COORDINATION OF WATER DEMAND AND SUPPLY MODELS: SILISTRA REGION CASE STUDY

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PREFACE

Water resource systems have been an important 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 modeling techniques, to generate inputs for planning, design, and operational decisions.

In 1978, it was decided that parallel to the continuation of demand studies, an attempt would be made to integrate the results of our studies on water demands with water supply considerations. This new task was named "Regional Water Management" (Task 1, Resources and Environment Area)..

One of the case studies in this Task, carried out by the Resources and Environment Area in collaboration with several Bulgarian institutions and the Regional Development Task of IIASA, is concerned with water resources management in the Silistra region of Bulgaria. This paper presents an approach to coordination of the linear water demand and supply models developed earlier for agricultural water use in the Silistra Region, (RR-80-38, WP-81-93). An iterative procedure interfacing these models is based on the sequential coordination of water demands and marginal costs of water.

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ABSTRACT

To date, the economic analysis of water use, especially in a regional context, is unthinkable without the coordination of water demand and supply issues. The point is that water supply costs and water demand are closely interrelated. The paper presents one of the possible approaches to water supply-demand balancing. Specifically, it is concerned with the coordination of the two regional models--agricultural water demand and water supply models for the Silistra region of Bulgaria. Both these models were developed at IIASA separately in 1977 and 1979 respectively. The approach is based on the search for the equilibrium state for water demands and marginal costs of water. The procedure of the search for the equilibrium point developed is the iterative process of interacting the two models mentioned above. The paper does not attempt to find theoretical proofs for the existence and uniqueness of the equilibrium state for the two models, or the convergence of the iterative process. The main working tool in the water demand and supply coordination chosen was computer experiments. The interactive runs of these models were done on the IIASA PDP 11/45 and Pisa (Italy) IBM 365/170 computers. Convergence of the iterative process above occured in the five iterations. One of the interesting results of the modeling effort is the economic inexpedience of irrigation for some agricultural areas with high enough marginal costs of water. In the paper, the Silistra agricultural water demand and supply models, the principles of their coordination, and results of runs are presented.

CONTENTS

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1. INTRODUCTION

In water resources management, the supply and demand sides have usually been studied separately. There are several reasons for this.

Firstly, water demand and water supply activities are often carried out by different organizations. Secondly, in trying to apply contemporary optimization techniques, there are computational advantages; even for a single region the integrated demand-supply model can involve thousands of variables. Thirdly, the use of separate demand and supply models allows better interpretation of the driving forces and results obtained for each of the models. Fourthly, each of the models can easily be replaced with other simpler or more sophisticated models, i.e. a system of separate models is more flexible than a single demand-supply model. Finally, incompatibility of objectives in the separate models can be easily handled.

Separate treatment of demand and supply, however, requires the development of appropriate techniques for coordination of the solutions of both models. In this respect, two basic approaches have been developed.

The first approach assumes that both models can be joined into one. A good example of this approach is an integration of demand and supply optimization models in one model. After running of the integrated model, not only the overall solution to the demand-supply problem is obtained but also the solutions of each particular model are determined.

The second approach envisages a proper multi-stage coordination procedure between the demand and supply models. This approach has many ramifications depending on the kind of variables exchanged between the models and the way this exchange is carried out. The most advanced approaches are based on a price coordination method (Haines, 1973; Findeisen, 1978; Guariso et al., 1978). The method is well suited for integrated problems having an utility, or objective function which is a sum of the utility functions for the separate demand and supply problems. If the utility function is not separable, then the so-called direct coordination methods are applied (Findeisen, 1978). In case of no common utility function, a vector optimiation (Pareto optimality) is usually adopted.

This paper discusses a procedure based on the price coordination method to obtain an equilibrium solution for the Silistra region water demand and supply models. The paper however, does not contain theoretical proofs for the existence and uniqueness of the equilibrium solution. Instead, only computer experiments are shown.

The paper is structured in the following way: Sections 2 and 3 provide background information about the water supply and demand models; Section 4 describes the coordination procedure which is applied to obtain the results, discussed in Section 5.

2. WATER SUPPLY MODEL

The proposed Silistra water supply system is shown in Figure 1. It is envisaged to construct a system of three reservoirs and six pumping stations connected by a number of canals. To formally describe this system, the following notation is introduced:

