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AGRICULTURAL WATER DEMANDS: PRELIMINARY RESULTS OF SILISTRA CASE STUDY

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PREFACE

Interest in water resources systems has been a critical part of resources and environment related research at IIASA since its inception. As demands for water increase relative to supply, the intensity and efficiency of water resources 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 resources development alternatives aided by application of mathematical modelling techniques, to generate inputs for planning, design and operational decisions.

In the years of 1976 and 1977 IIASA has initiated a concentrated research effort focusing on *modelling and forecasting of water demands*. Our interest in water demands derived itself from the generally accepted realization that these fundamental aspects of water resources management have not been given due consideration in the past.

This paper, the second in the IIASA water demand series and undertaken at IIASA in collaboration with the Bulgarian Ministry of Agriculture and Food Industry reflects our desire to demonstrate the applicability of the results from our studies on water demand modelling and forecasting.

The results presented in this report are of a preliminary nature and can only be interpreted within the limitations of the model's objective and input data. Since this objective and these data may not be fully reflective of actual conditions in the Silistra region, the results of the model should not be taken as specific policy recommendations for the development of this region.

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ABSTRACT

Preliminary results of the Silistra Water for Irrigation Model (SWIM) for determining agricultural water demands in the Silistra region of Bulgaria are presented. For various areas of irrigated and non-irrigated land, and various volumes of water supply, SWIM uses linear programming to select the optimal combination of crop areas and production inputs so as to maximize annual net benefits from crop production in excess of target production quantities of each crop. Both normal and dry weather conditions are examined. The region's import-export balance is investigated for areas of irrigated land between 10,000 and 50,000 hectares and it is shown that total costs of crop production are minimized when the region is just self-sufficient in crop production. By means of demand curves it is demonstrated that the marginal values of land and water for irrigation are greater than their unit costs of development so that it is optimal to develop irrigation to the maximum area considered by the model.

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CONTENTS

1. INTRODUCTION

The Silistra region having a population of 200,000 and covering a territory of about 2700 km^2, is situated in the north-eastern part of Bulgaria. The agricultural activities in the region are concentrated in a large agro-industrial complex called Drustar. The term agro-industrial complex means that all individual enterprises dealing with crop production and it's processing as well as with livestock growing and processing are coordinated by one administrative body. This body is responsible for overall planning, development, and management of the complex. Since the complex is developing rapidly, it is essential to choose the best way of directing future agriculture activities and investments. In the list of problems to be investigated in this respect, water resources appear to have a key role. The reason is at least twofold:

a) a vast irrigation development is to take place in the coming 5-10 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 in the region.

b) water resources in the region are rather scarce being limited to the bordering Danube river. No other rivers exist in the region. Ground water is available only in small quantities in depth exceeding 400 m. which makes it an unimportant resource.

To overcome these difficulties intensive investigations have been carried out in this region over the past few years. As a result, a number of alternatives for augmenting the available water supply have been proposed. Some of them include construction of several reservoirs in various parts of the region; others envisage combine use of pumping stations and reservoirs, constructing long distance canals , etc. The common characteristic of all alternatives is that firstly, they rely on Danube river water (which is reliable but water use is restricted by several international agreements) and secondly, all of the alternatives are rather costly. Obviously one way of decreasing supply cost would be to reduce agricultural water demands for irrigation which constitute the major demand part of the region keeping at the same time the production targets at the desired level. It is furthermore obvious that reducing agricultural water demands involves additional costs. The problem is: are these costs greater than the supply cost and where is the point at which the water resource system is in equilibrium, e.g. the point at which incremental cost of additional supply is equal to incremental benefit from demanded water?

The main objective of the study is to make a thorough analysis of factors that influence both agricultural water demands and associated agricultural production taking into account the major goal of the Drustar complex, which is to maximize the total agricultural and livestock production within the limited regional resources. In the course of the study we have focused the main objective towards providing an adequate answer to the following questions:

- what is the amount of crops able to be produced from the complex given various possible volumes of water supply within the constraints of available resources of other types: labor, machinery, fertilizer, etc?

- how much area should be developed for irrigation and which crops should be irrigated?

- what is the export-import balance in the complex in case of favourable and unfavourable weather conditions?

- what is the marginal productivity of water and irrigated land in the complex i.e. how much would the benefit (or cost) change if one additional unit of water or irrigated land were provided?

The scope of the study is closely related to the aforementioned problems. To provide an adequate answer to them at least three major activities are worth modelling: feed crop production, non-feed crop production (tobacco, vegetables, vineyards, etc.), and livestock production. Only the first activity, which has the greatest direct impact on water resources, is paid appropriate attention in the model. The non-feed crop production has less impact on water resources because of small area occupied by these crops and less water demands (about 10%) when compared with feed crop ones. Bulgarian scientific organizations and IIASA have been intensively studying livestock production (Carter, Csaki, and Propoi, 1977; Propoi, 1977). For this reason the livestock feed requirements are considered as being externally specified in the model.

The model reported herein is a preliminary one using data mainly provided for us in a development plan for the complex prepared for the Bulgarian government agency Rodopaimpex by the consulting firm Globe Services International. A draft of the report describing the model was translated into the Bulgarian language and reviewed in Bulgaria during August 1977. As a result, some better data were obtained and many suggestions received for extending the model structure to more closely represent the Drustar complex. On this basis a second version of this model has been developed. Since the later version omits some of the features of the earlier one, we have decided to publish this complete description of the preliminary model and its results at this time and to report on the subsequent work on this model when it is complete.

2. DESCRIPTION OF THE MODEL

2.1 Overview

The Silistra Water for Irrigation Model (SWIM) has been developed to estimate the amount of water needed for irrigation in the Drustar complex. In the conventional approach to evaluating these water demands the following method is usually employed:

- the area to be developed for irrigation is specified;
- the area of each type of crop to be grown with irrigation is decided taking into account the crop production from nonirrigated land;
- considering the weather conditions, the depth of water which must be irrigated onto each crop is determined;
- the total volume of water needed for the irrigated area is found as the product of the depth required for each crop and the crop's area, summed over all the irrigated crops.

Clearly this method should be applied a number of times to estimate the effect on water demands of different assumptions concerning the area of land to be developed for irrigation, weather conditions, crop production, etc.

With SWIM the conventional approach is both computerized and extended. One can follow the conventional approach, in which case for a given area of irrigated land SWIM determines the optimal crop distribution for maximum production on both irrigated and nonirrigated land and the volume of water needed for irrigation under normal weather or drought conditions. However, SWIM can also operate in the opposite direction: for a given volume of water available, SWIM can determine the optimal crop distribution, which crops are irrigated, and hence the area of land which should be developed for irrigation. Moreover, since SWIM is computerized, with little extra cost it can be used many times to determine the optimal solution for different assumptions concerning irrigated land area, water availability, weather conditions, etc.

A verbal description of SWIM now follows. A detailed mathematical description is given in Appendix 2.

In SWIM, the crop production system of the Drustar complex is visualized as shown in figure (2.1). The system consists of three parts: resource inputs, crop production, and crop outputs. These outputs may be used to meet the requirements of the population and livestock in the region, or they may be exported to other regions within or outside the country.

From the overall viewpoint, Drustar is an agricultural-industrial complex whose primary output is from animals: pigs, dairy cows, cattle, and sheep. Based on the necessary diets of these animals, and the number of the different types of animals in the complex, the total amounts of feed required for livestock of each of the crop outputs may be calculated and these are considered as being externally specified to SWIM. Likewise the requirements of the population for cooking oil and flour are externally specified. All of these requirements are met in the solutions of SWIM. Any extra production beyond these requirements is assumed to be sold for export at internal Bulgarian prices. In case of unfavourable weather, maize grain can be imported at a price greater than that for export (for example 50% greater).

The objective of SWIM is to maximize the value of these exports minus the costs of all production, including the costs of the crop outputs used within the region. All costs and prices are measured in Bulgarian Leva (1 Lv= 1$US). The production costs are calculated in the following way. For each crop the basic unit of production is one hectare. The amounts of the input resources of water, seeds, fertilizer, fuel, labor, and machinery needed for one hectare of crop are estimated, and their costs computed as the product of the amount of the resource and its unit cost. All other production costs which are not directly connected to the input resources (such as the cost of storage buildings, or administration) are summed up and assigned to the unit hectare of each crop as a lumped cost. For any area of each crop the corresponding production cost can then be calculated. There are seven crops, see figure (2.1), each of which may or may not be irrigated, so SWIM considers 14 crop alternatives in all.

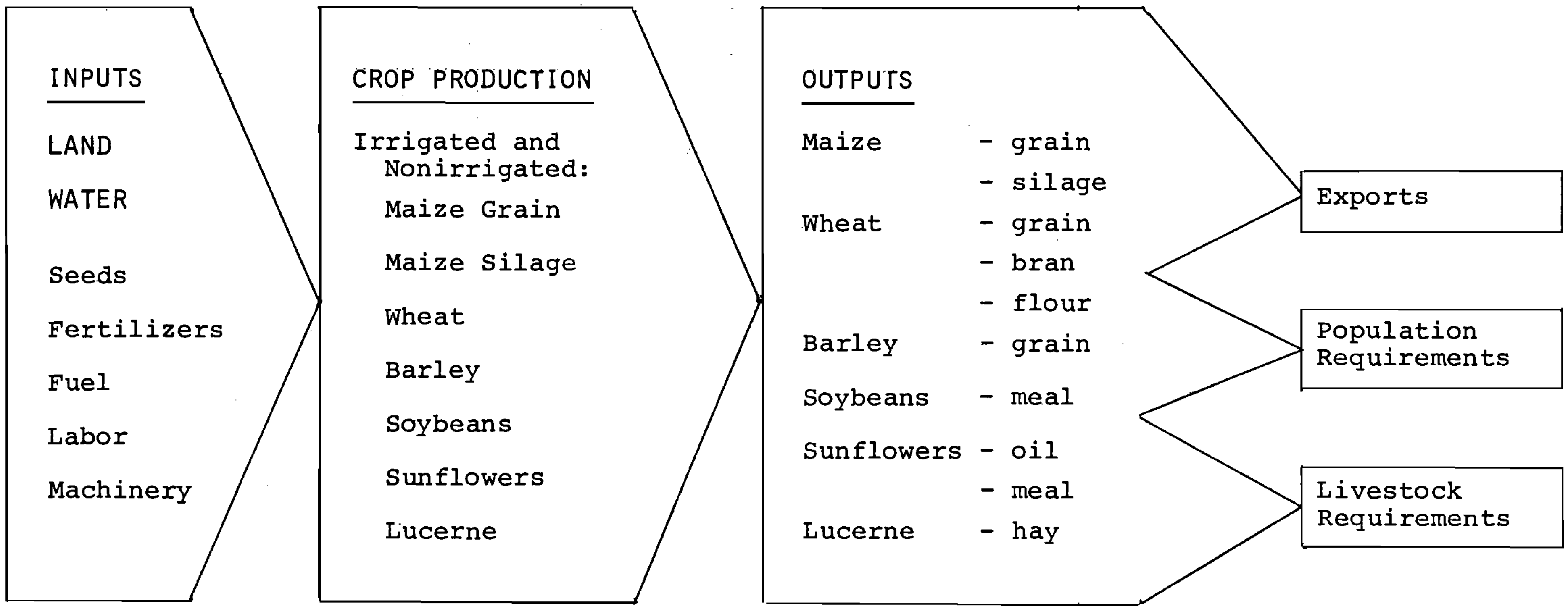


FIGURE 2.1 CROP PRODUCTION SYSTEM OF SILISTRA REGION

SWIM determines the optimal area of each crop alternative so as to meet all the production requirements and maximize the objective previously stated.

SWIM is formulated and solved on the computer as a linear program. All quantities to be optimized in SWIM are included as decision variables (e.g. areas of each crop, amounts of each resource used). These variables are interrelated through a number of constraint equations which express the physical limitations of the system (e.g. sum of all crop areas must equal the total area, water used cannot exceed water available). All of these equations are linear which means that a change in one variable leads to directly proportional changes in all the other variables related to it. SWIM currently contains 60 decision variables interrelated through 70 constraint equations involving 400 data values. It has been solved more than 50 times for the different sets of conditions described in this report.

In the following sections, the structure of SWIM is described in more detail following the scheme of Figure (2.1). In section (2.2) the methods of calculating the amounts of resource inputs and their unit costs are given. Section (2.3) describes the production schedule of field operations for each crop and their cost. The crop outputs are shown in detail in section (2.4).

2.2 Input Resources

2.2.1 Land

There are 151,785 ha of arable land in the complex of which 30,185 ha is assumed to be used for growing special crops for domestic consumption as follows:

- Tobacco	5,450 ha
- Drybeans	9,000 ha
- Flax	2,500 ha
- Vegetables	3,000 ha
- Vineyards and Orchards	10,235 ha

Because data on water requirements of these crops were not available to us, SWIM does not consider their irrigation needs. The remaining arable land amounts to 121,600 ha of which a small part (about 3000 ha) must be reserved for seed production. SWIM determines this seed area in its solution.

The main soil type of the region is Chernozem (Black Earth), which is subject to erosion in some areas. Although there are natural variations in soil structure and productivity in the district, we have no data at present on the variation in crop yields for different soil types so SWIM considers the whole 121,600 ha to be a homogeneous block of uniform soil type and productivity. No costs of land are included in SWIM. Small amounts of land may be needed for pasture for sheep grazing but these have not been included in SWIM.

2.2.2 Water

The Danube River is the only source of irrigation water for the region as there are no other significant rivers and groundwater is available only at great depth (400-600 metres). The climate is moderate with an average annual rainfall of 550 mm. However the summer is hot and potential evaporation exceeds average rainfall throughout the growing season from April through September, as shown in table (2.1). Thus irrigation is necessary to ensure consistently high crop yields. Because of the rolling hills, potential for erosion, and scarcity of water resources, sprinkler irrigation is the only application method being considered in the complex. Although there will be losses in transportation and application of the irrigation water we do not have sufficiently good information to include these losses in SWIM at the present time. Hence the volumes of water computed are the volumes needed to be delivered to the root zone of the plants. The amounts of water needed in other parts of the agricultural-industrial complex, such as for cleaning and processing in animal production, are not considered separately in SWIM because it is assumed that this water will eventually be irrigated onto the land as a method of waste disposal of manure, etc.

Table 2.1 Rainfall, Evaporation, & Moisture Deficit

Month	Rainfall (mm)	Evaporation (mm)	Deficit (mm)
January	38	14	+24
February	31	20	+11
March	33	42	- 9
April	43	74	-31
May	52	98	-46
June	76	122	-46
July	65	141	-76
August	36	135	-99
September	48	93	-45
October	44	54	-10
November	34	27	+ 7
December	46	17	+29

Table 2.2 Depth & Period of Irrigation

Crop	Period Irrig.	April	May	June	July	August	Total	Total Depth in Drought
Lucerne	Apr 15 to June 30	78	231	231	-	-	540	648
Maize Silage	May 20 to Aug 30	-	22	66	109	143	340	408
Maize Grain	May 20 to Aug 30	-	22	66	109	143	340	408
Wheat	Apr 1 to May 30	36	54	-	-	-	90	108
Barley	Apr 1 to May 30	36	54	-	-	-	90	108
Soybeans	June 1 to Aug 30	-	-	48	79	103	230	276
Sunflowers	June 1 to July 31	-	-	49	80	-	129	155

The depth of water needed for irrigation by each crop is estimated where possible by reference to Donev (1972). This total depth is then divided into the depth needed in each month of the irrigation period in proportion to the deficit of rainfall in that month. The results are given in table (2.2).

To estimate the crop water requirements under drought conditions, all the irrigation depths are arbitrarily increased by 20% over those for normal weather conditions. It would be relatively easy to modify the water requirements in SWIM to reflect those measured in individual years, where data are available.

In all cases the total volume water made available was assumed to have a unit cost for pumping of 0.022 Lv/cubic metre.

2.2.3 Seeds

All seeds required are assumed to be grown within the complex on irrigated land. SWIM 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. Seed crop yields are assumed to be the same as the irrigated field crop yields in the case of grains. The cost of seed production is assessed as 90% current Bulgarian price plus 10% foreign import price. This cost includes the production, processing, and distribution of the seed. The data used for seed planting rates, seed crop yields, costs, and seed area, are given in table A3.1 in Appendix 3.

2.2.4 Fertilizers and Pesticides

Three nutrients must be supplied with fertilizers: nitrogen, phosphorus and potassium. The corresponding fertilizers are ammonium sulphate (34% active nitrogen), super phosphate (20%

active phosphorus), and potassium sulphate (44.5% active potassium). The amount of each fertilizer needed per hectare is calculated in the following way: first, the amount of each nutrient removed by crop production is estimated; next, to compute the amount of nutrients needed to be applied, the removal amounts are modified to allow for application losses and the natural ability of the soil to absorb or release nutrients; finally the amounts of fertilizers required are found using the proportion of active nutrient in each.

SWIM calculates the total amounts of fertilizers needed for all crops. These total amounts must be decreased to allow for the nutrient value of the manure being supplied to the land by irrigating animal wastes. For 1980 conditions, the amounts of active nutrients in the manure are taken to be 2419 tons nitrogen (N), 1738 tons phosphorus (P_2O_5) and 3086 tons of potassium (K_2O); these amounts represent about a quarter of the total requirements for nitrogen and phosphorus, and half the total requirement for potassium.

Where possible the fertilizer application rates have been compared with national average application rates for Bulgaria, as given in the Bulgarian Statistical Yearbook (1975) and found to be not excessive. Also, the total amounts of fertilizers needed in the complex are not excessive when compared with the total production of fertilizers in Bulgaria.

The fertilizer costs are taken as 107.10 Lv/ton for ammonium sulphate, 58.00 Lv/ton for superphosphate, and 86.75 Lv/ton for potassium sulphate. All data on fertilizer quantities are given in table A3.2 in Appendix 3. Fertilizer application costs are given the production cost tables for each crop in Appendix 4, calculated at 3 Lv/Ha per trip over the field.

As far as pesticides are concerned, there are too many individual chemicals involved to make an accounting for each one separately as is done for fertilizers. Instead, a lumped cost per hectare is specified for each crop for chemicals and is given in the production cost tables in Appendix 4.

2.2.5 Fuel

The fuel needed by the field machinery is computed on the basis of amounts used for individual field operations: plowing, cultivation, planting, and harvesting, as shown in table A3.3 of Appendix 3. For irrigated crops, the fuel use for harvesting is higher than for nonirrigated crops because of the higher yield. The average fuel consumption per hectare for tractors varies from 25 to 30 litres/hr depending on the crop. Fuel is assumed to cost 0.072 Lv/litre.

