			
irr, 80	0.480	0.38	0.28
irr, 100	0.600	0.40	0.30
non	0.400	0.35	0.25
Tobacco			
irr, 80		0.40	0.25
irr, 100		0.50	0.32
non		0.60	0.40
Vegetables			
irr, 100	0.75	0.60	0.27

[a]Irrigated, 80-percent fertilizer.
[b]Irrigated, 100-percent fertilizer.
[c]Nonirrigated.

TABLE A.3 Amount of nitrogen, phosphorus, and potassium in animal wastes (ton/animal/yr).

Animal	Nitrogen	Phosphorus	Potassium
Cows	0.1042	0.0444	0.0743
Pigs	0.0364	0.026	0.0156
Sheep	0.0098	0.007	0.0042
Hens	0.00077	0.00055	0.00033

TABLE A.4 Labor requirements (man-h/ha).

Crop	Tractor h					Combine h	
	Plowing	Cultivation	Planting	Harvest	Total	June–July	Aug–Oct
Lucerne							
irr[a]	0.31	0.10	0.20	2.48	3.09		
non[b]	0.31	0.10	0.20	2.00	2.61		
Maize silage							
irr	0.94	0.48	0.33	2.50	4.25		
non	0.94	0.48	0.33	2.30	4.05		
Maize silage II							
irr	0.94	0.48	0.33	2.50	4.25		
Maize grain							
irr	0.94	0.48	0.35		1.77		0.80
non	0.94	0.48	0.35		1.77		0.80
Wheat							
irr	0.53	0.21	0.35		1.09	0.54	
non	0.53	0.21	0.35		1.09	0.54	
Barley							
irr	0.52	0.16	0.25		0.93	0.48	
non	0.52	0.16	0.25		0.93	0.48	
Soybeans							
irr	2.50	0.10	0.60		3.20		2.72
non	2.50	0.10	0.60		3.20		1.80
Sunflowers							
irr	0.80	0.32	0.44		1.56		0.56
non	0.80	0.32	0.44		1.56		0.56

[a] Irrigated.
[b] Nonirrigated.

TABLE A.5 Fuel requirements (l/ha).

Crop	Plowing	Cultivation	Planting	Harvesting (incl. straw)	Total fuel
Lucerne					
irr[a]	17	4	6	50	77
non[b]	17	4	6	42	69
Maize silage					
irr	21	20	5	126	172
non	20	19	5	68	112
Maize silage II					
irr	21	20	5	126	172
Maize grain					
irr	21	20	6	53	100
non	21	20	6	38	85
Wheat					
irr	8	4	7	41	60
non	8	4	7	34	53
Barley					
irr	9	4	7	37	57
non	9	4	7	30	50
Soybeans					
irr	19	3	9	34	65
non	19	3	9	34	65
Sunflowers					
irr	15	7	7	26	55
non	15	7	7	23	52

[a] Irrigated.
[b] Nonirrigated.

TABLE A.6 Irrigation schedule of crops.

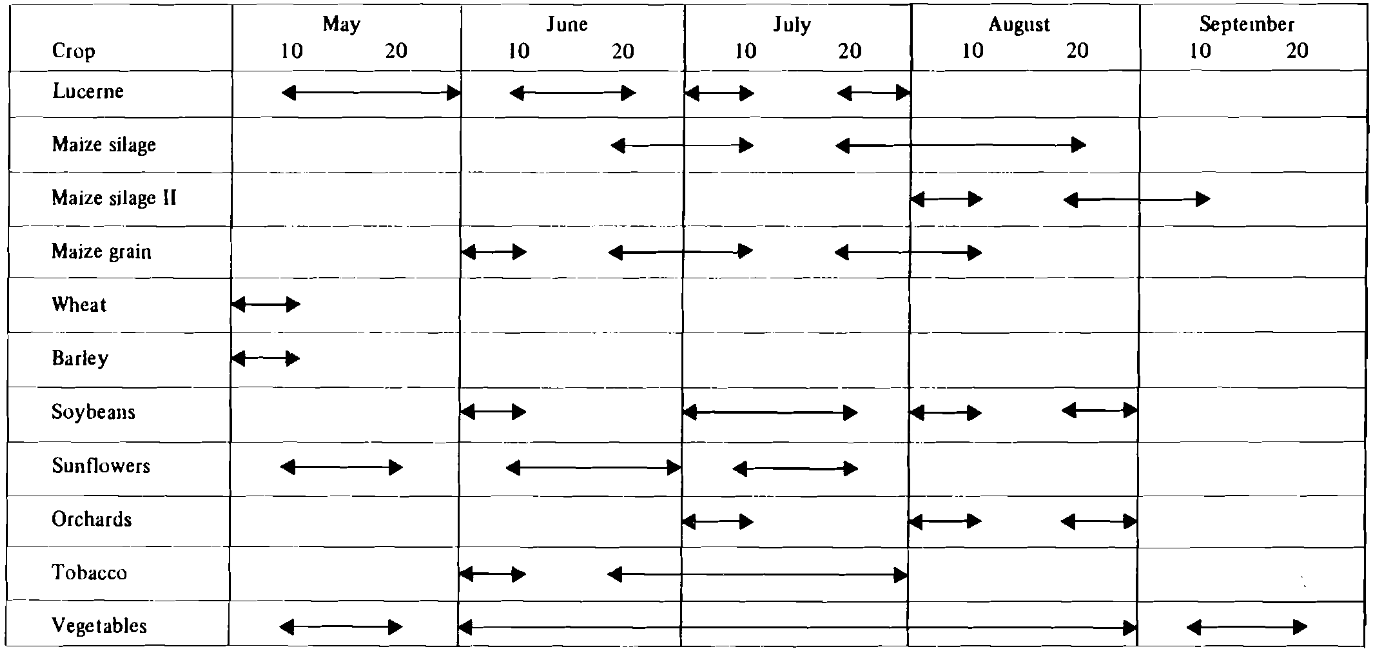
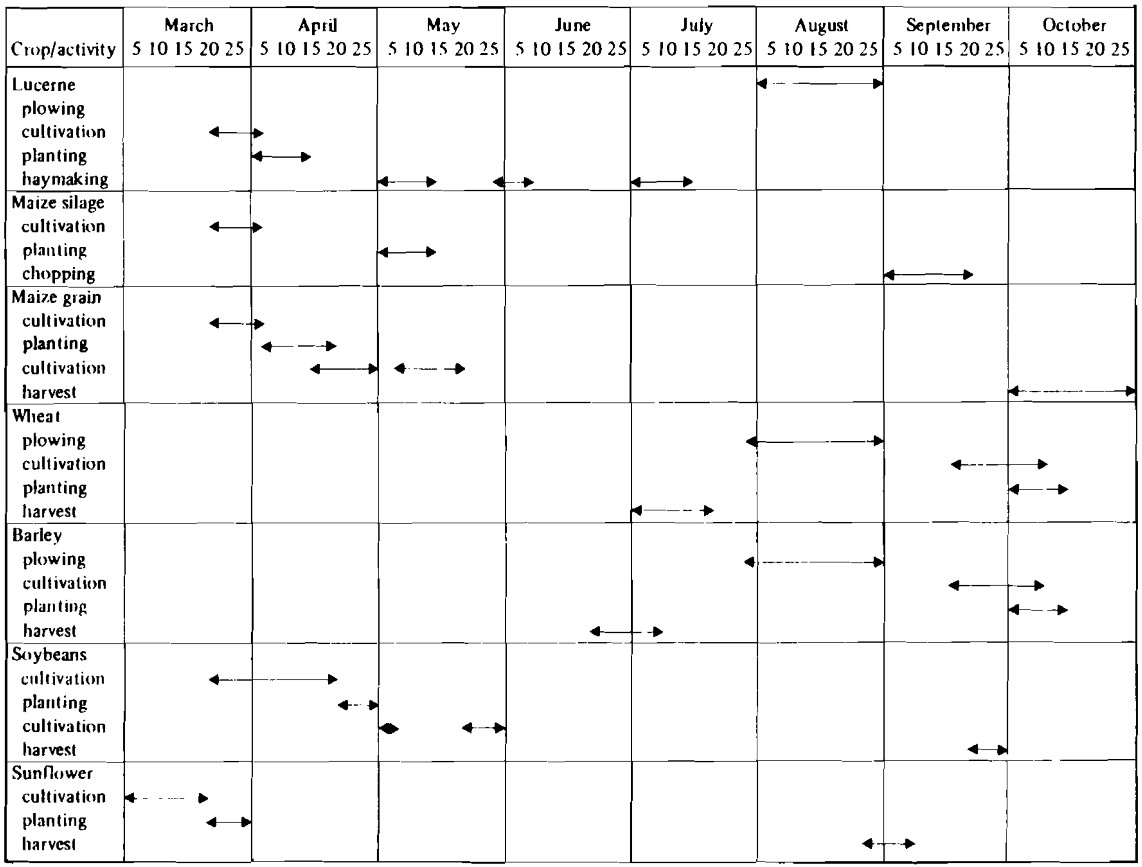


TABLE A.7 Schedule of field operations.



Appendix B

TABLES OF ANIMAL DIETS

This appendix contains the minimum and maximum amounts of energy content in the various feedstuffs forming the diet of each animal. The numbers of feed units (energy content) of each crop product are also given.

TABLE B.1 Animal diets (feed units/structural animal).

Animal	Concentrated forage		Green forage		Silage		Hay		Roughage		Minimum amount of total feed units required
	min	max	min	max	min	max	min	max	min	max	
Cows	4,284	5,881	404	901	549	929	437	1,029	0	354	6,415
Pigs	1,037										1,037
Sheep	118	158			51	94	49	90	0	54	370
Hens	57										57

TABLE B.2 Energy content of various forages.

Forage	feed units/ton
Concentrated	
maize grain	1,300
barley	1,200
wheat	1,200
wheat bran	370
soybean meal	1,150
sunflower meal	950
Green	
lucerne	200
Silage	
lucerne	340
maize silage	300
maize silage II	300
lucerne haylage	340
Hay	
lucerne	340

TABLE B.3 Energy content of roughages.

Roughage	feed units/ha
Maize grain stalks	
irrigated	
100% fertilizer	158
80% fertilizer	145
nonirrigated	72
Wheat straw	45
Barley straw	44
Sunflower residuals	830

Appendix C

TABLES OF PRODUCTION COSTS

For each crop, the following tables show all production costs associated with field cultivation activities. The costs are either attached to the land area (cost/ha) or to the input resources (cost/unit amount). The fixed costs attached to land are depreciated capital investments (machinery purchase). The variable costs include costs of application of the input resources (fertilizers and chemicals), labor other than that for operation of machines, and maintenance of the equipment. The total cost attached to land (e.g., 74.80 Lv/ha in Table C.1) is the unit cost used in the objective function of the linear programming for the crop area decision variable. The total land and resource cost (e.g., 163.71 in Table C.1) is the total production cost per hectare.