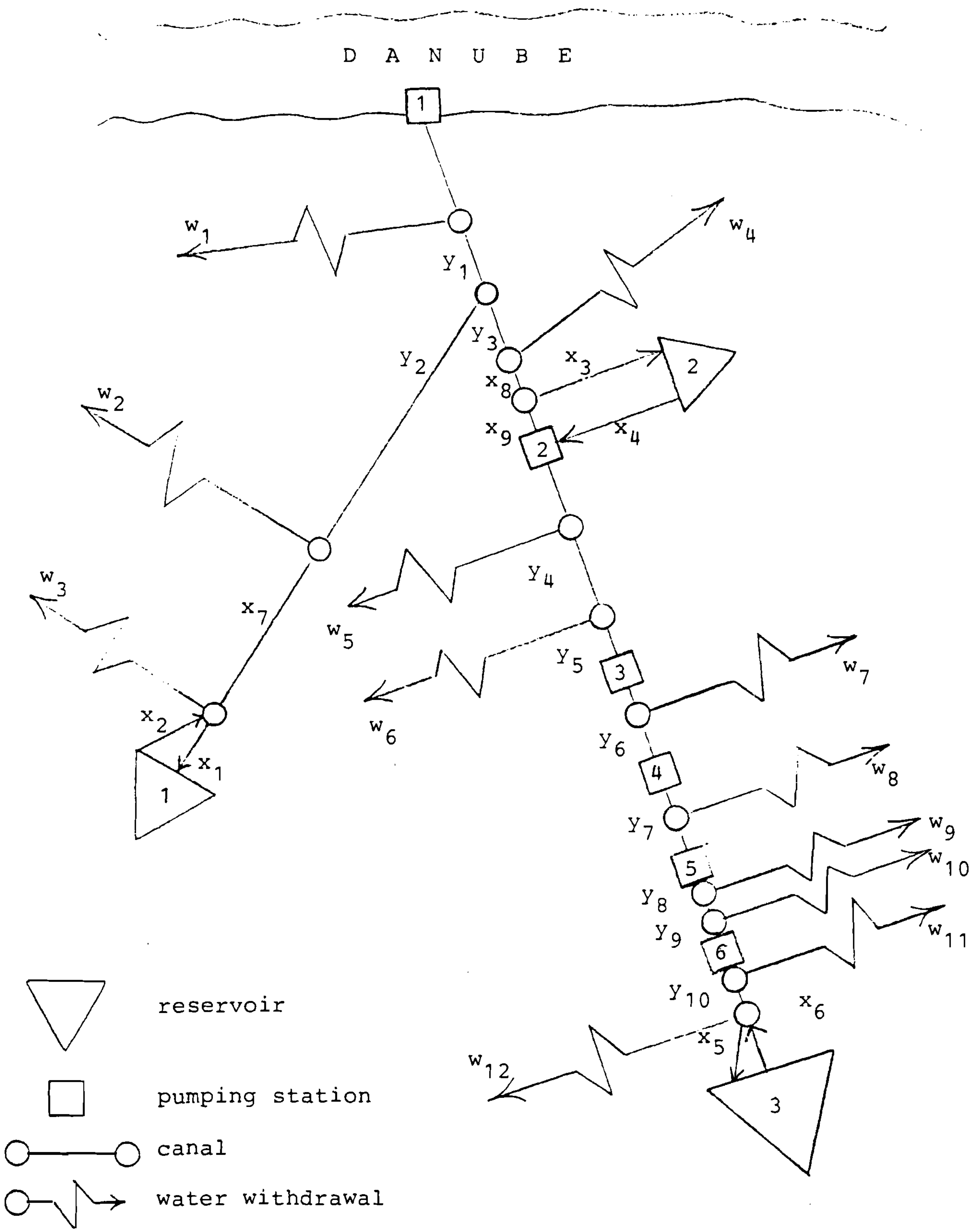

Figure 1. Silistra Water Supply System.

w_j^i = irrigation water flow for irrigated area j in time period i $(i = 1,\ldots,8)$; $(j = 1,\ldots, 2)$;

y_s^i = water flow in canal s $(s = 1,\ldots,10)$ in time period i;

x_p^i = water flow in distributing canal p $(p = 1,\ldots,9)$ in time period i;

S_k^i = active water storage in reservoir k $(k = 1,2,3)$ in time period i;

V_k = capacity of reservoir k;

Z_s = discharge capacity of canals;

Z_{11} = discharge capacity of the canal leaving reservoirs 3;

Z_{12} = capacity of pumping station 2.

The water resources available are considered as unlimited because of the abundance of water in the Silistra site of the Danube river. This allows the consideration of only within-year regulation of water resources. A year is divided into nine time intervals (Figure 2). In the supply model, the first time interval of December, January and February is omitted because during these winter months, the whole water supply system does not operate. The sixth interval--the first ten days of August--is a period of the most intensive irrigation for all areas. In addition, due to the small size of the Silistra region, the transit time delays of water in canals are not taken into account.

The irrigation system parameters depend on water demands w_j^i which are exogenous variables determined by the water demand model described in Section 3.

The objective of the supply model is to find the least-cost water supply system. A measure for the total costs associated with the establishment and operation of the water supply system is the generalized annual cost associated with:

(i) establishment of reservoirs, pumping stations and canals;

(ii) losses of the submerged arable lands;

(iii) operation of reservoirs, pumping stations and canals; and

Number of irr. interval	0	1	2	3	4	5	6	7	8
Months	December January February	October November March April	May	First 20 days of June	Last 10 days of June	July	First 10 days of August	Last 20 days of August	September
Length of time interval (month) (τ_i)	3	4	1	$\frac{2}{3}$	$\frac{1}{3}$	1	$\frac{1}{3}$	$\frac{2}{3}$	1
	out of work	no irrigation					the most intensive irrigation		

Figure 2. Irrigation time intervals.

(iv) consumption of electrical energy by pumping stations.

In these terms, the objective function E can be written as follows:

$$E = \sum_{k=1}^{3} b_k V_k + \quad ,$$

capital and operating costs of reservoirs;

$$\sum_{s=1}^{12} a_s Z_s + \quad , \qquad (1.1)$$

capital and operating costs of canals and pumping stations;

$$\sum_{\alpha, i} e_\alpha \tau^i y_\alpha^i + e_2 \sum_i \tau^i x_9^i \quad , \qquad \alpha = 1,5,6,7,9 \quad ; \quad i = 1,\ldots,8 \quad .$$

costs of electrical energy for pumping stations.

The first set of constraints is the balance relations among the water demands for different irrigated areas and the water flows in canals:

$$\begin{aligned}
y_1^i - y_2^i - y_3^i &= w_1^i \quad , \qquad i = 1,\ldots,8 \quad , \\
y_2^i - x_7^i &= w_2^i \quad , \\
x_7^i + x_2^i - x_1^i &= w_3^i \quad , \\
y_3^i - x_8^i &= w_4^i \quad , \\
x_9^i - y_4^i &= w_5^i \quad , \\
y_{r-2}^i - y_{r-1}^i &= w_r^i \quad , \qquad r = 6,\ldots,11 \quad , \\
x_6^i - x_5^i + y_{10}^i &= w_{12} \quad .
\end{aligned} \qquad (1.2)$$

The water storages in reservoirs are described as follows:

$$s_k^{i+1} = s_k^i + \tau^i \; (x_{2k-1}^i - x_{2k}^i) \quad , \qquad k = 1,2,3 \;, \quad i = 1,\ldots,7 \;,$$
$$s_k^1 = s_k^8 + \tau^8 \; (x_{2k-1}^8 - x_{2k}^8) \quad , \tag{1.3}$$

where τ^i is the length of time interval i. The last relation in (1.2) illuminates the fact that the water stored in any reservoir at the end and at the beginning of a year must be equal--a condition of a year cycle.

The following set of constraints reflects the fact that the release from any reservoir cannot be more than the water stored in it.

$$\tau^i x_{2k}^i - s_k^i \leq 0 \quad , \qquad k = 1,2,3 \;, \qquad i = 1,\ldots,8 \quad . \tag{1.4}$$

Finally, some obvious physical constraints are:

$$\begin{aligned}
& x_3^i - x_8^i \leq 0 \quad , && i = 1,\ldots,8 \;, \\
& x_9^i + x_3^i - x_4^i - x_8^i = 0 \quad , && \\
& s_k^i \leq V_k \quad , && k = 1,2,3 \;, \\
& y_s^i \leq Z_s \quad , && s = 1,\ldots,10 \;, \\
& x_6^i \leq Z_{11} \;, && \\
& x_9^i \leq Z_{12} \;. &&
\end{aligned} \tag{1.5}$$

In addition, non-negativity conditions for all decision variables should be specified.