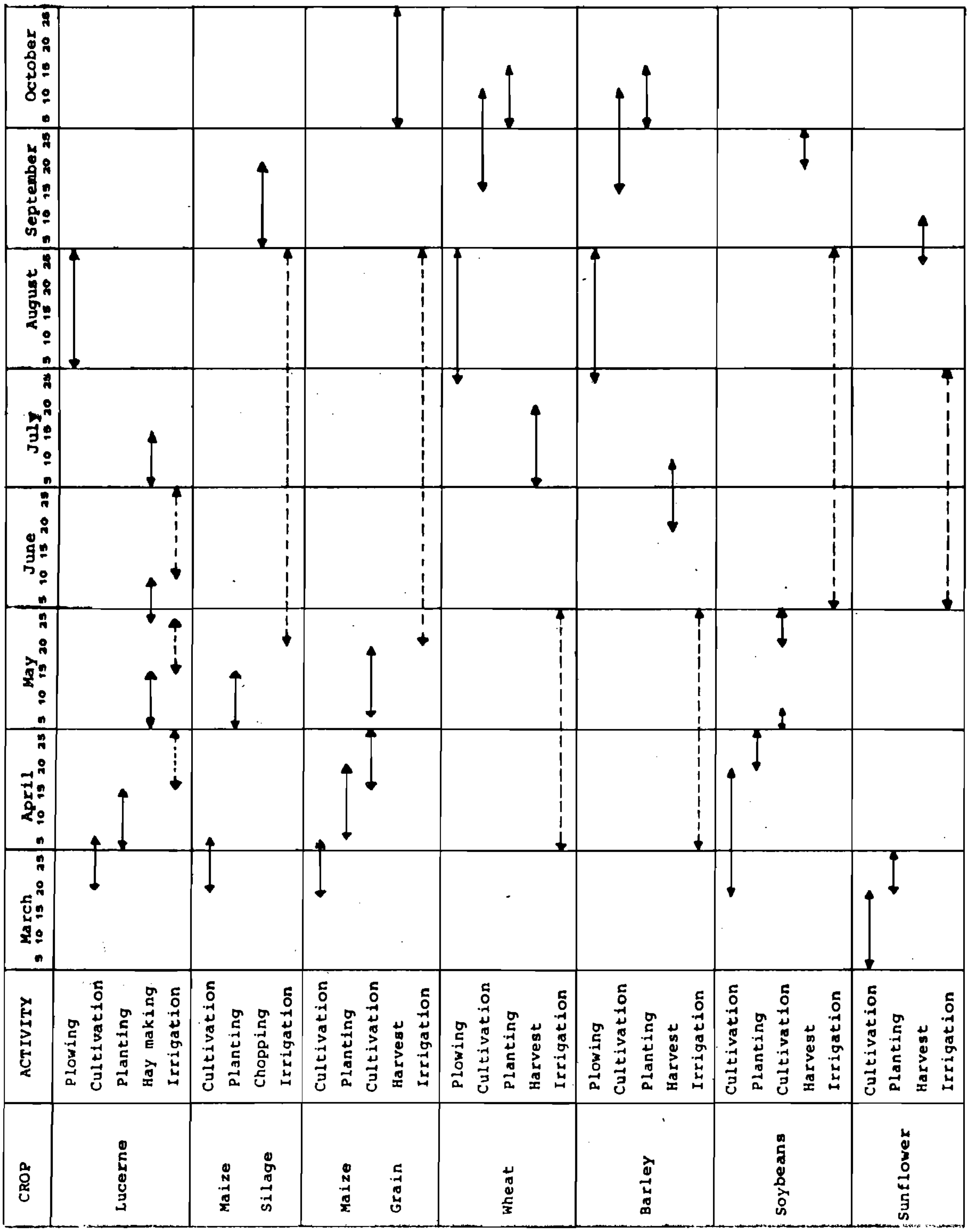
2.2.6 Labor

The labor needed for field operations is calculated on the basis of the number of hours each machine is in the field, assuming one operator per machine, as shown in table A3.4 of Appendix 3. This labor has a cost of 2 Lv/hour. The additional labor required for administration and support services is not directly computed but is assigned a cost of 2.82 Lv/Ha. Labor for irrigation is included in the costs of irrigation.

2.2.7 Machinery

To determine the number of machines, such as tractors, which 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. The schedule of field operations is shown in figure (2.2). SWIM determines the number of tractors, combine harvesters, and silage choppers in the following way. Allowing for some lost time due to bad weather during the critical period, and a 10 hour working day, the number of working hours is known. The area per hour which a machine can cover is also known; hence, the area which can

FIGURE 2.2 SCHEDULE OF FIELD OPERATIONS



be covered by one machine during the critical period can be computed, and once the crop distribution is fixed, the number of machines may be determined.

For tractors, the critical period occurs during spring cultivation from 20 March to 20 April, for combine harvesters it occurs during the soybean-maize harvest from 20 September to 30 October, and for silage choppers it occurs during the maize silage harvest in July.

To determine the number of center-pivot irrigation sprinklers, the critical period is in June when lucerne, maize grain, maize silage, and soybeans could be irrigated. It is assumed that one sprinkler can irrigate 52 hectares during this period, so the number of sprinklers can be found from the crop areas. In the case of wheat and barley it is assumed that if these are irrigated the same sprinklers can be used as for maize grain and silage, and soybeans. If insufficient sprinklers are available then they must be purchased especially for wheat and barley. Likewise, the sprinklers needed for irrigating lucerne can also be used to irrigate sunflowers.

The costs of machinery other than irrigation sprinklers are given for each crop in the production cost tables in Appendix 4. The fixed costs are based on capital costs of the machines, depreciated over their working life; the variable costs are calculated to account for maintenance and lubrication. The capital cost of developing irrigated land is taken as 2000 Leva/Ha, which is depreciated over 40 years to give 50 Leva/Ha in each year. The depreciated capital cost of irrigation sprinklers is also taken as 50 Leva/Ha. The variable costs of irrigation include the cost of labor and maintenance of the equipment.

2.3 Crop Production and Outputs

2.3.1 Production Costs

Moving now to the central box of figure (2.1), the crop production schedule and costs are described. Only one year of crop production is considered. At present, SWIM does not explicitly account for crop rotation from year to year, or double cropping within one year, but these refinements could be included if necessary. The schedule of field operations for all crops is shown in figure (2.2). While lucerne is the only perennial crop considered, wheat and barley are planted in the autumn for harvest the following summer. All other crops are planted and harvested within one growing season. The crop production costs per hectare for each crop, both irrigated and nonirrigated are given in Appendix 4.

Lucerne is assumed to be grown only for hay and is replanted every three years. Accordingly, the costs associated with planting have been depreciated in a straight line fashion over this period. No allowance has been made for the ability to supply nitrogen of the legumes, lucerne and soybeans, except that no nitrogen fertilizers are required for them. Maize is grown both for fodder as silage, and grain. When maize is harvested as grain it is assumed that the stalks are plowed back into the soil; for wheat and barley, likewise, it is assumed that the straw is not harvested.

2.3.2 Crop Yields

Crop yields are the most sensitive parameters of SWIM. The relation between crop yield, weather, and irrigation is central to any analysis of irrigation. The yields used in SWIM under normal weather conditions are based where possible on average yields obtained in the Drustar complex, as shown in table (2.3). When the crops are not grown with irrigation at present in the region, the increase in yield due to irrigation can only be assumed. For such crops, where no better data are available, the increase in yield typical for Bulgaria as a whole has been adopted.

In the case of the decrease in yield in response to drought, percentages of decrease in yield used were chosen as follows: maize, 50%; soybeans and sunflowers, 30%; wheat, barley, and lucerne, 15%. Wheat, barley, and, lucerne are more drought-resistant 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 has a large response

Crop	Nonirrigated		Irrigated
	Drought	Normal	
Lucerne	5.1	6.0	10.6
Maize Silage	14.0	28.0	50.0
Maize Grain	2.35	4.7	8.6
Wheat	2.72	3.2	3.7
Barley	2.63	3.1	3.6
Soybeans	1.05	1.5	2.7
Sunflowers	1.4	2.0	2.2

Table 2.3 Crop Yields (in Tons/Ha)

to 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 adding 20% more irrigation water.

2.3.3 Processing

The crops harvested from the field can be processed into a number of outputs. Since the requirements for feeding livestock are expressed in terms of processed outputs, SWIM has some processing activities included within it. The fodder crops, lucerne hay and maize silage are not processed off the farmland. Wheat may be milled for flour in which case 78% of the grain becomes flour and 14% becomes wheat bran which is fed to livestock. Both soybeans and sunflowers are crushed and the oil is extracted. The residual is livestock meal which comprises 75% by weight of the soybean grain and 41% of the sunflower seeds. Maize and barley must be milled before being fed to pigs but there are no significant weight losses in this process.

2.3.4 Requirements for Population and Livestock

The requirements of population for crop outputs are taken as 40,000 tons of flour and 8,400 tons of cooking oil for 1980. The requirements for livestock for 1980 conditions are calculated on the basis of the diet of each animal and the estimated number of animals in the complex. The numbers of animals assumed are: 23,760 breeding sows; 434,404 pigs raised for slaughter; 24,000 dairy cows with associated calves and heifers; and 80,000 ewes. The corresponding feed requirements assumed by SWIM are: 174,100 tons of maize grain, 327,000 tons of maize silage; 37,380 tons of soybean or sunflower meal; 117,100 tons of lucerne hay; and 2805 tons of wheat bran. These values for amounts of feed requirements can easily be changed in SWIM if necessary. It is assumed that 1.1 ton of barley grain can substitute for 1 ton of maize grain.

2.3.5 Imports and Exports

Maximization of production is a goal of the agricultural-industrial complex. Once the livestock and population feed requirements are met, SWIM exports extra production of maize, wheat, and barley grain at internal Bulgarian prices of 113, 114, and 101 Leva/ton, respectively. In case of unfavorable weather conditions when the production requirements as specified in the previous section cannot be met, maize grain can be imported to the region at a price of 170 Leva/ton.

3. RESULTS OF APPLICATION OF THE MODEL

When the capital investment required to develop the Drustar agricultural-industrial complex is considered, a significant part of this investment must be devoted to the development of irrigated land and the water supply facilities needed for this irrigation. SWIM is applied to measure the benefits and water demands of various levels of irrigation development, both under normal weather conditions and under drought conditions. Two basic decisions are investigated:

- How much land should be developed for irrigation?
- How much water should be made available for irrigation?

The major results of these investigations are summarized in this section while the details are tabulated in Appendix 1.

3.1 Land for Irrigation

Of the 121,600 ha of arable land considered in SWIM, it is expected that between 25,000 and 40,000 hectares will be developed for irrigation by 1980, the year for which SWIM is applied. The range of development from 10,000 ha to 50,000 ha of irrigated land is investigated in 5,000 ha steps by repetitively running SWIM on the computer, with each computer run having a different amount of irrigated land available. All water needed is assumed to be available. Two series of computer runs were performed, one for normal weather conditions and another for drought weather conditions. In each run, SWIM determines the optimal crop distribution on both irrigated and nonirrigated land to maximize production while also meeting the minimum production requirements for livestock and population. The results for various levels of irrigated land development are shown in figures (3.1) to (3.8).

3.1.1 Water Demands

In figure (3.1), the volume of water needed, or water demand, for irrigation is plotted for both normal weather and drought conditions. For drought conditions, about 3900 cubic metres per hectare (390 mm) are required, which is an increase of between 25% and 55% over the water demand in normal weather conditions as shown in figure (3.2). In SWIM, the crop water requirements are increased by 20% for drought conditions and it appears from figure (3.2) that for large areas of irrigation the water demands increase by a little more than 20%, because different crops are being irrigated.

3.1.2 Crop Distribution

The distribution of crops grown for different areas of irrigation under normal weather and drought conditions are shown in figures (3.3), and (3.4), respectively. In these figures the vertical axis represents the total arable land and the horizontal axis the amount of this land which is irrigated. The 45^0 line beginning at the origin is the boundary between irrigated and nonirrigated land. The area of each crop grown for a given area of irrigated land is plotted cumulatively in a vertical direction, beginning at the bottom with the seeds area, which is always irrigated, continuing with the irrigated crops, and then the nonirrigated crops. In some cases, one crop may be grown partially irrigated and partially nonirrigated e.g. maize silage for 10,000 ha irrigated land in figure (3.3). By looking from left to right across each figure, the change in the crop distribution as more land is irrigated can be observed. In normal weather conditions, soybeans is the first crop irrigated, followed by maize grain once soybeans are completely irrigated.

A very important feature of the results, which is the substitution of water for land, can be observed by comparing the total areas of soybeans in figure (3.3) for 10,000 and 15,000 ha of irrigated land. These areas are 19925 ha and 15883 ha, respectively. In both cases the total production in tons of soybeans is the same but because a greater proportion of the crop is grown under irrigation in the second case, where it gives a higher yield, the total land area occupied by soybeans decreases, thus leaving more land available for growing other crops without irrigation. Hence water and capital investment in irrigation are being substituted for arable land to grow the same amount of soybeans. This is a key feature of the operation of SWIM and it underlies all the results which follow.

By comparing figures (3.3) and (3.4), it can be seen that different crops are grown under irrigation in drought conditions as compared to normal weather conditions. In a drought, maize silage is irrigated first instead of soybeans, followed by maize grain, and then soybeans for large areas of irrigated land. The reason that maize is irrigated first is that this crop is the most sensitive to drought (50% loss in nonirrigated yield) compared with soybeans and sunflowers (30% loss in nonirrigated yeild), and lucerne, wheat, and barley (15% loss in nonirrigated yield). The losses in yield of nonirrigated sunflowers, wheat and lucerne mean that larger areas of these crops are required to grow the production requirements in drought conditions. For lower irrigated area in drought conditions, a small area of barley is grown as a substitute for maize grain in feeding livestock. In normal weather conditions, the yield of maize grain (4.7 ton/ha) is much higher than that of barley (3.1 tons/ha), so that it is more productive to grow maize grain than barley, and barley does not appear in the crop distribution.

3.1.3 Imports and Exports

If the production from the complex is not sufficient to meet the livestock requirements, SWIM may import maize grain from outside the complex in sufficient quantities to allow the requirements to be met but at a very high price (170 Lv/ton compared with the normal price 113 Lv/ton). Conversely, when there is a production surplus, SWIM can export maize grain, wheat, barley from the region.

The balance of imports and exports is given in figure (3.5), which demonstrates that it requires very little irrigation (6,890 ha) for the region to become self-sufficient (no imports or exports) in normal weather conditions but in drought conditions a much larger area of irrigated land (32,750 ha) is required to achieve self-sufficiency. Figure (3.6), which has a rather unusual shape, shows the corresponding total production costs, including the costs of imports. Under drought conditions the minimum total costs (Lv 21.7 million) are attained just at the point of self-sufficiency. If less land is irrigated, total costs rise because of the cost of imported maize which outweighs the savings made by irrigating less land. Even if imported maize were priced at the export price of 113 Lv/ton the total cost would still rise slowly if less land is irrigated, assuming the same amounts of imports are required.

Since imports are not required under normal weather conditions, the total cost curve is continually rising as more land is irrigated and the production surplus is exported. Another striking feature of figure (3.6) is that total production costs are very similar under both weather conditions when the area of irrigated land is greater than that needed for self-sufficiency. Of course, the difference is that in normal weather conditions, exports are much larger in this range of irrigated land development.

To determine whether it is economic to develop more irrigated land than that needed to achieve self-sufficiency, the value of the surplus production which can be exported should be compared to the extra costs necessary to produce this surplus. These extra production costs can be found by subtracting the total production cost to achieve self-sufficiency from the total production costs when more land is irrigated to produce exports. The net value, or net benefit, of exports is then found by subtracting these extra production costs from the value of the exports, and is plotted in figure (3.7), which shows that the net value of exports continually increases, in a linear fashion, as more land is irrigated. The benefit-cost ratio, which is the value of exports divided by the extra production costs, is fairly constant at 2.0 for normal weather conditions and 2.4 in drought conditions.

3.1.4 Value of Irrigated Land

While it might be expected that the cost of developing each new unit (hectare) of land for irrigation would not change greatly with the scale of development, the value of each new unit of irrigated land might change quite considerably with the scale of development. Intuitively, it seems clear that the first units of irrigated land will have the greatest value, as measured by extra production, because the crops giving the best response to water can be irrigated. As more land is irrigated, less responsive crops are included so that value of each new unit, or marginal value, of irrigated land decreases with the scale of irrigation development. (This marginal value is the shadow price of the constraint on irrigated land in SWIM.) In the economics of supply and demand, the optimal scale of irrigated land development occurs when the cost of developing each new unit of irrigated land is equal to that unit's marginal value.

Figure (3.8) shows the demand curve for irrigated land which is the change in the marginal value of irrigated land with the scale of irrigated land development, for normal weather and drought conditions. As expected, the marginal value of irrigated land in drought conditions is much higher than in normal weather conditions. In figure (3.8) each demand curve is composed of horizontal segments, where the marginal value does not change with the area of irrigated land, and inclined segments (dashed) in which there are considerable differences in marginal value. In the solutions of SWIM, the horizontal segments occur when each new hectare of land is being used to irrigate the same crop as the previous hectare, while the inclined segments occur when a new crop begins to be irrigated, or when self-sufficiency is attained. Actually, if all possible areas of irrigated land had been evaluated, the dashed segments would be vertical, and located at the exact point where a new crop begins to be irrigated.

The cost of irrigated land development of 103.25 Lv/ha, which is assumed in SWIM is also plotted in Figure (3.8). Since this cost line always lies below the demand curves, it may be concluded that the marginal value of irrigated land is always greater than the unit cost of developing it within the range of area considered and the accuracy of SWIM.

3.2 Water For Irrigation

In section (3.1), the area of irrigated land is considered as the limiting resource with all water demands able to be met; in this section, water is considered as the limiting resource with up to 40,000 ha available for irrigation development. Two series of computer runs were performed, one for normal weather conditions and one for drought conditions. In each series, the first computer run was made assuming all of the optimal amount of water demanded for 40,000 ha of irrigated land is available. It should be noted that this optimal amount is higher for drought conditions (159.26 x $10^6 m^3$) than for normal weather conditions (122.64 x $10^6 m^3$). Succeeding runs were then made limiting the available water to 10%, 20%,..., 90% of the optimal amount.

It is found that it is not economical to develop all of the 40,000 ha of irrigated land when the water demanded is not available, figure (3.9). As expected, for a given amount of water available, the optimal area of irrigated land is less in the case of drought conditions than in normal weather conditions because the crop water requirements are higher in a drought.

The corresponding crop distributions are shown in figures (3.10) and (3.11) (which can be compared with figures (3.3) and (3.4), respectively). The distribution for normal weather conditions, figure (3.10), is very similar to that discussed previously, figure (3.3). For drought conditions, figure (3.11), the solution is identical to the previous case, figure (3.4) for sunflowers, lucerne, wheat, and maize silage, but non-irrigated barley assumes a more important role as a substitute for maize grain in livestock feed.

The amount of available water and production cost necessary to reach self-sufficiency in the complex can be found from the balance of imports and exports as in section (3.1.3). Figure (3.12) shows that this production cost is the minimum attainable for the range of water availability considered.

The demand curve for water can be developed using the same method described in section (3.1.4) for irrigated land. As shown in figure (3.13), the marginal value of water is higher in drought conditions than in normal weather conditions, and for both weather conditions the demand curves lie above the unit cost of pumping water (0.022 Lv/m^3) so that it is always optimal to supply all the water demand.

3.3 Input Resources

Besides land and water, SWIM also determines the required amounts of the other input resources: seeds, fertilizers, fuel, labor, and machinery. As can be seen from the tabulated results in Appendix 1, these amounts do not vary a great deal in the various solutions of SWIM, so only average data are given in this section.

The distribution of water required over the irrigation season from April to August is approximately as follows: April, 2%; May, 8%; June, 20%; July, 30% and August 40%.

The required input resources when 40,000 ha of land are irrigated consist of:

- 2870 ha of land for seed production;
- 24,000 tons of ammonium sulphate; 30,000 tons of superphosphate; 7,500 tons of potassium sulphate;
- 7 million litres of fuel;
- 240,000 hours of labor for operating machines;
- 120 tractors;
- 75 combine harvesters;
- 35 silage choppers;
- 710 centre-pivot sprinklers.