TABLE C.1 Nonirrigated lucerne production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				11.00			
variable		3.20	46.00	8.70	5.90		
Total		3.20	46.00	19.70	5.90		74.80
Attached to resources							
seeds							
ton/ha	0.0066						
Lv/ton	5,504.00						
ammonium sulfate							
ton/ha		0.10					
Lv/ton		93.72					
superphosphate							
ton/ha		0.30					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.09					
Lv/ton		85.20					
fuel							
l/ha				69.00			
Lv/l				0.19			
operator-hour							
h/ha					2.61		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	36.32	35.57		13.11	3.91		88.91
TOTAL land & resources (Lv/ha)	36.32	38.77	46.00	32.81	9.81		163.71

TABLE C.2 Irrigated lucerne production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				27.00			
variable		3.20	46.00	23.00	15.40	29.45	
Total		3.20	46.00	50.00	15.40	29.45	144.05
Attached to resources							
seeds							
ton/ha	0.0066						
Lv/ton	5,504.00						
ammonium sulfate							
ton/ha		0.19					
Lv/ton		93.72					
superphosphate							
ton/ha		0.44					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.13					
Lv/ton		85.20					
fuel							
l/ha				77.00			
Lv/l				0.19			
operator-hour							
h/ha					3.09		
Lv/h					1.50		
water							
m^3/ha						3,000.00	
Lv/m^3						0.017	
Total (Lv/ha)	36.32	56.06		14.63	4.63	51.00	162.64
TOTAL land & resources (Lv/ha)	36.32	59.26	46.00	64.63	20.03	80.45	306.69

TABLE C.3 Nonirrigated maize silage production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				40.00			
variable		8.00	7.68	34.47	12.88		
Total		8.00	7.68	74.47	12.88		103.03
Attached to resources							
seeds							
ton/ha	0.03						
Lv/ton	660.00						
ammonium sulfate							
ton/ha		0.36					
Lv/ton		93.72					
superphosphate							
ton/ha		0.55					
Lv/ton		61.77					
potassium sulfate							
ton/ha							
Lv/ton							
fuel							
l/ha				112.00			
Lv/l				0.19			
operator-hour							
h/ha					4.05		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	19.80	67.71		21.28	6.07		144.86
TOTAL land & resources (Lv/ha)	19.80	75.71	7.68	95.75	18.95		217.89

TABLE C.4 Irrigated maize silage production costs.

Cost	Seeds	Fertil- izer	Chem- icals	Machin- ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				25.00			
variable		8.00	8.60	20.00	20.60	29.45	
Total		8.00	8.60	45.00	20.60	29.45	111.65
Attached to resources							
seeds							
ton/ha	0.04						
Lv/ton	660.00						
ammonium sulfate							
ton/ha		0.80					
Lv/ton		93.72					
superphosphate							
ton/ha		0.90					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.27					
Lv/ton		85.20					
fuel							
l/ha				172.00			
Lv/l				0.19			
operator-hour							
h/ha					4.25		
Lv/h					1.50		
water							
m^3/ha						3,000.00	
Lv/m^3						0.017	
Total (Lv/ha)	26.40	153.57		32.68	6.37	51.00	270.02
TOTAL land & resources (Lv/ha)	26.40	161.57	8.60	77.68	26.97	80.45	381.67

TABLE C.5 Irrigated maize silage II production costs.

Cost	Seeds	Fertilizer	Chemicals	Machinery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				25.00			
variable		8.00	8.60	20.00	20.60	29.45	
Total		8.00	8.60	45.00	20.60	29.45	111.65
Attached to resources							
seeds							
ton/ha	0.019						
Lv/ton	660.00						
ammonium sulfate							
ton/ha		0.80					
Lv/ton		93.72					
superphosphate							
ton/ha		0.525					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.27					
Lv/ton		85.20					
fuel							
l/ha				172.00			
Lv/l				0.19			
operator-hour							
h/ha					4.25		
Lv/h					1.50		
water							
m^3/ha						1,800.00	
Lv/m^3						0.017	
Total (Lv/ha)	12.54	130.41		32.68	6.37	30.60	212.60
TOTAL land & resources (Lv/ha)	12.54	138.41	8.60	77.68	26.97	60.05	324.25

TABLE C.6 Nonirrigated maize grain production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				32.00			
variable		8.00	26.00	24.45	7.15		
Total		8.00	26.00	56.45	7.15		97.60
Attached to resources							
seeds							
ton/ha	0.015						
Lv/ton	660.00						
ammonium sulfate							
ton/ha		0.24					
Lv/ton		93.72					
superphosphate							
ton/ha		0.30					
Lv/ton		61.77					
potassium sulfate							
ton/ha							
Lv/ton							
fuel							
l/ha				85.00			
Lv/l				0.19			
operator-hour							
h/ha					2.57		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	9.90	41.02		16.15	3.85		70.92
TOTAL land & resources (Lv/ha)	9.90	49.02	26.00	72.60	11.00		168.52

TABLE C.7 Irrigated maize grain production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				23.00			
variable		8.00	24.90	21.00	11.12	29.45	
Total		8.00	24.90	44.00	11.12	29.45	117.47
Attached to resources							
seeds							
ton/ha	0.02						
Lv/ton	660.00						
ammonium sulfate							
ton/ha		0.53					
Lv/ton		93.72					
superphosphate							
ton/ha		0.60					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.20					
Lv/ton		85.20					
fuel							
l/ha				100.00			
Lv/l				0.19			
operator-hour							
h/ha					2.57		
Lv/h					1.50		
water							
m^3/ha						3,000.00	
Lv/m^3						0.017	
Total (Lv/ha)	13.20	103.77		19.00	3.85	51.00	190.82
TOTAL land & resources (Lv/ha)	13.20	111.77	24.90	63.00	14.97	80.45	308.29

TABLE C.8 Nonirrigated wheat production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				25.00			
variable		9.00	9.90	20.00	4.00		
Total		9.00	9.90	45.00	4.00		67.90
Attached to resources							
seeds							
ton/ha	0.28						
Lv/ton	130.00						
ammonium sulfate							
ton/ha		0.25					
Lv/ton		93.72					
superphosphate							
ton/ha		0.28					
Lv/ton		61.77					
potassium sulfate							
ton/ha							
Lv/ton							
fuel							
l/ha				53.00			
Lv/l				0.19			
operator-hour							
h/ha					1.63		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	36.40	40.72		10.07	2.44		89.63
TOTAL land & resources (Lv/ha)	36.40	49.72	9.90	55.07	6.44		157.53

TABLE C.9 Irrigated wheat production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				25.00			
variable		9.00	9.90	20.00	4.00	29.45	
Total		9.00	9.90	45.00	4.00	29.45	97.35
Attached to resources							
seeds							
ton/ha	0.28						
Lv/ton	130.00						
ammonium sulfate							
ton/ha		0.325					
Lv/ton		93.72					
superphosphate							
ton/ha		0.364					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.22					
Lv/ton		85.20					
fuel							
l/ha				60.00			
Lv/l				0.19			
operator-hour							
h/ha					1.63		
Lv/h					1.50		
water							
m^3/ha						600.00	
Lv/m^3						0.017	
Total (Lv/ha)	36.40	71.68		11.40	2.44	10.20	132.12
TOTAL land & resources (Lv/ha)	36.40	80.68	9.90	56.40	6.44	39.65	229.47

TABLE C.10 Nonirrigated barley production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				20.00			
variable		3.00	9.60	15.80	1.80		
Total		3.00	9.60	35.80	1.80		50.20
Attached to resources							
seeds							
ton/ha	0.19						
Lv/ton	120.00						
ammonium sulfate							
ton/ha		0.167					
Lv/ton		93.72					
superphosphate							
ton/ha		0.15					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.07					
Lv/ton		85.20					
fuel							
l/ha				50.00			
Lv/l				0.19			
operator-hour							
h/ha					1.41		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	22.80	30.87		9.50	2.11		65.28
TOTAL land & resources (Lv/ha)	22.80	33.87	9.60	45.30	3.91		115.48

TABLE C.11 Irrigated barley production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				20.00			
variable		3.00	9.60	15.80	1.80	29.45	
Total		3.00	9.60	35.80	1.80	29.45	79.65
Attached to resources							
seeds							
ton/ha	0.209						
Lv/ton	120.00						
ammonium sulfate							
ton/ha		0.21					
Lv/ton		93.72					
superphosphate							
ton/ha		0.24					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.135					
Lv/ton		85.20					
fuel							
l/ha				57.00			
Lv/l				0.19			
operator-hour							
h/ha					1.41		
Lv/h					1.50		
water							
m^3/ha						600.00	
Lv/m^3						0.017	
Total (Lv/ha)	25.08	46.00		10.83	2.11	10.20	94.22
TOTAL land & resources (Lv/ha)	25.08	49.00	9.60	46.63	3.91	39.65	173.87

TABLE C.12 Nonirrigated soybean production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				32.00			
variable		10.75	73.00	18.00	9.36		
Total		10.75	73.00	50.00	9.36		143.11
Attached to resources							
seeds							
ton/ha	0.10						
Lv/ton	700.00						
ammonium sulfate							
ton/ha		0.12					
Lv/ton		93.72					
superphosphate							
ton/ha		0.225					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.07					
Lv/ton		85.20					
fuel							
l/ha				65.00			
Lv/l				0.19			
operator-hour							
h/ha					5.00		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	70.00	31.11		12.35	7.50		120.96
TOTAL land & resources (Lv/ha)	70.00	41.86	73.00	62.35	16.86		264.07

TABLE C.13 Irrigated soybean production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				32.00			
variable		10.75	73.00	18.00	9.36	29.45	
Total		10.75	73.00	50.00	9.36	29.45	172.56
Attached to resources							
seeds							
ton/ha	0.10						
Lv/ton	700.00						
ammonium sulfate							
ton/ha		0.17					
Lv/ton		93.72					
superphosphate							
ton/ha		0.32					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.11					
Lv/ton		85.20					
fuel							
l/ha				65.00			
Lv/l				0.19			
operator-hour							
h/ha					5.92		
Lv/h					1.50		
water							
m^3/ha						3,000.00	
Lv/m^3						0.017	
Total (Lv/ha)	70.00	45.07		12.35	8.88	51.00	187.30
TOTAL land & resources (Lv/ha)	70.00	55.82	73.00	62.35	18.24	80.45	359.86

TABLE C.14 Nonirrigated sunflower production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				20.57			
variable		9.00	26.00	16.80	5.00		
Total		9.00	26.00	37.37	5.00		77.37
Attached to resources							
seeds							
ton/ha	0.06						
Lv/ton	307.00						
ammonium sulfate							
ton/ha		0.40					
Lv/ton		93.72					
superphosphate							
ton/ha		0.32					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.02					
Lv/ton		85.20					
fuel							
l/ha				52.00			
Lv/l				0.19			
operator-hour							
h/ha					2.12		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)	18.42	58.96		9.88	3.18		90.44
TOTAL land & resources (Lv/ha)	18.42	67.96	26.00	47.25	8.18		167.81

TABLE C.15 Irrigated sunflower production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				20.50			
variable		9.00	26.00	16.80	5.00	29.45	
Total		9.00	26.00	37.30	5.00	29.45	106.75
Attached to resources							
seeds							
ton/ha	0.066						
Lv/ton	307.00						
ammonium sulfate							
ton/ha		0.52					
Lv/ton		93.72					
superphosphate							
ton/ha		0.416					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.026					
Lv/ton		85.20					
fuel							
l/ha				55.00			
Lv/l				0.19			
operator-hour							
h/ha					2.12		
Lv/h					1.50		
water							
m^3/ha						2,400.00	
Lv/m^3						0.017	
Total (Lv/ha)	20.26	76.64		10.45	3.18	40.8	151.33
TOTAL land & resources (Lv/ha)	20.26	85.64	26.00	47.75	8.18	70.25	258.08

TABLE C.16 Nonirrigated orchards production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				100.00			
variable		3.00	230.00	33.00	18.00		
Total		3.00	230.00	133.00	18.00		384.00
Attached to resources							
seeds							
ton/ha							
Lv/ton							
ammonium sulfate							
ton/ha		0.40					
Lv/ton		93.72					
superphosphate							
ton/ha		0.35					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.25					
Lv/ton		85.20					
fuel							
l/ha				70.00			
Lv/l				0.19			
operator-hour							
h/ha					56.00		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)		80.41		13.30	84.00		177.71
TOTAL land & resources (Lv/ha)		83.41	230.00	146.30	102.00		561.71