Thus, the set of relations (1.1)-(1.5) forms a linear programming model for the water supply system. The quantities y_s^i, x_p^i, x, V_k, Z_s, and S_j^i are decision variables. The cost coefficients b_k, a_s e are given by the Sofia Institute for Water Projects. The model has been run on the SNUCE IBM 370/165 computer in Pisa, Italy.

The more detailed description of the Silistra water supply model and running results are available in Chernyatin (1979). In the coordination procedure (see Section 4) the marginal cost concept is used. For the supply model, two types of marginal water costs--seasonal and mean annual--are evaluated. By definition, the seasonal unit cost c_j^i of water in irrigated area j is the increment of the optimal value of objective function E caused by the unit increment of water consumption in irrigated area j at time period i. The seasonal unit water costs obtained by running the model depend essentially on the geographical location of the irrigated area and the season of water consumption. By definition, annual marginal cost c_j of water for irrigated area j, is the increment of the optimal value of objective function E when the unit increment of water consumption in area j is distributed over all the time intervals according to the time table for irrigation in this area. In the model, this marginal cost is determined as the weighted sum

$$c_j = \sum_{i=2}^{8} \delta_j^i c_j^i \quad , \qquad \sum_{i=2}^{8} \delta_j^i = 1 \quad , \tag{1.6}$$

where weights δ_j^i (i = 2,...,8) are equal to

$$\delta_j^i = \tau^i w_j^i / \sum_{i=2}^{8} \tau^i w_j^i \quad .$$

The runs of the model show that the mean annual unit costs of water also depend on the lcoation of the irrigated area. These unit costs are inputs to the agricultural water demand model.

3. WATER DEMAND MODEL

The water demand model used in the coordination procedure is a further refinement of SWIM1 and SWIM2 water demand model available elsewhere (Gouevsky, Maidment 1977; Gouevsky, Maidment Sikorski, 1980). The last reference provides a detailed description of SWIM2. That is why on the major modeling points will be discussed here as well as some of the latest changes in the model structure made to reflect the aforementioned water supply model.

The main objective of the water demand model is to make a comprehensive analysis of factors that influence agricultural water demands and the associated agricultural production in the eleven subregions, taking into account the major goal of the region, which is to maximize the total net benefit from crop and livestock production with the limited regional resources.

The model is intended to provide information for:

- estimation irrigation and livestock water demands and their distribution over the twelve subregions and in eight irrigation intervals during the irrigation season in a given year;
- forecasting the growth in these demands in response to different scenarios of growth in the number of of livestock in the region;
- determining what proportion of the arable land within the region and in the subregions should be developed for irrigation;
- evaluating the impact on water demands of various factors, including weather variability, and the availability of other input resources;
- estimating the demand function for water.

For modeling purposes agricultural production system has been broken down into a number of successive subsystems as shown in Figure 3. Input resources, such as land, water, fertilizers, labor, machinery, capital investments, go into producing crops whose output is processed for internal marketing, feeding of livestock or sold outside of the region.

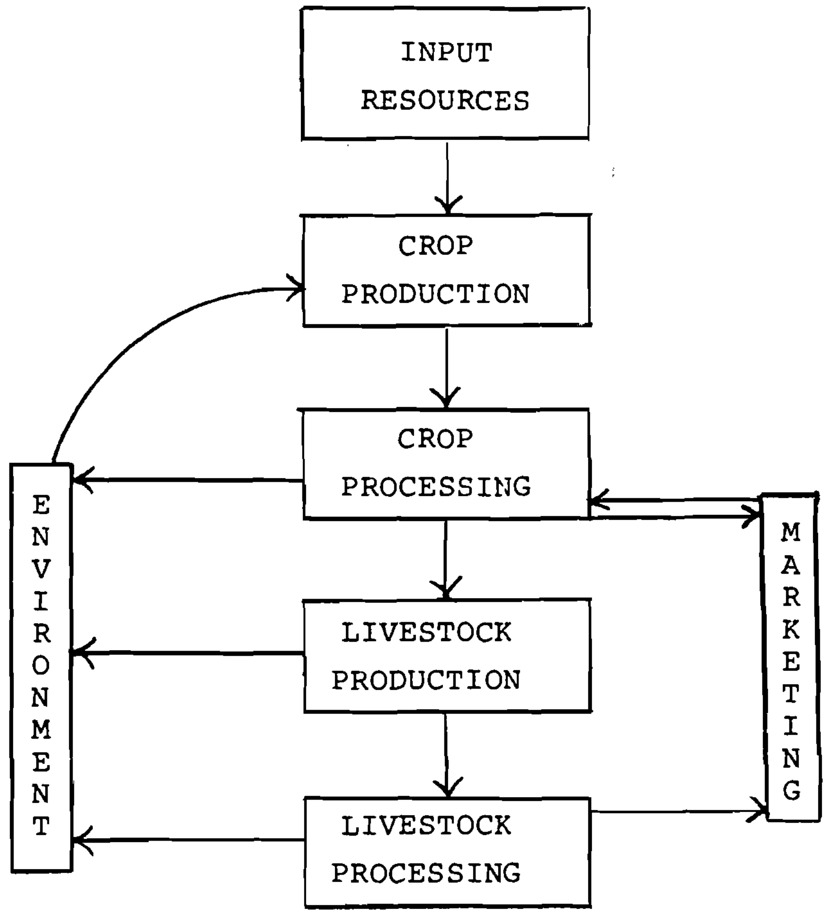

Figure 3. Agricultural Production System.

Crop production, supplemented by purchases from the market is fed to livestock whose products are processed and sold. Livestock production and processing may have substantial environmental impacts, such as those due to feedlot influents, and these impacts may, in turn, affect crop production.

In the process of modeling agricultural production and deriving water demands, the following assumptions have been made:

a) the region is divided into 12 subregions. The agricultural system in each of them is modeled for a one-year time frame;
b) crop areas in each subregion as well as amounts of crop production, number of livestock, water demands are decision variables connected to each other through a linear relationship;
c) economies of scale are not explicitly included;

d) the Danube river is the only source of water. The model computes the total amount of irrigation water as well as its distribution among subregions and various crops using 15 ten-day time intervals during the irrigation season, May-September. Additional accounting constraints are introduced to allow for eight time intervals for which the supply model is designed. Unit crop demands (m^3/ha) are calculated by means of a soil moisture balance model;

e) each group is assume to be grown in each of the 12 subregions; it may be irrigated or not.

f) capital investments are split into two parts: irrigation capital investments (sprinklers) and investments (for machinery, feedlots, and perennial crops (orchards). The only cost of capital investments included in the water demand model is their depreciation over the life time of the equipment.