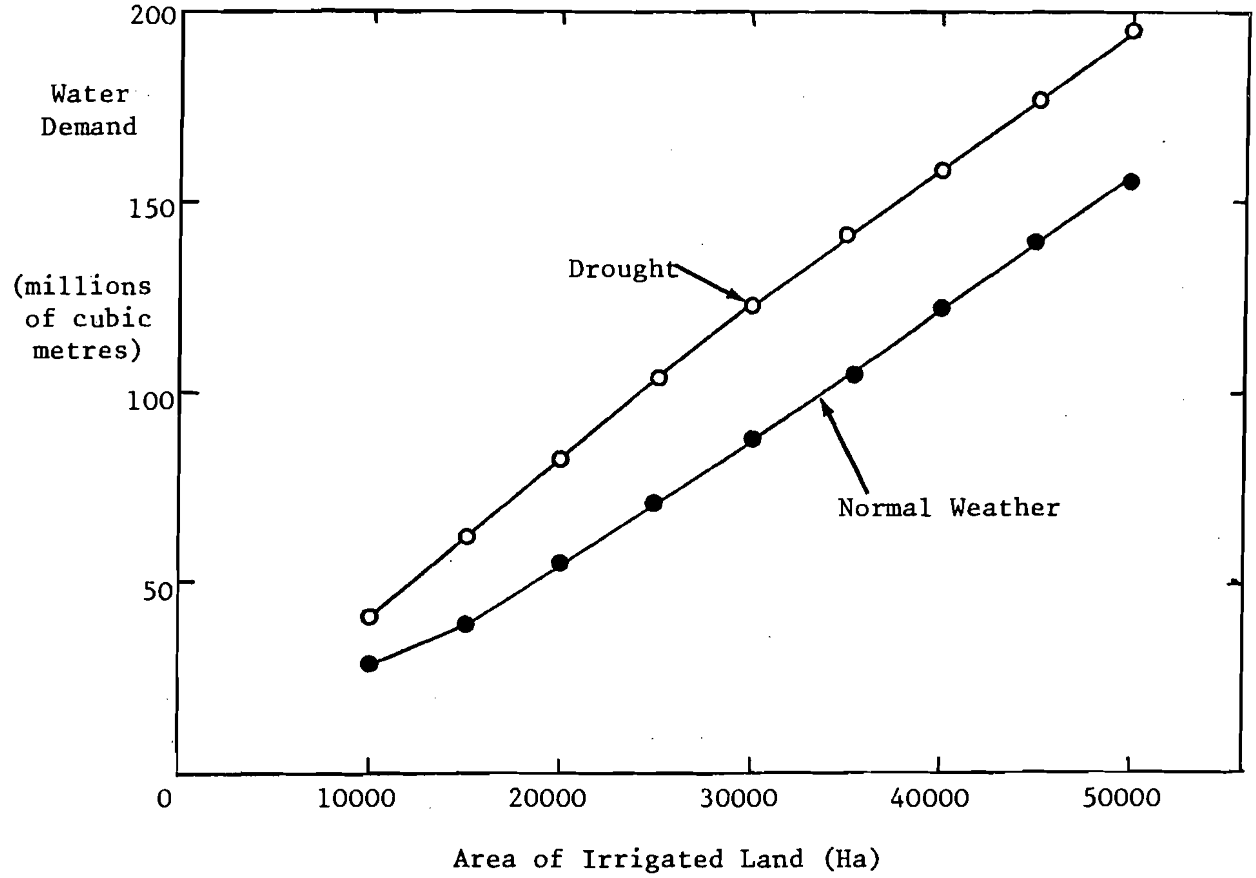


Figure 3.1 Water Demand vs. Area of Irrigated Land

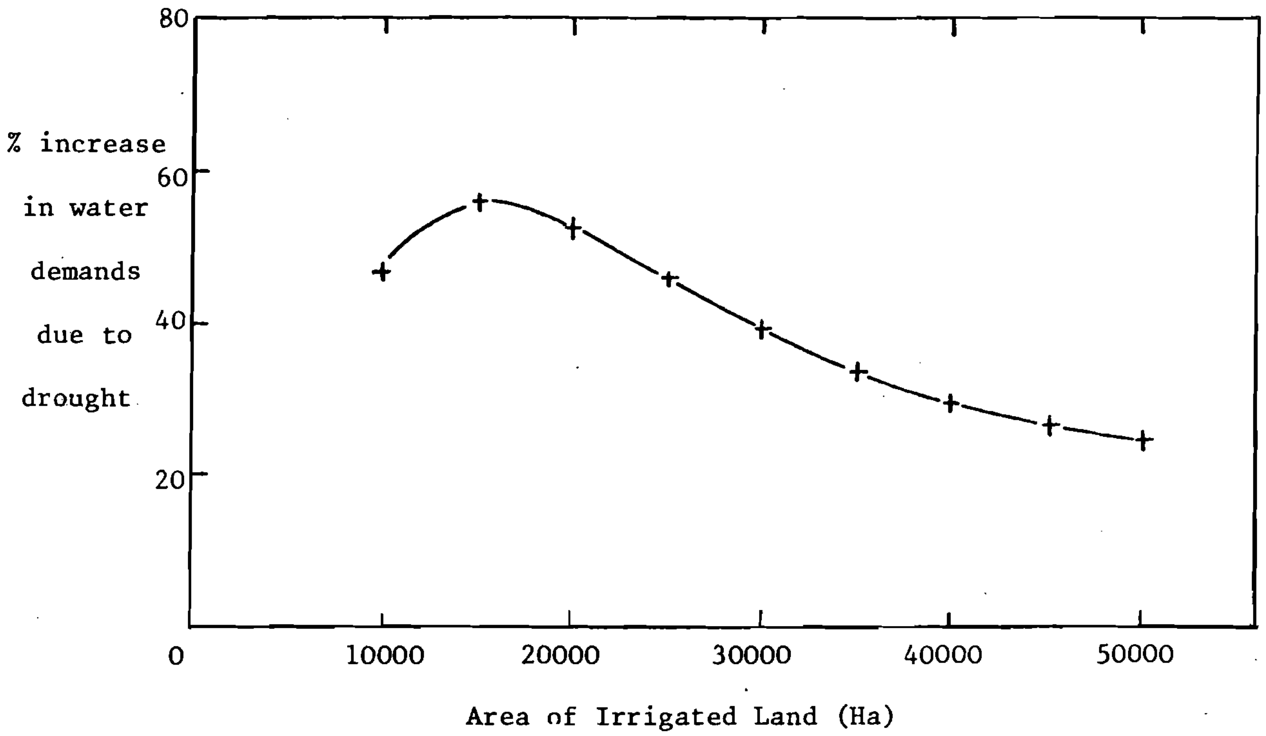


Figure 3.2 Increase in Water Demands due to Drought vs. Area of Irrigated Land

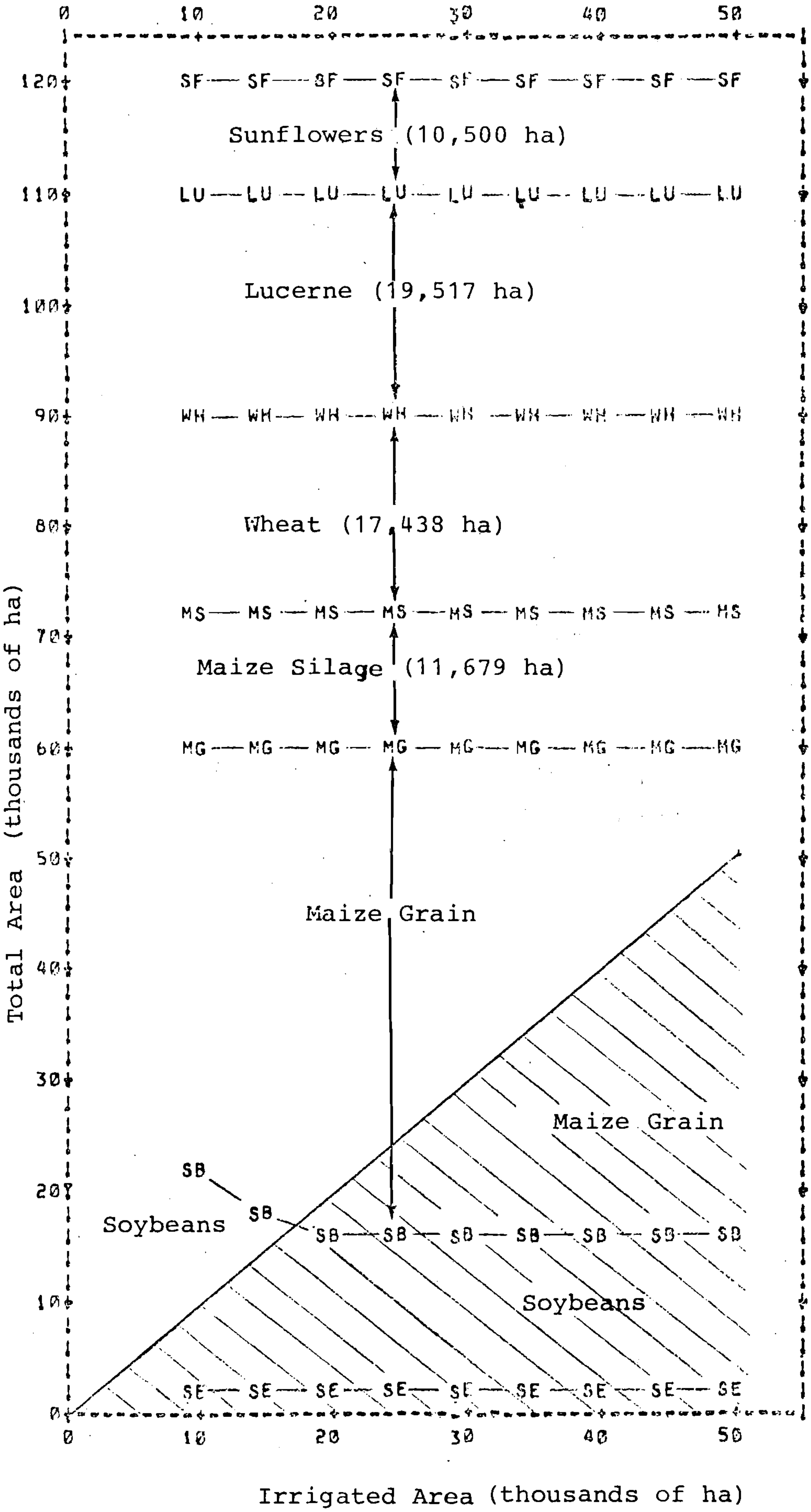


Fig. 3.3 Crop Distribution vs. Area of Irrigated Land (Normal weather)
(shaded portion is area irrigated)

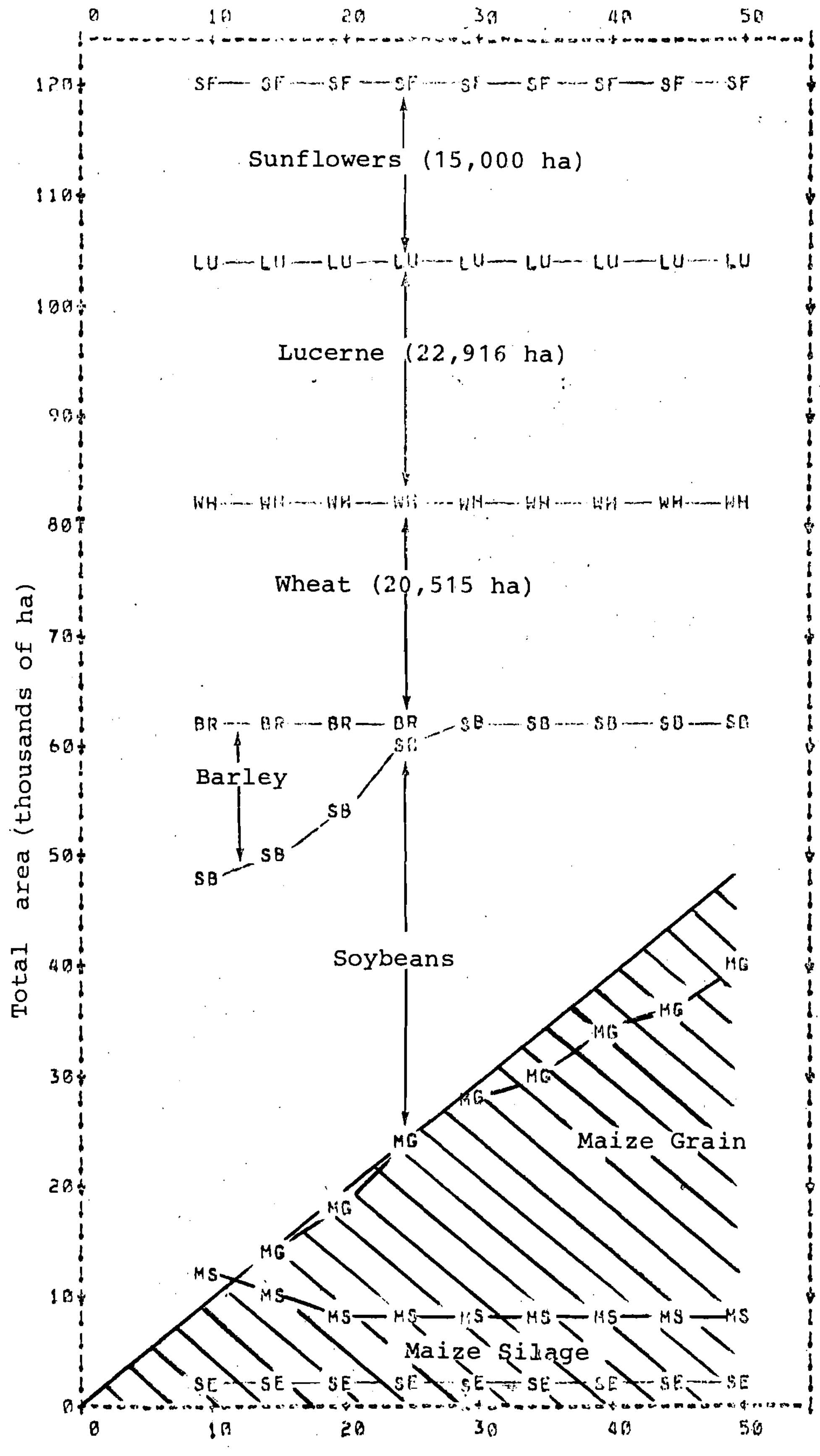


Fig. 3.4 Crop Distribution vs. Area of Irrigated Land (Drought)
(shaded portion is area irrigated)

