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# MULTIOBJECTIVE DECISION MAKING AS A TOOL FOR INDUSTRIAL WATER MANAGEMENT

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## SYNOPSIS

Two practical applications of multiobjective decision making (MODM) to regional industrial water management are presented. Regional development often results in conflicting objectives such as the satisfaction of various water requirements (industrial, agricultural and domestic) under limited resources or else, the maximization of economic benefits versus minimization of environmental disruption caused by industry. When the above objectives are measured in non-commensurate units, MODM provides an approach to select the "best" industrial water management scheme. The two case studies illustrating the methodology are as follows:

1. The Eocene region in Hungary has considerable industrial potential (mining and metallurgy). However, the regional water resources system has to satisfy not only industrial water demands but also domestic water requirements and environmental objectives. Among various available MODM techniques, compromise programming has been used to find the most satisfactory solution.

2. The Bakony region in Hungary has wide potential for mining, agriculture and tourism. The regional water resources system, principally a karstic aquifer, has to satisfy conflicting interests (industrial, environmental). MODM has again been applied to find a trade-off.

# RESUMÉ

## Gestion multicritère des eaux à usage industriel

La décision multicritère /DMC/ est appliquée à deux cas d'espèce de gestion régionale des eaux à usage industriel. Lorsque la demande en eau pour divers secteurs /industriel, agricole, domestique/ est supérieure à l'approvisionnement, il s'ensuit des conflits. Il en est de même lorsque l'on cherche à maximiser une fonction économique et, en même temps, à minimiser les effects négatifs du développement industriel sur l'environnement. Si les objectifs se mesurent en unités non commensurables - ce qui est le cas général -, la DMC permet de trouver une solution de compromis. Les deux cas d'espèce présentés ont les caractéristiques suivantes:

1. La région éocene hongroise possède un potentiel industriel considérable /mines et métallurgie/. Le système de ressources en eau régional doit répondre aux exigences de la consommation industrielle, domestique et de protection de l'environnement. La technique de DMC "copromise programming" est choisie, parmi d'autres possibles, afin de trouver un "satisfactum".
2. La région de Bakony en Hongrie occidentale est en cours de développement minier, agricole et touristique. La gestion des eaux de la région, provenant en majeure partie d'une nappe karstique, est sujette aux conflits de ces trois intérèts. Comme précédemment, on fait appel à la DMC pour parvenir à une solution de compromis.

# RESUMEN

## Análisis de fin multiple para la economia de agua industrial

Aqui quiere presentarse dos aplicaciones prácticas del análisis de fin multiple para la economia regional de agua industrial. El desarrollo regional esta motivado frecuentamente por intereses contradictorios. En el caso de que estos fines fuesen medidos por unidades incompatibles, puede selectarse la politica "mejor" de economia de agua industrial por el análisis de fin multiple. Los métodos se presenta por dos estudios de caso:

1. La región eocena en Hungria tiene una potencia industrial importante /para la mineria e industria de metales/. Pero el sistema de economia regional de agua tiene que satisfacer los fines no solo de la industria, sino los mismos de la población y de la protección del ambiente. Entre los métodos posibles se fue utilizado el programa de compromiso.
2. La región de loma de Bakony en Hungria sirve asi mismo para la mineria, agricultura y turismo. La base de la economia regional de agua esta formada por una albuhera cárstica, la cual tiene que servir intereses contradictorios /desarrollo industrial, protección del ambiente/ asi mismo. Se ha selectado la solución en este caso tambien por el análisis de fin multiple.

## INTRODUCTION

The purpose of this paper is to show how conflicting interests related to industrial water management can be accounted for by multiobjective decision making (MODM). The specific problem addressed is the selection of such a strategy for one or more industrial complexes. This selection is made by trading off economic objectives and environmental protection. The set of goals related to industrial economy and environmental protection is acknowledged to be non-commensurable (monetary versus physical units) and, as such, an optimum solution cannot be found so that a "satisfactum" is sought (Simon, 1957). In the sections that follow, the problem of industrial development versus environmental protection is defined. Then, elements of a dynamic model available to MODM are introduced, followed by a presentation of two examples taken from regional industrial analyses in Hungary. Finally, conclusions are drawn in the last section.

## INDUSTRIAL DEVELOPMENT VERSUS ENVIRONMENTAL DISRUPTION

There is a world-wide concern that industrial development leads to environmental disruption. There are three general possibilities that will tend to maintain harmony between industry and environment (Kneese and Bower, 1972):

a) The control of technology and emissions
b) Modification of the assimilation capacity of the environment
c) Utiliization of the residuals.