The following description formalizes the relationships among the various variables into an aggregated linear programming format. A more detailed description is available in (Gouevsky, Maidment, Sikorski, 1980).

For ease in the explanation, all decision variables and constraints in the water demand model are aggregated into 14 decision vectors and 18 sets of constraints. The objective function B, which has been adopted for the agricultural production in the region, maximizes the annual net benefits, i.e. the different between the value of marketed livestock and crop production, and their production costs. Vector quantities are indicated by underlining.

$$\begin{aligned} B = \max\ [&\underbrace{\underline{b}^1\underline{v}^1 + \underline{b}^2\underline{v}^2 + \underline{b}^3\underline{v}^3 + \underline{b}^4\underline{v}^4 + \underline{b}^5\underline{q}^2}_{\text{crop and livestock production benefits}} \\ &- \underbrace{\underline{c}^1\underline{y}}_{\text{crop production cost}} - \underbrace{\underline{c}^2\underline{w}^1 - \underline{c}^3\underline{w}^2}_{\text{crop processing cost}} - \underbrace{\underline{c}^4\underline{q}^1}_{\text{livestock production cost}} \\ &- \underbrace{\underline{p}^1\underline{x}^1 - \underline{p}^2\underline{x}^2 - \underline{p}^3\underline{x}^3 - \underline{p}^4\underline{x}^4 - \underline{p}^5\underline{x}^5}_{\text{input resources cost}}\ , \end{aligned} \qquad (3.1)$$

where

$\underline{b}^1$, $\underline{b}^2$ = benefits from crop production (grain, vegetables, tobacco and fruits) sold to meet population requirements in Silistra;

$\underline{v}^1$, $\underline{v}^2$ = amounts of these crop products;

$\underline{b}^3$, $\underline{v}^3$ = benefits per unit of grain exports and quantities of grain exported, respectively;

b^4, v^4 = benefits per unit of crop products (vegetables, fruits, tobacco) exported, and quantities of crop products exported, respectively;

$\underline{b}^5$, $\underline{q}^2$ = benefits per unit of livestock products, and quantities of livestock products, respectively;

$\underline{c}^1$, $\underline{y}$ = crop production costs per hectare, and areas of crop alternatives, respectively;

$\underline{c}^2$, $\underline{w}^1$ = unit costs of processing fodder products, and amounts of these products, respectively;

$\underline{c}^3$, $\underline{w}^2$ = unit costs of processing grain products and amounts of these products, respectively;

$\underline{c}^4$, $\underline{q}^1$ = production costs per animal, and numbers of animal, respectively;

$p^1, p^2, \ldots, p^5$ = are prices of input resources (irrigation water, irrigation equipment, fertilizers, machinery and capital investments); and

$x^1, x^2, \ldots, x^5$ = quantitites of input resources.

The objective function, B, is maximized subject to the following set of constraints.

Land Use

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

$$A_{1,1}\ \underline{y} \leq \underline{\ell}\ , \tag{3.2}$$

where

$A_{1,1}$ = matrix which sums up the irrigated and/or nonirrigated land used in each of the 12 subregions, as well as takes care of crop rotation;

$\underline{\ell}$ = comprises the areas available for crop production land in the eleven subregions, and the the available irrigated land.

Irrigation and Livestock Drinking Water Demands

$$A_{1,2}\,\underline{y} + A_{9,2}\,\underline{q}^1 - \underline{x}^1 = 0 \quad , \tag{3.3}$$

where

$A_{1,2}$ = irrigation crop water use coefficients per hectare;

$A_{9,2}$ = livestock drinking water use coefficients per animal;

$\underline{x}^1$ = volumes of irrigation (for twelve subregions and eight irrigation time intervals) and livestock water demands.

Irrigation Equipment

$$A_{1,3}\,\underline{y} - \underline{x}^2 = 0 \quad , \tag{3.4}$$

where

$A_{1,3}$ = irrigation equipment requirements per hectare for the twelve subregions;

$\underline{x}^2$ = is the number of sets of irrigation equipment required.

Fodder and Grain Production

$$A_{1,4}\,\underline{y} - \underline{w}^1 = 0 \quad , \tag{3.5}$$

$$A_{1,5}\,\underline{y} - \underline{w}^2 = 0 \quad , \tag{3.6}$$

where

$A_{1,4}$, $A_{1,5}$ = yields of fodder and grain crops, respectively;

$\underline{w}^1$, $\underline{w}^2$ = quantities of fodder and grain products, respectively.

Grain Production Balance

Grain produced must equal grain used:

$$A_{3,5}\ \underline{w}^2 - A_{4,6}\ \underline{v}^1 - A_{6,6}\ \underline{v}^3 - A_{8,6}\ \underline{v}^5 = 0 \quad , \tag{3.7}$$

where

$A_{3,6}$, $A_{6,6}$ and $A_{8,6}$ = matrices which sum up, respectively, total grain production, population requirements of grain, exports and grain products for livestock;

$\underline{v}^1$ = quantities of population corp products;

$\underline{v}^3$ = amounts of grain exports;

$\underline{v}^5$ = amounts of grain products for livestock.

Production Balance of Vegetables, Tobacco and Fruits

$$A_{1,7}\ \underline{y} - A_{5,7}\ \underline{v}^2 - A_{7,7}\ \underline{v}^4 = 0 \quad , \tag{3.8}$$

where

$A_{1,7}$, $A_{5,7}$ and $A_{7,7}$ = matrices which sum up production of vegetables, tobacco, fruits, their population requirements, and their exports;

$\underline{v}^2$ = amounts of these crops which go to the Silistra population;

$\underline{v}^4$ = amounts of exports of vegetables, tobacco and fruits.

Livestock Foodstuff Requirements

Livestock feed production must at least meet minimum requirements:

$$A_{2,8}\, \underline{w}^1 + A_{8,8}\, \underline{v}^5 - A_{9,8}\, \underline{q}^1 \geq 0 \quad , \tag{3.9}$$

where

$A_{2,8}$, $A_{8.8}$ and $A_{9,8}$ = matrices which sum up fodder products, grain livestock products, and animal diet requirements for these products, respectively.