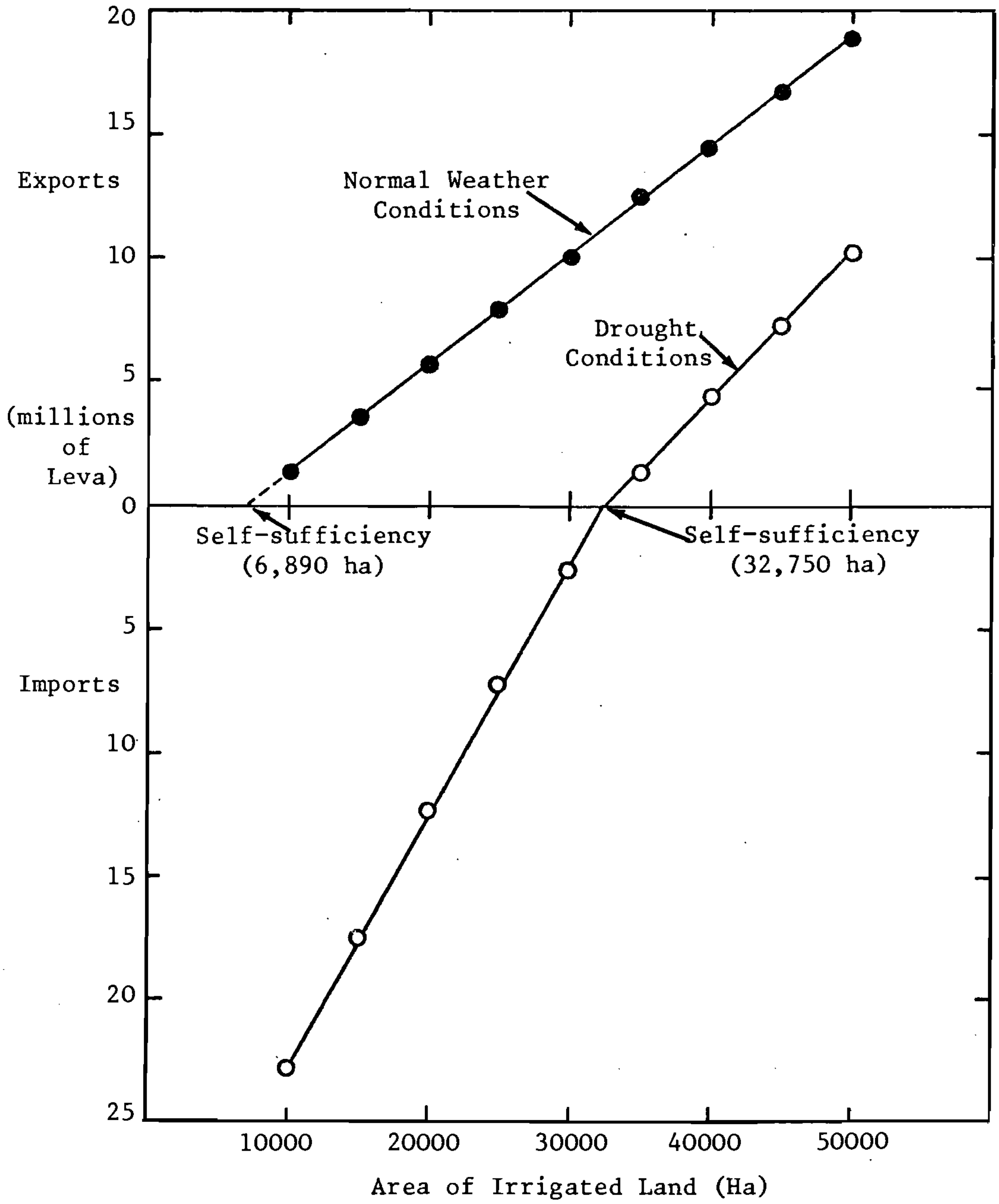


Figure 3.5 Value of Imports and Exports vs. Area of Irrigated Land

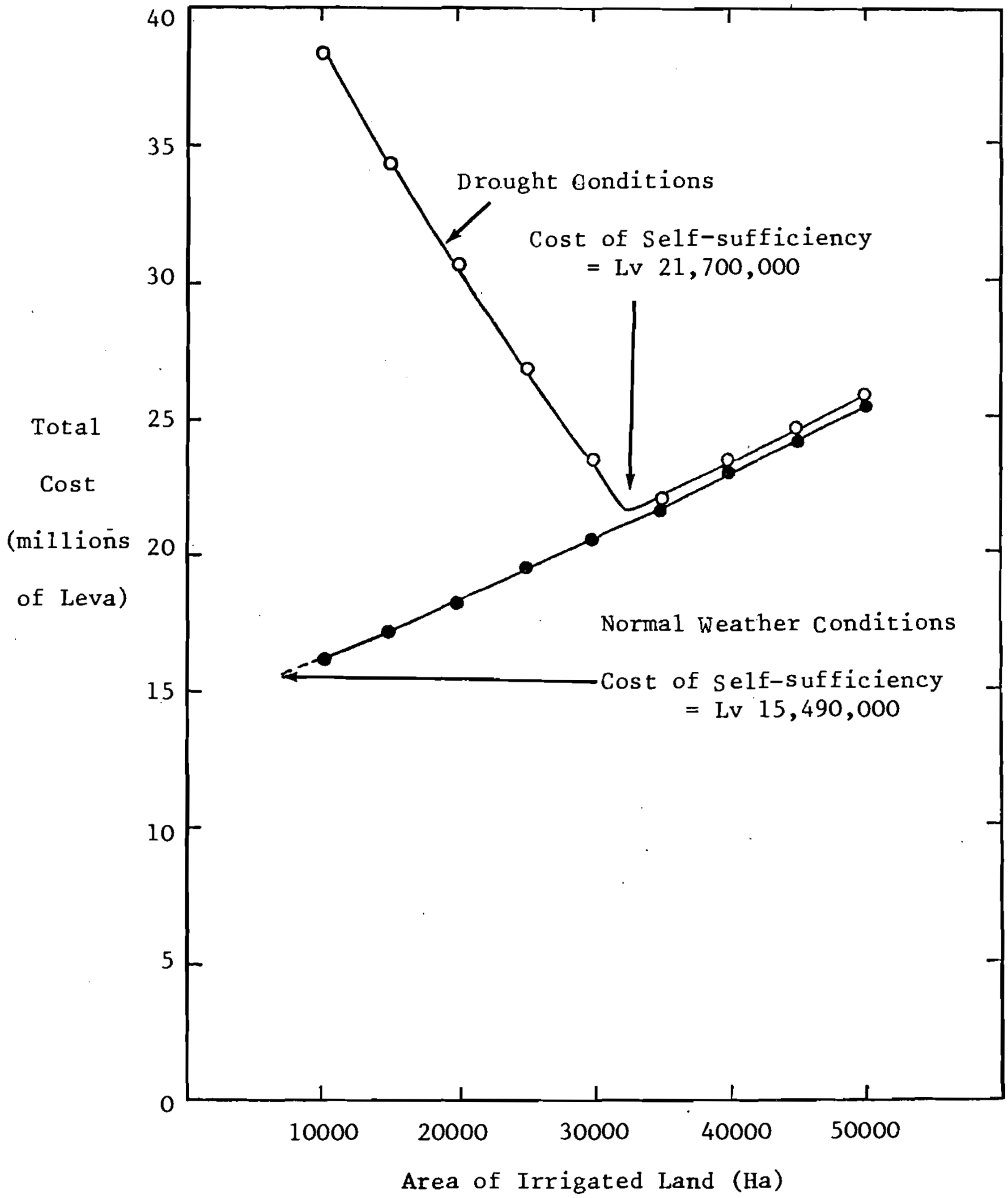


Figure 3.6 Total Costs vs. Area of Irrigated Land

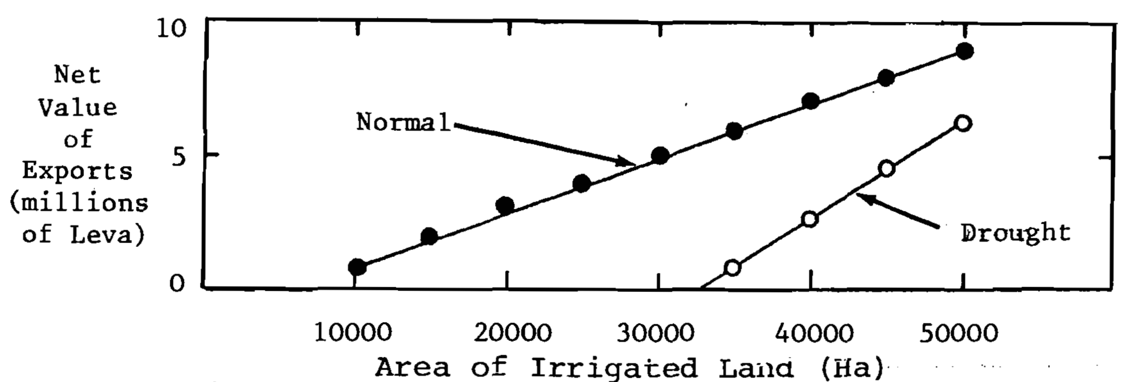


Figure 3.7 Net Value of Exports vs. Area of Irrigated Land

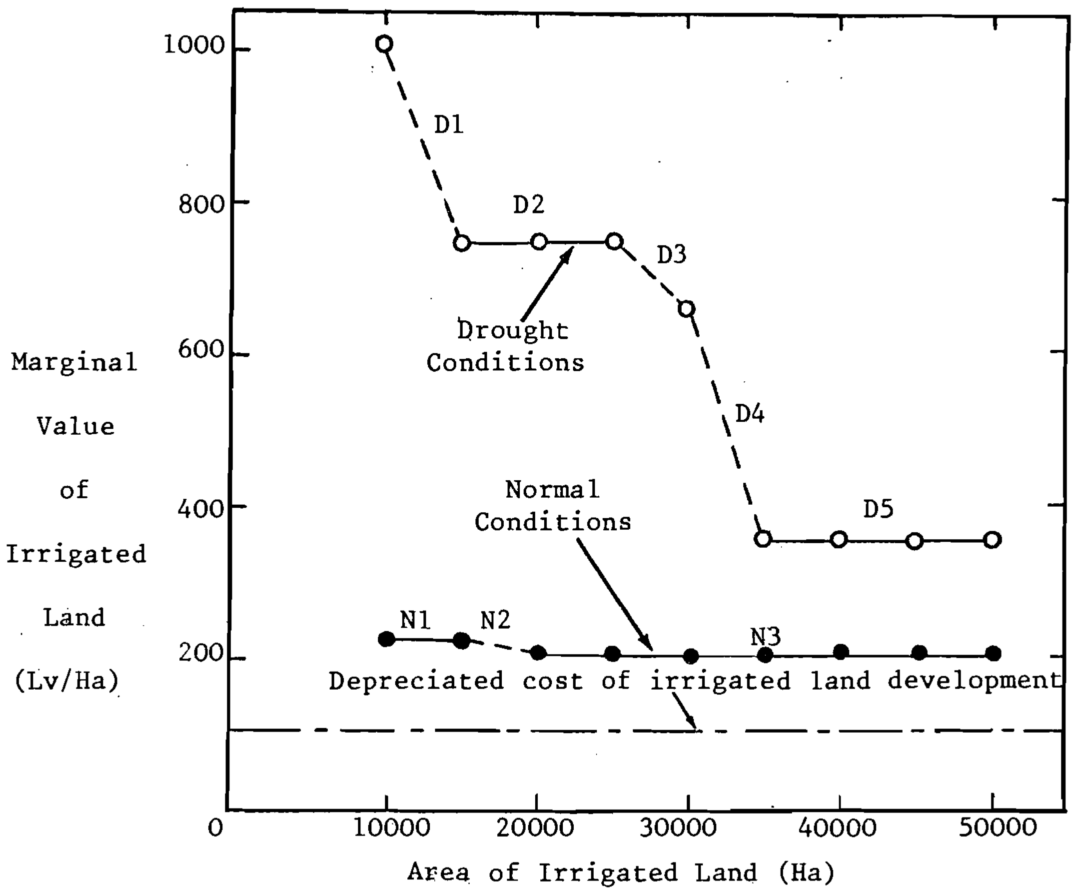


Figure 3.8 Demand Curves for Irrigated Land

Explanation of Regions of Demand Curves:

D1- Maize grain begins to be irrigated, barley area decreasing

D2- More irrigated maize grain grown, barley area decreasing

D3- Barley not grown, soybeans begin to be irrigated

D4- Region becomes self sufficient, maize grain begins to be exported

D5- Increasing irrigation of soybeans and maize grain

N1- More soybeans irrigated, nonirrigated maize grain grown

N2- All soybeans irrigated, maize grain begins to be irrigated

N3- More maize grain irrigated

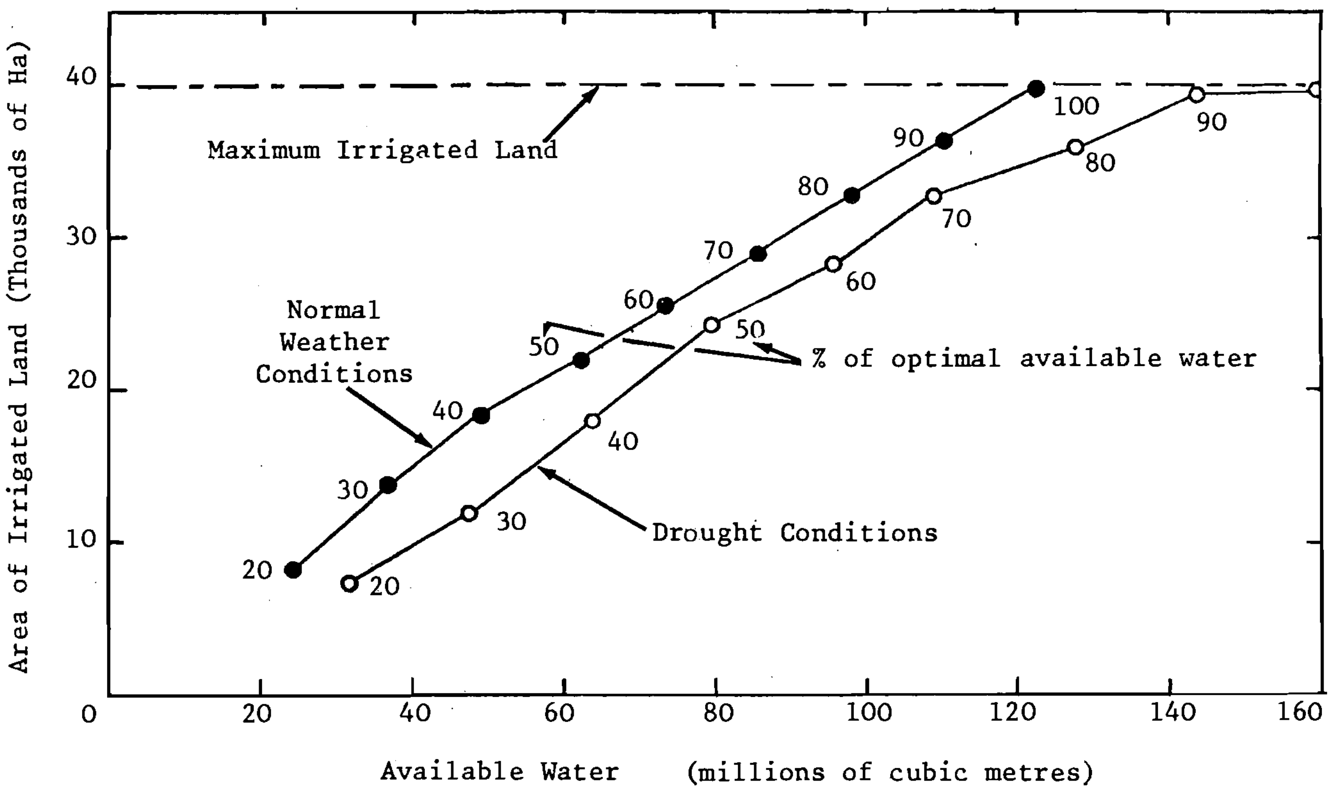


Figure 3.9 Area of Irrigated Land vs. Available Water

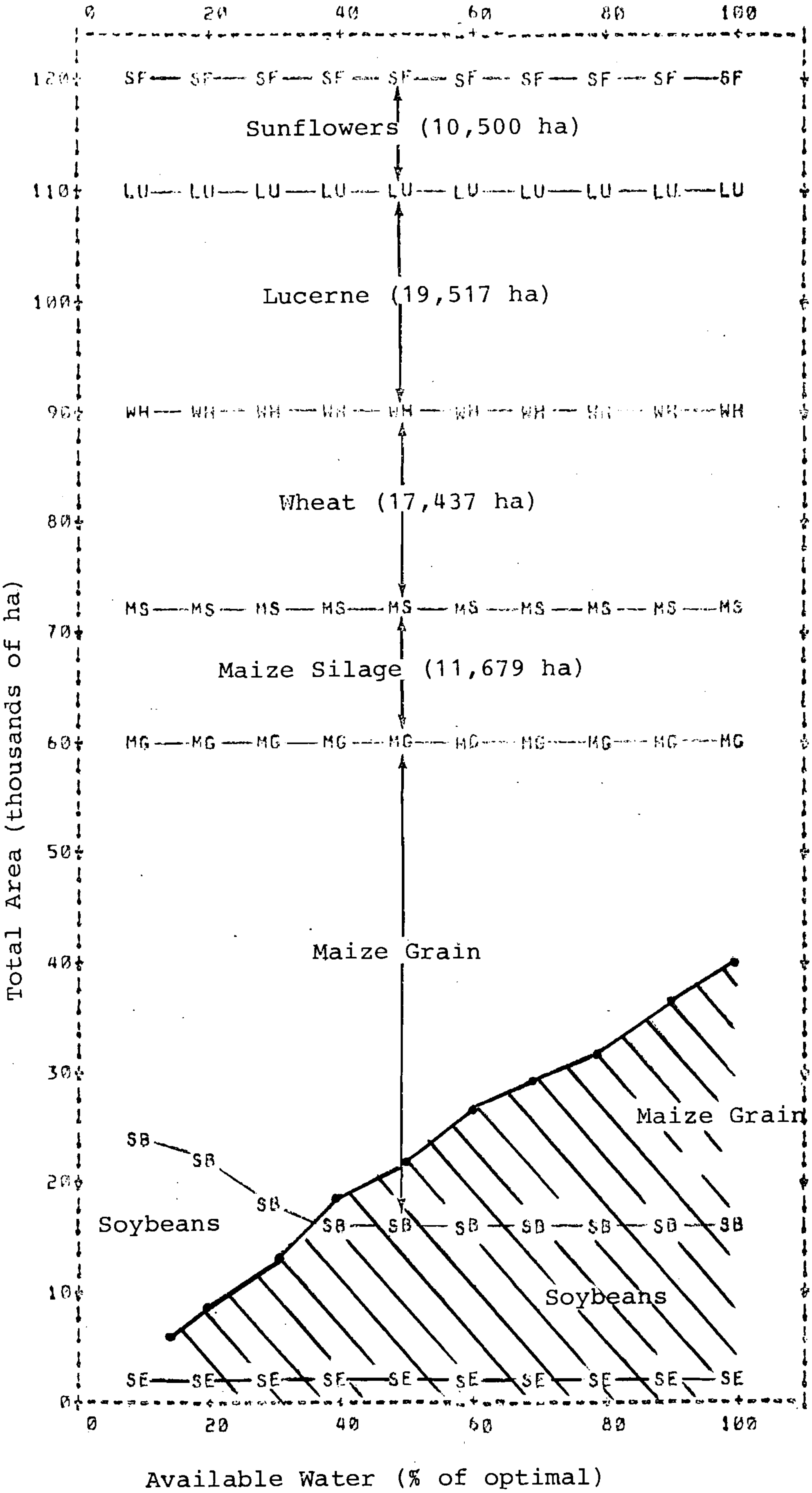


Fig 3.10 Crop Distribution vs. Available Water (Normal Weather)
(shaded portion is irrigated area)

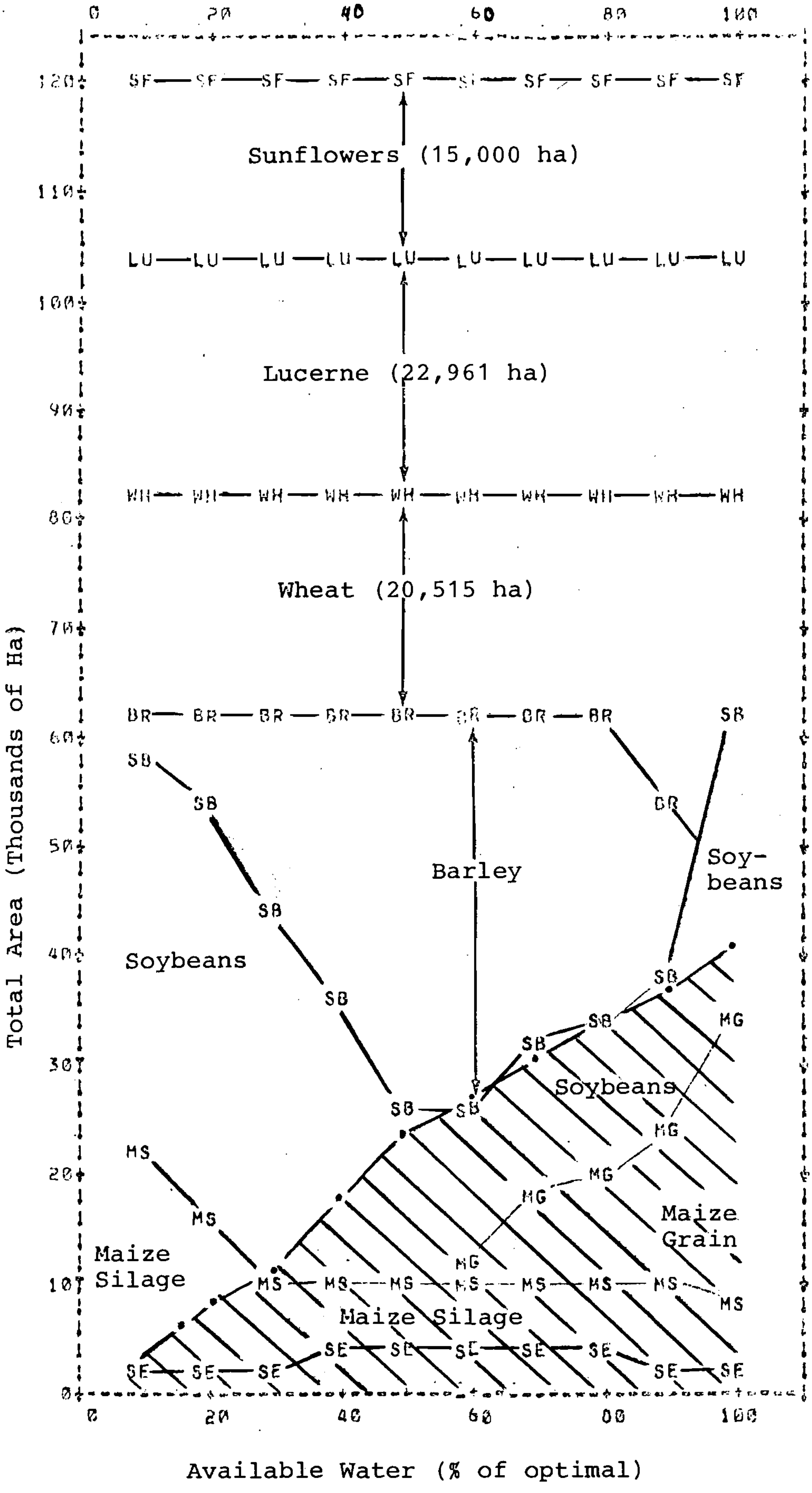


Fig. 3.11 Crop Distribution vs. Available Water (Drought)
(shaded portion is irrigated area)

