APPLICATION OF A SIMULATION MODEL FOR A LARGE-SCALE KARSTIC WATER AQUIFER

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ABSTRACT : Mining activity, water management and the environment is interrelated in a regional karstic water aquifer. A proper operation of existing works and the optimal development requires the knowledge of water movement in that aquifer. The simulation nethod elaborated is based on a finite difference solution of the two-dimensional, unsteady flow equation. Inputs of the model are rainfall over the area and water intakes at different points. Output yields the piezometric heights in grid points, and system outflow. The simulation model can be connected to a decision model which helps to choose the best alternatives for mine water management, water supply and environmental protection.

RESUME : Les travaux miniers, les conditions d'utilisation des eaux souterraines et l'environnement sont en inter-relation pour un aquifère régional d'eau karstique. Pour diriger convenablement les travaux entamés et pour assurer leur progrès optimal, on doit connaître les facteurs influant sur l'écoulement des eaux en-dedans de cet aquifère. La méthode de simulation décrite, mise au point à cet effet, est basée sur la solution par la méthode des différences finies d'une équation bi-dimensionnelle d'écoulement non-continu. Pour le modèle employé les entrées sont constituées par le volume des précipitations affectant le territoire et celui des eaux drainées en différents points, tandis que les sorties consistent en hauteurs piézomètriques dans les points de réseau et volumes écoulés à partir du système.

RESUMEN : En los acuíferos kársticos regionales las actividades mineras, y la gestión del agua y del ambiente están muy interconectadas. Para enfocar convenientemente todos los trabajos, y conseguir un desarrollo óptimo, se necesita conocer los factores que condicionan el flujo del agua subterránea. El método de simulación descrito se basa en una solución, en diferencias finitas, de la ecuación bidimensional de flujo transitorio. Las entradas son los valores de la precipitación sobre el área y las aguas infiltradas en diferentes puntos. Las salidas son los niveles piezométricos en los nudos considerados y los caudales transferidos a partir del sistema. Este modelo puede conectarse a un modelo de decisión, lo cual ayuda a encontrar las mejores alternativas para la gestión del agua de la mina, los abastecimientos y la protección ambiental.

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## 1. INTRODUCTION

The karstic aquifer in the Hungarian Transdanubian Mountain /TM/ has increasingly been affected by regional mining activity, water supply withdrawals and thermal water recharge. As a result of man-made interventions, level of the karstic water has been sinking. This paper underlines the necessity of using a simulation model /SM/ being capable of forecasting and interacting with a decision model. Several similar models are known from literature [De WIEST, 1965; WITHERSPOON and FREEZE, 1972; BREDEHOEFT and YOUNG, 1970; NEUMAN, 1975; KISIEL and DUCKSTEIN, 1976; HELWEG and LABADIE, 1977; PINDER and FRIND, 1972], though rarely are they used for karstic aquifers [YEVJEVICH, 1976]. The main idea of this paper is to show that the elaboration and direct application of such a model is not necessarily an end in itself but a further objective is to incorporate it into a multiobjective decision model /MDM/. This MDM would help decision-makers to find the best compromise among the various, sometimes conflicting goals of karstic water utilization, constrained by the physical laws governing karstic water movement. Thus, the model discussed in this paper is regarded as an integral part of a multiobjective analysis.

In Section 2 present situation of the aquifer is evaluated, as compared to the earlier, undisturbed state.

The aquifer system is described in Section 3, then Section 4 shows the development of the mathematical model.