Livestock Products

$$A_{9,9}\, \underline{q}^1 - \underline{q}^2 = 0 \quad , \qquad (3,10)$$

where

$A_{9,9}$ = amount of livestock products generated per animal.

Fertilizers, Machinery and Capital Investments

Nutrients needed must be supply by fertilizer or manure:

$$A_{1,10}\, \underline{y} - A_{9,10}\, \underline{q}^1 - \underline{x}^3 = 0 \quad , \tag{3.11}$$

where

$A_{1,10}$, $A_{9,10}$ = matrices of crop fertlizer requirements and manure generation, respectively.

Machines needed must be available:

$$A_{1,11}\, \underline{y} - \underline{x}^4 = 0 \quad , \tag{3.12}$$

where

$A_{1,11}$ = number of each type of machine needed per hectare of crop production;

$\underline{x}^4$ = total number of each type of machines needed in the complex.

Capital investment used are:

$$A_{1,12}\,\underline{y} + A_{9,12}\,\underline{g}^1 + A_{12,12}\,\underline{x}^2 + A_{14,12}\,\underline{x}^4 - \underline{x}^5 = 0 \quad , \tag{3.13}$$

where:

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

$\underline{x}^5$ = amounts of capital investment for different purposes.

It should be noted that the depreciated cost of capital is contained in the costs of those decision vectors requiring capital investment.

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

Constrained Input Resources

Input resources used cannot exceed those available.

$$\underline{x}_1 \leq \underline{w} \quad , \tag{3.14}$$

$$\underline{x}^3 \leq \underline{f} \quad , \tag{3.15}$$

$$\underline{x}^5 \leq \underline{k} \quad , \tag{3.16}$$

where

w, f, k = amounts of available water, fertilizers, and capital investment, respectively.

Constrained Outputs

Some production outputs must meet target levels.

$$\underline{v}^1 \geq \underline{q} \quad , \tag{3.17}$$

$$\underline{v}^2 \geq \underline{r} \quad , \tag{3.18}$$

$$\underline{q}^1 \geq \underline{n} \quad , \tag{3.19}$$

where

q, r, n = targets of levels of grain products for the regional population(flour, cooking oil, vegetables, fruits, tobacco) and number of livestock (cows, sheep, pigs, hens).

The total dimension of the decision vectors $\underline{y}$, $\underline{w}^i$, $\underline{v}^i$, $\underline{q}^i$ and $\underline{x}^i$ is 420 decision variables interrelated by 230 constraints.

For the purpose of integration of the water demand and water supply models the former was reduced to a size of 100 constraints and 149 variables thus making it possible to run it on the PDP11/70 at IIASA. The reduction, however, does not change the solution much because only unbinding or accounting constraints were taken out.

4. COORDINATION PROCEDURE

The employed coordination procedure is based on the theory of economic efficiency of water resource systems. The basic notion of this theory is the conception of the equilibrium point. One way of characterizing this point is to say that it represents the amount of water for which the price equals the incremental or marginal cost of supply of this amount. This condition, namely that price equals marginal cost, has in turn, been proposed as a guide to resource allocation (Lange, 1952).

The procedure for integration by using marginal values has been set up as shown in Figure 4. At the beginning, "guess water demands" are fed into the supply model. It produces 96 marginal supply costs for these demands. These marginal costs are averaged over time for each subregion. Thus, only 12 marginal values enter the objective function of the demand model at the next iteration. The demand model is run again; 96 water demands are produced and fed back to the respective right hand side of the supply model. This procedure has been repeated until both marginal costs of supply and marginal benefits as well as the respective water demands and amount of water supplied coincide.

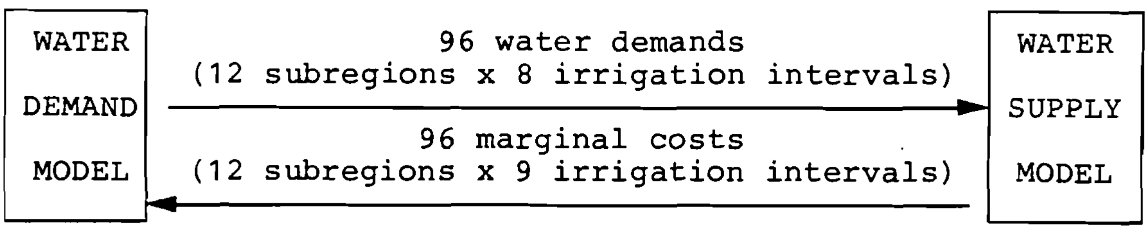

Figure 4. Variables to be exchanged between two models.

5. RESULTS

The coordination procedure described above has been implemented to find an equilibrium solution for the water demand model run on IIASA's PDP 11/70 computer and the supply model was run on the CNUCE IBM 370/165 computer in Pisa, Italy.

The procedure starts with guess demands (Table 1) which are fed to the supply model to produce marginal values of water. These values are shown in the second column of Table 2. The marginal supply costs at the fifth iteration as shown in Table 2,

Table 1. Water demands at the first iteration (m^3/s).

	IRRIGATION TIME INTERVALS							
Sub-region	1	2	3	4	5	6	7	8
1	0	0.248	0.317	1.191	0.897	1.294	0.582	0.242
2	0	0.179	0.228	0.859	0.61	0.961	0.42	0.174
3	0	4.015	5.127	19.248	13.674	20.927	9.419	3.914
4	0	0.383	0.488	1.833	1.302	1.993	0.898	0.373
5	0	0.626	0.8	3.003	2.133	3.264	1.469	0.61
6	0	0.413	0.528	1.983	1.408	2.155	0.97	0.403
7	0	0.257	0.328	1.229	0.873	1.337	0.602	0.25
8	0	0.887	1.135	4.263	3.027	4.634	2.086	0.867
9	0	1.057	1.35	5.069	3.6	5.51	2.48	1.03
10	0	0.525	0671	2.522	1.791	2.741	1.234	0.512
11	0	0.414	0.53	1.987	1.411	2.16	0.972	0.404
12	0	7.413	9.467	35.551	25.248	38.64	17.39	6.569

Table 2. Marginal costs (lv/m^3).