TABLE C.17 Irrigated orchards production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				100.00			
variable		3.00	230.00	33.0	20.00	29.45	
Total		3.00	230.00	133.00	20.00	29.45	415.45
Attached to resources							
seeds							
ton/ha							
Lv/ton							
ammonium sulfate							
ton/ha		0.60					
Lv/ton		93.72					
superphosphate							
ton/ha		0.40					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.30					
Lv/ton		85.20					
fuel							
l/ha				87.00			
Lv/l				0.19			
operator-hour							
h/ha					69.00		
Lv/h					1.50		
water							
m^3/ha						2,500.00	
Lv/m^3						0.017	
Total (Lv/ha)		106.50		16.53	103.50	42.50	269.03
TOTAL land & resources (Lv/ha)		109.50	230.00	149.53	123.50	71.95	684.48

TABLE C.18 Nonirrigated tobacco production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				25.00			
variable		5.00	240.00	5.00	8.00		
Total		5.00	240.00	30.00	8.00		283.00
Attached to resources							
seeds							
ton/ha							
Lv/ton							
ammonium sulfate							
ton/ha							
Lv/ton							
superphosphate							
ton/ha		0.60					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.40					
Lv/ton		85.20					
fuel							
l/ha				150.00			
Lv/l				0.19			
operator-hour							
h/ha					25.00		
Lv/h					1.50		
water							
m^3/ha							
Lv/m^3							
Total (Lv/ha)		71.14		28.50	37.50		137.14
TOTAL land & resources (Lv/ha)		76.14	240.00	58.50	45.50		420.14

TABLE C.19 Irrigated tobacco production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				20.00			
variable		3.00	240.00	5.00	8.00	29.45	
Total		3.00	240.00	25.00	8.00	29.45	305.45
Attached to resources							
seeds							
ton/ha							
Lv/ton							
ammonium sulfate							
ton/ha							
Lv/ton							
superphosphate							
ton/ha		0.50					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.40					
Lv/ton		85.20					
fuel							
l/ha				100.00			
Lv/l				0.19			
operator-hour							
h/ha					25.00		
Lv/h					1.50		
water							
m^3/ha						2,500.00	
Lv/m^3						0.017	
Total (Lv/ha)		64.96		19.00	37.50	42.50	163.96
TOTAL land & resources (Lv/ha)		67.96	240.00	44.00	45.50	71.95	469.41

TABLE C.20 Irrigated vegetables production costs.

Cost	Seeds	Fertil-izer	Chem-icals	Machin-ery	Labor	Irrigation	Total costs
Attached to land (Lv/ha)							
fixed				38.00			
variable		10.00	184.00	12.00	40.00	29.45	
Total		10.00	184.00	50.00	40.00	29.45	313.45
Attached to resources							
seeds							
ton/ha	0.35						
Lv/ton	240.00						
ammonium sulfate							
ton/ha		0.75					
Lv/ton		93.72					
superphosphate							
ton/ha		0.60					
Lv/ton		61.77					
potassium sulfate							
ton/ha		0.27					
Lv/ton		85.20					
fuel							
l/ha				270.00			
Lv/l				0.19			
operator-hour							
h/ha					180.00		
Lv/h					1.50		
water							
m^3/ha						4,300.00	
Lv/m^3						0.017	
Total (Lv/ha)	84.00	130.35		51.30	270.00	73.10	608.75
TOTAL land & resources (Lv/ha)	84.00	140.35	184.00	101.30	310.00	102.55	922.20

Appendix D

COEFFICIENTS FOR IRRIGATION WATER USE

This appendix describes how the coefficients for irrigation water use in SWIM2 are derived. The general method is described first, followed by the details of rainfall, evapotranspiration, soil moisture capacity, the computation of the coefficients, and irrigation efficiency.

The aim of the computation is to find irrigation water use coefficients and an irrigation efficiency to use in the SWIM2 model to calculate the total volume of irrigation water over time, $W(t)$, that must be withdrawn from the Danube River.

$$W(t) = \frac{1}{e} \sum_{s=1}^{3} \sum_{i=1}^{11} \sum_{q=1}^{2} I_{si}^{q}(t)\, Y_{si}^{q} \qquad \text{(D.1)}$$

where

$W(t)$ is irrigation water demanded ($m^3/10$ days) in the complex

e is the irrigation efficiency

Y_{si}^{q} is amount of land (ha) in subregion s needed for production of crop i on an irrigated area using technology q

$I_{si}^{q}(t)$ is the irrigation water use coefficient in normal weather (m^3/ha/10 days) of crop i in subregion s using technology q at time t, $t = 1, \ldots, T$

There are 21 ($T = 21$) periods over the 7-month time horizon from 1 March to 31 September. Each month comprises three periods: days 1–9, 10–19, and 20–end. Although irrigation is not necessary before 1 May, the calculations of irrigation water use coefficients begin on 1 March to allow for soil moisture depletion during March and April. Hence, in the SWIM2 model, irrigation water use is accounted for in 15 periods, 3 per month from 1 May to 30 September.

The total water used in the irrigation season, X_{20} (m^3/yr), is computed as

$$X_{20} = \sum_{t=1}^{15} W(t) \qquad t = 1,2, \ldots, 15 \qquad \text{(D.2)}$$

The input data needed for SWIM2 to determine $W(t)$ and X_{20} are the irrigation water use coefficients $I_{si}^{q}(t)$ and the irrigation efficiency e, which is assumed to be constant for all crops and time periods. It is furthermore assumed that $I_{si}^{q}(t)$ do not vary with subregions s and with the technology of producing crops q. Since all calculations that follow exemplify the way that these coefficients are obtained for any of the 11 crops, the index i is omitted. In the text that follows, the irrigation water use coefficient in period t will be denoted by I_t.

D.1 METHOD

The analysis is carried out for 10 crops: lucerne, maize silage, maize silage II (sown after the barley and wheat harvests), maize grain, wheat, barley, soybeans, sunflowers, tobacco, and vegtables, under two weather conditions: average weather and a 1-in-4 dry year. The 1-in-4 dry year is chosen because this is the weather condition assumed by the Bulgarian Research Institute Vodproject in its design of pumps and pipelines for a new irrigation area in the Drustar complex. The calculations are not done for orchards although they are included in SWIM2 as a crop activity. The root depths appropriate for orchards in Silistra were not known precisely at the time and it was thought better to use directly the coefficients proposed by Vodproject, Sofia, than to assume a root depth arbitrarily.

Data on monthly mean rainfall, temperature, humidity, and wind speed, measured in Silistra in each year from 1961 to 1970, are used in deriving the SWIM2 coefficients. Average weather conditions for each month are estimated by averaging the 10 yr of data. The weather conditions for 1961 are chosen as the 1-in-4 dry year from a probability analysis of the rainfall that is described in Section D.2.

For each crop, the general soil moisture balance model shown in Figure D.1 is used:

$$
\begin{aligned}
&S_t = S_{t-1} + R_t - E_t + I_t - D_t \qquad t = 1,2,\ldots,T \\
&S_t, S_{t-1}, R_t, E_t, I_t, D_t \geq 0
\end{aligned}
\tag{D.3}
$$

where

S_t, S_{t-1} is available soil moisture at the end of periods t and $t-1$, respectively (mm)

R_t is rainfall in period t (mm/10 days)

E_t is evapotranspiration in period t (mm/10 days)

I_t is irrigation water use in period t (mm/10 days)

D_t is drainage in period t (mm/10 days)

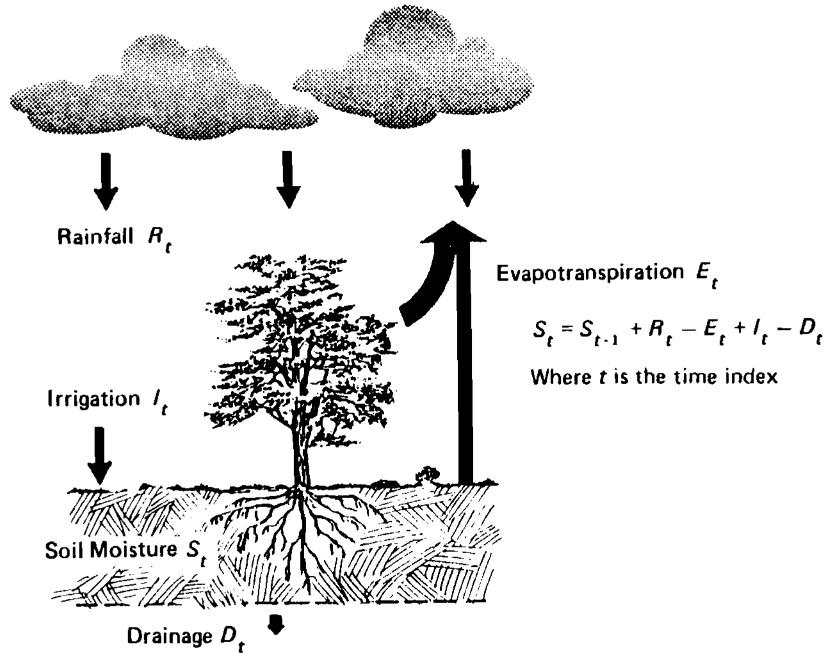


FIGURE D.1 Soil moisture balance model. Two analyses were done for each crop for average weather conditions (1961–1970) and for the 1-in-4 dry year (1961).

In the application of this model, a number of rules are specified to determine when irrigation and drainage occur. These are detailed in Section D.5. The calculations were done using a FORTRAN computer program that was run on the PDP 11/45 at IIASA; (a listing of the program is attached to the computational results in Gouevsky *et al.* (1978)).

The various components of the soil moisture balance model are described below in more detail.

D.2 RAINFALL

The mean monthly rainfall data recorded in Silistra from 1961 to 1970 are shown in Table D.1. To determine which year could be adopted as representing the 1-in-4 dry year, a probability analysis of both annual and irrigation season (May–September) rainfall is carried out (Chow 1964, Section 8).

In each case, the data are ranked according to depth of rainfall and assigned a rank number m ($m = 1$ for the greatest depth). The probability P that the actual rain fall R_a will equal or exceed each data value R is then estimated as:

$$P(R_a \geqslant R) = m/(n + 1) \qquad \text{(D.4)}$$

TABLE D.1 Monthly mean rainfall recorded at Silistra (mm).

Month	Year 1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Average 1961–70
Jan	27	20	35	6	0	161	26	56	15	8	35.4
Feb	28	38	45	21	36	8	18	14	130	82	42.0
Mar	24	40	18	8	25	43	27	14	18	58	27.5
Apr	27	71	21	11	34	23	12	1	48	26	27.4
May	58	38	34	39	137	50	16	8	53	104	53.7
Jun	38	12	31	67	31	116	80	36	136	54	60.1
Jul	54	21	21	30	33	20	31	66	99	55	43.0
Aug	29	2	26	68	6	37	52	58	36	104	41.8
Sep	0	3	31	107	0	92	36	49	10	2	33.0
Oct	17	20	11	33	6	31	22	32	0	56	22.8
Nov	9	41	7	37	54	151	4	65	4	36	40.8
Dec	41	23	40	24	60	96	53	21	186	16	56.0
Annual total	352	329	320	451	422	828	377	420	735	601	483.5

where n is the number of data ($n = 10$). The resulting probabilities are shown in Table D.2 and plotted in Figure 8. As an example of the exceedance probability calculations, consider the annual rainfall for 1961 (352 mm). This rainfall has rank 8 out of 10, so the probability that the observed rainfall in any given year will exceed 354 mm is estimated as 8/11 or 0.7273.

The rainfall in the 1-in-4 dry year will be exceeded in 3 years out of 4, or 75 percent of the time. The nearest exceedance probability to 0.75 is 0.7273 for rank $m = 8$. Since this probability happens to correspond to the year 1961 for both the annual and irrigation season rainfalls, the data for 1961 are adopted as representing the 1-in-4 dry year. It may be noted in passing that a similar attempt was made to locate an average year in Table D.2 (exceedance probability = 0.5), but no year was so clearly an average year as 1961 was a dry year. The nearest year to the average was 1968, for which a complete analysis of irrigation water use coefficients was carried out. It turned out, however, that the rainfall in March and April was abnormally low in 1968 so that the resulting irrigation water use coefficients were distorted by these unusual weather conditions. For this reason, the 1968 results were discarded and an average year was defined from the mean monthly data averaged over the 1961–70 period.