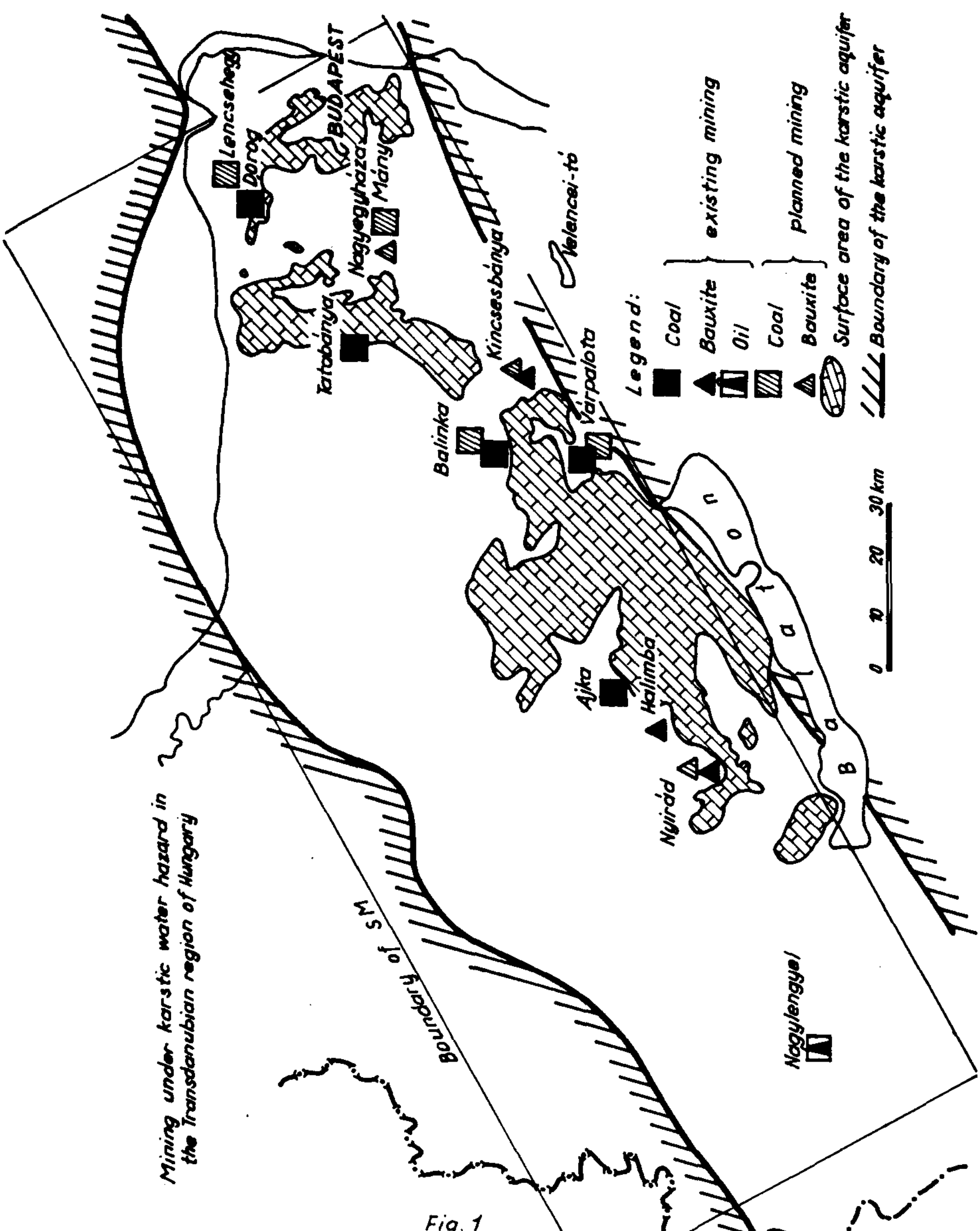
Application and on-going improvement of the model is discussed in Section 5. Also, conclusions reached so far are summarized.

## 2. PRESENT SITUATION

A great part of Hungarian mineral resources /coal, bauxite, manganese, oil/ are located in the vicinity or directly in the main karstic aquifer system of the TM /Fig. 1/. Here, mining activity under water hazard requires karstic water withdrawals. As a result of mine water pumping /Fig. 2/ original hydrologic conditions in the aquifer have gradually distorted. Since the natural recharge volume is finite and rapidly approached by the withdrawals, further interventions should be carefully planned with the forecast of ensuing impact.