The above general problem is now specified for the case of water related technology and water related environment. Note, however, that the methodology can be used for other effects of industry on the environment, such as effect on air and land use.

Typical examples of the above three groups of control actions:

a) water recirculation, underwater mining, wastewater treatment
b) wastewater storage, modification of aquifer properties by grouting
c) extraction of metals or generation of gas from sludge.

Depending on the technology, the industrial plant(s) may require given amounts, quality and levels or stage of water.

Water level requirement is pertinent, for instance, to the case of a surface intake or mining operation under a water hazard. Industrial production and related economic performance measures such as benefit-cost are strongly connected to the technology, and thus, to the required water. On the other hand, environmental impact is caused by fulfilling water requirements (e.g., less water downstream) and by discharge of used and polluted waters.

The usual approach is to set limits for environmental impact in the form of regulations and seek maximum industrial economy of performance under such constraints. Or else, under a prescribed industrial production level, one may seek to minimize environmental impact. In this paper, a simultaneous consideration of both factors is envisioned. Regardless of the type of problem, a model of both industrial production and environmental effects is required. The production model yields economic performance and emission data as related to the technology and, thus, to water use. The environmental model calculates the spatial environmental impact as caused by meeting water requirements and disposal of wastewater. The next section shows how these elements can be embedded in a general dynamic model amenable to MODM.

## MODEL ELEMENTS

Five model elements--input, state, state transition function, output and output function--are defined (Booth, 1967; Wymore, 1976; Duckstein and Bogardi, 1978) for time $t = 0,1,\ldots,T$, where T is the total planning horizon.

a) The input I(t) comprises

(i) natural elements (wind, rainfall, evaporation,...)
(ii) physical properties of the region (area, soil, topography, mineral resources,...)
(iii) non-controllable economic, social and environmental elements (capital, machine, manpower and water requirements, environmental standards,...)
(iv) control actions or decisions (capacity increase, technology, wastewater treatment, effluent charges,...)

b) The state S(t) includes the production characteristics such as the level of industrial development, and the environmental elements such as "downstream hydrology" (flow, level, quality)

c) The state transition function $\Phi$ calculates the state at time (t+1) as a function of state and input at t:

$$S(t+1) = \Phi(S(t),I(t)) \tag{1}$$

The production state can be calculated by the production model; for instance, capacity at time (t+1) can be determined from capacity at time t and inputs such as capacity increase at t. The environmental state transition function is represented by the environmental model. Typical examples are the partial differential equations describing the movement of water and solid material in surface or underground waters. Note that the numerical solutions of such equations are generally calculated for discrete time steps as in Eq. (1).

d) The output, R(t) also has economic and environmental elements. Economic output can be loss, cost or benefit risk. Usually, total period economic output such as discounted net benefit is considered. The environmental output may include elements of the state vector itself, say quantity and quality downstream flow.

e) The output function $\Psi$ calculates the output vector as function S(t) and I(t):

$$R(t) = \Psi\ (S(t),I(t)) \tag{2}$$

Examples for the output function are the calculation of discounted net benefit by well known formulas or of downstream flow by the state transition function.

Given the above model elements, one may select one output to be optimized, leading to a classical optimization problem or, several outputs may be considered jointly, leading to a multiobjective problem. The level of remaining outputs constitutes constraints. In the next section, MODM is applied to regional problems that have been defined within the above systems framework.

## EXAMPLES OF APPLICATION

Two case studies are briefly described. Both deal with regional (multiplant) industrial development (mining and electricity generation and bauxite extraction) interacting with a large-scale aquifer.

### Mining in the Hungarian Eocene Region

Large-scale mining development for electricity generation is being planned in the Eocene region of Hungary over the next 50 years (Fig. 1). Coal resources are located below the underground (karstic) water level; thus, mining activity necessarily includes water control of the underground water. 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. A falling water level would have adverse environmental effects, because, for example, the thermal waters of Budapest receive their natural recharge from this karstic aquifer. Three non-commensurate objectives are associated with these three aspects of water control, supply and recharge.

Three alternative mine water control technologies are available: a) artificial sealing which reduces the total yield of mine water that has to be pumped to the surface; b) INSTANTAN protection (Kapolyi, 1976) which lets water inrushes occur in special cuts and holes instead of active workplaces; c) passive protection, in which inrush activity follows its natural course and disturbs the mining operation in a random manner.

The mining industrial objective is total discounted economic benefit to be maximized over the mine lifetime. Since annual production and mining technology are given, maximizing benefit is equivalent to minimizing water-related costs.

