MULTIOBJECTIVE ANALYSIS OF REGIONAL MINE WATER CONTROL AND ENVIRONMENTAL PROTECTION

Szidarovszky, F.

University of Agriculture
Villányi ut 35. Budapest XI. Hungary

Bogárdi, I.

Mining Development Institute
Mikoviny u. 2-4, 1037 Budapest, Hungary

Gershon, M.

Computing Associates International
6420 E. Broadway, Suite B 200
Tucson, Ar. 85721, USA

ABSTRACT

Dynamic compromise programming methodology is applied to determine a mineral extraction policy for coal mines under water hazard. This methodology has been developed for dynamic multiobjective problems that are fully quantifiable. It makes use of the LPNORM concept of multiobjective programming which includes goal programming, compromise programming, and the cooperative game theory approach, essentially transforming the dynamic multiobjective problem into a classical dynamic programming problem of increased dimensionality. The regional groundwater system under consideration is located in the Transdanubian Mountain region of Hungary. The system is modeled in terms of three objectives: cost of mining, water supply, and thermal water recharge /environmental/.

INTRODUCTION

Large-scale mining development of coal and bauxite is being planned in the Transdanubian Mountain region of Hungary over the next 50 years /Fig. 1./. Mineral resources are located below the underground /karstic/ water level; thus, mining activity necessarily includes water control. At the same time, the principal water supply source of the region is provided by the karstic water, which is to be delivered to a rapidly growing number of municipal and industrial users. But then, a sinking water level has adverse environmental effects, because the thermal waters of Budapest receive their natural recharge from this karstic aquifer. These three aspects /water control, supply and recharge/ are now taken as three non-commensurable objectives.

This multiobjective development problem has a strong dynamic character. As a result, the conflict resolution may use a dynamic multiobjective model such as the one shown in this paper.

An extension of compromise programming [1] to dynamic problems seems to hold the most promise as a dynamic multiobjective programming solution technique. Two algorithms [2, 3] have been developed for this purpose. The formulations of these two methods are very similar, but the method of Szidarovszky allows the multiobjective problem to be completely transformed into a dynamic programming problem. The method of Opricovic requires that an optimization problem be solved as a subproblem at each step of the recursive dynamic procedure. The method of Szidarovszky will be applied to a real problem in the next section.

METHODOLOGY

Consider a discrete multiobjective dynamic programming problem having the general form

$$s_m = f_m/s_{m-1}, x_m/ \quad /s_0 \text{ is given}/$$

$$\sum_{m=1}^{M} g_{mi}/s_m, x_m/ \rightarrow \max \quad /i = 1,2,\ldots,n/$$

where s_m are the state variables, and x_m are the decision variables. Remember that no restrictions are made about the decision and state spaces. By transforming our dynamic programming problem into the generalized goal programming problem [2], we have

$$s_m = f_m/s_{m-1}, x_m/ \quad /s_0 \text{ is given}/$$

$$\sum_{m=1}^{M} g_{mi}/s_m, x_m/ \geq \phi_{i*} \quad /i = 1,2,\ldots,n/$$

$$u = \left\{ \sum_{i=1}^{n} v_i/\phi_i^* - \sum_{m=1}^{M} g_{mi}/s_m, x_m// \right\} \rightarrow \min$$

where ϕ_i^* and ϕ_{i*} are the maximal and minimal values of the ith objective, the v_i are arbitrary functions, and u is a distance metric. Since function u is strictly monotone increasing or decreasing, this problem is equivalent to finding an optimal /maximal or minimal/ point of the function

$$z = \sum_{i=1}^{n} v_i/\phi_i^*/ - \sum_{m=1}^{M} g_{mi}/s_m, x_m//$$

subject to the same constraints. By introducing the new variables

$$\phi_i^* = \sum_{m=1}^{M} \phi_{mi}^* \quad /\forall_i/$$

$$d_{mi} = \phi_{mi}^* - g_{mi}/s_m, x_m/ \quad /\forall_i, \forall_m/$$

$$D_{mi} = \sum_{l=1}^{m} d_{li}, \quad D_{0i} = 0, \quad /\forall_i, \forall_m/$$