It would have been desirable to have a longer data series for rainfall to evaluate the design conditions more properly but, unfortunately, these data were not available. It would also have been desirable to use effective rather than total rainfall. The irrigation water use coefficients found from our analysis turn out to be a little higher, in most cases, than those computed by Vodproject, Sofia. If effective rainfall had been used, this difference would have been accentuated so this point was not pursued further.

TABLE D.2 Probability analysis of rainfall.

Rank (m)	Exceedance probability	May–September		Annual	
		Year	Rainfall (mm)	Year	Rainfall (mm)
1	0.0909	1969	334	1966	828
2	0.1818	1970	319	1969	735
3	0.2727	1966	315	1970	601
4	0.3636	1964	311	1964	451
5	0.4545	1968	217	1965	422
6	0.5454	1967	215	1968	420
7	0.6363	1965	207	1967	377
8[a]	0.7273	1961	179	1961	352
9	0.8182	1963	143	1962	329
10	0.9091	1962	76	1963	320

[a] 1-in-4 dry year.

D.3 EVAPOTRANSPIRATION

Evapotranspiration includes both evaporation of water from the soil surface and transpiration through the plant leaves. Since the contribution of these two components varies according to the stage of plant growth, the actual evapotranspiration E_t is found as:

$$E_t = k_c P_t \tag{D.5}$$

in which k_c is a coefficient depending on the crop and its stage of growth and P_t is the potential evapotranspiration (mm/10 days) for a reference crop (grass) grown over a wide area with unlimited soil moisture.

Potential evapotranspiration was computed using the Penman method as described by Doorenbos and Pruitt (1977). Of all the methods of measuring potential evapotranspiration without an evaporation pan, the Penman method has been found in many parts of the world to be one of the best. Potential evapotranspiration is found as the sum of an energy component (from solar radiation) and an aerodynamic component (from transport of the moisture away from the plant and soil surface).

This requires concurrent measured data on temperature, humidity, wind speed, and cloudiness. Monthly mean data for 1961–70 were obtained for the first three of these factors (Tables D.3 to D.5). Cloudiness was estimated by relating it to temperature using 1974 data. Temperature and cloudiness have a hysteresis-type relationship owing to the heating and cooling of the earth (Figure D.2). Given the monthly mean temperature the cloudiness can then be found. For radiation calculations Silistra is located at latitude 44° N.

TABLE D.3 Monthly mean temperature recorded at Silistra (°C).

Month	Year 1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Average 1961–70
Jan	−0.5	−1.5	−7.3	−4.7	1.3	−1.1	−2.3	−1.3	−5.5	0.5	−2.24
Feb	2.2	0.3	−0.2	0.3	−2.1	6.7	−0.3	3.9	−0.5	2.0	1.23
Mar	9.1	4.6	3.2	4.6	5.8	7.3	6.9	6.5	1.7	7.3	5.70
Apr	14.6	12.0	10.6	12.7	9.1	14.0	11.0	15.0	10.9	13.8	12.37
May	15.8	18.2	17.8	17.6	16.0	17.1	17.0	20.7	18.7	15.5	17.44
Jun	21.2	20.3	21.7	22.2	21.4	19.5	19.8	21.5	20.3	20.3	20.82
Jul	22.5	23.3	24.3	22.7	23.2	23.6	28.0	22.3	20.5	23.6	23.40
Aug	22.4	24.5	24.3	21.3	20.7	22.9	23.3	21.1	22.6	21.6	22.47
Sep	18.4	18.4	19.6	13.7	19.6	17.8	19.2	18.6	18.2	17.3	18.08
Oct	12.4	13.4	13.1	14.6	11.0	16.5	14.0	11.8	11.8	10.9	12.95
Nov	9.4	10.0	10.7	8.9	5.4	8.1	8.0	7.8	11.4	8.9	8.86
Dec	0.6	−1.5	−1.3	3.4	3.7	2.1	2.1	0.1	1.5	3.4	1.41

TABLE D.4 Monthly mean humidity recorded at Silistra (%).

Month	Year 1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Average 1961–70
Jan	83	89	82	83	83	88	81	82	84	86	84.1
Feb	80	81	83	83	77	80	83	82	87	82	81.8
Mar	65	77	75	80	77	74	75	67	86	73	74.9
Apr	66	70	73	65	74	74	67	56	70	68	68.3
May	77	66	72	72	72	68	67	62	62	74	69.2
Jun	72	65	60	71	67	70	70	66	73	71	68.5
Jul	65	65	67	65	63	66	62	66	76	68	66.3
Aug	64	59	62	67	65	70	80	73	68	72	68.0
Sep	62	67	66	74	69	74	74	73	74	69	70.2
Oct	79	75	73	76	70	78	80	75	71	76	75.3
Nov	79	86	70	84	83	89	80	89	66	76	80.2
Dec	81	85	85	87	89	85	81	85	89	86	85.3

TABLE D.5 Monthly mean wind speed recorded at Silistra (m/sec).

Month	Year 1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Average 1961–70
Jan	2.1	2.4	4.5	3.8	3.4	2.7	2.5	4.1	3.9	2.6	3.20
Feb	2.7	4.6	3.8	4.4	4.8	2.7	3.2	2.3	4.3	3.4	3.62
Mar	3.6	4.6	4.5	3.3	3.0	3.0	2.5	3.5	4.7	2.7	3.54
Apr	4.1	3.5	3.6	4.0	3.6	2.8	3.6	4.3	3.5	3.1	3.61
May	3.4	3.6	3.3	3.5	2.8	4.3	3.6	4.2	3.9	3.2	3.58
Jun	2.7	2.2	3.4	2.7	3.1	0.6	2.5	2.7	3.1	2.3	2.53
Jul	3.7	3.1	2.4	2.5	2.6	2.4	1.8	2.6	2.1	2.6	2.58
Aug	2.8	2.7	3.3	2.7	2.4	2.6	1.7	2.5	2.0	2.2	2.49
Sep	2.4	3.1	2.2	3.7	2.3	2.0	2.1	2.4	2.1	1.7	2.40
Oct	3.6	2.8	2.8	2.2	1.6	2.1	2.3	1.9	1.8	2.1	2.32
Nov	2.4	3.0	3.4	2.5	2.2	2.6	2.2	3.4	3.9	3.2	2.88
Dec	3.6	5.2	2.7	2.7	1.8	2.7	3.5	2.1	3.9	2.3	3.05

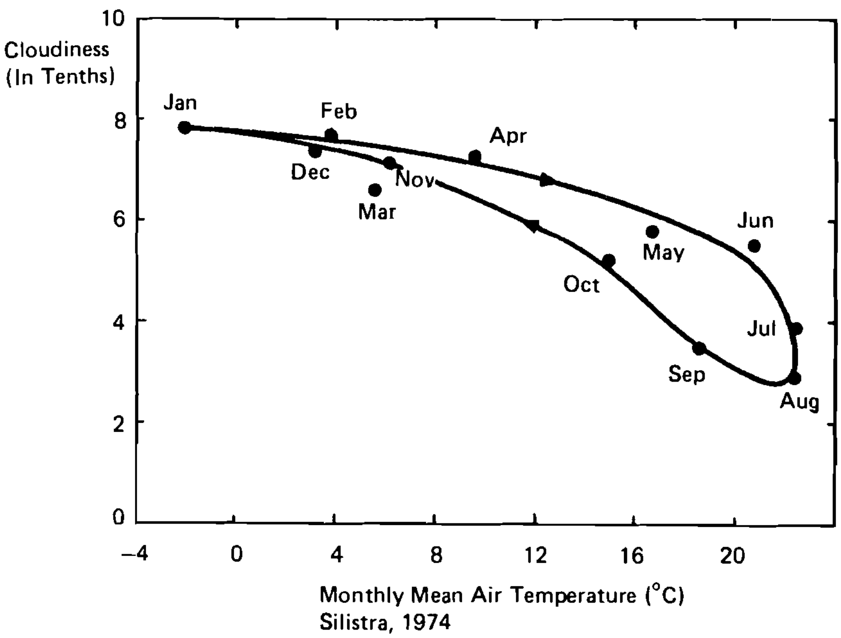


FIGURE D.2 Cloudiness and temperature.

All of these data are inputs to the calculation of potential evapotranspiration by the Penman method. The data obtained at each step in the calculations are shown in Table D.6, in which Doorenbos and Pruitt's notation is used. It may be noted that evapotranspiration is computed from March to October 1961, since the other months do not enter the soil moisture analysis. The average January temperature (– 2.24 °C) is too low to permit calculation of evapotranspiration.

The crop coefficients k_c are estimated for each plant and stage of growth also by reference to Doorenbos and Pruitt (1977). The scheduling of planting and harvesting in the Drustar complex was considered in defining the length and timing of the growing season for each crop. This growing season was further subdivided for definition of k_c according to the growth characteristics of each crop. Generally, actual evapotranspiration is around 0.4 of the potential when the crop has just been sown; the proportion rises as the crop grows to a maximum when full vegetative growth has been completed; as the grain is being formed evapotranspiration again falls below the potential. Values of k_c can therefore be defined for the various stages of crop growth, as shown in Figure D.3. The values adopted for each crop are shown in Table D.7.

D.4 SOIL MOISTURE CAPACITY

The soil moisture available to plants is contained in the depth d in meters of the soil penetrated by the roots. The amount of moisture contained in this zone varies with the characteristics of the soil. A water-holding capacity H (mm water/m soil) may be defined as the amount of water retained in the soil once it has been saturated and after all drainage has ceased. Soils with fine texture (silt-clay) have a high water-holding capacity (200 mm/m), while sandy soils have a lower value of H (60 mm/m).

Not all moisture contained in the soil is available to the plants because their roots do not penetrate everywhere and some water is bound very tightly to the soil particles. Some proportion p (usually 50 percent) of the total soil moisture is considered to be readily available to the plants. The plant can therefore be regarded conceptually as if it were sitting in a tank of water (see Figure D.4) whose capacity S_c is computed as:

$$S_c = pHd \qquad \text{(D.6)}$$

For the Drustar complex, the fine chernozem soil is predominant, so a value of 200 mm/m (Doorenbos and Pruitt 1977: 86) is adopted for H. The values for p and d for each crop are given in Table D.8. The resulting values of S_c range from 24 mm (vegetables) to 220 mm (lucerne). As mentioned previously, it was not possible to estimate reliably the root depth d for orchards so the irrigation water use coefficients proposed for orchards by the Vodproject, Sofia, were adopted without further analysis.

TABLE D.6 Evapotranspiration data from Penman method.