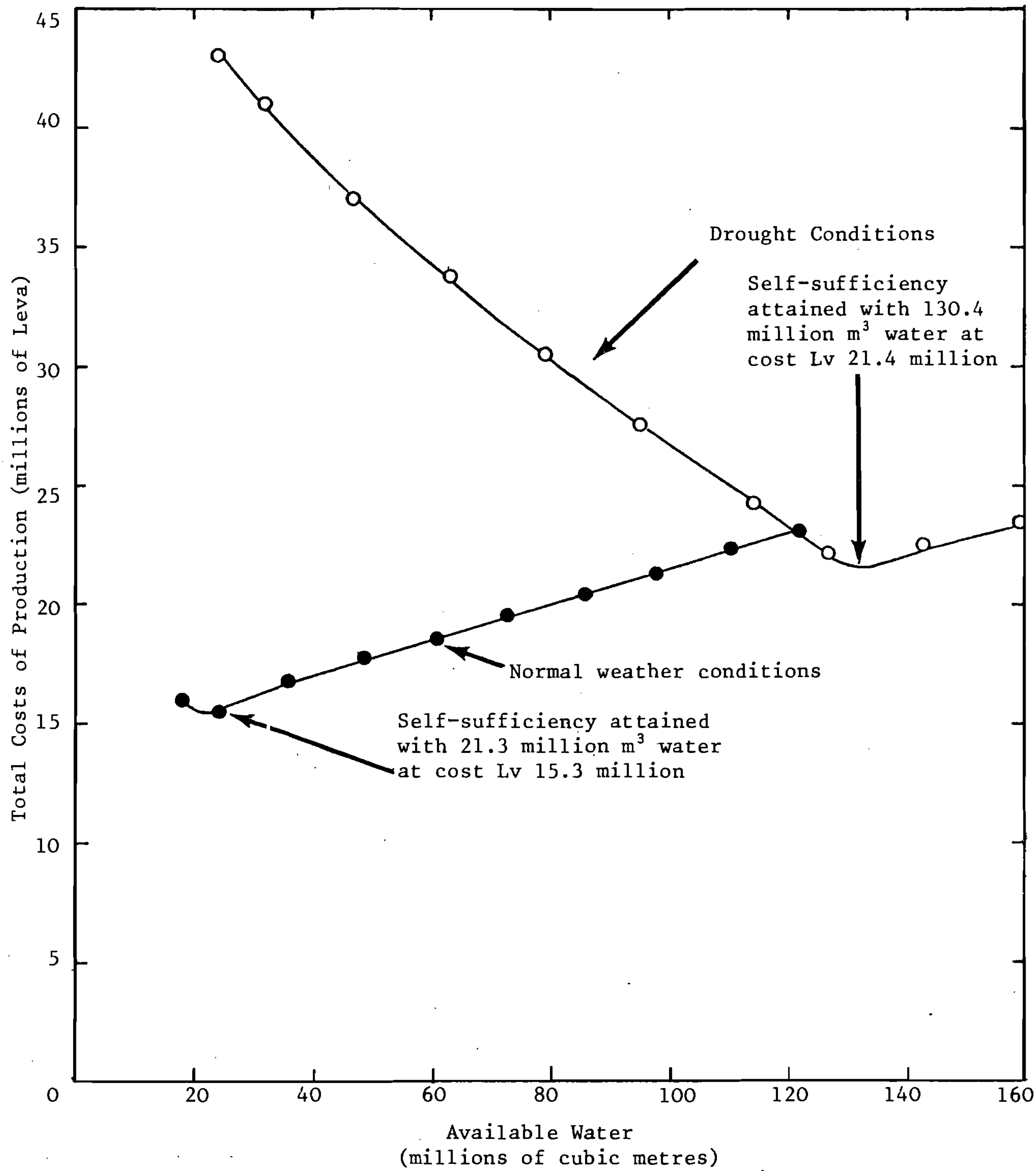


Figure 3.12 Production Costs vs. Available Water

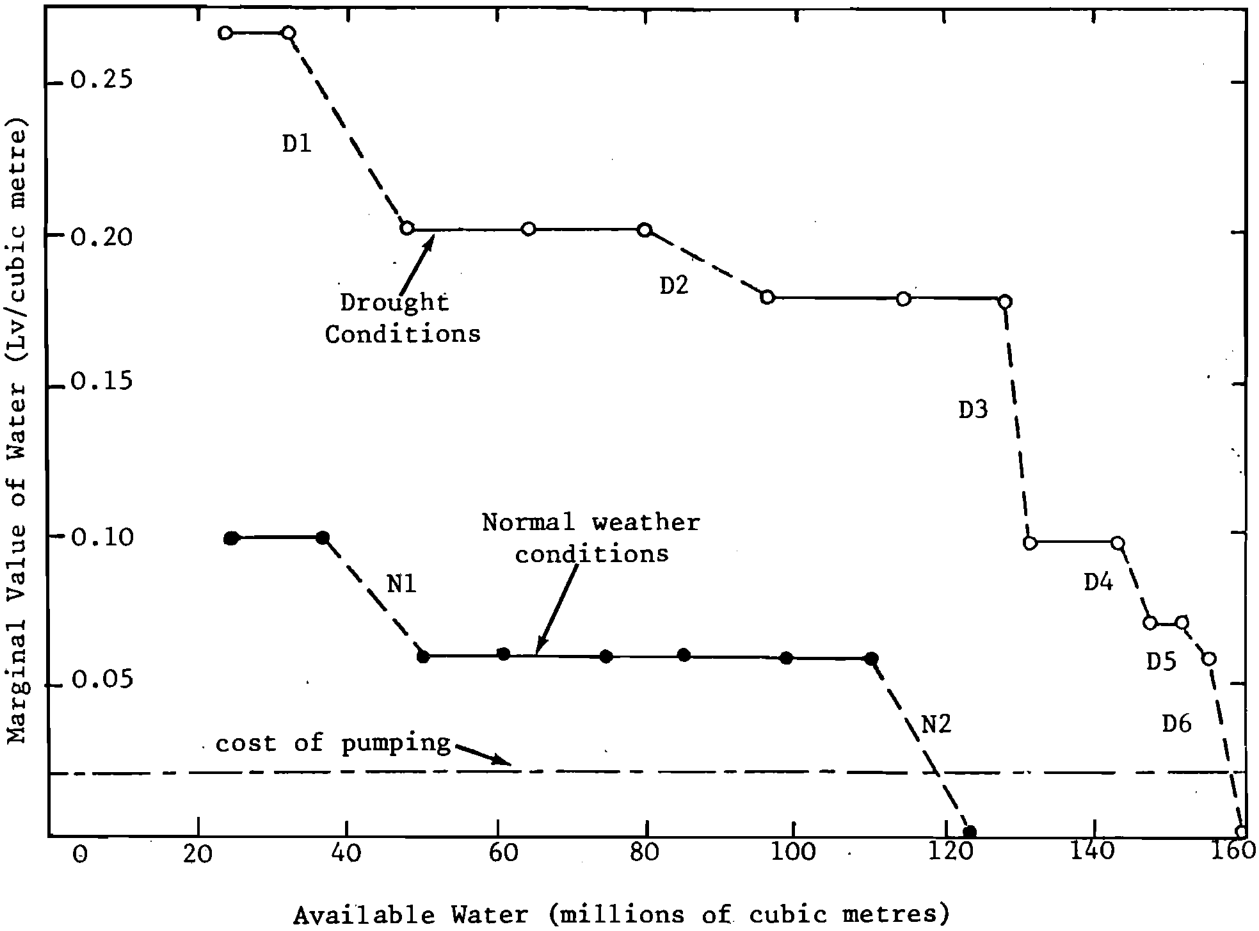


Figure 3.13. Demand Curves for Water

Explanation of Regions of Demand Curves:

D1- Soybeans begin to be irrigated

D2- Irrigated maize grain begins to be grown

D3- Region reaches self-sufficiency, export of wheat begins

D4- Nonirrigated soybeans begin to be grown

D5- No more barley grown, export of maize begins, exports of wheat decrease

D6- Exports of wheat cease

N1- Irrigated maize grain begins to be grown

N2- Irrigated area becomes limiting factor

4. CONCLUSIONS

The development of land and water for irrigation in the Drustar agricultural-industrial complex in 1980 is investigated for both normal weather and drought conditions. The major results are:

a) 33,000 ha of irrigated land and 135 million cubic metres per year of water are needed for the complex to be self-sufficient in drought conditions. At this level of development, 100,000 tons of maize grain could be exported from the complex under normal weather conditions.

b) The total costs of crop production are minimized at the point when the complex is just self-sufficient.

c) The marginal values of land and water developed for irrigation are always greater than their unit costs of supply in the range of development considered.

d) The optimal distribution of crops to be grown on both irrigated and nonirrigated land is determined for all cases investigated.

These results are preliminary and should only be interpreted as being indicative of the kind of questions the model can answer. However, we consider that the data and structure of the model could be improved and extended through further discussion with Bulgarian experts to make the model sufficiently reliable for actual decision-making. Improvements in the data could include:

- Crop yields without irrigation for various weather conditions.
- The relation between crop yields and water applied by irrigation.
- Costs and technology of crop production, especially for irrigation.

Extensions to the structure of the model could involve:

- Breaking down the complex on the basis of soil type into sub-regions which have different crop yields and water requirements.
- Introducing the livestock of the complex into the model and considering different diets for them.

- Taking account of other crops which could be grown in the complex.
- Adding the dynamics of change from year to year, such as crop rotations and grain storage.
- Incorporating the facilities needed for water supply, such as dams, pumps, and channels.

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Ministry of Information and Communications, *Statisticheski godishnik* (Statistical Yearbook) for Peoples Republic of Bulgaria, Sofia 1975.

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Appendix 1

TABLES OF COMPUTATIONAL RESULTS

The following four tables give the detailed data produced by SWIM computer printouts for each of the series of computer runs carried out: varying the amount of irrigated land, and the amount of water, both under normal weather conditions and drought conditions. A glossary of the terms used in the print-outs is included to aid in the interpretation of the results.

GLOSSARY OF TERMS

	UNIT	
PW	$m^3 x 10^6$	Amount of irrigation water
DLPW	Lv/m^3	Marginal value of water
NL	Ha	Total irrigated land required
DLNL	Lv/Ha	Marginal value of irrigated land
ALUI	Ha	Irrigated land for growing lucerne
ALUN	Ha	Nonirrigated land for growing lucerne
AMSI	Ha	Irrigated land for growing maize silage
AMSN	Ha	Nonirrigated land for growing maize silage
AMGI	Ha	Irrigated land for growing maize grain
AMGN	Ha	Nonirrigated land for growing maize grain
AWHI	Ha	Irrigated land for growing wheat
AWHN	Ha	Nonirrigated land for growing wheat
ABRI	Ha	Irrigated land for growing barley
ABRN	Ha	Nonirrigated land for growing barley
ASBI	Ha	Irrigated land for growing soybeans
ASBN	Ha	Nonirrigated land for growing soybeans
ASFI	Ha	Irrigated land for growing sunflowers
ASFN	Ha	Nonirrigated land for growing sunflowers
AS	Ha	Irrigated land for seeds
IMAZ	Tn	Maize grain import
EMAZ	Tn	Maize grain export
EWHT	Tn	Wheat export
EBRL	Tn	Barley export

	UNIT	
TAPR	$m^3 x 10^6$	Total irrigation water in April
TMAY	$m^3 x 10^6$	Total irrigation water in May
TJUN	$m^3 x 10^6$	Total irrigation water in June
TJUL	$m^3 x 10^6$	Total irrigation water in July
TAUG	$m^3 x 10^6$	Total irrigation water in August
IREQ	-	Number of irrigation sprinklers
AMN	Tn	Ammonium sulphate fertilizer
SPH	Tn	Super phosphate fertilizer
POT	Tn	Potassium sulphate fertilizer
FUL	litres	Fuel
TRH	Hrs	Tractor hours
CJH	Hrs	Combine June-July hours
CHS	Hrs	Combine August-October hours
TRS	-	Number of tractors
CMB	-	Number of combines
SCB	-	Number of silage combines
TEXB	$Lv \times 10^6$	Value of exports
COST	$Lv \times 10^6$	Total cost of production
OBJ	$Lv \times 10^6$	Value of exports minus cost of production

I I A S A PDP 11/45 COMPUTER

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SILISTRA AGRICULTURAL-INDUSTRIAL COMPLEX
WATER DEMAND STUDY

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YEAR: 1980 WEATHER: NORMAL
VARYING THE AREA OF IRRIGATED LAND WITH UNCONSTRAINED WATER

AREA (HA)	10000	15000	20000	25000	30000	35000	40000	45000	50000	121000
PW	28.409	39.917	54.640	71.640	88.640	105.640	122.640	139.640	156.640	347.360
DLPW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WL	10000.000	15000.000	20000.000	25000.000	30000.000	35000.000	40000.000	45000.000	50000.000	111100.000
DLNL	-226.610	-226.618	-201.783	-201.783	-201.783	-201.783	-201.783	-201.783	-201.783	0.000
ALUI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11047.169
ALUN	19516.666	19516.666	19516.666	19516.666	19516.666	19516.666	19516.666	19516.666	19516.666	0.000
AMSI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6540.000
AMSN	11678.571	11678.571	11678.571	11678.571	11678.571	11678.571	11678.571	11678.571	11678.571	0.000
AMGI	0.000	0.000	2926.130	7925.132	10924.134	17923.137	22922.139	27921.141	32920.141	62282.750
AMGN	39602.824	43696.504	42467.262	37467.262	32467.262	27467.262	22467.262	17467.262	12467.262	0.000
AWHI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	15001.061
AWHN	17437.500	17437.500	17437.500	17437.500	17437.500	17437.500	17437.500	17437.500	17437.500	0.000
ABRI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ABRN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ASBI	7060.498	12112.541	14207.407	14207.407	14207.407	14207.407	14207.407	14207.407	14207.407	14207.407
ASBN	12864.438	3770.759	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ASFI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ASFN	10500.000	10500.000	10500.000	10500.000	10500.000	10500.000	10500.000	10500.000	10500.000	10500.000
AS	2939.502	2867.459	2866.463	2867.461	2868.459	2869.457	2870.455	2871.453	2872.451	1941.593
IMAZ	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EMAZ	11953.268	31193.555	50580.840	70872.258	89563.680	109060.000	128550.000	148040.000	167530.000	361450.000
EWHT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EBRL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TAPR	1.699	1.699	1.699	1.699	1.699	1.699	1.699	1.699	1.699	15.044
TMAY	4.792	4.793	5.438	6.538	7.638	8.738	9.838	10.938	12.038	51.569
TJUN	8.154	10.556	13.483	16.783	20.083	23.383	26.683	29.983	33.283	80.560
TJUL	6.022	9.954	14.783	20.233	25.683	31.133	36.583	42.033	47.483	86.647
TAUG	7.761	12.914	19.236	26.386	33.536	40.686	47.836	54.986	62.136	113.570
TREQ	135.562	232.561	328.964	424.945	520.926	616.906	712.887	808.868	904.849	1686.285
AMN	17671.590	18827.605	19926.307	20984.314	22042.320	23100.328	24158.334	25216.342	26274.348	37043.316
SPH	26516.367	27289.787	27976.082	28600.650	29225.234	29849.811	30474.387	31098.961	31723.537	38937.797
POT	6501.865	6622.440	6777.743	6957.662	7137.582	7317.501	7497.420	7677.339	7857.258	9264.396
FUL	6.769	6.809	6.838	6.858	6.878	6.898	6.918	6.939	6.959	7.492
TRH	203170.000	203710.000	203932.000	203932.000	203932.000	203932.000	203932.000	203932.000	203932.000	211500.000
CJM	6347.250	6347.250	6347.250	6347.250	6347.250	6347.250	6347.250	6347.250	6347.250	6661.692
CMS	25097.516	25692.943	26431.201	27270.641	28110.078	28949.518	29788.957	30628.396	31467.834	43057.520
TRS	118	121	121	121	121	121	121	121	121	146
CMP	61	63	65	67	69	72	74	76	79	111
SCB	34	34	34	34	34	34	34	34	34	27
TEXB	1.351	3.525	5.716	7.918	10.121	12.323	14.526	16.728	18.931	40.644
COST	16.129	17.161	18.227	19.480	20.674	21.868	23.061	24.255	25.448	38.509
OBJ	14.778	13.636	12.571	11.562	10.553	9.545	8.535	7.527	6.517	-2.335

Table A1.1 Results of Varying Irrigated Land (Normal Weather)

I I A S A PDP 11/45 COMPUTER

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* SILISTRA AGRICULTURAL-INDUSTRIAL COMPLEX *
* WATER DEMAND STUDY *

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YEAR: 1980 WEATHER: DROUGHT
VARYING THE AREA OF IRRIGATED LAND WITH UNCONSTRAINED WATER AND MAIZE IMPORTS ALLOWED

AREA (HA)	10000	15000	20000	25000	30000	35000	40000	45000	50000	121000
PW	41,604	62,319	83,433	104,550	123,470	141,360	159,260	177,160	195,050	434,360
DLPW	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
NL	10000,000	15000,000	20000,000	25000,000	30000,000	35000,000	40000,000	45000,000	50000,000	121000,000
DLNL	-1007,661	-746,614	-746,614	-746,614	-658,969	-355,311	-355,311	-355,311	-355,311	-109,997
ALUI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	11847,169
ALUN	22960,785	22960,785	22960,785	22960,785	22960,785	22960,785	22960,785	22960,785	22960,785	0,000
AMSI	5757,442	6540,000	6540,000	6540,000	6540,000	6540,000	6540,000	6540,000	6540,000	6540,000
AMSN	2794,858	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
AMGI	0,000	4317,640	9545,185	14772,729	18547,932	21645,211	24742,488	27839,766	30937,043	63071,785
AMGN	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
AWHI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	14640,000
AWHN	20514,707	20514,707	20514,707	20514,707	20514,707	20514,707	20514,707	20514,707	20514,707	600,000
ABRI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
ABRN	13796,323	11591,174	6591,173	1591,174	0,000	0,000	0,000	0,000	0,000	0,000
ASBI	0,000	0,000	0,000	0,000	1325,655	3270,099	5214,543	7156,988	9103,432	14207,407
ASBN	36533,336	36533,336	36533,336	36533,336	33124,500	28124,510	23124,510	18124,510	13124,509	0,000
ASFI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	9545,456
ASFN	15000,000	15000,000	15000,000	15000,000	15000,000	15000,000	15000,000	15000,000	15000,000	0,000
AS	4242,550	4142,360	3914,815	3687,270	3586,413	3544,691	3502,969	3461,247	3419,524	1940,100
IMAZ	134270,000	103520,000	73823,141	42531,254	14667,774	0,000	0,000	0,000	0,000	0,000
EMAZ	0,000	0,000	0,000	0,000	0,000	11968,816	38605,406	65241,996	91878,586	360240,000
EWHT	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
EBRL	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
TAPR	2,685	2,639	2,536	2,432	2,399	2,399	2,399	2,399	2,399	17,665
TMAY	8,683	9,963	11,193	12,422	13,372	14,191	15,011	15,830	16,649	61,033
TJUN	11,353	15,396	19,545	23,693	27,434	30,985	34,535	38,086	41,636	102,910
TJUL	8,217	14,895	21,746	28,597	34,771	40,628	46,486	52,343	58,200	114,170
TAUG	10,665	19,425	28,414	37,402	45,491	53,161	60,830	68,500	76,169	137,500
IREQ	110,543	208,467	308,836	409,204	507,141	603,942	700,743	797,544	894,345	1821,436
AMN	11811,613	12823,868	14524,299	16228,729	17809,215	19339,580	20869,943	22400,309	23930,670	37851,164
SPH	25874,268	26398,057	26869,762	27341,469	28039,615	28843.457	29647,301	30451,145	31254,986	39398,625
POT	7803,811	7763,160	8024,068	8284,977	8448,711	8567,086	8685,462	8803,837	8922,212	9399,225
FUL	6,363	6,402	6,482	6,562	6,616	6,658	6,700	6,742	6,784	7,523
TRH	190760,000	194840,000	196730,000	198620,000	199510,000	199920,000	200330,000	200740,000	201150,000	211650,000
CJH	12489,215	11686,540	9866,540	8246,540	7467,353	7467,353	7467,353	7467,353	7467,353	6879,601
CHS	15594,268	18020,781	20958,662	23896,541	25451,582	26361,141	27270,701	28180,260	29089,818	43972,524
TRS	71	77	87	96	100	102	103	105	107	144
CHB	30	37	45	54	58	60	63	66	68	112
SCB	32	27	27	27	27	27	27	27	27	27
TEXB	0,000	0,000	0,000	0,000	0,000	1.352	4,362	7,372	10,382	41,611
COST	38,375	34,414	30,681	26,948	23,514	22,254	23,487	24,721	25,956	41,330
OBJ	38,375	34,414	30,681	26,948	23,514	20,902	19,125	17,349	15,572	-0,281

Table A1.2 Results of Varying Irrigated Land (Drought)

I I A S A PDP 11/45 COMPUTER

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*********************************************
*                                           *
* SILISTRA AGRICULTURAL-INDUSTRIAL COMPLEX  *
*            WATER DEMAND STUDY             *
*                                           *
*********************************************
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YEAR: 1980 WEATHER: NORMAL
VARYING THE WATER WITH CONSTRAINED AREA OF IRRIGATED LAND < 40000