function z can be rewritten as

$$z = \sum_{i=1}^{n} v_i/D_{Mi}/ = \sum_{i=1}^{n} \sum_{m=1}^{M} [v_i/D_{mi}/ - v_i\ /D_{m-1,i}/ + \sum_{i=1}^{n} v_i/0/$$

$$= \sum_{m=1}^{M} \sum_{i=1}^{n} [v_i/D_{mi}/ - v_i/D_{mi} - \phi_{mi}^* + g_{mi}/s_m, x_m//\,] + \sum_{i=1}^{n} v_i/0/$$

Thus the optimization problem of function z is equivalent to optimizing the function

$$\sum_{m=1}^{M} \left\{ \sum_{i=1}^{n} [v_i/D_{mi}/ - v_i/D_{mi} - \phi_{mi}^* + g_{mi}/s_m, x_m//\,] \right. .$$

Let us define functions G_m by the following equation

$$G_m/s_m, D_{m1}, \ldots, D_{mn}, x_m/ =$$

$$= \sum_{i=1}^{n} [v_i/D_{mi}/ - v_i/D_{mi} - \phi_{mi}^* + g_m/s_m, x_m//$$

then our problem has the form

$$s_m = f_m/s_{m-1}, x_m/ \quad /s_0 \text{ is given}/$$

$$D_{mi} = D_{m-1,i} + \phi_{mi}^* - g_{mi}/f_m/f_m/s_{m-1}, x_m/, x_m/,$$

$$D_{0i} = 0 \quad /\forall_i/$$

$$D_{Mi} \lesseqgtr \phi_i^* - \phi_{i*} \quad /\forall_i/$$

$$\sum_{m=1}^{M} G_m/s_m, D_{m1}, \ldots, D_{mn}, x_m/ \rightarrow \text{opt},$$

which is a regular dynamic programming problem with decision variable x_m and state variables $s_m, D_{m1}, \ldots, D_{mn}$ at stage m. There will be one additional state variable /D/ added for every objective.

THE DYNAMIC MULTIOBJECTIVE MODEL /Fig. 2./

The vector $\underline{d}$ /i,j,k,t/ of decision variables is defined at stage t with the following elements:

x/i,t/ = the incremental yield of withdrawal from mine i;

xm/i,t/ = the incremental inrush yield allowed in workings;

xd/i,t/ = the incremental inrush yield allowed into INSTANTAN cuts and drillings;

xg/i,t/ = the incremental yield of water prevented from entering the mine by sealing or grouting;

v/i,k,t/= the incremental yield of water conveyed from mine i to recharge point k;

y/i,j,t/= the incremental yield of water supplied from mine or other intake i to water requirement point j.

With the above defined vector of decision the following vector of state variables referring to the level of development at stage t is defined

$$\underline{S}/i,j,k,t/ = \sum_{e=1}^{t} \underline{d}\ /i,j,k,e/ \qquad /1/$$

The initial state, that is, the existing level of development is known

$$\underline{S}/i,j,k,t = 0/ = \underline{S}/0/ \qquad /2/$$

State transition functions

These functions show how the level of development, that is, the state at stage t depends on the state at stage /t-1/ and the decision /incremental development/ at t:

$$\underline{S}/i,j,k,t/ = \underline{S}/i,j,k,t-1/ + \underline{d}\ /i,j,k,t/ \qquad /3/$$

Contraints

1. The volume of minewater X/i,t/ withdrawn from mine i at stage t consists of the sum of the water amount entering workings and that appearing in the INSTANTAN system:

$$XM/i,t/ + XD/i,t/ = X/i,t/ \qquad /4/$$

2. The amount of minewater withdrawn from and the amount of mine water sealed in mine i at stage t equal the total amount of minewater

$$X/i,t/ + XG/i,t/ = A/i,t/ \qquad /5/$$

Naturally, $A/i,t/ = \sum_{e=1}^{t} a/i,e/$ where a/i,e/ is the minewater increment.