	T_{av} (°C)	RH_{av} (%)	Wind (U) (m/sec)	Cloud (tenths)	e_a (mbar)	e_d (mbar)	e_a-e_d (mbar)	$f(U)$	$1-W$	Aero. Term. $(1-W)f(U)(e_a-e_d)$	R_a (mm/day)
Average 1961–70											
Feb	1.2	82	3.6	7.6	6.7	5.5	1.21	1.11	0.58	0.78	7.6
Mar	5.7	75	3.5	7.4	9.1	6.8	2.27	1.09	0.51	1.26	10.6
Apr	12.4	68	3.6	6.8	14.4	9.8	4.61	1.11	0.41	2.10	13.7
May	17.4	69	3.6	6.0	19.9	13.7	6.2	1.11	0.35	2.41	16.1
Jun	20.8	69	2.5	5.1	24.6	17.0	7.6	0.90	0.30	2.05	17.2
Jul	23.4	66	2.6	3.5	28.8	19.0	9.8	0.88	0.28	2.41	16.6
Aug	22.5	68	2.5	2.8	27.3	18.6	8.7	0.90	0.29	2.27	14.7
Sep	18.1	70	2.4	3.7	20.7	14.5	6.2	0.83	0.34	1.75	11.9
Oct	13.0	75	2.3	5.6	15.0	11.3	3.7	0.81	0.41	1.23	8.7
Nov	8.9	80	2.9	6.5	11.4	9.1	2.28	0.95	0.47	1.02	6.0
Dec	1.4	85	3.1	7.7	6.8	5.8	1.02	0.99	0.58	0.58	4.7
1961											
Mar	9.1	65	3.6	7.0	11.6	7.5	4.06	1.11	0.46	2.07	10.6
Apr	14.6	66	4.1	6.5	16.6	11.0	5.6	1.23	0.38	2.62	13.7
May	15.8	77	3.4	6.3	18.0	13.8	4.13	1.06	0.36	1.58	16.1
Jun	21.2	72	2.7	4.9	25.2	18.1	7.06	0.90	0.30	1.91	17.2
Jul	22.5	65	3.7	3.8	27.3	17.7	9.54	1.13	0.29	3.13	16.6
Aug	22.4	64	2.8	2.9	27.1	17.3	9.75	0.92	0.29	2.60	14.7
Sep	18.4	62	2.4	3.6	21.2	13.1	8.04	0.83	0.34	2.21	11.9
Oct	12.4	79	3.6	5.8	14.4	11.4	3.0	1.11	0.42	1.40	8.7

(TABLE D.6 *Continued.*)

	$^n/N$	R_a	R_{ns}	$f(T)$	$f(e_d)$	$f(^n/N)$	R_{n1}	R_n	W	Rad. Term. WR_n (mm/day)	P (mm/day)	P (mm/mo.)
Average 1961–70												
Feb	0.34	3.19	2.39	11.2	0.237	0.406	1.08	1.31	0.42	0.55	1.33	37
Mar	0.36	4.56	3.42	12.0	0.225	0.424	1.15	2.27	0.49	1.11	2.37	73
Apr	0.42	6.30	4.73	13.2	0.202	0.478	1.27	3.46	0.59	2.04	4.14	124
May	0.50	8.05	6.04	14.0	0.177	0.55	1.36	4.68	0.65	3.04	5.45	169
Jun	0.55	9.03	6.77	14.8	0.158	0.595	1.39	5.38	0.70	3.77	5.82	175
Jul	0.70	9.96	7.47	15.3	0.148	0.73	1.65	5.82	0.72	4.19	6.60	205
Aug	0.76	9.26	6.95	15.1	0.150	0.784	1.78	5.17	0.71	3.67	5.94	184
Sep	0.66	6.90	5.18	14.2	0.172	0.694	1.70	3.48	0.66	2.30	4.05	122
Oct	0.52	4.44	3.33	13.3	0.192	0.568	1.45	1.88	0.59	1.11	2.34	73
Nov	0.45	2.85	2.14	12.5	0.207	0.505	1.31	0.83	0.53	0.44	1.46	44
Dec	0.33	1.95	1.43	11.2	0.234	0.397	1.04	0.42	0.42	0.18	0.77	24
1961												
Mar	0.40	4.77	3.56	12.6	0.219	0.46	1.27	2.26	0.54	1.24	3.31	103
Apr	0.45	6.50	4.88	13.6	0.194	0.505	1.33	3.65	0.62	2.20	4.82	145
May	0.47	7.81	5.86	13.8	0.176	0.523	1.27	4.59	0.64	2.94	4.52	140
Jun	0.56	9.11	6.84	14.8	0.153	0.604	1.37	5.47	0.70	3.83	5.74	172
Jul	0.67	9.71	7.28	15.1	0.155	0.703	1.65	5.63	0.71	4.00	7.13	221
Aug	0.75	9.19	6.89	15.1	0.157	0.775	1.84	5.05	0.71	3.59	6.19	192
Sep	0.69	7.08	5.31	14.3	0.181	0.721	1.87	3.44	0.68	2.34	4.61	138
Oct	0.15	4.39	3.30	13.2	0.191	0.559	1.48	1.82	0.58	1.06	2.46	76

AFTER: Calculated using methodology from Doorenbos and Pruitt 1977.

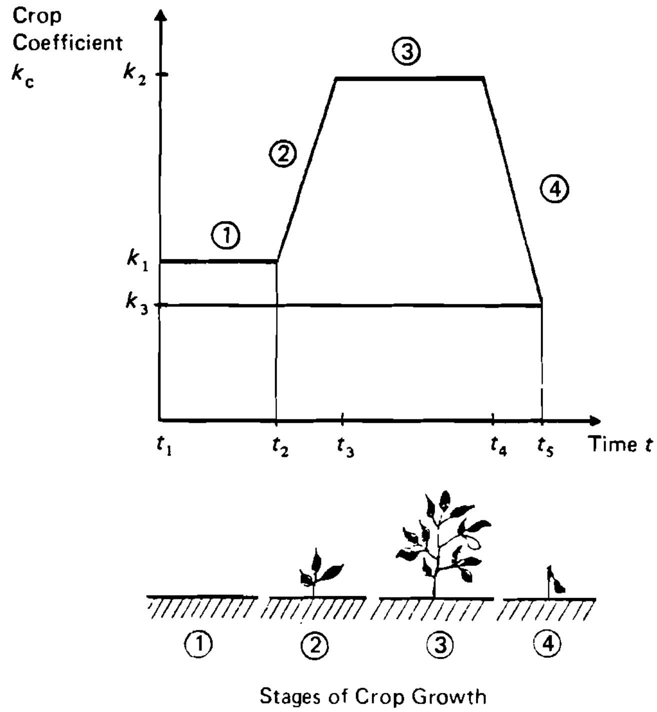


FIGURE D.3 Parameters of the crop coefficients.

TABLE D.7 Crop coefficients.

Crop	t_1	t_2	t_3	t_4	t_5	k_1	k_2	k_3
Lucerne[a,b]		3	7	19		0.38	0.80	
Maize silage[b]	7	10	14	19		0.38	1.00	
Maize silage II[b]	13	15	18	22		0.28	1.00	
Maize grain	5	8	12	18	22	0.38	1.00	0.55
Wheat[a]		3	6	10	13	0.38	1.00	0.25
Barley[a]		3	6	10	12	0.38	1.00	0.25
Soybeans	6	8	12	18	21	0.38	0.80	0.45
Sunflowers	3	6	10	15	18	0.38	0.90	0.4
Tobacco	5	8	12	15	18	0.38	0.90	0.4
Vegetables	6	9	12	18	21	0.38	1.00	0.4

MAR APR MAY JUN
NOTE: The time index t refers to 10-day periods as follows: 1 2 3 4 5 6 7 8 9 10 11 12
JUL AUG SEP OCT
13 14 15 16 17 18 19 20 21 22. Times given in the table refer to the beginning of the period. The stages of crop growth are shown in Figure D.3.

[a]No stage 1.

[b]No stage 4.

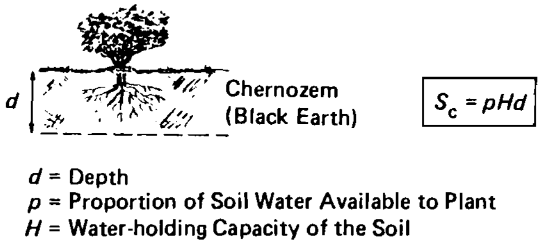


FIGURE D.4 Soil moisture capacity.

TABLE D.8 Values of d and p and resulting soil moisture capacity for each crop.

Crop	Root depth d (m)	Proportion p	Soil moisture capacity S_c (mm)[a]
Lucerne	2.0	0.55	220
Maize silage	1.5	0.50	150
Maize silage II	1.0	0.50	100
Maize grain	1.5	0.60	180
Wheat	1.2	0.55	132
Barley	1.2	0.55	132
Soybeans	1.0	0.50	100
Sunflowers	1.2	0.45	108
Tobacco	1.0	0.35	70
Vegetables	0.6	0.20	24

[a] $S_c = 200\,pd$.

It should be noted that the soil moisture capacities so computed refer to the water available to the plants, not to the total water in the soil. The soil moisture analysis described in Section D.5 also refers to this available water.

D.5 COMPUTATION OF CROP WATER USE COEFFICIENT

All of the input data needed to compute the crop water use coefficients I_t by means of Eq. (D.3) have now been developed. Rainfall and potential evapotranspiration may be compared in Table D.9. In an average year potential evapotranspiration exceeds rainfall from March through October or November, which creates a potential moisture deficit throughout the growing seasons. The accumulated precipitation over the winter months (November to February) exceeds potential evapotranspiration so the soil moisture reservoir can be assumed full on 1 March, the date on which the earliest field cultivation operations begin.

To facilitate the computation it is assumed that a standard depth of irrigation water of 60 mm could be applied in one irrigation during a 10-day period. This standard depth is also used by the Vodproject in their analysis for the Silistra

TABLE D.9 Rainfall and potential evapotranspiration for Silistra (mm/month).

	Potential Evapotranspiration		Rainfall	
Month	1961–70	1961	1961–70	1961
Jan			35	27
Feb	37		42	28
Mar	73	103	28	24
Apr	124	145	27	27
May	169	140	54	58
Jun	175	172	60	38
Jul	205	221	43	54
Aug	184	192	42	29
Sept	122	138	33	0
Oct	73	76	23	17
Nov	44		41	9
Dec	24		56	41

region. The choice of the 60-mm irrigation depth is made because most of the crops have more than 150 mm of available moisture; to refill this amount in one irrigation would require continuous sprinkling for about 1 day, which would probably be an excessive irrigation time because the land is sloping and the soil is susceptible to erosion.

The irrigation equipment is assumed to be of the "Blue Arrow" type which consists of stationary pipes and sprinklers that are towed by tractor from one position in the field to the next. Under standard conditions, "Blue Arrow" applies 6.9 mm/h so the 60-mm depth adopted corresponds to an irrigation time of 8.7 h in each position. This is consistent with the usual practice, enabling the sprinklers to be moved twice a day, once in the morning and once in the evening.

The computations are begun on 1 March when it is assumed that the soil moisture reservoir is full ($S_0 = S_c$). Rainfall and potential evapotranspiration are considered to be constant over the month and the values of R_t and P_t for each 10-day period are found as one-third of the monthly values given in Table D.9. To get E_t, Eq. (D.5) is used. Since the value of k_c in this equation can change within the month, E_t is not constant over the month. Computations proceed forward in time. Typically, in each 10-day period, a trial value S'_t of soil moisture at the end of the period is computed as:

$$S'_t = S_{t-1} + R_t - E_t \qquad \text{(D.7)}$$

Various possibilities exist depending on the value of S'_t.

- If $S_t' > S_c$, then drainage D_t

$$D_t = S_t' - S_c \tag{D.8}$$

occurs and the final soil moisture $S_t = S_c$
- If $S_c - 60 < S_t' \leqslant S_c$, then no irrigation or drainage occurs and $S_t = S_t'$
- If $S_t' \leqslant S_c - 60$, then irrigation I_t of 60 mm occurs and $S_t = S_t' + 60$

A slightly different procedure is adopted for vegetables since their S_c of 24 mm is so small. I_t is computed so as to meet the deficit of rainfall and no drainage is assumed to occur.

The calculations are terminated on 30 September since only harvesting remains to be done after this date. Near the end of the growing season it is not appropriate to continue irrigating grain crops because dryer soils encourage the formation of grain and make it easier for the harvesting machines to function. To account for this, the accumulated deficit S_t'' until the end of the growing season is computed:

$$S_t'' = \sum_{\tau=t+1}^{T} (E_\tau - R_\tau) \tag{D.9}$$

When the available soil moisture S_t is sufficient to meet this expected deficit, i.e., $S_t \geqslant S_t''$, then irrigation calculations are terminated. It should be noted that this soil moisture refers to available rather than total moisture in the soil. Allowing S_t to fall near zero at the end of the growing season means that the crop is at no time under moisture stress. Considerable moisture may still remain in the soil – see Eq. (D.6).