Sub-region	Marginal supply cost at 1st iteration	Marginal supply cost at 5th iteration	Marginal benefit of demand at 6th iteration
1	0.0267	0.026	0.026
2	0.0357	0.0374	0.0374
3	0.0353	0.0374	0.0374
4	0.036	0.052	0.052
5	0.0454	0.0736	0.0736
6	0.0569	0.0799	0.0799
7	0.0803	0.0996	0.0996
8	0.2054	0.1005	0.1005
9	0.1151	0.1011	0.1011
10	0.1165	0.1011	0.1011
11	0.1177	0.1032	0.1032
12	0.0613	0.0616	0.0616

when fed to the demand model, produce the same marginal benefits The obtained water demands at this iteration also equal the water supplies. Hence, the marginal values and the respective amount of water at iteration 5 have been accepted as equilibrium marginal values. The corresponding water demands for the last iteration are shown in Table 3. This table indicates that some of the initially guessed demands have changed substantially (e.g., see the demand for subregion 1 at time interval 1). Ultimately, the results indicate that subregions 7, 8, 9, 10 and 11 are to be irrigated inefficiently.

It would also be quite interesting how decision variables in both demand and supply models behave over the iteration process. Figure 5 exemplifies the behavior of net benefit generated by the demand model. The net benefit varies less than 1.3% while the total irrigation water and total irrigation land exhibit variations of up to 8% (see Figure 6). Almost the same apply to the results of the water supply model. The objective function which accounts for annual operation and maintenance costs varies up to 5% among iterations (if the first iteration is excluded which was by all means an initial guess). It can be seen from Table 4 that the supply system utilizes only one out of three initially planned reservoirs to be built. This is so, because the equilibrium solution converges to lower water demands that have been assumed in the beginning. Figure 7 illustrates the changes over iterations in capacities of the largest pumping station (1) and reservoir (3) and in annual cost of the water supply system.

Irrigated crops and animals have a similar pattern of behavior from one iteration to another. The maize grain area changes less than 0,6%, the soybean area is practically constant, the number of animals varies with less than 1,5%. Irrigated lucern, however, varies from 0 to 3500 ha with a final value equal 0 because it is substituted for maize silage.

More profound variations can be found when considering subregions characteristics. For example, water demands for the subregions with higher marginal costs of supply may change

Table 3. Water demands at the final iteration (m^3/s).

	IRRIGATION TIME INTERVALS							
Sub-region	1	2	3	4	5	6	7	8
1	0	0.00086	1.4959	0.0949	2.7398	0.7624	1.1204	0.0013
2	0	0.00062	1.0785	0.0684	1.9754	0.5497	0.8078	0.0009
3	0	0.0138	24.177	1.5338	44.282	12.322	18.108	0.021
4	0	0.3327	0.2394	0.0494	0.3522	1.526	0.542	0.357
5	0	0.545	0.392	0.0809	0.577	2.499	0.887	0.552
6	0	0.359	0.259	0.0534	0.381	1.649	0.586	0.364
7	0	0	0	0	0	0.0011	0.0006	0.0004
8	0	0	0	0	0	0.0038	0.0021	0.0014
9	0	0	0	0	0	0.0045	0.0025	0.0016
10	0	0	0	0	0	0.0022	0.0012	0.0008
11	0	0	0	0	0	0.0018	0.001	0.0006
12	0	7.413	9.467	35.551	25.248	38.64	17.39	6.569

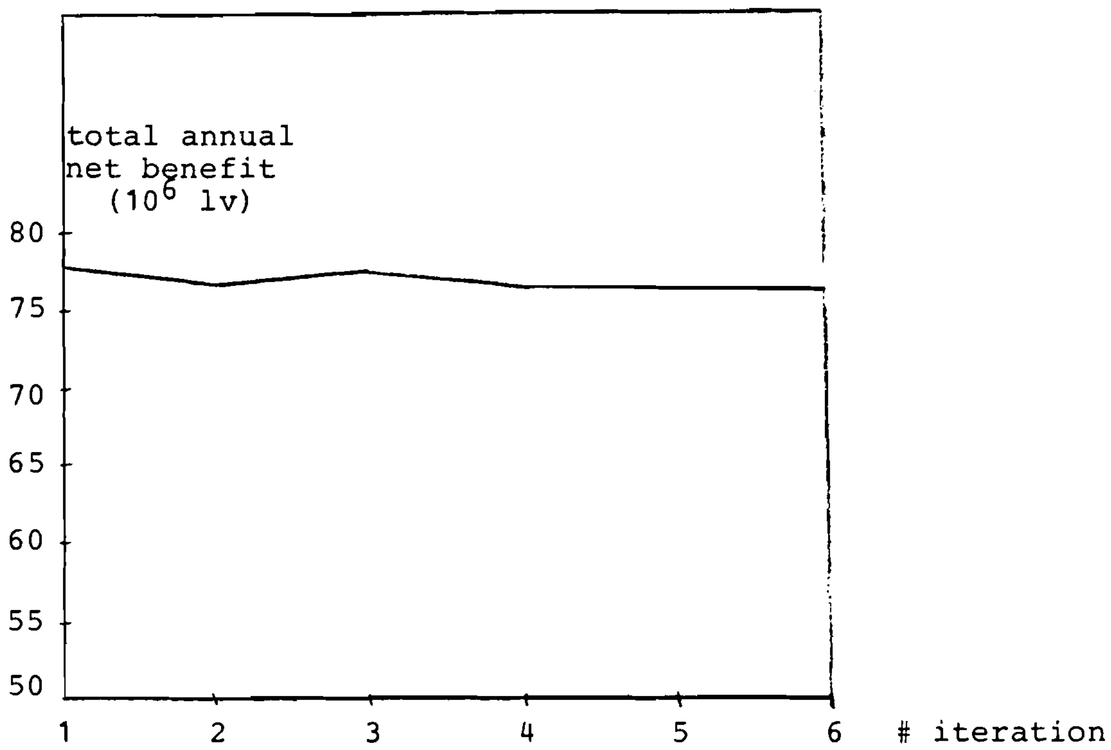

Figure 5. Total annual net benefit from regional agricultural activities.