3. Water requirements must be satisfied at each point j and stage t:

$$\sum_{i} Y/i,j,t/ = R/j,t/ \qquad /6/$$

4. The total water allocated from mine i cannot exceed the total withdrawal:

$$Y/i,j,t/ + \sum_{k} V/i,k,t/ \leqq X/i,t/ \qquad /7/$$

5. The recharge q/t/ of thermal water does not have to exceed the present satisfactory value of $q/0/ = 30 m^3/min$.

$$q/t/ \leqq q/0/ = 30\ m^3/min \qquad /8/$$

Objective functions

I. Mining objective

Mining objective is to minimize total water related costs of a number n_1 of mines, consisting of capital and operation costs, and the economic losses caused by minewater:

$$f_1 = \sum_{i=1}^{n_1} \sum_{t=1}^{T} D_t \Big\{ \sum_{u=1}^{6} CA\left[i,j,k,u,t,\underline{S}/t-1/,\underline{d}/t/\right] + $$
$$+ OP\left[i,k,u,t,\underline{S}/t/\right] + L\left[i,t,u,\underline{d}/t/\right] \Big\} \qquad /9/$$

where D/t/ = discount factor;

u = the serial number of elements in the decision vector; u = 1 refers to withdrawals x, u = 2 to working mine water yield xm, u = 3 to INSTANTAN yield, u = 4 to sealed mine water yield xa, u = 5 to water conveyance v and u = 6 to amount of supplied water y;

CA = capital cost function;
OP = operation cost function;
L = loss function, L/u=1,3,4,5,6/ = 0

II. Water-supply objective

Regional water-supply objective aims at satisfying water requirements with minimum costs.

$$f_2 = \sum_{i=1}^{n_1+n_2} \sum_{y=1}^{m} \sum_{t=1}^{T} D_t \Big\{ CA\big[i,j,t,u=6,\underline{S}/t-1/,\ \underline{d}/t/\big] + OP\big[i,j,t,u=6,\underline{S}/t/\big] \Big\} \qquad /10/$$

where n_2 is the number of water intakes in addition to mines, and m is the number of water requirement points.

III. Environmental objective

The environmental objective refers to the maximization of underground thermal water recharge for each stage, q/t/, as related to withdrawals and artificial mine-water recharge. The calculation of q/t/ requires the use of a physical system model describing the motion of underground water in the karst [4].

The system model includes a relationship between water recharge q for Budapest thermal waters and the decision variables:

$$q/t/ = h\big[\underline{X}/t/,\ \underline{Y}/t/,\ \underline{V}/t/\big] \qquad /11/$$

where $\underline{X}$/t/ is the yield vector of mining withdrawals, $\underline{Y}$/t/ that of water supply withdrawals, and $\underline{V}$/t/ is the vector of artificial recharge. The present case study involves three mines $\underline{X}$ = X/1/, X/2/, X/3/ . t ree other water supply sites $\underline{Y}$ = Y/4/, Y/5/, Y/6/ and two artificial recharge sites $\underline{V}$ = V/1/, V/2/ .

To estimate relationship Eq. /11/, sample sets of values of $\underline{X},\underline{Y},\underline{V}$, are selected at random and, for each set of values, the system model is used to calculate the discharge q. These calculated values have been fitted by least squares to a linear function of the decision variables to yield the function:

$$q/t/ = 30.5 - 0.021X/1,t/ - 0.012X/2,t/ - 0.014X/3,t/ - 0.006Y/4,t/ - 0.0021Y/5,t/ - 0.0042Y/6,t/ + 0.07V/1,t/ + 0.14V/2,t/ \qquad /12/$$

The standard error of estimate of the fit is 0.15 m/min.