An example of this calculation for maize grain under average weather conditions is shown in Table D.10. Irrigation occurs when S_t' falls to 120 mm or below. The calculations are determined after period 16 because available soil moisture (S_t = 145 mm) is enough to meet the expected future deficit (S_t'' = 136 mm).

In all, 20 analyses of this type are carried out (10 crops, 2 weather conditions). The values of I_t so derived for each irrigated crop in each 10-day period are then substituted into SWIM2's tableau in the column of that irrigated crop activity, and the row of that 10-day period and weather condition. SWIM2 computes $W(t)$ and X_{20} – see Eqs. (D.1) and (D.2) as part of its solution procedure, given also the estimate of irrigation efficiency detailed in section D.6. The sum over all periods of the I_t values for each crop is shown in Table D.11. The details of the distribution of I_t over time are contained in the computational results in Gouevsky *et al.* (1978).

D.6 IRRIGATION EFFICIENCY

The crop water use coefficients determined by the analysis described in the preceding sections represent the amount of water actually needed in the root

TABLE 10 Soil moisture balance for maize grain (Silistra region, average weather conditions, soil moisture capacity – 180 mm).

	March			April			May			June			July			August			September		
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
P_t	24	24	24	41	41	41	56	56	56	58	58	58	68	68	68	61	61	61	41	41	41
k_c	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.48	0.59	0.69	0.79	0.90	1.00	1.00	1.00	1.00	1.00	0.89	0.78	0.66	0.55
E_t	9	9	9	16	16	16	21	27	33	40	46	52	68	68	68	61	61	54	32	27	23
R_t	9	9	9	9	9	9	18	18	18	20	20	20	14	14	14	14	14	14	11	11	11
S_{t-1}	180	180	180	180	173	166	159	156	147	132	172	146	174	180	126	132					
S'_t	180	180	180	173	166	159	156	147	132	112	146	114	120	126	72	85					
S_t	180	180	180	173	166	159	156	147	132	172	146	174	180	126	132	145					
S''_t																136	89	49	28	12	0
D_t	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
I_t	0	0	0	0	0	0	0	0	0	60	0	60	60	0	60	60					

TABLE D.11 Crop water use coefficients (mm).

Crop	Average year	1-in-4 dry year
Lucerne	300	420
Maize silage	300	360
Maize silage II	180	300
Maize grain	300	420
Wheat	60	120
Barley	60	120
Soybeans	300	360
Sunflowers	240	300
Tobacco	250	300
Vegetables	450	530
Orchards	180	240

zone of the plants. To find the corresponding amount of water needed to be withdrawn from the Danube River, estimates of leaching requirements and irrigation efficiency must be made.

The quality of the irrigation water withdrawn from the Danube River is not high. Drinking water for livestock must be pumped from groundwater. Although no data on water quality were obtained during the course of the project, it may be presumed that the Danube River contains some salts and other wastes from the six countries upstream of Silistra. To ensure that these salts do not remain in the root zone following irrigation and cause soil salinization and crop damage, enough extra water must be irrigated onto the land to wash, or leach, the salts down through the root zone of the plants. This leaching requirement is estimated to be 15 percent of the intake water using the procedure of Ayers and Westcot (1976). Local experts in Silistra say that problems of soil salinization or drainage associated with irrigation in the Drustar complex have not yet occurred on the 11,400 ha under irrigation, but such problems may occur in the future.

Irrigation efficiency estimates must account for the losses in bringing water to the field and in applying it to the soil. Using the procedure of Bos and Nugteren (1974), application losses are estimated at 30 percent of intake water. These losses are due to the evaporation of water between the time it leaves the sprinkler and the time it hits the ground, and to the nonuniform areal distribution of sprinkling.

Losses of 5 percent have been allowed in the conveyance system. These are rather low but may be attainable in the Drustar complex because the water is pumped in a closed system diirectly up from the Danube River to the fields. These data for losses assume very efficient management of irrigation.

The total of the losses and leaching requirements is 50 percent of the intake water from the Danube (Figure D.5). While this percentage may seem rather low,

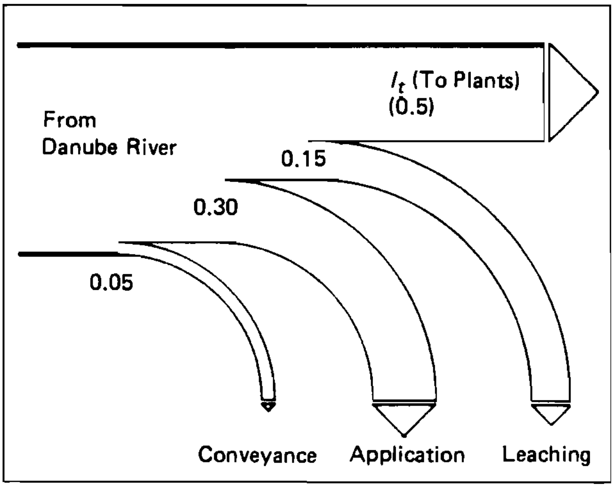


FIGURE D.5 Components of water use.

the international survey carried out by Bos and Nugteren (1974) demonstrates that only a very few irrigation projects have a project efficiency (water used by crop/intake water from source) as high as 50 percent. Most often the efficiency is around 30 percent. Thus the estimate of 50 percent made here could be assumed as being near the maximum attainable and is consistent with the goals of advanced technology and efficient management adopted by the planners of the Drustar complex.

Appendix E

MATHEMATICAL DESCRIPTION OF SWIM2

This appendix formalizes the description of the model in Section 2. Following Figure 5, all input resources, crop production alternatives, crop products, and livestock variables have been designated by X, Y, V, and Q, respectively. The further subdivision of these variables is explained below.

E.1 OBJECTIVE FUNCTION

The objective function OB adopted for the Drustar agricultural–industrial complex maximizes the annual net benefit, i.e., the difference between the benefit from the marketed products and the total production cost in the complex:

$$OB = \max\Bigg[\underbrace{\sum_{j=1}^{4} b_j Q_j}_{\substack{\text{livestock}\\ \text{production}\\ \text{benefits}}} + \underbrace{\sum_{g=14}^{24} b_g V_g}_{\substack{\text{crop pro-}\\ \text{duction}\\ \text{benefits}}} - \underbrace{\sum_{r=1}^{24} P_r X_r}_{\substack{\text{input re-}\\ \text{sources}\\ \text{cost}}}$$

$$- \underbrace{\sum_{s=1}^{3} \sum_{i=1}^{11} \sum_{k=1}^{2} \sum_{q=1}^{2} C_{si}^{kq} Y_{si}^{kq}}_{\substack{\text{crop}\\ \text{production}\\ \text{cost}}} - \underbrace{\sum_{i=1}^{11} C_i W_i}_{\substack{\text{crop pro-}\\ \text{cessing}\\ \text{cost}}} - \underbrace{\sum_{j=1}^{4} C_j Q_j}_{\substack{\text{live-}\\ \text{stock pro-}\\ \text{duction}\\ \text{cost}}}\Bigg] \qquad \text{(E.1)}$$

where

Q_j is the number of animals j; j = 1 (cows), j = 2 (sheep), j = 3 (pigs), j = 4 (hens)

b_j is the export benefit from animal j (Lv/animal)

V_g is the amount of crop product g for export, for meeting population demands, or for reserves; g = 14 (cooking oil), g = 15 (flour), g = 16 (domestic fruits), g = 17 (export fruits), g = 18 (tobacco), g = 19 (vegetables), g = 20 (reserves of maize grain), g = 21 (reserves of wheat), g = 22 (reserves of barley), g = 23 (reserves of soybeans), and g = 24 (reserves of sunflowers)

b_g is the benefit from commodity g (Lv/ton)

X_r is the amount of input r required for the crop and livestock production in the complex, $r = 1, \ldots, 24$

P_r is the price (Lv/unit of resource) of input r

Y_{si}^{kq} is amount of land (ha) in subregion s, s = 1, 2, 3, needed for production of crop i on irrigated (k = 1) or nonirrigated (k = 2) land with 80-percent fertilizer application (q = 1) or 100-percent fertilizer application (q = 2). The crops i are as follows: i = 1 (lucerne), i = 2 (maize silage), i = 3 (maize silage II), i = 4 (maize grain), i = 5 (wheat), i = 6 (barley), i = 7 (soybeans), i = 8 (sunflowers), i = 9 (orchards), i = 10 (tobacco), and i = 11 (vegtables)

C_{si}^{kq} is the cost (Lv/ha) for producing crop i on land located in subregion s with technologies k and q

W_i is the amount (tons) of total crop product i subject to processing, $i = 1, \ldots, 11$

C_i is the cost (Lv/ton) of processing (grain drying, transportation to storage) of crop product i

C_j is the cost (Lv/animal) of providing farm houses for animal j

E.2 CONSTRAINTS

There are three general types of constraints in the model: physical constraints (irrigated and nonirrigated land, water and fertilizer availability), demand constraints, and material balance constraints (equations). For ease in comparing the mathematical description and the linear programming format, the constraints are expressed in detail.

E.2.1 Physical Constraints

E.2.1.1 IRRIGATED LAND

The amount of land already developed and the amount to be developed are constrained in the three subregions by the following inequalities:

$$\sum_{\substack{i=1\\ i\neq 3}}^{11} \sum_{q=1}^{2} Y_{si}^{1q} - I_s \leqslant EI_s \qquad s = 1,2,3 \tag{E.2}$$

where

Y_{si}^{1q} is the area (ha) of crop i planted in subregion s on irrigated land (k = 1) at rate of fertilizer application q

I_s is the amount of irrigated land (ha) to be developed in subregion s

EI_s is the amount (ha) of irrigated land already developed in subregion s; EI_s is a given constant for all s

E.2.1.2 IRRIGATED AND NONIRRIGATED LAND IN EACH SUBREGION

SWIM2 accounts explicitly for crops planted on irrigated and nonirrigated land in the following way:

$$\sum_{\substack{i=1\\i\neq 3}}^{11} \sum_{q=1}^{2} Y_{si}^{2q} + I_s + AS \leqslant AL_s \qquad s = 1,2,3 \tag{E.3}$$

where

Y_{si}^{2q} is the area (ha) of crop i in subregion s fertilized at rate q on nonirrigated land ($k = 2$)

AL_s is the total arable land (ha) in subregion s

AS is the area (ha) of crops for seeds (crops for seeds are planted on nonirrigated area only in region 2, i.e., $AS = 0$ for $s = 1,3$)

E.2.1.3 TOTAL IRRIGATED LAND TO BE DEVELOPED

$$IL = \sum_{s=1}^{3} I_s \tag{E.4}$$

where IL is the total irrigated land (ha) to be developed in the region

E.2.1.4 AREAS OF TOBACCO, ORCHARDS AND MAIZE SILAGE II

Although tobacco and orchards may be grown on irrigated or nonirrigated areas, the total amount of land occupied by the crops is restricted.

$$\sum_{k=1}^{2} \sum_{q=1}^{2} Y_{si}^{1q} \leqslant A_{is} \qquad s = 1,2,3 \qquad i = 9,10 \tag{E.5}$$

where

A_{is} is the area (ha) allowed for growing orchards ($i = 9$) and tobacco ($i = 10$) on subregion s

$$\sum_{q=1}^{2} Y_{s3}^{1q} - 0.5 \sum_{q=1}^{2} Y_{s5}^{1q} - \sum_{q=1}^{2} Y_{s6}^{1q} \leqslant 0 \qquad s = 1,2,3 \tag{E.6}$$

where

Y_{s3}^{1q} is the area (ha) of maize silage II planted on half of the area Y_{s5}^{1q} of wheat, and all the area Y_{s6}^{1q} of barley in subregion s using technology q; $k = 1$ because maize silage II is grown only on irrigated area

E.2.1.5 CROP ROTATION

Crop rotation is taken into account in SWIM2 by constraining the ratio of field crops (lucerne, wheat, and barley; $i = 1, 5, 6$) to interrow-cultivated crops (maize silage, maize grain, soybeans, and sunflowers ($i = 2, 4, 7, 8$)).

$$\sum_{i=1,5,6} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} Y_{si}^{kq} - 0.95 \sum_{i=2,4,7,8} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} Y_{si}^{kq} \geqslant 0 \quad \text{(E.7)}$$

$$\sum_{i=1,5,6} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} Y_{si}^{kq} - 1.3 \sum_{i=2,4,7,8} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} Y_{si}^{kq} \leqslant 0 \quad \text{(E.8)}$$

E.2.2 Demand Constraints

This set of constraints spells out all crop and livestock production requirements for population, export, and reserves.