A simple technological model is as follows:

The volume of minewater X(i,t) withdrawn from mine i at stage t consists of the sum of the water amount XM(i,t) entering workings and that amount XD(i,t) appearing in the INSTANTAN system:

$$XM(i,t) + XD(i,t) = X(i,t) \tag{3}$$

The sum of minewater volume withdrawn from mine i and volume XG(i,t) sealed in mine i at stage t equals the total amount of minewater available A(i,t):

$$X(i,t) + XG(i,t) = A(i,t) \tag{4}$$

Another expression for A(i,t) is $A(i,t) = \sum_{e=1}^{t} a(i,e)$ where a(i,e) is the minewater increment given from the planned production schedule (Schmieder et al., 1975).

The objective of regional industrial water supply is to minimize the disutility of water shortage. This disutility can be measured as water volume, a water shortage index, or monetary loss. In the present study, it is assumed that water requirements must be fully satisfied, and thus, the proxy of supply cost is used to represent the second objective.

The environmental objective is to maintain the existing flow of Budapest thermal waters. Two alternative courses of action are available for reaching this environmental goal. The first one consists in controlling the withdrawal of karstic water for both mining and industrial water supply, so that sufficient natural recharge for Budapest thermal waters are maintained along the edge of the aquifer. The second course consists in providing artificial recharge of the aquifer at proper sites so as to compensate for the effect of large water withdrawals.

Elements of the regional model are given in Fig. 2. The vector $\underline{d}(i,j,k,t)$ of decision variables (inputs) is defined at stage t by means of the following incremental elements:

$x(i,t)$ = withdrawal from mine i
$xm(i,t)$ = inrush yield allowed in workings
$xd(i,t)$ = inrush yield allowed into INSTANTÁN cuts and drillings
$xg(i,t)$ = yield of water prevented from entering the mine by sealing or grouting
$v(i,k,t)$ = yield of water conveyed from mine i to recharge point k
$y(i,j,t)$ = yield of water supplied from mine or other intake i to water requirement point j

With the above decision vector, the following state variable vector referring to the level of development at stage t is defined as:

$$\underline{S}(i,j,k,t) = \sum_{e=1}^{t} \underline{d}(i,j,k,e) \qquad (5)$$

The production state transition function shows how the level of development, that is, the state of stage t+1 depends on the state at stage t and the decision on incremental development at t:

$$\underline{S}(i,j,k,t+1) = \underline{S}(i,j,k,t) + \underline{d}(i,j,k,t) \qquad (6)$$

The environmental state transition function calculates the underground recharge to Budapest thermal levels:

$$g(t) = h[\underline{X}(t),\underline{Y}(t),\underline{V}(t)] \qquad (7)$$

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.

To estimate the relationship in Eq. (7), sample sets of values of $\underline{X}$, $\underline{Y}$, $\underline{V}$ are selected at random and, for each set of values, a computer-simulation groundwater model is used to calculate the discharge q (Szilagyi et al., 1978). These calculated values have been fitted by least squares to a linear function (Szidarovszky and Bogardi, 1980).

Now, the three objective functions, to be minimized, are:

$$f_1 = \sum_{i=1}^{n_1} \sum_{t=1}^{T} D(t) \left[ \sum_{u=1}^{4} CA(i,j,k,u,t,\underline{S}(t-1),\underline{d}(t)) + OP(i,k,u,t,\underline{S}(t)) + L(i,t,u,\underline{d}(t)) \right] \qquad (8)$$

where

n = number of mines
D(t) = discount factor
u = serial number of decision vector elements
u = 1 refers to withdrawals x, u = 2 to workings mine water yield xm, u = 3 to INSTANTAN yield, u = 4 to sealed mine water yield xa, u = 5 to water conveyed v and u = 6 to amount of water supplied y
CA = capital cost function
OP = operation cost function
L = loss function, $L(u=1,3,4,5,6) = 0$

$$f_2 = \sum_{i=1}^{n_1+n_2} \sum_{y=1}^{m} \sum_{t=1}^{T} D(t)[CA(i,j,t,u=6,\underline{S}(t-1),\underline{d}(t)) + OP(i,j,t,u=6,\underline{S}(t))] \qquad (9)$$

where $n_2$ is the number of water intakes other than mine sites, and m is the number of water requirement points.

$$-f_3 = -q(t) \qquad (10)$$

Multiobjective techniques that can be used to solve the above problem include compromise programming (Zeleny, 1973; Duckstein and Opricovic, 1980), cooperative game theory (Szidarovszky et al., 1978), and many others as discussed in Gershon (1981) or Goicoechea et al. (1981). A linear version of the compromise programming technique leads to the general results shown in Fig. 2.