Preference structure

The relative importance of the different objectives from a national policy viewpoint is expressed as a preference structure. Since this structure would be extremely difficult to assess [5], it is appropriate to investigate the sensitivity of the solution to a change in preferences, within reasonable bounds of preferences. For example, it would not be realistic to neglect totally the environmental objective or else, to regard the water supply objective as being much more important than the other two.

Preference structure can be considered also in a dynamic sense. Table 3 shows five sets of preferences used for the case study.

The first three sets of weights do not change in time and express that the mining objective is slightly more important than the environmental objective, and somewhat more important than the water supply objective. The environmental objective has a fairly high weight in every case.

Sets 4 and 5 consider changing preferences; set 4 gives increasing weight to mining economics, and set 5, to the environmemtal objective.

The above dynamic multiobjective model has been transformed into a dynamic programming problem as shown in the previous section.

APPLICATION OF THE MODEL

The decision-maker is often eager to receive numerical results as soon as possible in order to bring timely decisions. Also, available data permit to use only simplified models in the first step. That was the situation in the present illustrative case. Data referring to objective function parameters were available only as average, unit cost figures. As a result, the present application uses a linear version of the model. Note that, in a linear model no economy in scale can be considered, that is, functions of CA do not depend on the existing level of development, but only on capacity increments.

Unit cost values for objective functions /18/ and /19/ are given in [6] and numerical results are presented and discussed in [7]. As examples, the ideal solutions for mining, /Fig. 1./ and water-supply /Fig. 3./ can be compared with a compromise solution /Fig. 4./, all referring to stage 4. Conclusions of the numerical solution can be summarized as follows:

1. Dynamic MODM may lead to a harmonic sequential regional development of mining, water-supply and environmental protection.

2. Though depending on the preference structure, compromise solutions such as the one shown in Fig. 3. are always superior to separate optimal solutions. In fact, separate mining or water-supply optima are not feasible since the simultaneous recharge for the Budapest thermal baths is far from being sufficient.

3. Compromise solutions are characterized by a./ large-scale sealing in mines; b./ development of water works at sites /5,6/ affecting natural underground recharge in a least way; c./ a moderate amount of arti icial recharge at site /2/ as close as possible to Budapest.

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TABLE 1.

AVERAGE YIELD OF MINEWATER, A/i,t/, IN m/min.

Mine i	Years: 1980-85 1	1985-90 2	1990-95 3	1995-2000 4
1	50	50	50	50
2	80	110	120	120
3	25	50	60	80

TABLE 2.

DRINKING WATER REQUIREMENTS, R/j,t/ IN m/min.

Site j	Periods t			
	1	2	3	4
1	10	25	30	33
2	5	12	14	14
3	50	70	80	83
4	6	12	13	14
5	7	12	13	14
6	50	70	80	83
7	15	20	28	28

TABLE 3.

PREFERENCE STRUCTURE

	mining	water-supply	environment
1	0.4	0.3	0.3
2	0.4	0.2	0.4
3	0.5	0.2	0.3
4	0.3, 0.3, 0.4, 0.5	0.2	0.5, 0.5, 0.4, 0.3
5	0.5, 0.4, 0.3, 0.3	0.2	0.3, 0.4, 0.5, 0.5