E.2.2.1 CROP CONSTRAINTS

The amount of crop products generated from each crop is as follows (all amounts are in tons unless otherwise indicated):

$$W_i = \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} d_{si}^{kq} Y_{si}^{kq} \qquad i = 1, \ldots, 11 \qquad \text{(E.9)}$$

where

d_{si}^{kq} is crop yield (ton/ha)
W_i is total crop production of crop i

Some of the crop products W_i are processed further to obtain subproducts V_g in the following way:

E.2.2.1.1 Lucerne Subproducts.

$$W_1 = \sum_{g=1}^{4} a_{1g} V_g \qquad \text{(E.10)}$$

where

W_1 is lucerne production
V_g, $g = 1, 2, 3, 4$, are the amounts of lucerne green chop, hay, haylage, and silage, respectively

a_{1g} is a rate of conversion of lucerne production into green chop, hay, haylage, and silage

E.2.2.1.2 Maize Silage Balance

$$V_5 = W_2 + W_3 \tag{E.11}$$

where

V_5 is the total amount of maize silage
W_2 is the amount of maize silage
W_3 is the amount of maize silage II

E.2.2.1.3 Wheat Subproducts

$$W_5 = M_w + V_8 + V_{21} \tag{E.12}$$

$$V_{15} = a_F M_w \tag{E.13}$$

$$V_{15} \geqslant PF \tag{E.14}$$

$$V_{13} = a_B M_w \tag{E.15}$$

where

W_5 is wheat grain production
M_w is wheat milled for flour and bran
V_8 is the amount of wheat feedstuff
V_{21} is the amount of wheat reserves
V_{15} is flour production
a_F is the amount of flour produced from one ton of wheat
PF is the amount of flour for meeting population requirements
V_{13} is bran production
a_B is the amount of bran produced from one ton of wheat; note that $a_F + a_B < 1$ because of losses associated with flour and bran production

E.2.2.1.4 Sunflower Subproducts

$$W_8 = V_9 + V_{24} \tag{E.16}$$

$$V_{14} = a_L V_9 \tag{E.17}$$

$$\nu_{14} = \geqslant \text{Oil} \tag{E.18}$$

$$V_{12} = a_{\mathrm{M}} V_9 \qquad \text{(E.19)}$$

where

W_8 is sunflower grain production
V_9 is sunflower for oil and meal production
V_{24} is the amount of sunflower reserves
V_{14} is sunflower oil production
V_{12} is sunflower meal production
a_{L} and a_{M} are the amount of oil and meal in one ton of sunflower production; $a_{\mathrm{L}} + a_{\mathrm{M}} < 1$ since amounts of oil and sunflower meal cannot exceed the total sunflower production
Oil is the specified amount of cooking oil for meeting population requirements

E.2.2.1.5 Other Grain Products Balance

$$W_4 = V_6 + V_{20} \qquad \text{(E.20)}$$

$$W_6 = V_7 + V_{22} \qquad \text{(E.21)}$$

$$W_7 = V_{10} + V_{23} \qquad \text{(E.22)}$$

where

W_4, W_6, and W_7 are the amounts of maize grain, barley, and soybeans
V_6, V_7, and V_{10} are the amounts of maize grain feedstuff, barley feedstuff, and soybeans feedstuff
V_{20}, V_{22}, and V_{23} are amounts of reserves of maize grain, barley, and soybeans

E.2.2.1.6 Roughage Production. Various roughages (stalks, straw) can be processed further to obtain forage for some of the animals (cows, sheep). In the model only the nutrient content of stalks and straw is taken into account in the following way:

$$V_{11} = \sum_{s=1}^{3} \sum_{\substack{i=4 \\ i \neq 7}}^{8} \sum_{k=1}^{2} \sum_{q=1}^{2} f_{si}^{kq} Y_{si}^{kq} \qquad \text{(E.23)}$$

where

f_{si}^{kq} is the feed unit content per hectare of crop i planted in subregion s using technologies k and q
V_{11} is the total amount of feed units of the roughage forage

E.2.2.1.7 Fruit Production

$$W_9 = V_{16} + V_{17} \tag{E.24}$$

$$V_{16} \geqslant PR \tag{E.25}$$

where

W_9 is total fruit production
V_{16} is fruit production for domestic consumption PR
V_{17} is fruit production for export

E.2.2.1.8 Tobacco and Vegetable Production. Tobacco and vegetables are not subject to any constraints except for the constrained area already explained in Section E.2.1.4. Tobacco and vegetable products are denoted by V_{18} and V_{19}

E.2.2.1.9 Crop Production Reserves. To meet crop production requirements in case of drought, reserves are built up in the following way:

$$V_g = h \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} Y_{sg}^{kq} \left(d_{sg}^{kq} - d_{sg}^{-kq}\right), \qquad g = 20,21,22,23,24 \tag{E.26}$$

where

V_g is the amount of reserves of crop product g
$g = 20$ (maize grain), $g = 21$ (wheat), $g = 22$ (barley)
$g = 23$ (soybeans), $g = 24$ (sunflowers)
h is a coefficient taking into account how many successive years in a given sequence are dry
Y_{sg}^{kq} is the area of crop i producing crop product g, $i = 4, 5, 6, 7, 8$ for $g =$ 20, 21, 22, 23, 24, respectively
d_{sg}^{kq} is the crop yield of crop i producing crop product g in normal weather
d_{sg}^{-kq} is the crop yield of crop i producing crop product g in dry weather

E.2.2.2 LIVESTOCK PRODUCTION CONSTRAINTS

E.2.2.2.1 Livestock Feedstuff. There are five types of feedstuff required by the animals in the complex: green forage, hay, silage, concentrated forage, and roughage. To account for them the following equations are introduced:

$$F_g = V_1 f_{1g} \tag{E.27}$$

$$F_h = V_2 f_{2h} \tag{E.28}$$

$$F_s = (V_3 f_{3s} + V_4 f_{4s} + V_5 f_{5s}) \tag{E.29}$$

$$F_r = V_{11} \tag{E.30}$$

$$F_c = (V_6 f_{6\,c} + V_7 f_{7\,c} + V_8 f_{8\,c} + V_{10} f_{10\,c} + V_{13} f_{13\,c} + V_{15} f_{15\,c}) \tag{E.31}$$

where

F_g, F_h, F_s, F_r, and F_c are total amounts of feed units (f.u.) of green forage, hay, silage, roughage, and concentrated forage available to animals

V_1 is the amount of green forage (tons)

V_2 is the amount of hay (tons)

V_3, V_4, and V_5 are the amounts (tons) of lucerne haylage, silage, and maize silage (including maize silage II)

V_{11} is the amount of roughage feed units

V_6, V_7, V_8, V_{10}, V_{13}, and V_{15} are the amounts (tons) of maize grain, barley, wheat, soybean, bran, and sunflower meal allocated to livestock production

$f_{1\,g}, \ldots, f_{15\,c}$ is the feed unit content in 1 ton of each product

E.2.2.2.2 Livestock Diets. To ensure certain productivity of animals, they have to be fed by some or by all of the products specified in Eqs. (E.27)–(E.31). Furthermore, each animal diet is specified within the following upper and lower limits:

$$Q_j D_{\alpha j}^{\min} \leqslant F_{\alpha j} \leqslant Q_j D_{\alpha j}^{\max} \qquad \alpha = g,h,s,r,c \qquad j = 1,2,3,4 \tag{E.32}$$

$$\sum_{\text{all } \alpha} F_{\alpha j} \geqslant A_j \qquad j = 1,2,3,4 \tag{E.33}$$

$$\sum_{j=1}^{4} F_{\alpha j} = F_\alpha \qquad \alpha = g,h,s,r,c \tag{E.34}$$

where

Q_j is the number of animals j, $j = 1$ (cows), $j = 2$ (sheep), $j = 3$ (pigs), $j = 4$ (hens)

$D_{\alpha j}^{\min}$ and $D_{\alpha j}^{\max}$ are the minimum and maximum amount of feed units of feedstuff α required by animal j

$F_{\alpha j}$ is the total amount of feed units fed to animal j

A_j is the total amount of feed units required by animal j

F_α is the total amount of feed units of feedstuff α required in the complex

E.2.2.2.3 Protein Content of Livestock Feedstuff. Feed units are the energetic component of animal diets. The other component to be supplied to livestock is protein. There are several ways to account for protein content in the livestock diets; the simplest one has been chosen, i.e., to specify the ratio B of high-protein feeds to low-protein ones:

$$V_{10} + V_{12} \geqslant B(V_6 + V_7 + V_8 + V_{13}) \qquad \text{(E.35)}$$

where

V_{10} and V_{12} are the tons of soybeans and sunflower meal in livestock diets
V_6, V_7, V_8, and V_{13} are the tons of maize grain, barley, wheat, and wheat bran in livestock diets

E.2.2.2.4 Livestock Balance. To account for the existing livestock and that which is to be developed in the future, the following equations are introduced in SWIM2:

$$(Q_j - Q_j^E) + I_j - Q_j^D = 0 \qquad j = 1,2,3,4 \qquad \text{(E.36)}$$

where

Q_j is the total number of animals j grown in the complex
Q_j^D is the number of animals j to be developed in the complex
Q_j^E is the number of existing animals j
$I_j \geqslant 0$ is a dummy variable, i.e., the number of animals to be developed Q_j^D is equal to 0 if $Q_j < Q_j^E$, and $Q_j^D = Q_j - Q_j^E$ if $Q_j - Q_j^E$; in other words, either I_j or Q_j^D is equal to 0.

In addition to Eq. (E.36) there are three more equations that keep the ratio between animals in a certain proportion corresponding to their present numbers.

$$Q_j = R_j Q_1 \qquad j = 2,3,4 \qquad \text{(E.37)}$$

where

R_j is the ratio of the number of animals of type j to the present number of the first animal (cows)
Constraint (E.37) is relaxed when SWIM2 is used as a forecasting tool.

E.2.3 Material Balance of Input Resources

The material balance equations, while not actual constraints, take into account various inputs to crop and livestock production, like seeds, fertilizers, water, machinery, labor, fuel, and capital investments. The structure of SWIM2 allows these inputs to be constrained when necessary, as was done with water, capital investments, and fertilizers.

E.2.3.1 SEED REQUIREMENTS

SWIM2 computes the amount of all seeds and the respective seed areas required for growing crops.

$$X_r = \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} S_{sr}^{kq} Y_{sr}^{kq} \qquad r = 1,5,6,7,8 \qquad \text{(E.38)}$$

$$X_2 = \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{g=1}^{2} \sum_{r=1}^{4} S_{sr}^{kq} Y_{sr}^{kq} \qquad \text{(E.39)}$$

where

X_r is the number of tons of seeds required to produce crop r; $r = 1$ (lucerne), $r = 2$ (maize silage), $r = 3$ (maize silage II), $r = 4$ (maize grain), $r = 5$ (wheat), $r = 6$ (barley), $r = 7$ (soybeans), $r = 8$ (sunflowers)

Y_{sr}^{kq} is the amount of land (ha) occupied by crop r in subregion s with irrigation ($k = 1$) or without ($k = 2$) using fertilizer application rate q

S_{sr}^{kq} is the seeding rate (ton/ha) required to produce crop r on irrigated ($k = 2$) land using fertilizer application rate q

Equation (E.39) takes care of different crops using the same kind of seeds; in our case these crops are maize silage, maize silage II, and maize grain.