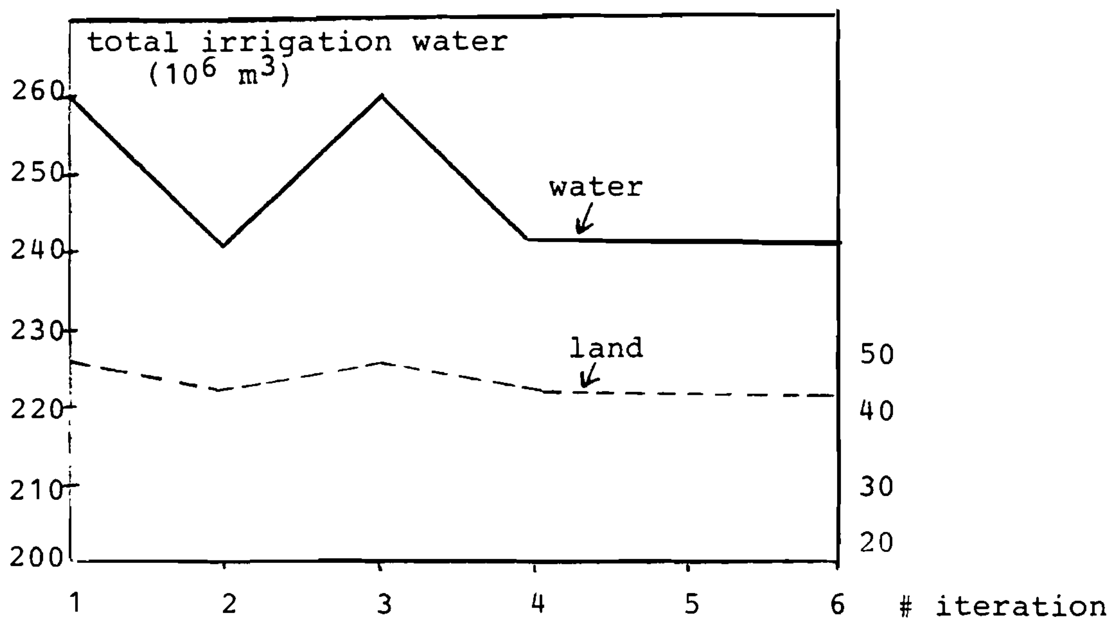

Figure 6. Total irrigation water and total irrigation land.

Table 4. Characteristics of regional water supply system.

Iter-ation	Annual cost of supply system 10^6 lv/year	Capacity of pumping station #1 m^3/s	Capacity of reservoir #1 $10^6 m^3$	Capacity of reservoir #2 $10^6 m^3$	Capacity of reservoir #3 $10^6 m^3$
1	29.4	38.054	5.249	2.46	131.645
2	20.574	26.859	0	0	108.515
3	20.042	23.77	0	0	110.275
4	20.577	26.858	0	0	108.521
5.	19.578	24.079	0	0	106.774
6.	19.578	24.079	0	0	106.774

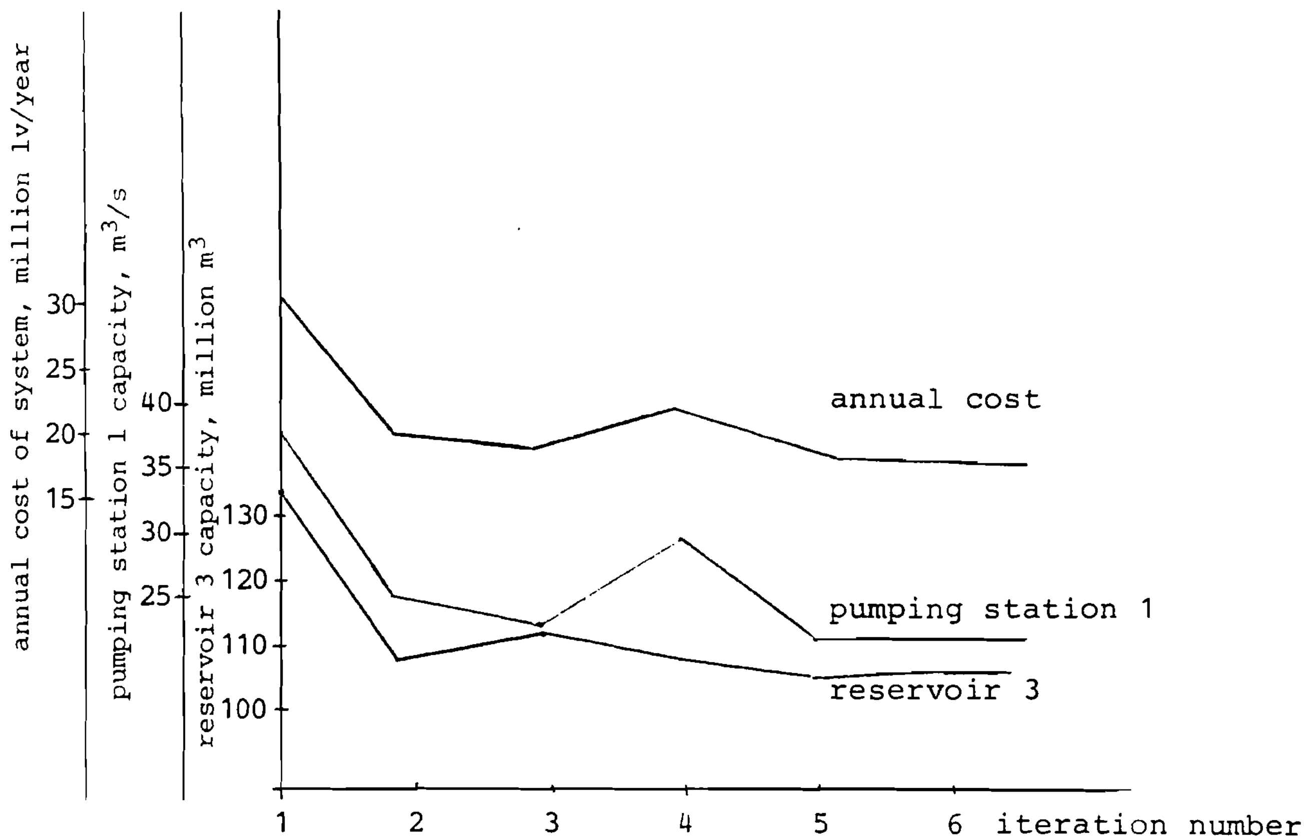

Figure 7. Behavior of the water supply system over the iteration process.

dramatically over the iteration procedure--as shown on Figure 8 for three particular subregions. The shift in water demands is due to changing of marginal value of water supply (Figure 9).