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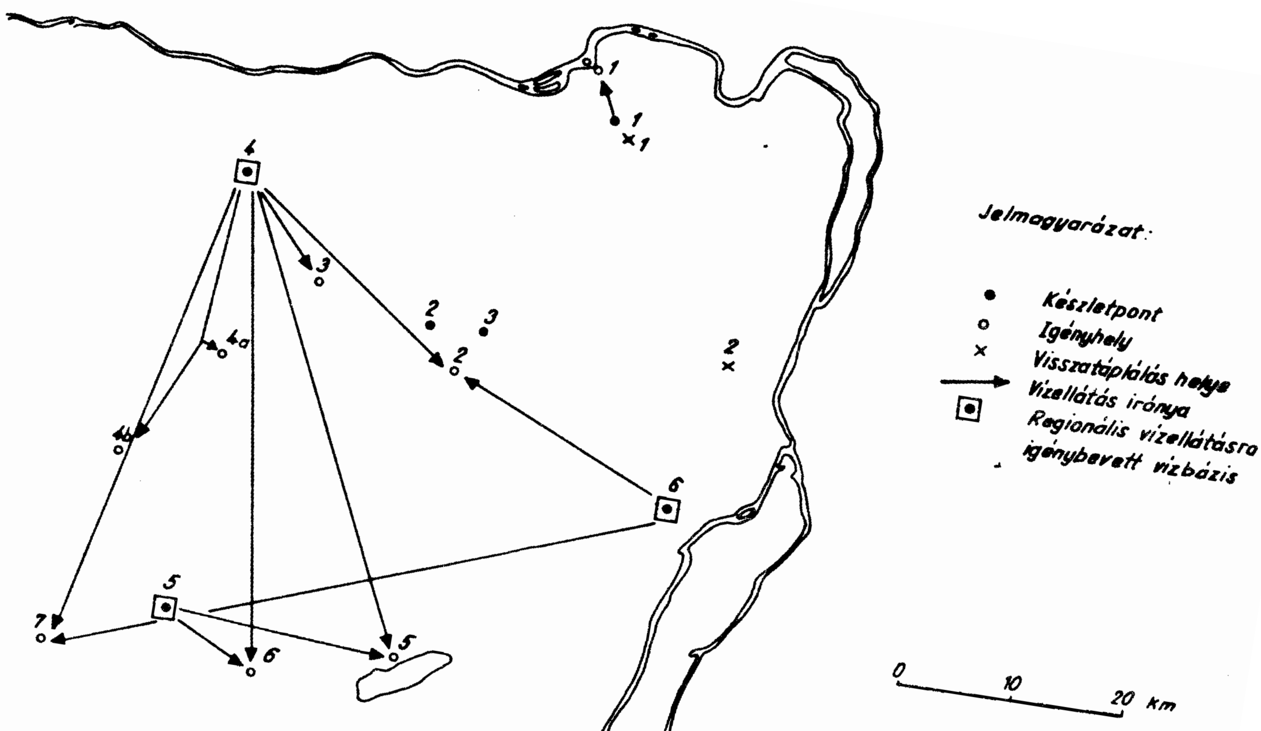


A bányászat szempontjából optimális megoldás. (4. időszak)