To determine the total seed area the following equation has been introduced in SWIM2:

$$AS = \sum_{s=1}^{3} \sum_{r=1}^{8} \sum_{k=1}^{2} \sum_{q=1}^{2} \frac{S_{sr}^{kq}}{d_{sr}^{kq}} Y_{sr}^{kq} \qquad \text{(E.40)}$$

where

AS is the area (ha) occupied by all seeds

d_{sr}^{kq} is the crop yield (tons/ha); in SWIM2 $k = 2$ because seeds are grown on nonirrigated land

E.2.3.2 FERTILIZER REQUIREMENTS

There are three essential types of fertilizers used in the Drustar complex: ammonium sulfate, superphosphate, and potassium sulfate. The first set of constraints describes the required amount of each fertilizer:

$$x_r = \sum_{s=1}^{3} \sum_{i=1}^{11} \sum_{k=1}^{2} \sum_{q=1}^{2} f_{sir}^{kq} Y_{si}^{kq} - AP \sum_{j=1}^{4} m_{jr} Q_j \qquad r = 9,10,11 \quad \text{(E.41)}$$

where

x_r is the amount of fertilizer r required in the complex (tons); $r = 9$ (ammonium sulfate), $r = 10$ (superphosphate), $r = 11$ (potassium sulfate)

f_{sir}^{kq} is the fertilizer rate of fertilizer r for crop i planted in subregion s using technologies k and q (tons/ha)

Q_j is the number of animals of type j

m_{jr} is the amount of animal waste (manure) generated by animal j that can substitute for one ton of fertilizer r (tons/animal)

AP is the amount of manure that can be utilized: $0 \leqslant AP < 1$; this coefficient takes care of the fact that (a) manure is generated all year but it is used only during a few months, and (b) farm houses are concentrated on a restricted number of places and the use of the whole amount of manure involves substantial transportation costs

E.2.3.3 FUEL REQUIREMENTS

Fuel is required for operating tractors, various combines, and grain processing equipment. The total amount of fuel required, X_{12}, is determined by the following equation:

$$x_{12} = \sum_{i=1}^{11} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} L_{si}^{kq} Y_{si}^{kq} \qquad \text{(E.42)}$$

where

L_{si}^{kq} is the fuel rate for production of crop i in subregion s using technologies k and q (liters/ha)

E.2.3.4 LABOR REQUIREMENTS

The labor is actually the machine-hours of field work needed (assuming 1 operator/machine). SWIM2 does not account for labor required in the processing industry because these activities are not considered in detail in the model.

In principle, all machine-hours could be lumped together to obtain the total number of hours required. In this study, however, we separate machine-hours required for tractors, combines (June and July), and combines (August and October). The latter two can be operated by people coming from outside the region.

$$X_{13} = \sum_{i=1}^{11} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} t_{si}^{kq} Y_{si}^{kq} \qquad \text{(E.43)}$$

where

t_{si}^{kq} is the number of tractor-hours per hectare required for field activities on crop area Y_{si}^{kq}

X_{13} is the total number of tractor-hours for the whole corp area

$$X_{14} = \sum_{i=5}^{6} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} CJ_{si}^{kq} Y_{si}^{kq} \tag{E.44}$$

where

CJ_{si}^{kq} is the number of combine-hours per hectare in June and July required for the harvesting of crop area Y_{si}^{kq}; $i = 5$ (wheat), $i = 6$ (barley)

$$X_{15} = \sum_{i=4,7,8} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} CA_{si}^{kq} Y_{si}^{kq} \tag{E.45}$$

where

CA_{si}^{kq} is the number of combine-hours per hectare in August and September required for the harvesting of crop area Y_{si}^{kq}; $i = 4$ (maize grain), $i = 7$ (soybeans), $i = 8$ (sunflowers)

E.2.3.5 MACHINERY REQUIREMENTS

To convert the machine-hours already specified in the last section into a more meaningful number, which is the number of machines needed, an estimate has to be made about the critical time in the combination of activities on all crops when all tractors or combines are put into use.

E.2.3.5.1 Tractor Requirements

$$X_{16} = \frac{1}{T_t} \sum_{\substack{i=1 \\ i \neq 5,6}}^{11} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} m_{si}^{kq} Y_{si}^{kq} \tag{E.46}$$

where

X_{16} is the total number of tractors needed for crop production

m_{si}^{kq} is the number of machine hours per hectare for crop i planted in subregion s using technologies k and q over the critical period. In our case, this period is from 20 March to 20 April (see Table A.7)

T_t is the total number of hours available over the critical period; $T_t = (D - Dw)W_t$, where D is the number of calendar days in the critical period; D_w is the number of days taken off because of holidays or bad weather conditions in this period; W_t is working hours per day

E.2.3.5.2 Combine Requirements

$$X_{17} = \frac{1}{T_c} \sum_{i=4,7,8} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} mc_{si}^{kq} Y_{si}^{kq} \tag{E.47}$$

where

X_{17} is the total number of combines needed for crop harvesting

mc_{si}^{kq} is the number of machine hours per hectare for harvesting of crop i planted in subregion s using technologies k and q

T_c is the total number of hours available over the critical period; T_c is determined in the same way as T_t in (E.46).

E.2.3.5.3 Silage Chopper Requirements.

$$X_{18} - \frac{1}{T_{sc}} \sum_{i=2}^{3} \sum_{s=1}^{3} \sum_{k=1}^{2} \sum_{q=1}^{2} ms_{si}^{kq} Y_{si}^{kq} \qquad \text{(E.48)}$$

where

X_{18} is the number of silage choppers required

ms_{si}^{kq} is the number of machine hours per hectare for harvesting of maize silage and maize silage II over the critical period

T_{sc} is the total number of hours available over the critical period

E.2.3.5.4 Irrigation Equipment Requirements. To evaluate the amount of irrigation equipment, the productivity of this equipment (hectares per sprinkler) has to be found as well as the schedule of crop irrigation. The latter is needed to avoid excessive investment in a piece of equipment, i.e., to account for the fact that this equipment can be moved from one place to another over the irrigation season to irrigate different crops.

The information given in Table A.6 can serve as a guideline to determine the amount of irrigation equipment. It is obvious from this table that irrigation equipment for maize silage II is complementary to that for sunflowers. On the other hand, the equipment for wheat and barley can be combined and made complementary to that for all other crops. All these relationships can be formalized as follows:

$$X_{19} = \frac{1}{S_p} \left[\sum_{\substack{i=1 \\ i \neq 3,5,6}}^{11} \sum_{s=1}^{3} \sum_{q=1}^{2} Y_{si}^{1q} \right] + E^3 + E^{5,6} + D - EI \qquad \text{(E.49)}$$

where

S_p is the productivity of the irrigation equipment (ha/sprinkler)

Y_{si}^{1q} are irrigated areas of crop i planted in subregion s using technology q

E^3 is the extra irrigation equipment needed for maize silage II

$E^{5,6}$ is the extra irrigation equipment needed for wheat and barley

X_{19} is the total amount of new irrigation equipment needed

EI is the amount of existing irrigation equipment

D is a dummy variable: the amount of new irrigation equipment X_{19} is equal to zero if

$$\frac{1}{S_p}[\,\cdot\,] + E^3 + E^{5,6} < EI$$

and

$$X_{19} = \frac{1}{S_p}[\,\cdot\,] + E^3 + E^{5,6} - EI$$

if

$$\frac{1}{S_p}[\,\cdot\,] + E^3 + E^{5,6} \geqslant EI$$

In other words, either X_{19} or D is equal to zero.

The variables E^3 and $E^{5,6}$ are determined by Eqs. (E.50) and (E.51). Equation (E.50) takes into account that maize silage II is complementary to sunflowers, and Eq. (E.51) that wheat and barley are complementary to all other crops (except vegetables).

$$\frac{1}{S_p}\left[\sum_{s=1}^{3}\sum_{q=1}^{2} Y_{s8}^{1q} - \sum_{s=1}^{3}\sum_{q=1}^{2} Y_{s3}^{1q}\right] + E^3 - D^3 = 0 \qquad \text{(E.50)}$$

$$\frac{1}{S_p}\left[\sum_{i\neq 5,6,8}^{10}\sum_{s=1}^{3}\sum_{q=1}^{2} Y_{si}^{1q} - \sum_{i=5}^{6}\sum_{s=1}^{3}\sum_{q=1}^{2} Y_{si}^{1q}\right] + E^3 + E^{5,6} - D^{5,6} = 0 \qquad \text{(E.51)}$$

where

$E^{5,6}$ is the amount of extra irrigation equipment needed for wheat and barley; D^3 and $D^{5,6}$ are dummy variables with the same properties as D in (E.49).

E.2.3.5.5 Water Availability. SWIM2 accounts for both the total amount of irrigation water over time in normal weather and dry weather, and for the livestock drinking water.

The total amount of water for irrigation is determined by the following equation:

$$W(t) = \frac{1}{e}\sum_{i=1}^{11}\sum_{s=1}^{3}\sum_{q=1}^{2} I_{si}^{q}(t)Y_{si}^{q} \qquad t = 1,\ldots,T \qquad \text{(E.52)}$$

where

$I_{si}^{q}(t)$ is the irrigation water use coefficient in normal weather (m^3/ha) of crop i planted in subregion s using technology q at time t; t is a time index in 10-day periods over the irrigation season

$W(t)$ is the amount of water required for all crops at time t
e is irrigation efficiency

The irrigation water demanded by each of the three regions is:

$$W_s = \frac{1}{e} \sum_{i=1}^{11} \sum_{q=1}^{2} \sum_{t=1}^{15} I_{si}^q(t) Y_{si}^q \qquad s = 1,2,3 \tag{E.53}$$

The total irrigation water demanded, X_{20}, in the complex is $\Sigma_{s=1}^{3} W_s$.

SWIM2 also computes irrigation water demands in case of a dry year, X_{21}, in the following way:

$$X_{21} = \sum_{i=1}^{11} \sum_{s=1}^{3} \sum_{q=1}^{2} \sum_{t=1}^{15} \bar{I}_{si}^q(t) Y_{si}^q \tag{E.54}$$

where

$\bar{I}_{si}^q(t)$ is the irrigation water use coefficient in dry weather (m^3/ha) of crop i planted in subregion s using technology q at time t

To determine the livestock demands for drinking water, X_{22}, the following constraint is introduced in SWIM2:

$$X_{22} = \sum_{j=1}^{4} L_j Q_j \tag{E.55}$$

where

L_j is the livestock water use coefficient (m^3/animal)
Q_j is the number of animals j

E.2.3.5.6 Capital Investments. The capital investments are split into two parts: (a) irrigation capital investments and (b) investments for machinery and livestock farm houses.

$$X_{23} = \sum_{s=1}^{3} i_s I_s + c_c X_{19} \tag{E.56}$$

where

X_{23} is the capital investment in irrigation (Lv)
i_s is the capital investment to bring water to the field (Lv/ha)
I_s is the amount of irrigated land (ha) to be developed in subregion s
c_c is the capital cost of irrigation equipment (Lv/equipment)
X_{19} is the total amount of irrigation equipment required

$$X_{24} = i_t X_{16} + i_c X_{17} + i_p X_{18} + \sum_{j=1}^{4} h_j Q_j \tag{E.57}$$

where

X_{24} is the capital investment for machinery and livestock farm houses

i_t, i_c, i_p are the capital investments (Lv/machine) for tractors, combines, and choppers

h_j is the capital investment for livestock farmhouses (Lv/animal)

Q_j is the number of animals j

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