% OPT WATER	15%	20%	30%	40%	50%	60%	70%	80%	90%	100%
PW	16,396	24,528	36,792	49,056	61,320	73,584	85,848	98,112	110,380	122,640
DLPW	-0,195	-0,099	-0,099	-0,059	-0,059	-0,059	-0,059	-0,059	-0,059	0,000
NL	5649,661	8313,879	13642,316	18357,764	21964,813	25571,859	29176,908	32785,957	36393,004	40000,000
DLNL	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	-201,783
ALUI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
ALUN	19516,666	19516,666	19516,666	19516,666	19516,666	19516,666	19516,666	19516,666	19516,666	19516,666
AMSI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
AMSN	11678,571	11678,571	11678,571	11678,571	11678,571	11676,571	11676,571	11676,571	11678,571	11676,571
AMGI	0,000	0,000	0,000	1284,221	4890,550	8496,878	12103,206	15709,534	19315,863	22922,139
AMGN	36041,047	38222,336	42584,918	44109,500	40502,449	36895,402	33288,352	29681,305	26074,258	22467,262
AWHI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
AWHN	17437,500	17437,500	17437,500	17437,500	17437,500	17437,500	17437,500	17437,500	17437,500	17437,500
ABRI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
ABRN	0,000	0,000	0,000	0,000	0,000	0,000	2,000	0,000	0,000	0,000
ASBI	2664,877	5356,827	10708,727	14207,407	14207,407	14207,407	14207,407	14207,407	14207,407	14207,407
ASBN	20776,555	15931,045	6240,026	0,000	0,000	0,000	0,000	0,000	0,000	0,000
ABFI	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
ABFN	10500,000	10500,000	10500,000	10500,000	10500,000	10500,000	10500,000	10500,000	10500,000	10500,000
AS	2980,783	2957,052	2901,590	2866,135	2866,855	2867,575	2868,295	2869,015	2869,735	2870,455
IMAZ	4787,087	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
EMAZ	0,000	5468,979	25969,111	44178,937	58240,234	72301,531	86362,828	100420,000	114490,000	128550,000
EWHT	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
EBRL	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
TAPR	1,699	1,699	1,699	1,699	1,699	1,699	1,699	1,699	1,699	1,699
TMAY	4,790	4,791	4,793	5,076	5,870	6,664	7,457	8,251	9,044	9,838
TJUN	6,065	7,344	9,904	12,399	14,780	17,161	19,501	21,922	24,303	26,683
TJUL	2,563	4,669	8,881	12,993	16,925	20,856	24,788	28,720	32,651	36,583
TAUG	3,278	6,024	11,515	16,888	22,046	27,204	32,362	37,520	42,678	47,836
TRED	51,166	102,051	206,222	297,439	366,681	435,922	505,164	574,405	643,647	712,887
AMN	16665,742	17281,700	18513,732	19578,809	20342,064	21105,320	21868,576	22631,834	23395,092	24158,334
SPM	25843,439	26255,553	27079,775	27770,941	28221,518	28672,092	29122,660	29573,242	30023,810	30474,387
POT	6396,995	6461,231	6589,705	6718,649	6848,444	6978,240	7108,036	7237,831	7367,626	7497,422
FUL	6,733	6,755	6,798	6,831	6,846	6,860	6,875	6,889	6,904	6,918
TRM	282700,000	282990,000	283560,000	283930,000	283930,000	283930,000	283930,000	283920,000	283920,000	283920,000
CJM	6347,250	6347,250	6347,250	6347,250	6347,250	6347,250	6347,250	6347,250	6347,250	6347,250
CMS	24579,453	24896,723	25531,262	26155,488	26761,068	27366,648	27972,227	28577,807	29183,387	29788,957
TRS	116	117	120	121	121	121	121	121	121	121
CMB	62	62	62	64	66	67	69	71	72	74
SCB	34	34	34	34	34	34	34	34	34	34
TEXP	0,000	0,618	2,934	4,992	6,581	8,170	9,759	11,348	12,937	14,526
COST	16,246	15,782	16,881	17,895	18,756	19,617	20,478	21,339	22,200	23,061
OBJ	16,246	15,164	13,947	12,903	12,175	11,447	10,719	9,991	9,263	8,535

Table A1.3 Results of Varying Available Water (Normal Weather

I I A S A PDP 11/45 COMPUTER

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* SILISTRA AGRICULTURAL-INDUSTRIAL COMPLEX *
* WATER DEMAND STUDY *
****

YEAR: 1980 WEATHER: DROUGHT
VARYING THE WATER WITH CONSTRAINED AREA OF IRRIGATED LAND < 40000 AND MAIZE IMPORTS ALLOWED

% OPT WATER	15%	20%	30%	40%	50%	60%	70%	80%	90%	100%
PW	23.889	31.852	47.778	63.704	79.630	95.556	114.480	127.410	143.330	159.260
OLPW	-0.268	-0.268	-0.201	-0.201	-0.201	-0.177	-0.177	-0.177	-0.097	0.000
NL	5293.765	7489.250	11966.542	17995.756	24014.971	28438.172	32920.000	35980.984	39656.687	40000.000
DLNL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-355.311
ALUI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ALUN	22960.785	22960.785	22960.785	22960.785	22960.785	22960.785	22960.785	22960.785	22960.785	22960.785
AMSI	1525.673	3427.883	6540.000	6540.000	6540.000	6540.000	6540.000	6540.000	6540.000	6540.000
AMSN	17988.309	11114.705	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AMGI	0.000	0.000	0.000	0.000	0.000	2802.216	7486.010	10688.294	14665.604	24742.480
AMGN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AWHI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AWHN	28514.787	28514.787	28514.787	28514.787	28514.787	28514.787	28514.787	28514.787	27371.270	28514.787
ABRI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ABRN	3389.100	8067.219	17314.746	26073.584	34832.422	34686.336	30204.508	27143.525	16611.061	0.000
ASBI	0.000	0.000	1046.156	6795.120	12544.084	14207.407	14207.407	14207.407	14207.407	5214.543
ASBN	36533.336	36533.336	33843.223	19068.168	4277.117	0.000	0.000	0.000	0.000	23124.510
ASFI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ASFN	15000.000	15000.000	15000.000	15000.000	15000.000	15000.000	15000.000	15000.000	15000.000	15000.000
AS	3760.091	3981.367	4380.387	4655.636	4930.886	4888.548	4684.588	4545.282	4243.875	3502.969
IMAZ	164360.000	150840.000	120090.000	98749.117	73409.797	49733.359	22401.467	3734.446	0.000	0.000
EMAZ	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	38605.406
EWHT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	18649.858	0.000
EBRL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TAPR	2.469	2.566	2.758	2.939	3.121	3.118	3.025	2.961	2.027	2.399
TMAY	7.252	7.895	8.997	9.265	9.534	10.271	11.373	12.126	12.978	15.011
TJUN	8.018	9.517	12.557	15.787	19.017	22.176	25.894	28.434	31.591	34.535
TJUL	2.718	5.186	10.203	15.519	20.835	26.045	32.186	36.381	41.594	46.486
TAUG	3.448	6.688	13.263	20.193	27.123	33.947	42.003	47.506	54.345	62.830
TREQ	29.293	65.815	145.654	256.034	366.414	452.153	542.120	603.565	679.930	780.743
AMN	13932.470	12979.130	11780.733	13246.668	14792.603	16151.395	17675.602	18716.620	20153.666	20869.943
SPW	25140.637	25474.812	26290.572	27840.902	29391.232	30092.641	30515.463	30804.248	30865.283	29607.381
POT	9188.947	8566.318	7528.183	7421.122	7314.061	7422.945	7656.014	7816.541	8019.286	8685.462
FUL	6.586	6.442	6.333	6.316	6.299	6.338	6.409	6.458	6.526	6.780
TRH	202820.000	199200.000	192890.000	190790.000	188680.000	189090.000	190790.000	191950.000	193220.000	200330.000
CJM	8700.985	10403.820	13769.920	16958.137	20146.354	20093.188	18461.793	17347.596	16029.567	7467.353
CMS	15594.268	15594.268	15147.111	12689.839	10232.566	11896.468	13729.876	15528.436	17763.684	27278.781
TRS	78	75	68	57	45	47	56	61	68	103
CMB	38	38	29	22	15	18	25	30	36	63
SCB	58	86	27	27	27	27	27	27	27	27
TEXB	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.126	4.362
COST	43.117	40.985	36.915	33.713	30.511	27.583	24.237	21.952	22.333	23.487
OBJ	43.117	40.985	36.915	33.713	30.511	27.583	24.237	21.952	20.207	19.125

Table A1.4 Results of Varying Available Water (Drought,

Appendix 2

MATHEMATICAL DESCRIPTION OF THE MODEL

This section formalizes the verbal description of the model discussed in Section 2. Following Fig. 2.1 we have designated all input, production process, and output variables by x, y and Z respectively. The further subdivision of these variables is explained below.

A2.1 Objective Function

The objective function which has been adopted for Silistra agricultural-industrial comples maximizes the difference between benefit from additional amount of crops production and cost of the total crop production in the region, e.g.

$$OB = \max \left\{ \sum_{i=1}^{7} p_i^E Z_i^E - \left[\sum_{j=1}^{m} p_j x_j + \sum_{i=1}^{7} \sum_{k=1}^{2} c_k^i y_k^i + \sum_{i=1}^{7} c_i (Z_i + Z_i^E) + \sum_{i=1}^{7} p_i^I Z_i^I \right] \right\} \qquad (1)$$

where Z_i^E - is amount of i crop (Tn) produced for export to other regions/countries; i=1,...,7; i=1 (lucerne), i=2 (maize silage), i=3 (maize grain), i=4 (wheat), i=5 (barley), i=6 (soybeans), i=7 (sunflower).

p_i^E - is export price of i crop (Lv/Tn); i=1,...,7;

x_j - is amount of j input (Tn, ℓ, m^3, etc) required for the total crop production in the complex; j=1,...,m.

p_j - is price of j input (Lv/Tn, Lv/ℓ, Lv/m^3, etc); j=1,...,m.

y_k^i - is amount of land (ha) irrigated k=1, or non-irrigated k=2 needed for production of crop i; i=1,...,7.

c_k^i - is cost (Lv/Ha) of producing i crop on irrigated (k=1) or on nonirrigated (k=2) area; this cost includes all fixed and variable costs related to field cultivation activities that have not been included in the costs of the input resources.

z_i - is amount of production (Tn) from i crop produced in the complex to meet population's and live-stock requirements.

z_i^I - is amount of production (Tn) imported from other regions to meet the complex requirements.

p_i^I - is imported price (Lv/Tn) of crop i.

c_i - is cost (Lv/Tn) associated with processing of crop yield (transportation to storages and grain-drying).

A2.2 Constraints

A2.2.1 Physical Constraints

A2.2.1.1 Arable Land

The amount of arable land available for growing crops is constrained by the following inequality:

$$\sum_{i=1}^{7} \sum_{k=1}^{2} y_k^i + \sum_{i=1}^{7} y_{ks}^i \leq A - A_N \qquad (2)$$

where y_{ks}^i - is area (Ha) required for producing seeds for i crop; the index k=1 because seeds are assumed to be always irrigated

A - is total amount of arable land (Ha) available

A_N - is amount of arable land (Ha) needed for crops serving only population needs, e.g. tobacco, dry beans, flax, vegetables, vineyards, and orchards.

A2.2.1.2 Irrigated Land

This constraint takes care for the rate of irrigation land development in SWIM.

$$\sum_{i=1}^{7} y_1^i + \sum_{i=1}^{7} y_{ks}^i \leq I \qquad (3)$$

where I is total irrigation land available
k=1 (seeds are irrigated)

A2.2.1.3 Water Availability

The total amount of water available for irrigation (PW) is split into two parts, crop irrigation and seeds irrigation.

$$\sum_{i=1}^{7} w_i(t)\, y_k^i + \sum_{i=1}^{7} w_i(t)\, a_i\, y_{ks}^i - W(t) = 0 \quad ; t=1,2,3,4,5;\ k=1 \qquad (4)$$

$$\sum_{t=1}^{5} W(t) \leq PW \qquad (5)$$

where $w_i(t)$ - is amount of water (m^3/Ha) needed for optimum growth of crop i at time t; t refers to vegetation season; t=1 (April), t=2 (May), t=3 (June), t=4 (July), and t=5 (August).

a_i - is ratio between seeding rate (Tn/Ha) and crop yield of seed areas (Tn/Ha).

$W(t)$ - is a slack variable

PW - is total amount of water available for irrigation purposes (m^3).

A2.2.2 Production Requirement Constraints

This set of constraints spells out all crop production requirements for both population and livestock.

A2.2.2.1 Substitutional Crops

Some of the crops needed for livestock production can be substituted one for another according to their content of digestible nutrients and digestible protein.

A2.2.2.1.1 Substitution of Maize Grain and Barley

$$d_3 Z_3 + d_5 Z_5 \geq M \qquad (6)$$

where Z_3 and Z_5 - are amount of maize grain (Tn) and barley (Tn), respectively produced for meeting the requirements of maize grain M (Tn)

d_3 and d_5 - are substitutional coefficients for maize grain and barley.

A2.2.2.1.2 Substitution of Soybean and Sunflower

$$d_6 Z_6 + d_7 Z_7 \geq SM \quad (7)$$

where Z_6 and Z_7 - are amount of soybean (Tn) and sunflower (Tn), respectively produced for meeting the requirements of soybean meal SM (Tn); d_6 and d_7 take care of the ratio of substitution between soybean and sunflower.

A2.2.2.2 Nonsubstitutional Crops

These crops can not be substituted one for another either because of the difference in nutrients and protein or because of population food requirements. The following crops are nonsubstitutional: lucerne, maize silage, wheat, as well as part of sunflower production to produce oil. The constraints for these crops, taken into account in SWIM are as follows:

$$Z_1 \geq L \quad (8)$$

$$Z_2 \geq MS \quad (9)$$

$$d_B Z_4 \geq WB \quad (10)$$

$$d_F Z_4 \geq WF \quad (11)$$

$$d_S Z_7 \geq OL \quad (12)$$

where Z_1 - is amount of lucerne (Tn) produced to meet the requirements L (Tn).

Z_2 - is amount of maize silage (Tn) produced to meet the requirements MS(Tn).

Z_4 - is amount of wheat (Tn) produced to meet the requirements of wheat bran WB(Tn) and flour WF(Tn).

d_B - is amount of bran (Tn) produced from one ton of wheat.

d_F - is amount of flour (Tn) produced from one ton of wheat; note that $d_B + d_F < 1$ because of losses associated with flour and bran production.

Z_7 - is amount of sunflower produced (Tn).

OL - is total amount of oil needed for population (Tn).

d_W - indicates the oil content (Tn) in one ton of sunflower production; note that $d_s + d_7 < 1$ since amounts of oil and sunflower meal can not exceed the total sunflower production.

A2.2.3 Material Balance Constraints

The material balance equations, while not being actual constraints, take into account various inputs for and outputs from crop production. The structure of SWIM allows these inputs and outputs to be constrained when necessary.

A2.2.3.1 Seeds Requirements

$$-x_j + \sum_{i=2}^{3} \sum_{k=1}^{2} s_{kj}^i y_k^i = 0 \quad ; \begin{array}{l} j=1,2,\ldots,6 \\ i=j \quad \text{if } j=1 \\ i=2,3 \text{ if } j=2 \\ i=j+1 \text{ if } j>2 \end{array} \qquad (13)$$

where x_j - is amount of seeds (Tn) required to produce crop j; j=1 (lucerne); j=2 (maize silage & maize grain) j=3 (wheat); j=4 (barley); j=5 (soybean); j=6 (sunflower).

y_k^i - is amount of land (Ha) occupied by i crop when being irrigated (k=1) or nonirrigated (k=2)

s^i_{kj} - is crop j seeding rate (Tn/Ha) required to produce crop i on irrigated (k=1) or on non-irrigated (k=2) land (the subscripts i and j do not coincide because some of the seeds can be used to produce 2 crops, like maize grain and maize silage)

A2.2.3.2 Fertilizer Requirements

There are three essential type of fertilizers being used in Silistra agricultural-industrial complex: ammonium sulphate, super phosphate, and potassium sulphate. The following fertilizer balance constraints are included in SWIM:

$$-x_j + \sum_{i=1}^{7} \sum_{k=1}^{2} f^i_{kj}\, y^i_k = \bar{x}_j \quad ; \; j = 7,8,9 \qquad (14)$$

where x_j - is amount of j fertilizer (Tn) required in the complex.

$\bar{x}_j$ - is amount of manure (Tn) which can substitute j fertilizer

f^i_{kj}- is fertilizer rate (Tn/Ha) of j fertilizer for crop i when being irrigated (k=1) or nonirrigated (k=2).

A2.2.3.3 Fuel Requirements

Fuel is required for operating tractors, various combines and grain processing equipment. The total amount of fuel required, x_{10}, is determined by the following equation.

$$-x_{10} + \sum_{i=1}^{7} \sum_{k=1}^{2} u^i_k\, y^i_k = 0 \qquad (15)$$

where u^i_k - is fuel rate (ℓ/Ha) for production of crop i on irrigated (k=1) or nonirrigated (k=1) land.

A2.2.3.4 Labor Requirements

The labor is actually the machine-hrs. of field work needed (assuming 1 operator/machine). In principal, all machine-hrs. could be lumped together to obtain the total number of hrs. required. In this study however we separate machine-hrs. required for tractors, combines (June-July) and combines (August-October). The latter two can be operated by people coming outside from the region.

$$-x_{11} + \sum_{i=1}^{7} \sum_{k=1}^{2} t_k^i \, y_k^i = 0 \qquad (16)$$

where t_k^i - is amount of tractor-hrs/Ha needed for field activities on y_k^i crop area when being irrigated (k=1) or nonirrigated (k=2) x_{11} is total amount of tractor-hrs. for the whole crop area.

$$-x_{12} + \sum_{i=1}^{7} \sum_{k=1}^{2} CJ_k^i \, y_k^i = 0 \qquad (17)$$

where CJ_k^i -is amount of combine-hrs/Ha on June & July required for harvesting of y_k^i crop area.

x_{12} -is total amount of combine-hrs. on June & July.

$$-x_{13} + \sum_{i=1}^{7} \sum_{k=1}^{2} CA_k^i \, y_k^i = 0 \qquad (18)$$

where CA_k^i -is amount of combine-hrs/Ha in August-October requested for harvesting of y_k^i crop area.

x_{13} -is total amount of combine-hrs in August-October.

A2.2.3.5 Machinery Requirements

To convert the machine-hrs. already specified in 2.2.3.4 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 being pressed into use.

A2.2.3.5.1 Tractor Requirements

$$-x_{14} + \frac{1}{T_t} \sum_{i=1}^{7} \sum_{k=1}^{2} m_k^i \, y_k^i = 0 \qquad (19)$$

where m_k^i - is number of machine-hrs/Ha for crop i (irrigated, k=1, or nonirrigated, k=) over the critical period. In our case this period is in March & April (see Table A3.4).

T_t - is total time available over the critical period (hrs); $T_t = (D-D_w)w_t$, where D is number of calendar days in the critical period; D_w is number of days taken off due to holidays or bad weather conditions in this period; w_t is working hrs/day.

x_{14} -is total number of tractors needed for crop production.

A2.2.3.5.2 Combine Requirements

$$-x_{15} + \frac{1}{T_c} \sum_{i=1}^{7} \sum_{k=1}^{2} mc_k^i \, y_k^i = 0 \qquad (20)$$

where mc_k^i -is number of machine-hrs/Ha for harvesting of crop i (excluding maize silage) over the critical period. As it can be seen from Table A3.4 this period is in June-July.

T_c - is total time (hrs) available over the critical period; T_c is determined in the same way like in (19).

x_{15} -is total number of combines needed for crop harvesting (excluding maize silage)

A2.2.3.5.3 Silage Chopper Requirements

$$-x_{16} + \frac{1}{T_{sc}} \sum_{k=1}^{2} ms_k^2 \, y_k^2 = 0 \qquad (21)$$

where ms_k^2 -is number of machine-hrs/Ha for harvesting maize silage over the critical period (September);

T_{sc} - is total time available (hrs) over the critical period.

x_{16} - is number of silage choppers required.

A2.2.3.5.4 Irrigation Equipment Requirements

To evaluate the number of irrigation equipment one has to identify the productivity of this equipment (Ha/sprinkler) as well as the time table of crop irrigation. The latter is needed to avoid excessive investment for an equipment, e.g. to account for the fact that this equipment can be moved from one place to another over the vegetation season to irrigate different crops.

The information given in figure 2.2 can serve as a guideline to determine the number of irrigation equipment. It is obvious from this figure that the major irrigation activities are associated with maize silage, maize grain and soya. Wheat and barley can be combined and made complementary to maize and soya. On the other hand sunflower is complementary to lucerne. All these relationships can be formalized as follows.

$$\frac{1}{S_p}\left[Y_1^1 + Y_1^2 + Y_1^3 + Y_1^6\right] + E^{4,5} + E^7 = TE \qquad (22)$$

where S_p - is productivity of the irrigation equipment (Ha/sprinkler).