Though depending on the preference structure, compromise solutions such as the one shown in Fig. 2 are always superior to optimal solutions found stage by stage. In fact, separate mining or water-supply optima are not feasible since they would correspond to insufficient recharge for the Budapest thermal baths. 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 minimal way; c) a moderate amount of artificial recharge at site 2, which is the closest to Budapest.

## Bauxite Extraction in the Bakony Region, Hungary

In the Bakony region, there are several existing and planned sites for surface or underground mining (Fig. 3). In a number of sites, the groundwater level is higher than the bauxite deposits. For such cases, the allowable groundwater levels have an upper limit which are a function of the bauxite amount to be extracted. Two main technological options available for mining under a water hazard, are water level lowering and the decrease of local transmissivity by grouting.

The economic objective is to allocate production rates among mines at minimum total discounted cost. Other formulations of the economic objective are also possible as shown in Vizy et al. (1981). Among environmental factors, the impact of bauxite mining on the regional groundwater system is of greatest concern. The groundwater system is basically part of a large-scale karstic aquifer (Szilagyi, 1976). As a result of bauxite mining, the original state of the groundwater system has changed, such that a) the regional karstic water level has dropped and, b) the flow of several springs and thermal baths has become smaller or disappeared altogether. The environmental objective is, therefore, to minimize the deterioration of the environmental state. Since there is much discussion on which given values of flows represent a "sound" groundwater system, we have not assigned such fixed values but have taken two alternative approaches to the problem. First, a multiobjective approach is taken in which environmental flows are maximized as in the problem treated in the first part of this paper; second, a single objective approach is used in which environmental constraints are taken as fuzzy as in Bogardi et al. (1981).

Environmental protection may be provided by various combinations of mine water withdrawal control, decrease of local transmissivity and artificial recharge.

Elements of the regional model are shown in Fig. 4. Production state transition functions deal with

a) total quantity of bauxite extracted from mine i

$$X(i,t+1) = X(i,t) + x(i,t) \tag{11}$$

where x is the annual production and

b) groundwater level in mine i

$$Z(i,t+1) = \Phi[Z(i,t),Tr(j,t),q(i,t),v(k,t),tr(j,t)] \tag{12}$$

$$i = 1,\dots,M; \quad j = 1,\dots,J; \quad k = 1,\dots,K$$

where the state variable is: Tr = transmissivity and the decision variables are: q = withdrawal, v = recharge, and tr = transmissivity change.

Environmental state transition function $\Phi_e$ calculates the underground flow H(u,t+1) at control points n = 1,...,N as a function of those variables shown in Eq. (12).

State transition functions $\Phi_p$ and $\Phi_e$ have been estimated by a multivariate fitting of the finite difference solution of the partial differential equation describing regional groundwater movement (Szilagyi et al., 1978; Bogardi et al., 1981). The economic objective is to minimize total discounted costs:

$$\underset{(q,v,tr)}{\text{Min}} \sum_{t=1}^{T} D(t) \left\{ \sum_{i=1}^{M} [f(i,t,x(i,t) + f_q(i,t,q(i,t))] + \sum_{k=1}^{K} fv(k,t,v(k,t)) + \sum_{j=1}^{J} fg(j,t,tr(j,t)) \right\} \tag{13}$$

where $D(t)$ is the discount factor and f,fq, fv and fg are cost functions for mining, withdrawal, recharge and grouting, respectively. The environmental objective is to minimize the maximum deviation of underground control flows from given ideal values:

$$\min_{t} \max_{n} [HI(n,t) = H(n,t)] \tag{14}$$

for $t = 0,\ldots,T$ and $n = 1,\ldots,N$, under a set of natural, economic and technological constraints. The MODM technique selected here is based on compromise programming and fuzzy set theory (Zadeh et al., 1975). A solution algorithm based on discrete dynamic programming has been developed for the general nonlinear case in Gershon et al. (1981). Sample numerical results referring to a simplified example are given next. In this example, $T = 20$ years, divided into four stages, $M = 3$ (including one mine underwater hazard), $K = J = N = 1$.

Bauxite requirements, capacity units and ideal groundwater flow can be found in Table 1. Unit costs are: $f(1) = 100$, $f(2) = 320$ and $f(3) = 300$, all in Ft/ton, and $fg = 880$, $fv = 700 \cdot 10^3$, both in Ft/$m^3$/min/stage. The state transition functions for groundwater level is:

$$Z(3,t+1) = Z(3,t) - 0.127\ (1+Tr(1)q(3) + 0.039\ (1-Tr(1)V(1) + 7.28 \tag{15}$$

and for groundwater control flow:

$$H(t+1) = 36 - 0.041\ (1-Tr(1))q(3) + 0.13\ (1+Tr(1))V(1) \tag{16}$$

Results of compromise programming application are given in Table 2. As demonstrated in Bogardi et al. (1981), the compromise solution is much preferable to a purely economic optimum, which would result in the disruption of the thermal baths after 10 years. Naturally, if a realistic cost function could have been assigned to disruption of thermal baths, then a single objective optimization may have led to an acceptable solution. However, as mentioned before, no agreement could be obtained as to what constitutes "good" groundwater flow.