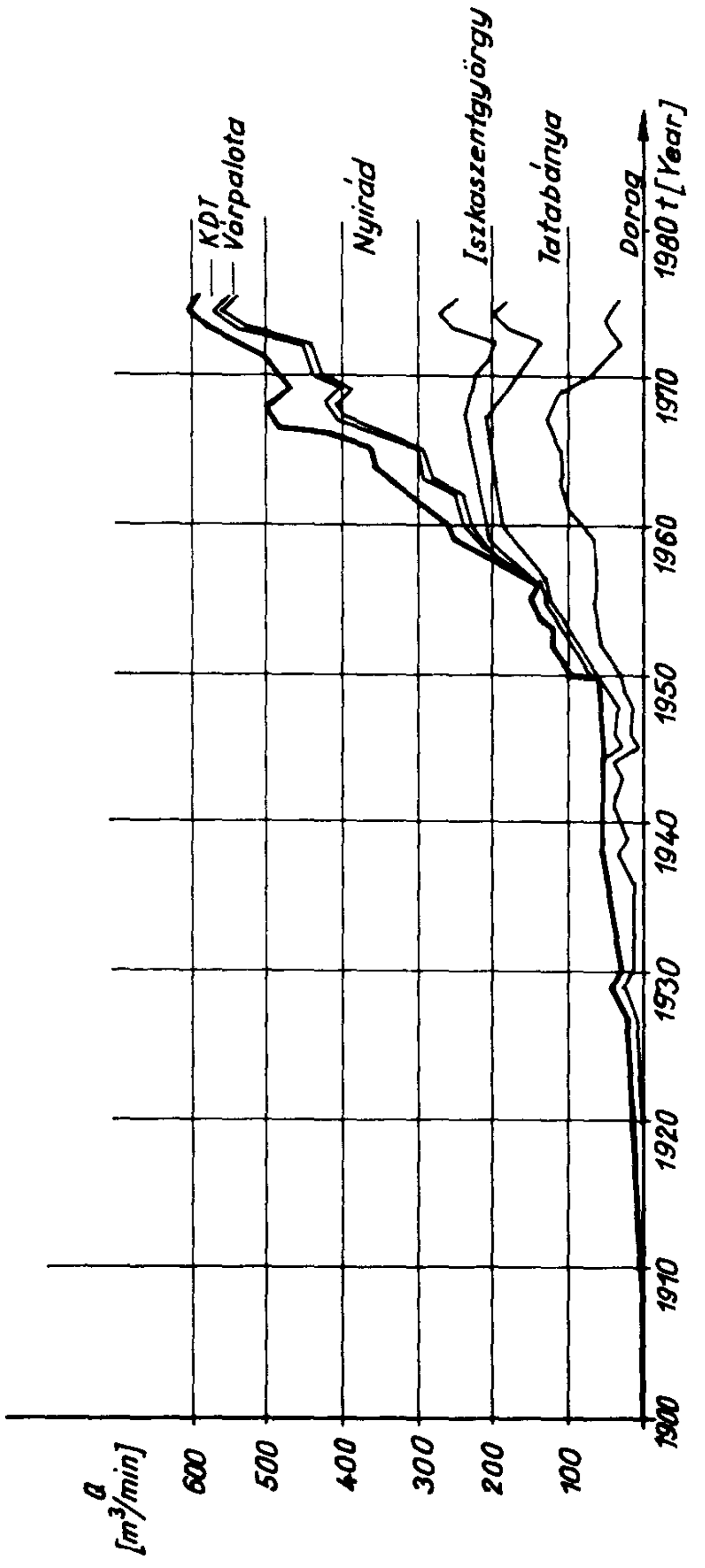
It is a further problem that world-famous thermal baths in Budapest and Héviz receive natural recharge also from that aquifer. As a consequence, further distortion of hydrologic conditions will result not only in a new /lower/ level equilibrium but the reduction of thermal water recharge.

As a third main factor, the use of karstic water for regional water supply complicates the situation. In fact, growing water demands /drinking and industrial/ call for the greater use of




Mining under karstic water hazard in the Transdanubian region of Hungary

Fig. 1




Total mining withdrawals in the region

Fig. 2

the karstic aquifer, more or less the only potential water resources in the region.