Y_1^1, Y_1^2, Y_1^3, Y_1^6 - are irrigated areas of lucerne, maize silage, maize grain, and soybeans respectively

$E^{4,5}$ - is irrigation equipment extra needed for wheat and barley

E^7 - is irrigation equipment extra needed for sunflowers.

TE - is total number of irrigation equipment needed

The variables $E^{4,5}$ and E^7 are determined by the equations (23) and (24).

The equation (23) take into account complementarity of sunflowers and lucerne irrigation equipment. The next one accounts for complementarity of wheat and barley with maize and soybeans.

$$\frac{1}{S_p}\left[y_1^1 - y_1^7\right] + E^7 - D^7 = 0 \tag{23}$$

$$\frac{1}{S_p}\left[y_1^2 + y_1^3 + y_1^6 - y_1^4 - y_1^5\right] + E^{4,5} - D^{4,5} = 0 \tag{24}$$

where $D^7 \geq o$ - is a dummy variable, e.g. number of irrigation equipment extra needed for sunflowers, E^7, is equal to 0 if $y_1^7 \geq y_1^1$ and $E^7 = \frac{1}{s_p}$ $[y_1^1 - y_1^7]$ if $y_1^7 > y_1^1$; in other words either E^7 or D^7 are equal to zero.

$E^{4,5} \geq 0$ - is number of irrigation equipment extra needed for wheat and barley.

$D^{4,5} \geq 0$ - is a dummy variable with the same properties like D^7.

A2.2.4 Exports, Import and Crop Yield Production

The yield of each crop is influenced by many factors like irrigated water, weather, cultivation practice, etc. To allow for variations in the yield, meeting at the same time crop requirements in the complex, the following constraints are adopted.

$$z_i^I - z_i^E - z_i + \sum_{k=1}^{2} \ell_k^i \, y_k^i = 0 \tag{25}$$

where ℓ_k^i - is yield of i crop (Tn/Ha) grown on irrigated (k=1) or on nonirrigated (k=2) area.

z_i - is total amount (Tn) from i crop available in the complex.

z_i^E - is amount of crop i (Tn) for export to other regions/countries.

z_i^I - is amount of crop i (Tn) imported from other regions in the complex.

Appendix 3

TABLES OF INPUT RESOURCES

The following tables give the data on input resources of seeds, fertilizer, fuel and labor in SWIM.

Crops		Seeding Rate	Seed Crop Yield	Cost of Seeds	a_i †	Model Designation		
1		2	3	4	5	6	7	8
	Irrigated/ nonirrig.	Tn/Ha	Tn/Ha	Lv/Tn	-	i	k	j
Lucerne	irr	0.020	0.2	5300	0.1	1	1	1
	non	0.020	0.2	5300	0.1		2	
Maize Silage	irr	0.019	8.6	700	0.0022	2	1	2
	non	0.0175	8.6	700	0.0020		2	
Maize Grain	irr	0.0175	8.6	700	0.0020	3	1	2
	non	0.0155	8.6	700	0.0018		2	
Wheat	irr	0.12	4.8	185	0.025	4	1	3
	non	0.10	4.8	185	0.021		2	
Barley	irr	0.22	4.2	160	0.0523	5	1	4
	non	0.20	4.2	160	0.0476		2	
Soybeans	irr	0.055	3.0	725	0.0183	6	1	5
	non	0.050	3.0	725	0.0167		2	
Sunflowers	irr	0.0165	2.6	365	0.0063	7	1	6
	non	0.015	2.6	365	0.0058		2	

Table A3.1 Seeds Requirements

Notes: † a_i = Column (2) ÷ Column (3)

CROPS		N removed	N needed	Ammonium sulphate	P removed	P needed	Super Phos-phate	K removed	K needed	Potas-sium Sulphate	Designation in the Model	
	1	2	3	4	5	6	7	8	9	10	11	12
	Irrigated/ nonirrig.	kg/Ha	kg/Ha	Tn/Ha	kg/Ha	kg/Ha	Tn/Ha	kg/Ha	kg/Ha	Tn/Ha	i	k
Lucerne	irr	*-	-	-	70	90	0.45	280	224	0.5034	1	1
	non	-	-	-	40	60	0.30	170	136	0.3056		2
Maize Silage	irr	235	282	0.8294	85	105	0.525	220	176	0.3955	2	1
	non	140	168	0.4941	48	68	0.34	125	100	0.2247		2
Maize Grain	irr	140	168	0.4941	65	85	0.425	45	36	0.0809	3	1
	non	80	96	0.2824	40	60	0.30	25	20	0.0449		2
Wheat	irr	66	79.2	0.2329	48	68	0.34	22	17.6	0.0396	4	1
	non	55	66	0.1941	40	60	0.30	18	14.4	0.0324		2
Barley	irr	60	72	0.2118	60	80	0.40	22	17.6	0.0396	5	1
	non	50	60	0.1765	50	70	0.35	18	14.4	0.0324		2
Soybeans	irr	*-	-	-	43	63	0.315	65	52	0.1169	6	1
	non	-	-	-	25	45	0.225	40	32	0.0719		2
Sunflowers	Irr	144	172.8	0.5082	48	68	0.34	48	38.4	0.0863	7	1
	non	120	144	0.4235	40	60	0.30	40	32	0.0719		2
Designation in the model				j=7 P_7			j=8 P_8			j=9 P_9		

Table A3.2 Fertilizer Requirements

Notes:-* these crops add N but we can not account for this without crop rotations.

		Plowing	Cultivation	Planting	Harvesting (incl. straw)	Total Fuel	Designation in the Model u_k^l	
1		2	3	4	5	6	7	8
		1/Ha	1/Ha	1/Ha	1/Ha	1/Ha	i	k
Lucerne	irr	6.6	1.54	1.23	52.65	62.02	1	1
	non	6.6	1.54	1.23	75.18	84.55		2
Maize Silage	irr	19.8	26.56	4.35	13.62	64.30	2	1
	non	19.8	26.56	4.35	19.47	70.18		2
Maize Grain	irr	19.8	26.56	4.35	9.45	60.16	3	1
	non	19.8	26.56	4.35	13.50	64.21		2
Wheat	irr	19.8	4.62	3.70	10.06	38.18	4	1
	non	19.8	4.62	3.70	12.58	40.70		2
Barley	irr	19.8	4.62	3.70	10.06	38.18	5	1
	non	19.8	4.62	3.70	12.58	40.70		2
Soybeans	irr	10.98	29.26	4.35	7.34	51.93	6	1
	non	10.98	29.26	4.35	8.15	52.74		2
Sunflowers	irr	19.8	14.63	4.35	8.15	46.93	7	1
	non	19.8	14.63	4.35	10.19	48.97		2

Table A3.3 Fuel Requirements

Notes: Price of fuel P_{10}, assumed to be 0.072 Lv/1

		Tractor-hours					Combine-hours		Designation in the Model	
		Plowing	Cultivation	Planting	Harvest	Total	June-July	Aug-Oct		
1		2	3	4	5	6	7	8	9	10
	irrigated nonirrig.	man hr/Ha	man hr/Ha	man hr/Ha	man hr/Ha	man hr/Ha	man hr/Ha	man hr/Ha	i	k
Lucerne	irr	0.183	0.0496	0.0493	3.00	3.28			1	1
	non	0.183	0.0496	0.0493	2.10	2.38				2
Maize Silage	irr	0.55	0.92	0.174	0.649	2.293			2	1
	non	0.55	0.92	0.174	0.454	2.098				2
Maize Grain	irr	0.55	0.92	0.174		1.644		0.562	3	1
	non	0.55	0.92	0.174		1.644		0.394		2
Wheat	irr	0.55	0.149	0.148	0.614	1.46	0.455		4	1
	non	0.55	0.149	0.148	0.491	1.288	0.364			2
Barley	irr	0.55	0.149	0.148	0.614	1.46	0.455		5	1
	non	0.55	0.149	0.148	0.491	1.338	0.364			2
Soybeans	irr	0.305	1.053	0.174		1.532		0.326	6	1
	non	0.305	1.053	0.174		1.532		0.293		2
Sunflowers	irr	0.55	0.618	0.174		1.342		0.408	7	1
	non	0.55	0.618	0.174		1.342		0.326		2
Designation in the Model						t_k^i	CJ_k^i	CA_k^j		

Table A3.4 Labor Requirements

Appendix 4

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 on a cost/ha basis or to the input resources on a cost/unit amount basis. The fixed costs attached to land are depreciated capital investments (machinery purchase). The total cost attached to land (e.g 70.51 in table A4.1) is the unit cost used in the linear programming for the crop area decision variable (c_k^i in equation 1). The total land and resource cost (e.g 159.02 in table A4.1) is the total production cost per ha.

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					17.60			
	Var. Costs Lv/Ha			3.00	31.55	15.54	2.82		
	Tot. Costs Lv/Ha			3.00	31.55	33.14	2.82		70.51
Costs Attached to Resources	Seeds	Tn/Ha	0.020						
		Lv/Tn	1767.5						
	Ammonium Sulphate	Tn/Ha							
		Lv/Tn							
	Super-phosphate	Tn/Ha		0.30					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.3056					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				62.03			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					2.389		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			35.35	43.91		4.47	4.78		88.51
Land & Resource Cost Lv/Ha			35.35	46.91	31.55	37.61	7.60		159.02

A4.1 Nonirrigated Lucerne Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					22.80		103.25	
	Var. Costs Lv/Ha			3.00	31.55	21.24	2.82	19.75	
	Tot. Costs Lv/Ha			3.00	31.55	44.04	2.82	123.00	204.41
Costs Attached to Resources	Seeds	Tn/Ha	0.020						
		Lv/Tn	1767.5						
	Ammonium Sulphate	Tn/Ha							
		Lv/Tn							
	Super-phosphate	Tn/Ha		0.45					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.5034					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				84.56			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					3.292		
		Lv/Hr					2.00		
	Water	m^3/Ha						54 00	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			35.35	69.77		6.09	6.58	118.80	236.59
Land & Resource Cost Lv/Ha			35.35	72.77	31.55	50.13	9.40	241.80	441.00

A4.2 Irrigated Lucerne Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					19.15			
	Var. Costs Lv/Ha			6.00	30.60	18.77	2.82		
	Tot. Costs Lv/Ha			6.00	30.60	37.92	2.82		77.34
Costs Attached to Resources	Seeds	Tn/Ha	0.0175						
		Lv/Tn	700.00						
	Ammonium Sulphate	Tn/Ha		0.4941					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.34					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.2247					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				64.34			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					2.098		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			12.25	92.13		4.63	4.20		113.21
Land & Resource Cost Lv/Ha			12.25	98.13	30.60	42.55	7.02		190.55

A4.3 Nonirrigated Maize Silage Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					22.00		103.25	
	Var. Costs Lv/Ha			6.00	30.60	22.32	2.82	19.75	
	Tot. Costs Lv/Ha			6.00	30.60	44.32	2.82	123.00	206.74
Costs Attached to Resources	Seeds	Tn/Ha	0.019						
		Lv/Tn	700.00						
	Ammonium Sulphate	Tn/Ha		0.8294					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.525					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.3955					
		Lv/Tn		86.75					
	Fuel	ℓ /Ha				70.18			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					2.293		
		Lv/Hr					2.00		
	Water	m^3/Ha						34 00	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			13.30	153.59		5.05	4.59	74.80	251.33
Land & Resource Cost Lv/Ha			13.30	159.59	30.60	49.37	7.41	197.80	458.07

A4.4 Irrigated Maize Silage Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					18.70			
	Var. Costs Lv/Ha			6.00	22.55	18.13	2.82		
	Tot. Costs Lv/Ha			6.00	22.55	36.83	2.82		68.2
Costs Attached to Resources	Seeds	Tn/Ha	0.0155						
		Lv/Tn	700.00						
	Ammonium Sulphate	Tn/Ha		0.2824					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.30					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0449					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				60.17			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					2.038		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			10.85	51.54		4.33	4.08		70.80
Land & Resource Cost Lv/Ha			10.85	57.54	22.55	41.16	6.90		139.00

A4.5 Nonirrigated Maize Grain Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					21.35		103.25	
	Var. Costs Lv/Ha			6.00	22.55	21.39	2.82	19.75	
	Tot. Costs Lv/Ha			6.00	22.55	42.74	2.82	123.00	197.11
Costs Attached to Resources	Seeds	Tn/Ha	0.0175						
		Lv/Tn	700.00						
	Ammonium Sulphate	Tn/Ha		0.4941					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.425					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0809					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				64.22			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					2.206		
		Lv/Hr					2.00		
	Water	m^3/Ha						3.400	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			12.25	84.59		4.62	4.41	74.80	180.67
Land & Resource Cost Lv/Ha			12.25	90.59	22.55	47.36	7.23	197.80	377.78

A4.6 Irrigated Maize Grain Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					13.35			
	Var. Costs Lv/Ha			3.00	6.65	12.64	2.82		
	Tot. Costs Lv/Ha			3.00	6.65	25.99	2.82		38.46
Costs Attached to Resources	Seeds	Tn/Ha	0.1						
		Lv/Tn	185.00						
	Ammonium Sulphate	Tn/Ha		0.1941					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.3					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0324					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				38.18			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.211		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			18.50	41.00		2.75	2.42		64.67
Land & Resource Cost Lv/Ha			18.50	44.00	6.65	28.74	5.24		103.13

A4.7 Nonirrigated Wheat Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					14.54		50.00	
	Var. Costs Lv/Ha			3.00	6.65	14.11	2.82	19.75	
	Tot. Costs Lv/Ha			3.00	6.65	28.65	2.82	69.75	110.87
Costs Attached to Resources	Seeds	Tn/Ha	0.1						
		Lv/Tn	185						
	Ammonium Sulphate	Tn/Ha		0.2329					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.34					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0396					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				40.69			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.302		
		Lv/Hr					2.00		
	Water	m^3/Ha						900	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			18.5	48.10		2.93	2.60	19.80	91.93
Land & Resource Cost Lv/Ha			18.5	51.10	6.65	31.58	5.42	89.55	202.80

A4.8 Irrigated Wheat Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					13.35			
	Var. Costs Lv/Ha			3.00	6.65	12.64	2.82		
	Tot. Costs Lv/Ha			3.00	6.65	25.99	2.82		38.46
Costs Attached to Resources	Seeds	Tn/Ha	0.2						
		Lv/Tn	160						
	Ammonium Sulphate	Tn/Ha		0.1765					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.35					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0324					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				38.18			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.211		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			32.00	42.01		2.75	2.42		79.18
Land & Resource Cost Lv/Ha			32.00	45.01	6.65	28.74	5.24		117.64

A4.9 Nonirrigated Barley Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					14.54		50.00	
	Var. Costs Lv/Ha			3.00	6.65	14.11	2.82	19.75	
	Tot. Costs Lv/Ha			3.00	6.65	28.65	2.82	69.75	110.87
Costs Attached to Resources	Seeds	Tn/Ha	0.22						
		Lv/Tn	160						
	Ammonium Sulphate	Tn/Ha		0.2118					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.4					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0396					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				40.69			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.302		
		Lv/Hr					2.00		
	Water	m^3/Ha						900	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			35.20	49.31		2.93	2.60	19.80	109.84
Land & Resource Cost Lv/Ha			35.20	52.31	6.65	31.58	5.42	39.55	220.71

A4.10 Irrigated Barley Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					13.64			
	Var. Costs Lv/Ha				28.00	12.05	2.82		
	Tot. Costs Lv/Ha				28.00	25.69	2.82		56.51
Costs Attached to Resources	Seeds	Tn/Ha	0.050						
		Lv/Tn	725.00						
	Ammonium Sulphate	Tn/Ha							
		Lv/Tn							
	Super-phosphate	Tn/Ha		0.225					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0719					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				51.93			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.825		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			36.25	19.29		3.74	3.65		62.93
Land & Resource Cost Lv/Ha			36.25	19.29	28.00	29.43	6.47		119.44

A4.11 Nonirrigated Soybean Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					14.12		103.25	
	Var. Costs Lv/Ha				28.00	12.64	2.82	19.75	
	Tot. Costs Lv/Ha				28.00	26.76	2.82	123.00	180.58
Costs Attached to Resources	Seeds	Tn/Ha	0.055						
		Lv/Tn	725.00						
	Ammonium Sulphate	Tn/Ha							
		Lv/Tn							
	Super-phosphate	Tn/Ha		0.315					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.1169					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				52.74			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.858		
		Lv/Hr					2.00		
	Water	m^3/Ha						2300	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			39.88	28.41		3.80	3.72	50.60	126.41
Land & Resource Cost Lv/Ha			39.88	28.41	28.00	30.56	6.54	173.60	306.99

A4.12 Irrigated Soybean Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					15.37			
	Var. Costs Lv/Ha			6.00	10.00	14.10	2.82		
	Tot. Costs Lv/Ha			6.00	10.00	29.47	2.82		48.29
Costs Attached to Resources	Seeds	Tn/Ha	0.015						
		Lv/Tn	365.00						
	Ammonium Sulphate	Tn/Ha		0.4235					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.300					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0719					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				46.93			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.67		
		Lv/Hr					2.00		
	Water	m^3/Ha							
		Lv/m^3							
Resource Cost Lv/Ha			5.48	68.99		3.38	3.34		81.19
Land & Resource Cost Lv/Ha			5.48	74.99	10.00	32.85	6.16		129.48

A4.13 Nonirrigated Sunflower Production Costs

			SEEDS	FERTILIZER	CHEMICALS	MACHINERY	LABOR	IRRIGATION	TOTAL COSTS
Costs Attached to Land	Fixed Costs Lv/Ha					16.33		50.00	
	Var. Costs Lv/Ha			6.00	10.00	15.26	2.82	19.75	
	Tot. Costs Lv/Ha			6.00	10.00	31.59	2.82	69.75	120.16
Costs Attached to Resources	Seeds	Tn/Ha	0.0165						
		Lv/Tn	365.00						
	Ammonium Sulphate	Tn/Ha		0.5082					
		Lv/Tn		107.10					
	Super-phosphate	Tn/Ha		0.340					
		Lv/Tn		58.00					
	Potassium Sulphate	Tn/Ha		0.0863					
		Lv/Tn		86.75					
	Fuel	ℓ/Ha				48.97			
		Lv/ℓ				0.072			
	Operator-Hours	Hr/Ha					1.75		
		Lv/Hr					2.00		
	Water	m^3/Ha						1290	
		Lv/m^3						0.022	
Resource Cost Lv/Ha			6.02	81.63		3.53	3.50	28.38	123.06
Land & Resource Cost Lv/Ha			6.02	87.63	10.00	35.12	6.32	98.13	243.22

A4.14 Irrigated Sunflower Production Costs

Appendix 5

COMPUTER DATA STRUCTURE

The computational results were obtained using a linear programming system, LPS/11, available on IIASA PDP11/45 computer. To run the system one has to specify the LP matrix, RHS, and upper and/or lower bounds. Their values are produced on the base of mathematical description of the model (Appendix 2) and the Tables of Input Resources and Crop Production costs specified in Appendixes 3 and 4.

This appendix has an aim to specify the LP matrix, RHS, and bounds in a way that they can be reproduced in any computer having a LP system. To facilitate this aim a Glossary of Terms as well as the LP matrix are enclosed.