## CONCLUSIONS

Results of this paper lead to the following conclusions:

a) Industrial water management may have, in addition to economic consequences for the industry, substantial environmental impacts which themselves result in economic consequences at a later date.

b) A water management scheme is to be sought which results in a trade-off between economic efficiency and environmental protection.

c) MODM may be a useful tool to define a model and then to find a satisfactory solution.

d) A discrete dynamic model with five elements provides a good basis for an MODM approach.

e) Two examples of MODM application include regional industrial development interacting with a large-scale aquifer. In both cases, a compromise solution enables one to examine more meaningfully trade-offs than a strictly economic optimum would allow.

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## Table 1

### Data for Bauxite Example

| | Stages, years | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| **Bauxite Requirements** | | | | |
| Amount, $10^3$ tons | 2500 | 3800 | 4400 | 4700 |
| Module | 7.2 | 7.0 | 6.8 | 7.0 |
| **Mining capacity limits, $10^3$ tons** | | | | |
| mine 1 | 1000 | 1600 | 1600 | 1600 |
| 2 | 900 | 2000 | 2900 | 2900 |
| 3 | 1800 | 2700 | 3200 | 3200 |
| Minewater withdrawal capacity limits, mine 3, $m^3$/min | 310 | 350 | 400 | 400 |
| Recharge capacity limits, $m^3$/min | 10 | 30 | 50 | 50 |
| Grouting capacity, relative transmissivity | 0.4 | 0.4 | 0.4 | 0.4 |
| Ideal groundwater flow, $m^3$/min | 30 | 30 | 30 | 30 |

## Table 2

Results of Linear Compromise Programming

Range of Weights 0.4 - 0.6,

Medium Grouting

| Activity | Stages in four-year units | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Mine 1 production | 1000 | 1600 | 400 | 0 |
| Mine 2 production | 900 | 2000 | 2272 | 2128 |
| Mine 3 production | 600 | 200 | 1728 | 2572 |
| Water withdrawal | 0 | 45 | 328 | 364 |
| Recharge | 0 | 0 | 42 | 50 |
| Grouting | 0 | 0.1 | 0.1 | 0 |
| Underground control flow | 36 | 31 | 30 | 30 |

Total discounted costs: 3.103 X $10^9$ Ft.*

*Ft = Forint, Hungarian currency, worth about $0.04 U.S.