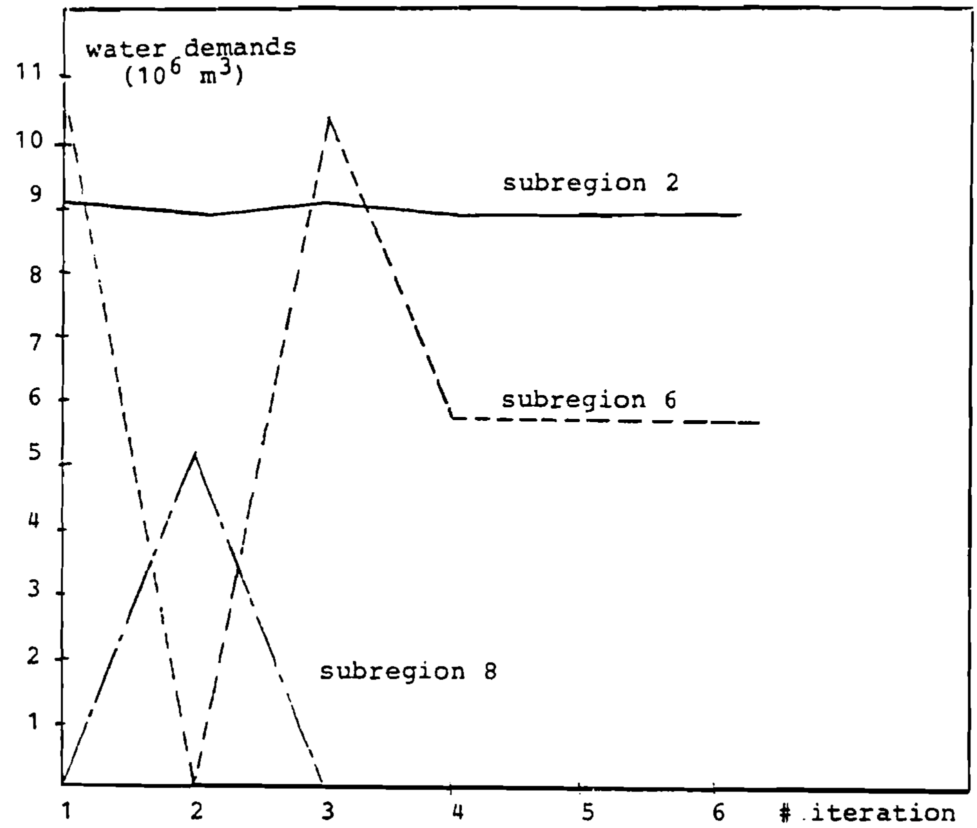

Figure 8. Water demands of particular subregions.

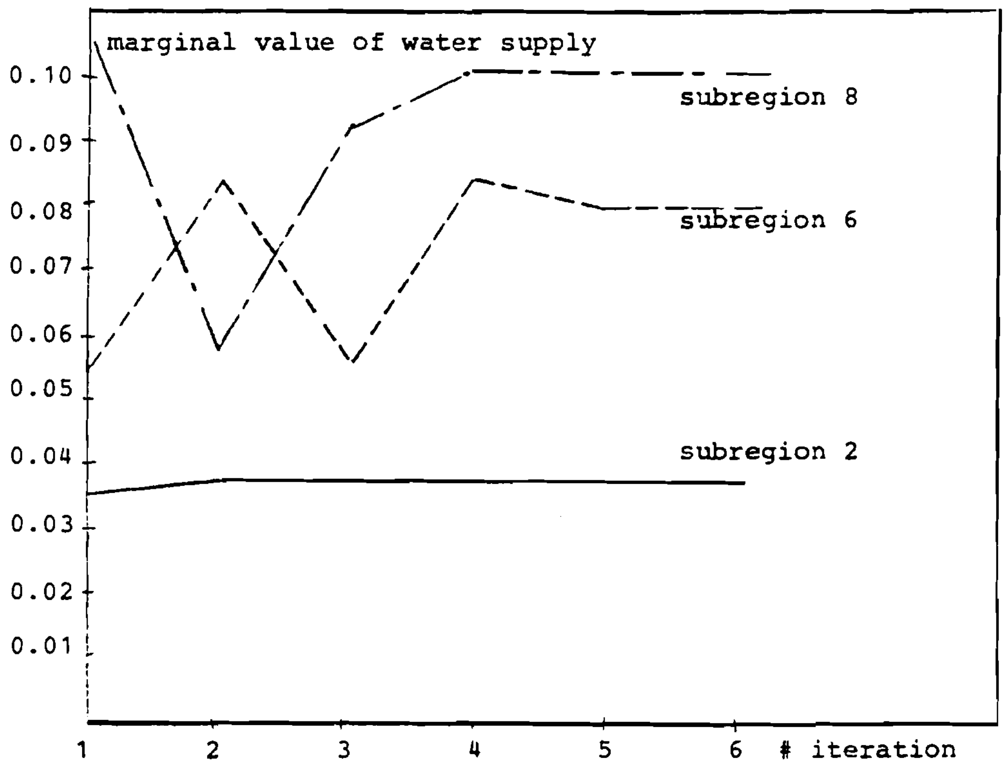

Figure 9. Marginal value of water supply for particular subregions.

6. CONCLUSIONS

One of the fundamental problems in modeling is making a trade-off between the size of models and man-and-computer power required to solve them. This has led to an increasing number of separate, detailed models which consequently are believed to be integrated to each other.

This paper attempts to solve the integration problem for two particular models: Silistra water demand model and Silistra water supply model. The first model is located on the IIASA PDP 11/70 computer, and the second is set up on the IBM 370/165 computer in Pisa, Italy. After the coordination has been done, the results obtained indicate the following:

-- after carrying out a limited number of alternate runs of the two models (in our case 5 iterations were enough) it is possible to obtain equilibrium marginal values for water, e.g. the point at which incremental costs of additional supply in the various subregions equal the incremental benefits whcih these supplies generate;

-- in our particular case, marginal values of water in all twelve subregions influence at most water demands and their distribution over time and space as well as the amount of irrigation land; such parameters, however, like total net benefits, number of animals and some of the beneficial non-substitutables in the region's crops (e.g. maize grain, soybean) did not change their amounts more than 1.5% during the iteration process. Changing of water demands causes reduction of reservoirs and pumping stations capacity. As a result, two out of three initially proposed reservoirs have been abandoned;

-- the coordination procedure can be made automatic, e.g. the decision maker, or the model builders, do not necessarily need to interfere with the co-ordination process; it is, however, advisable to design an interactive process thus having the decision maker evaluating the iterations and acting in case a decision is to be made whether to continue or to stop the iterations as well as when parameters exchanged between models are to be judged.

The future work in this respect will be directed to transfer the experience gained by running these two pilot models to coordinate water demand and water supply models for more sophisticated Silistra region models.

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