Fig. 1. ábra

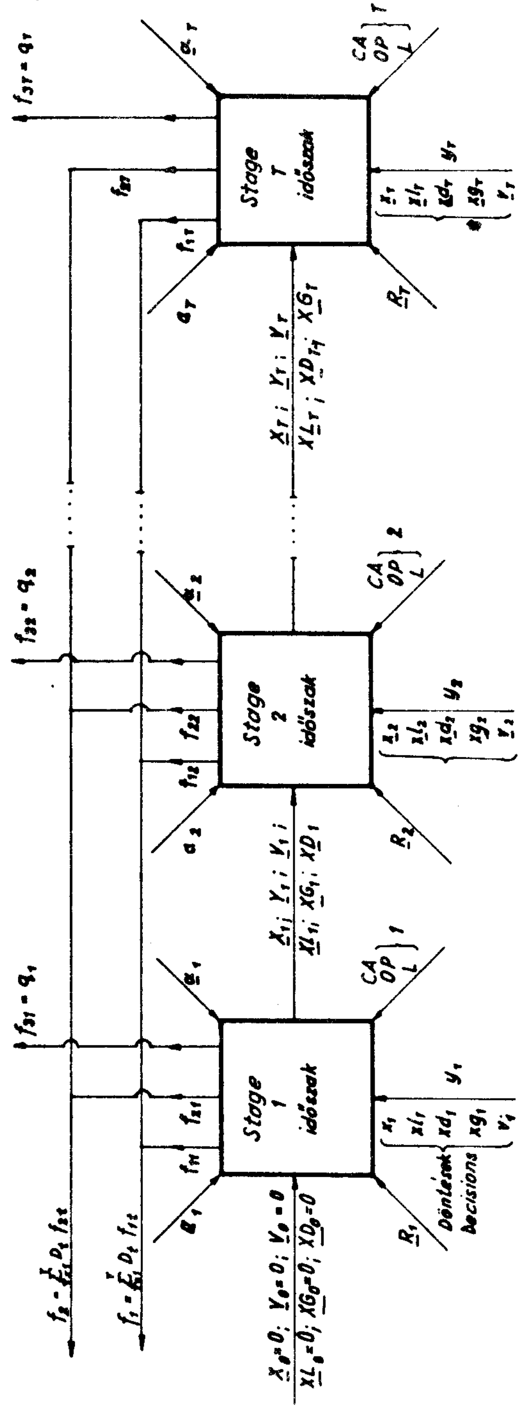

Stage 1 időszak
Stage 2 időszak
Stage T időszak
Döntések
Decisions

Fig. 2. ábra

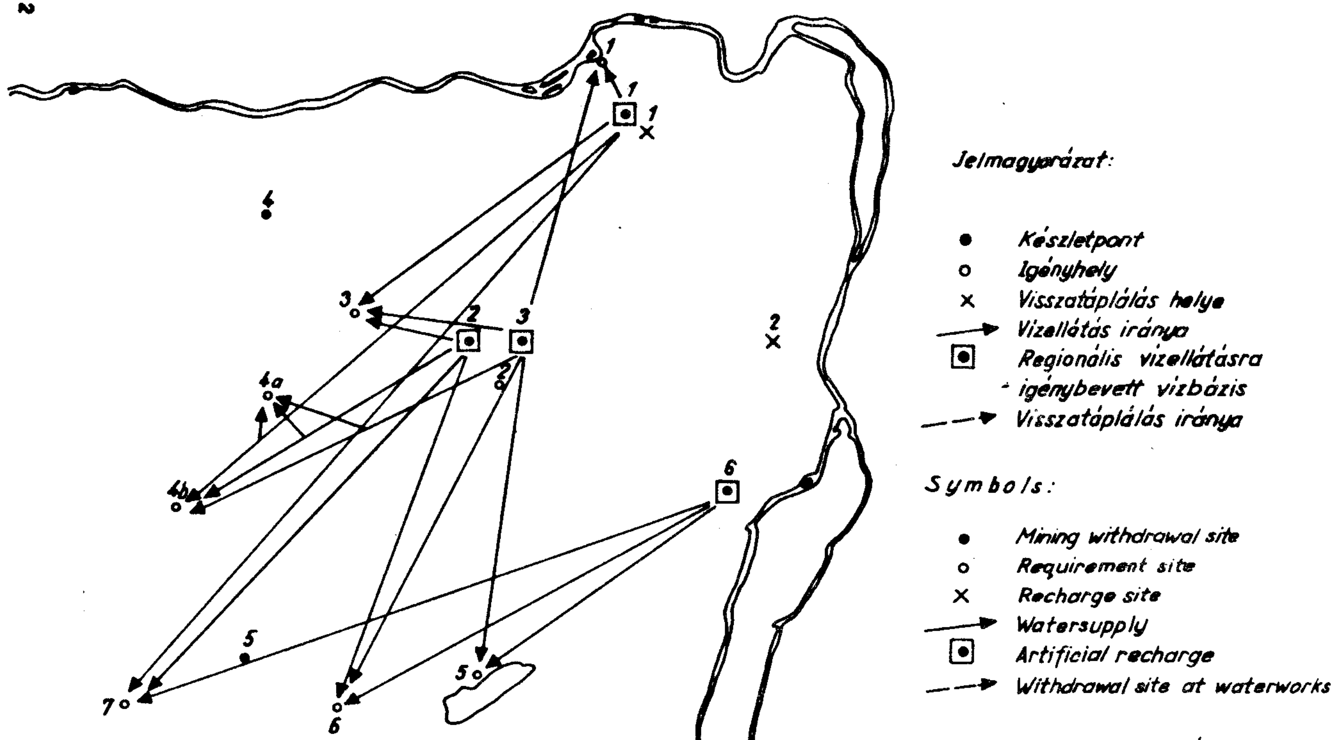