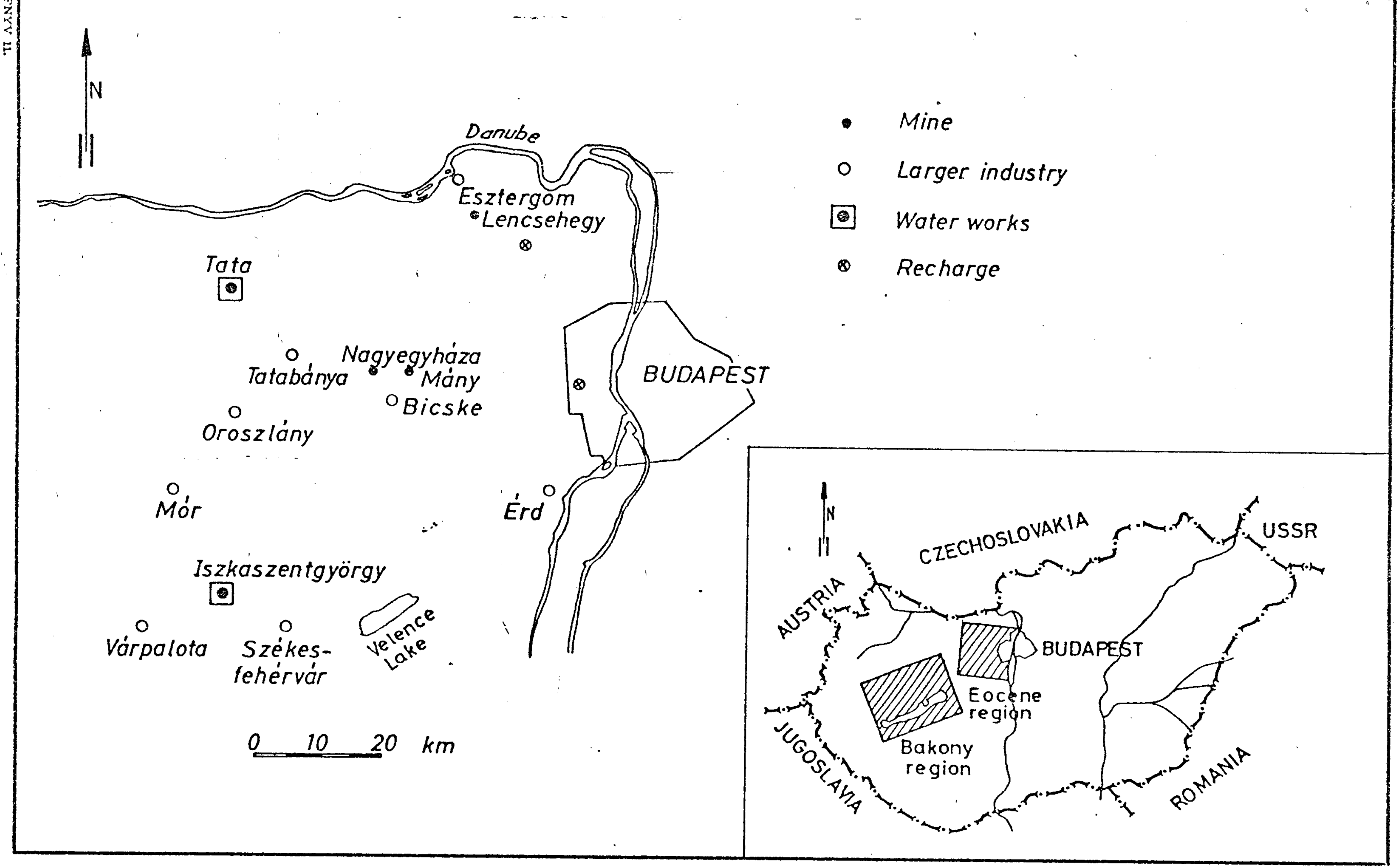

Figure 1. The Eocene Region in Hungary

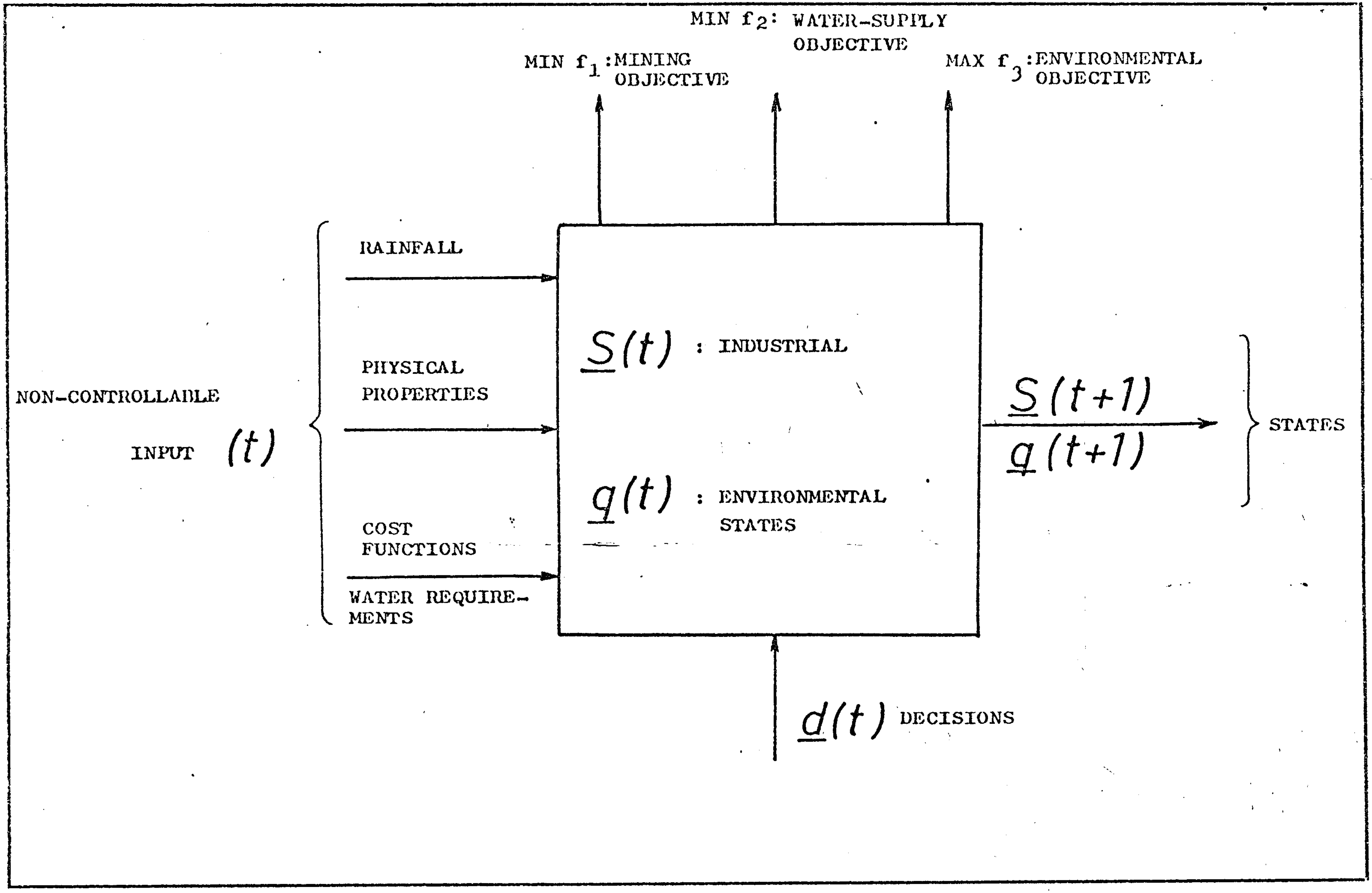