A.5 Glossary of terms

A.5.1 Description of Decision Variables (Columns)

	UNIT	
ALUI	Ha	Irrigated land for growing lucerne
ALUN	Ha	Nonirrigated land for growing lucerne
AMSI	Ha	Irrigated land for growing maize silage
AMSN	Ha	Nonirrigated land for growing maize silage
AMGI	Ha	Irrigated land for growing maize grain
AMGN	Ha	Nonirrigated land for growing maize grain
AWHI	Ha	Irrigated land for growing wheat
AWHN	Ha	Nonirrigated land for growing wheat
ABRI	Ha	Irrigated land for growing barley
ABRN	Ha	Nonirrigated land for growing barley
ASBI	Ha	Irrigated land for growing soybeans
ASBN	Ha	Nonirrigated land for growing soybeans
ASFI	Ha	Irrigated land for growing sunflowers
ASFN	Ha	Nonirrigated land for growing sunflowers
AS	Ha	Irrigated land for seeds
NL	Ha	Total irrigated land required
LUC	Tn	Amount of lucerne produced
MSL	Tn	Amount of maize silage produced
MGR	Tn	Amount of maize grain produced
WHT	Tn	Amount of wheat produced
BRL	Tn	Amount of barley produced
SOY	Tn	Amount of soybeans produced
SFL	Tn	Amount of sunflowers produced

	UNIT	
SLUC	Tn	Total amount of lucerne seeds required
SMZ	Tn	Total amount of maize seeds required
SWT	Tn	Total amount of wheat seeds required
SBR	Tn	Total amount of barley seeds required
SSY	Tn	Total amount of soybean seeds required
SSF	Tn	Total amount of sunflower seeds required
AMN	Tn	Ammonia sulphate fertilizer
SPH	Tn	Super phosphate fertilizer
POT	Tn	Potassium sulphate fertilizer
FUL	lit.	Fuel
TRH	Hrs	Tractor hours
CJH	Hrs	Combine June-July hours
CSH	Hrs	Combine August-October hours
TRS	-	Number of tractors
CMB	-	Number of combines
SCB	-	Number of silage choppers
PW	m^3	Amount of irrigation water
OIL	Tn	Sunflower oil
FLO	Tn	Flour
EMAZ	Tn	Maize grain export
IMAZ	Tn	Maize grain import
EWHT	Tn	Wheat export
EBRL	Tn	Barley export
IREQ	-	Number of irrigation sprinklers
IRSF	-	No. of irrigation sprinklers extra for sunflowers
DSFL	-	Dummy variable for sunflowers
IRWB	-	Number of irrigation equipment extra for wheat and barley

	UNIT	
DWB	Tn	Dummy variable for wheat and barley
TEXB	Lv	Total export benefits
IRAP	m^3	Crop irrigation water in April
IRMY	m^3	Crop irrigation water in May
IRJN	m^3	Crop irrigation water in June
IRJL	m^3	Crop irrigation water in July
IRAG	m^3	Crop irrigation water in August
APRS	m^3	Seed irrigation water in April
MAYS	m^3	Seed irrigation water in May
JUNS	m^3	Seed irrigation water in June
JULS	m^3	Seed irrigation water in July
AUGS	m^3	Seed irrigation water in August
TAPR	m^3	Total irrigation water in April
TMAY	m^3	Total irrigation water in May
TJUNE	m^3	Total irrigation water in June
TJULY	m^3	Total irrigation water in July
TAUG	m^3	Total irrigation water in August
TCOST	Lv	Total cost of production

A.5.2 Description of Rows (Constraints)

	UNIT	
OBJECT	Lv	Objective function
SEL	Tn	Lucerne seed balance
SEM	Tn	Maize seed balance
SEW	Tn	Wheat seed balance
SEB	Tn	Barley seed balance
SES	Tn	Soybean seed balance
SEF	Tn	Sunflower seed balance
FAM	Tn	Ammonium sulphate balance
FSP	Tn	Super phosphate balance
FPO	Tn	Potassium sulphate balance
RFL	lit.	Fuel balance
RLT	Hrs	Tractor hour balance
RLC	-	Combines (June-July) balance
RLS	-	Combines (August-October) balance
MTR	-	Balance of number of tractors
MCJ	-	Balance of number of combines
MCS	-	Balance of number of silage combines
SAR	Ha	Seed area balance
NLB	Ha	Irrigated land balance
CYL	Tn	Lucerne land yield balance
CYM	Tn	Maize silage yield balance
CYG	Tn	Maize grain yield balance
CYW	Tn	Wheat yield balance

	UNIT	
CYB	Tn	Barley yield balance
CYS	Tn	Soybean yield balance
CYF	Tn	Sunflower yield balance
ALD	Ha	Arable land balance
FRW	Tn	Wheat bran constraint
FRS	Tn	Constraint on substitution of soybeans & sunflowers
FRG	Tn	Constraint on substitution of maize grain & barley
SOL	Tn	Sunflower oil constraint
WFL	Tn	Wheat flour constraint
EXB	Lv	Export benefit balance
COST	Lv	Cost of production balance
EQIR1	-	Total irrigation equipment balance
EQIR2	-	Irrigation equipment balance for lucerne & sunflower
EQIR3	-	Irrigation equipment balance for maize & soybeans
TIRAP	m^3	Crop water irrigation balance in April
TIRMY	m^3	Crop water irrigation balance in May
TIRJN	m^3	Crop water irrigation balance in June
TIRJL	m^3	Crop water irrigation balance in July
TIRAG	m^3	Crop water irrigation balance in August
SIRAP	m^3	Seed water irrigation balance in April
SIRMY	m^3	Seed water irrigation balance in May
SIRJN	m^3	Seed water irrigation balance in June
SIRJL	m^3	Seed water irrigation balance in July
SIRAG	m^3	Seed water irrigation balance in August
APRIL	m^3	Total water irrigation balance in April
MAY	m^3	Total water irrigation balance in May
JUNE	m^3	Total water irrigation balance in June

	UNIT	
JULY	m^3	Total water irrigation balance in July
AUGT	m^3	Total water irrigation balance in August
GTOT	m^3	Total water irrigation balance over vegetation season

BOUND SET: OLIM (OLIM is the name of the bound set)

LOLUC	Tn	Lower limit of lucerne production
LOMSL	Tn	Lower limit of maize silage production
LOOIL	Tn	Lower limit of sunflower oil production
LOFLO	Tn	Lower limit of flour production
UPNL	Ha	Upper limit of irrigated land available
UPPW	m^3	Upper limit of irrigation water available

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COLUMNS 1 TO 10

	ALUI	ALUN	AMSI	AMSN	AMGI	AMGN	AWMI	AWMN	ABRI	ABRN
1 OBJECT	-224,41000	-70,51000	-206,74001	-77,34000	-197,11000	-68,20000	-110,87000	-38,46000	-110,87000	-38,46000
2 SEL	0,00670	0,00673								
3 SEM			0,01900	0,01750	0,01750	0,01550				
4 SEW							0,10000	0,10000		
5 SEB									0,22000	0,20000
6 SES										
7 SEF										
8 FAM			0,82940	0,49410	0,49410	0,28260	0,23290	0,19410	0,21100	0,17650
9 FSP	0,45000	0,30000	0,52500	0,34000	0,42500	0,30000	0,34000	0,30000	0,40000	0,35000
10 FPO	0,50340	0,39560	0,39550	0,22470	0,08090	0,04490	0,03960	0,03240	0,03960	0,03240
11 RFL	94,55000	52,02000	70,15000	64,33000	64,21000	60,16000	56,86000	51,11000	56,86000	51,11000
12 RLT	5,28000	2,34000	2,29300	2,09800	1,64400	1,64400	1,46000	1,29000	1,46000	1,34000
13 RLC							0,45500	0,36400	0,45500	0,36400
14 RLS					0,56200	0,39400				
15 MTR	0,14000	0,14000	0,17400	0,17400	0,49100	0,49100				
16 MCJ					0,56200	0,39400				
17 MCS			0,64900	0,45400						
18 SAR	0,10000	0,10000	0,00220	0,00200	0,00200	0,00180	0,02500	0,02800	0,05240	0,04760
19 NLB	1,00000		1,00000		1,00000		1,00000		1,00000	
20 CYL	10,60000	6,70000								
21 CYM			50,00000	28,00000						
22 CYG					5,60000	4,70000				
23 CYW							3,70000	3,20000		
24 CYB									3,60000	3,10000
25 CYS										
26 CYF										
27 ALD	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000	1,00000
28 FRW										
29 FRS										
30 FRG										
31 SOL										
32 RFL										
33 EXB										
34 COST	224,41000	70,51000	206,74001	77,34000	197,11000	68,20000	110,87000	38,46000	110,87000	38,46000
35 EQIR1	0,01920		0,01920		0,01920					
36 EQIR2	-0,01920									
37 EQIR3			-0,01920		-0,01920		0,01920		0,01920	
38 TIRAP	793,00000						360,00000		360,00000	
39 TIRMY	2310,00000		220,00000		220,00000		540,00000		540,00000	
40 TIRJN	2310,00000		660,00000		660,00000					
41 TIRJL			1090,00000		1090,00000					
42 TIRAG			1430,00000		1430,00000					
43 SIRAP	79,00000	79,00000					9,07000	10,16000	19,00000	17,26000
44 SIRMY	231,00000	231,00000	0,49000	0,44000	0,44000	0,40000	13,43000	15,24000	20,15000	25,57000
45 SIRJN	231,00000	231,00000	1,46200	1,33000	1,33000	1,19000				
46 SIRJL			2,40000	2,10000	2,10000	1,96000				
47 SIRAG			3,13000	2,85000	2,85000	2,56000				
48 APRIL										
49 MAY										
50 JUNE										
51 JULY										
52 AUGT										
53 GTOT										

A5.3 Linear Programming Matrix

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COLUMNS 11 TO 20

	ABBI	ASBN	ASFI	ASFN	AS	NL	LUC	MSL	MGR	WHT
1 OBJECT	-100,55000	-56,51000	-120,16000	-48,29000						
2 SEL										
3 SEM										
4 SEW										
5 SEB										
6 BES	0,05500	0,05000								
7 SEF			0,01500	0,01500						
8 FAM			0,50820	0,42350						
9 FSP	0,31500	0,22500	0,34000	0,30000						
10 FPO	0,11690	0,07190	0,08630	0,07190						
11 RFL	52,74000	51,93000	48,97000	46,93000						
12 RLT	1,53200	1,53200	1,34200	1,34200						
13 RLC										
14 RLS	0,32600	0,29300	0,40800	0,32600						
15 MTR	0,34200	0,34200	0,14800	0,14800						
16 MCJ	0,32600	0,29300								
17 MCS										
18 BAR	0,01830	0,01070	0,00630	0,00580	-1,00000					
19 NLB	1,00000		1,00000		1,00000	-1,00000				
20 CVL							-1,00000			
21 CVM								-1,00000		
22 CVG									-1,00000	
23 CVW										-1,00000
24 CVB										
25 CVS	2,70000	1,50000								
26 CVF			2,20000	2,00000						
27 ALD	1,00000	1,00000	-1,00000	1,00000	1,00000					
28 FRW										2,10000
29 FRS										
30 FRG									1,00000	
31 BOL										
32 WFL										2,70000
33 EXB										
34 COST	100,55000	56,51000	120,16000	48,29000						
35 EDIR1	0,01920									
36 EDIR2			0,01920							
37 EDIR3	-0,01920									
38 TIRAP										
39 TIRMY										
40 TIRJN	480,00000		490,00000							
41 TIRJL	790,00000		800,00000							
42 TIRAG	1030,00000									
43 BIRAP										
44 BIRMY										
45 BIRJN	0,75000	7,99000	3,00000	2,02000						
46 BIRJL	14,48000	13,21000	5,10000	4,66000						
47 BIRAG	18,06000	17,21000								
48 APRIL										
49 MAY										
50 JUNE										
51 JULY										
52 AUGT										
53 GTOT										

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COLUMNS 21 TO 30

	BRL	SDV	SPL	SLUC	SMZ	SWT	SBR	SSY	SSF	AMN
1 OBJECT				-5300.00000	-700.00000	-185.00000	-160.00000	-725.00000	-365.00000	-107.10000
2 SEL				-1.00000						
3 SEM					-1.00000					
4 SEW						-1.00000				
5 SEB							-1.00000			
6 SES								-1.00000		
7 SEF									-1.00000	
8 FAM										-1.00000
9 FSP										
10 FPD										
11 RFL										
12 RLT										
13 RLC										
14 RLS										
15 MTR										
16 MCJ										
17 MCS										
18 SAR										
19 NLR										
20 CYL										
21 CYM										
22 CYG										
23 CYW										
24 CYR	-1.00000									
25 CYS		-1.00000								
26 CYF			-1.00000							
27 ALD										
28 FRW										
29 FRS		0.75000	0.41000							
30 FRG	1.10000									
31 SOL			0.40000							
32 WFL										
33 EXB										
34 COST				5300.00000	700.00000	185.00000	160.00000	725.00000	365.00000	107.10000
35 EQIR1										
36 EQIR2										
37 EQIR3										
38 TIRAP										
39 TIRMY										
40 TIRJN										
41 TIRJL										
42 TIRAG										
43 SIRAP										
44 SIRMY										
45 SIRJN										
46 SIRJL										
47 SIRAG										
48 APRIL										
49 MAY										
50 JUNE										
51 JULY										
52 AUGT										
53 GTOT										

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COLUMNS 31 TO 40

	SPM	POT	FJL	TRM	CJM	CSM	TRS	CMB	SCB	PM
1 OBJECT	-58,00000	-46,75000	-0,07200	-2,00000	-2,00000	-2,00000				-0,02200
2 SEL										
3 SEM										
4 SEW										
5 SER										
6 SES										
7 SEP										
8 FAM										
9 FSP	-1,00000									
10 FPO		-1,00000								
11 RFL			-1,00000							
12 RLT				-1,00000						
13 RLC					-1,00000					
14 RLS						-1,00000				
15 MTR							-270,00000			
16 MCJ								-350,00000		
17 MCS									-160,00000	
18 SAR										
19 NLR										
20 CYL										
21 CYM										
22 CYG										
23 CYW										
24 CYR										
25 CYS										
26 CYP										
27 ALO										
28 FRW										
29 FRS										
30 FRG										
31 SOL										
32 HFL										
33 EXR										
34 COST	58,00000	46,75000	0,07200	2,00000	2,00000	2,00000				0,02200
35 EQIR1										
36 EQIR2										
37 EQIR3										
38 TIRAP										
39 TIRMY										
40 TIRJN										
41 TIRJL										
42 TIRAG										
43 SIRAP										
44 SIRMY										
45 SIRJN										
46 SIRJL										
47 SIRAG										
48 APRIL										
49 MAY										
50 JUNE										
51 JULY										
52 AUST										
53 GTOT										-1,00000

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COLUMNS 41 TO 50

	OIL	FLG	EMAZ	IMAZ	EWHT	EBRL	IREC	IHSF	DSFL	IHWB
1 OBJECT			113.00000	-170.00000	114.00000	101.00000		-5369.00000		-5369.00000
2 SEL										
3 SEM										
4 SEW										
5 SER										
6 SES										
7 SEF										
8 FAM										
9 FSP										
10 FPD										
11 RFL										
12 RLT										
13 RLC										
14 RLS										
15 MTR										
16 MCJ										
17 MCS										
18 SAR										
19 NLB										
20 CYL										
21 CYM										
22 CYG			-1.00000	1.00000						
23 CYW					-1.00000					
24 CYR						-1.00000				
25 CYS										
26 CYF										
27 ALD										
28 FRW										
29 FRS										
30 FRG										
31 SOL	-1.00000									
32 WFL		-1.00000								
33 EXB			113.00000		114.00000	101.00000				
34 COST				170.00000				5369.00000		5369.00000
35 EQIR1							-1.00000	1.00000		1.00000
36 EQIR2								-1.00000	1.00000	
37 EQIR3										-1.00000
38 TIRAP										
39 TIRMY										
40 TIRJN										
41 TIRJL										
42 TIRAG										
43 SIRAP										
44 SIRMY										
45 SIRJN										
46 SIRJL										
47 SIRAG										
48 APRIL										
49 MAY										
50 JUNE										
51 JULY										
52 AUGT										
53 STOT										

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COLUMNS 51 TO 60

	DWB	TEXB	IRAP	IRMY	IRJN	IRJL	IRAG	APRS	MAYS	JUNS
1 OBJECT										
2 SEL										
3 SEM										
4 SEW										
5 SEB										
6 SES										
7 SEF										
8 FAM										
9 FSP										
10 FPO										
11 RFL										
12 RLT										
13 RLC										
14 RLS										
15 MTR										
16 MCJ										
17 MCS										
18 SAR										
19 NLR										
20 CYL										
21 CYM										
22 CYG										
23 CYW										
24 CYR										
25 CYS										
26 CYF										
27 ALD										
28 FRW										
29 FRS										
30 FRG										
31 SOL										
32 WFL										
33 EXB		-1.00000								
34 COST										
35 EQIR1										
36 EQIR2										
37 EQIR3	1.00000									
38 TIRAP			-1.00000							
39 TIRMY				-1.00000						
40 TIRJN					-1.00000					
41 TIRJL						-1.00000				
42 TIRAG							-1.00000			
43 SIRAP								-1.00000		
44 SIRMY									-1.00000	
45 SIRJN										-1.00000
46 SIRJL										
47 SIRAG										
48 APRIL			1.00000					1.00000		
49 MAY				1.00000					1.00000	
50 JUNE					1.00000					1.00000
51 JULY						1.00000				
52 AUGT							1.00000			
53 GTOT			1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.20000

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COLUMNS 61 TO 68

		JULS	AUGS	TAPR	TMAY	TJUNE	TJULY	TAUG	TCOST
1	OBJECT								
2	SEL								
3	SFW								
4	SEW								
5	SFB								
6	SES								
7	SEF								
8	FAM								
9	FSP								
10	FPC								
11	RFL								
12	RLT								
13	RLC								
14	RLS								
15	MTR								
16	MCJ								
17	MCS								
18	SAR								
19	NLB								
20	CYL								
21	CYM								
22	CYG								
23	CYW								
24	CYB								
25	CYS								
26	CYF								
27	ALD								
28	FRW								
29	FRS								
30	FRG								
31	SOL								
32	WFL								
33	EXB								
34	COST								-1.00000
35	EQIR1								
36	FQIR2								
37	EQIR3								
38	TIRAP								
39	TIRMY								
40	TIRJN								
41	TIRJL								
42	TIRAG								
43	SIRAP								
44	SIRMY								
45	SIRJN								
46	SIRJL	-1.00000							
47	SIRAG		-1.00000						
48	APRIL			-1.00000					
49	MAY				-1.00000				
50	JUNE					-1.00000			
51	JULY	1.00000					-1.00000		
52	AUGT		1.00000					-1.00000	
53	CTOT	1.00000	1.00000						

```
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    RHS          1 TO   1

                  RHS
 1 OBJECT    N
 2 SEL       F
 3 SEM       E
 4 SEW       E
 5 SEB       E
 6 SES       E
 7 SEF       E
 8 FAM       E    7110.00000
 9 FSP       E    8690.00000
10 FPD       E    6935.00000
11 RFL       E
12 RLY       F
13 RLC       E
14 RLB       E
15 MTR       E
16 MCJ       E
17 MCS       F
18 SAR       F
19 NLR       F
20 CYL       E
21 CYM       E
22 CYG       F
23 CYW       E
24 CYB       E
25 CYS       E
26 CYP       E
27 ALD       L  121600.00000
28 FRW       G    2825.00000
29 FRB       G   37300.00000
30 FRG       G  174100.00000
31 SOL       F
32 WFL       F
33 EXR       E
34 COST      F
35 EQTR1     E
36 EQTR2     F
37 EQTR3     E
38 TIRAP     E
39 TIRMY     E
40 TIRJN     E
41 TIRJL     E
42 TIRAG     F
43 SIRAP     E
44 SIRMY     E
45 SIRJN     E
46 SIRJL     E
47 SIRAG     E
48 APRIL     E
49 MAY       E
50 JUNE      E
51 JULY      E
52 AUGT      E
53 GTOT      E
```

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ROUND SET:  OLIM
   LO  LUC        **********
   LO  MBL        **********
   LO  OIL        8400.00000
   LO  FLO        **********
   UP  NL         **********
   UP  PW         **********

  ROWS  COLUMNS  RHS-S  RANGES  BOUNDS  COEFS.  DENSITY
   53      68      1       0       1     379    0.1052

  396 TOTAL VALUES SPECIFIED,   0 COEFS ARE 0.0
```