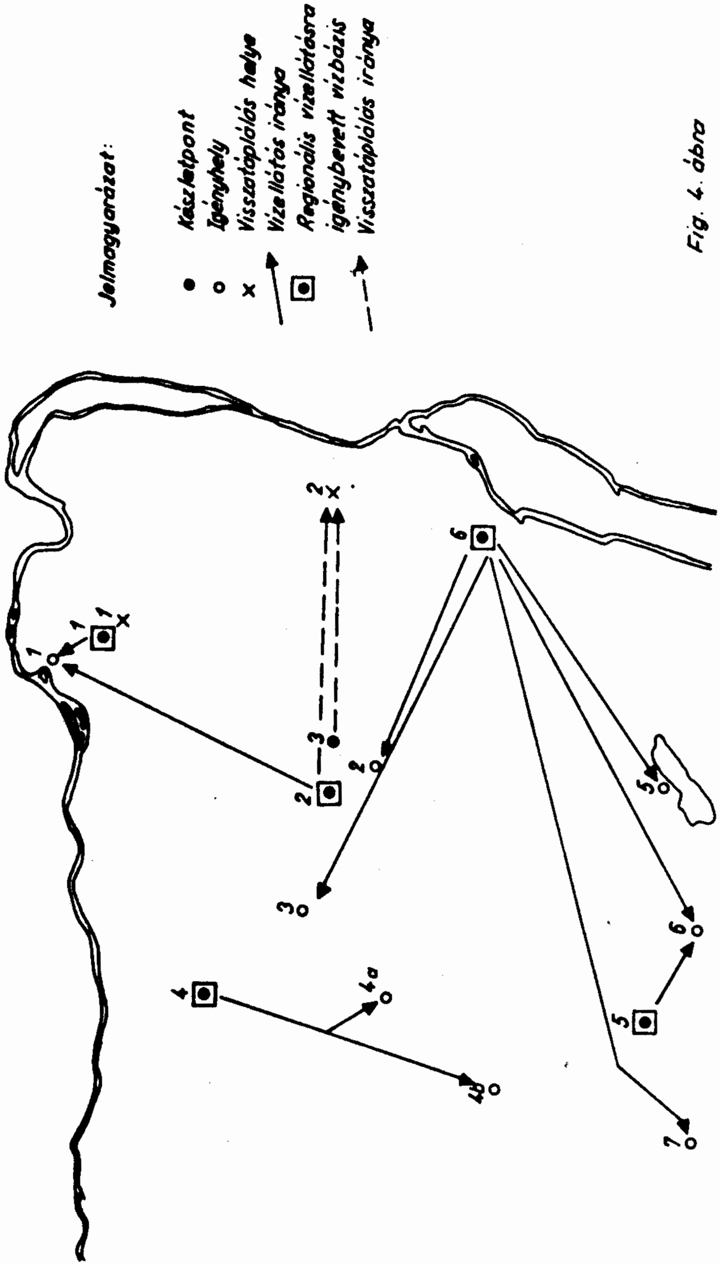


Fig. 3. ábra

A vízellátás szempontjából optimális megoldás. (2. időszak)



Kompromisszumos megoldás. (4. időszak)

Fig. 4. ábra