Figure 2. Model Element for the Eocene Region

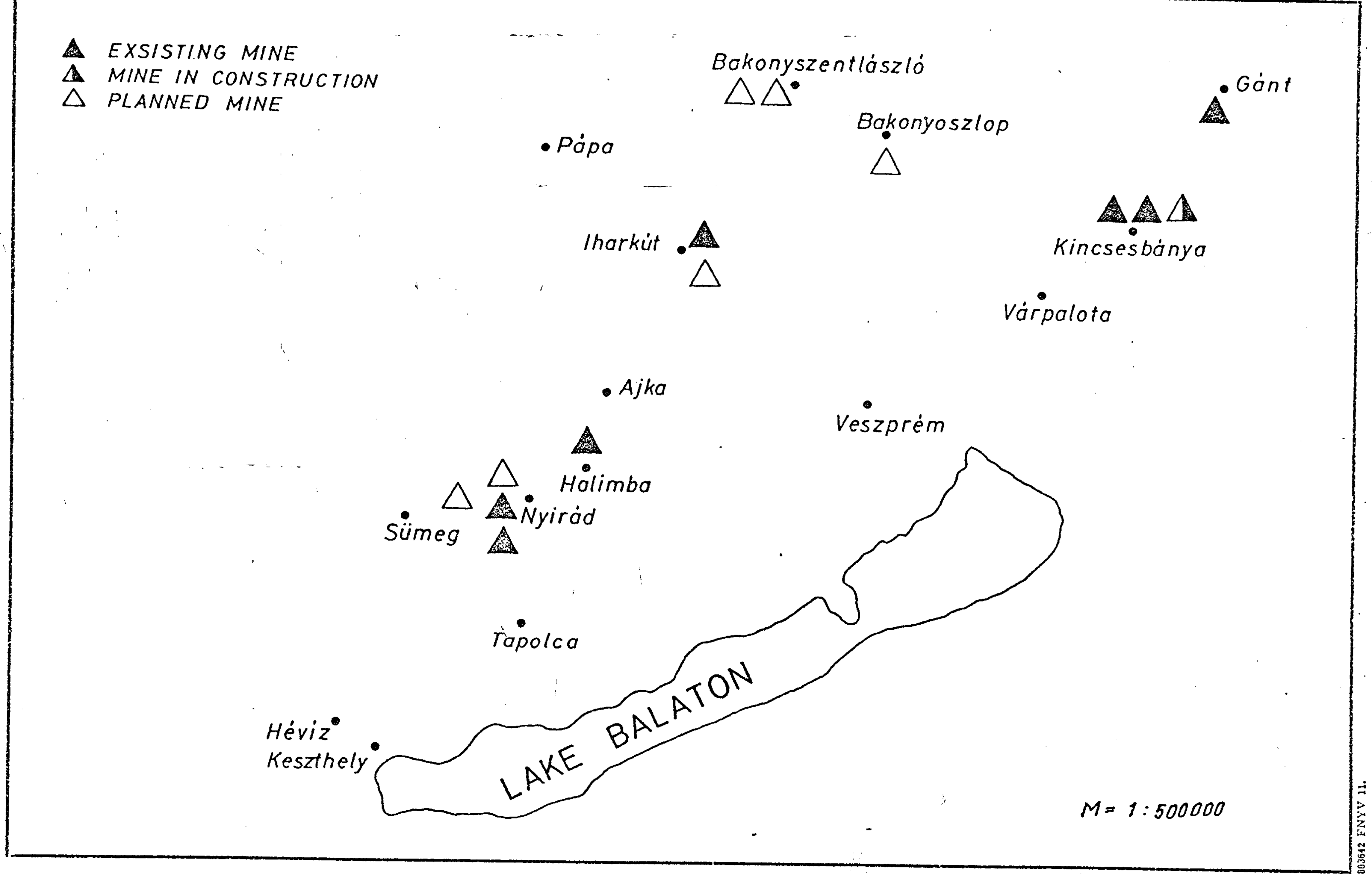

Figure 3. The Bakony Region in Hungary