Recently explored new mineral deposits in the region are located deeply under karstic water level. Mining of these minerals becomes necessary in order to meet national demands [KAPOLYI.1977]. As a result, further increase of mine water withdrawals is envisaged [SCHMIEDER et al., 1977], which may surmount natural recharge.

In this situation the need for a proper control is evident. Two main engineering alternatives are available to find a "satisfactum" among these conflicting effects:

a./ using such mining technologies under water hazard /e.g. sealing/ which result in smaller withdrawal;

b./ artificially recharging the pumped mine water into the aquifer in proper time and space in order to maintain the necessary underground recharge of thermal waters. A multiobjective analysis of these alternatives can be found in DUCKSTEIN et al. [1978]. Clearly, traditional design methods are not suitable for selecting the site, time and amount of artificial recharge. In order to find the "best" control strategy such a physical model is necessary which

a./ yields regional karstic water level fairly accurately, as affected by natural recharge /rainfall/, mining and water-supply withdrawals as well as artificial recharge;

b./ calculates underground outflow /recharge of thermal waters/ fairly accurately as related to the above variables;

c./ needs moderate computer time for the solution and can be connected to a decision model.

Model construction requires a proper knowledge of the system which is briefly described in the next Section.

## 3. SYSTEM DESCRIPTION

Average natural recharge of the karstic aquifer system in the TM is estimated as 700 $m^3$/min [SZILÁGYI, 1976]. This recharge stems from rainfall over an area of 1500 $km^2$ and the average infiltration ratio is 36 %. In its original, undisturbed state, outflow from the system has the following distribution:
36 % cold-water springs, 28 % lateral seepage toward porous basins encircling the TM, 17 % surface waters, 10 % thermal water recharge and 9 % seepage into the Danube.

At present, outflow distribution has completely changed:

Average total outflow has increased to 850 $m^3$/min, thus the average storage loss is 150 $m^3$/min. Outflow distribution: withdrawals: 65 %, springs: 10 %, lateral seepage: 10 %, surface waters: 3%, thermal water recharge: 8 %, Danube communication: 4 %.

The loss of karstic water resources covers almost the entire TM, and there is a continuous sinking trend in regional karstic water level, with "noises" due to random hydrologic effects /e.g. rainfall/ and changing actual amount of withdrawals. Fig. 3 compares karstic water levels with and without man-made effects for a characteristic section.

These significant changes have contributed to acquiring more knowledge on the structure, hydraulic properties of, and main processes in the system as well as on the connection with adjacent aquifer systems [SCHMIEDER, 1975]. That knowledge is a prerequisite to construct any kind of system model with the criteria specified earlier. However, information should be increased on that part of the TM which is not yet affected by man-made interventions. It is hoped that the SM outlined in the next Section will also help in that respect.

## 4. THE MATHEMATICAL MODEL /SM/

The mathematical model is now described for the calculation of karstic water flow in the main aquifer of the TM. Details of the model can be found in HEINEMANN and SZILÁGYI [1976].