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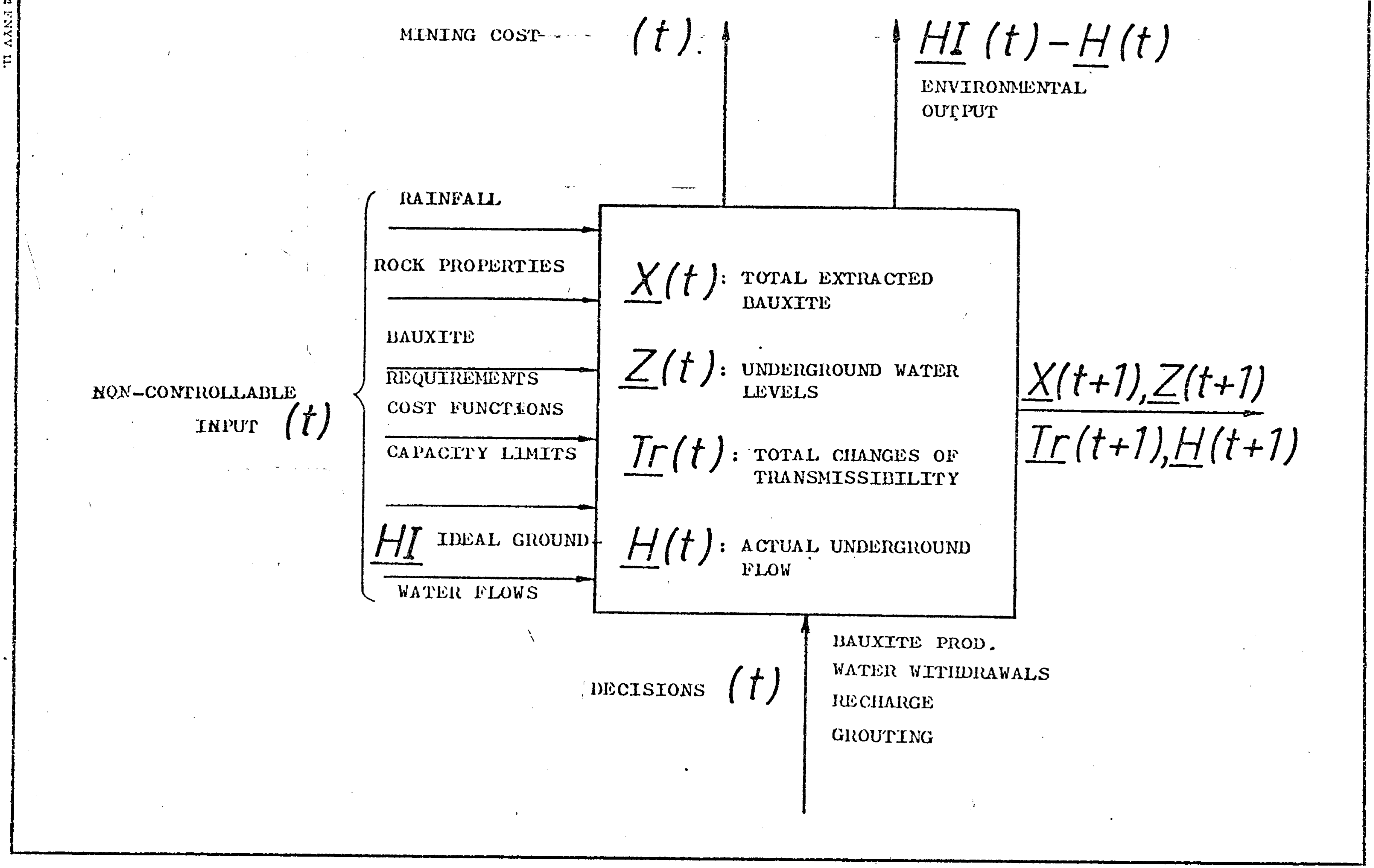

Figure 4. Model Elements for the Bakony Region