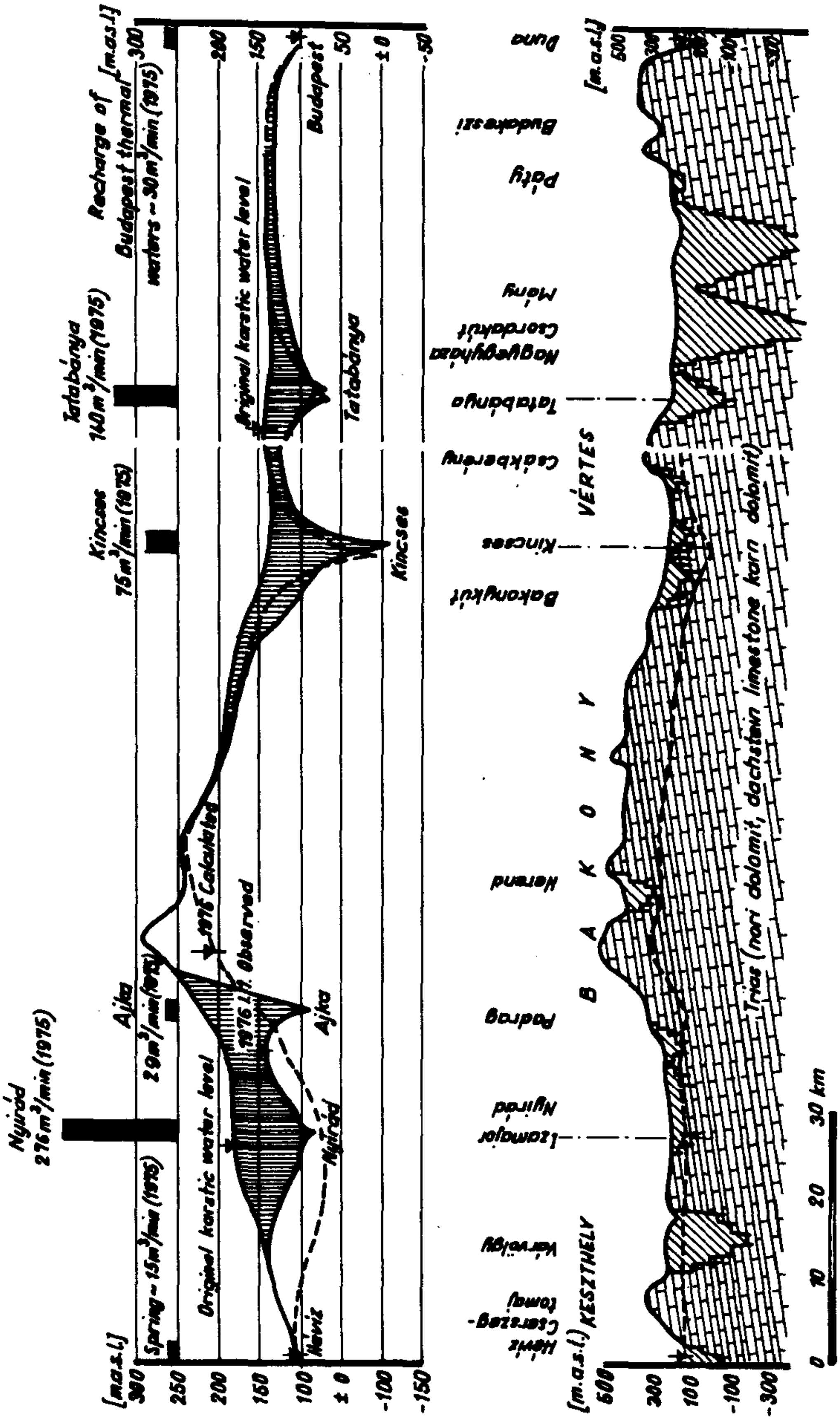
### 4.1. Principle of the model

It has been demonstrated that percelation in that regional karstic aquifer can be explained well by laminar motion and a mixed seepage /free surface and confined/ [SCHMIEDER, 1970]. Thus, seepage flow can be characterized in the karstic aquifer by the well-known two dimensional differencial equation for unsteady state [KISIEL and DUCKSTEIN, 1976]:

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} \frac{\partial h}{\partial y}\right) + q - w \qquad (1)$$

where: $h(x,y,t)$ is the piezometric level,
$K(x,y)$ is the aquifer conductivity,
$S(x,y)$ is the aquifer storage coefficient,
$q(x,y,t)$ is the natural recharge,
$w(x,y,t)$ is the withdrawal.

It is assumed that the aquifer is incompressible and anizotropic in the x and y directions. Along the vertical an average conductivity is taken into account. Water is regarded incompressible and of constant viscosity.




Observed and calculated piezometric level

Fig. 3

Equation 1 shows that seepage is induced in the aquifer by natural recharge $q(x,y,t)$ and withdrawal $w(x,y,t)$.

4.2. Initial and boundary conditions
Solution of equation 1 requires initial conditions $h(x,o) = \xi(x)$, and boundary conditions: $h(x,t) = \eta(x,t)$. For the calibration and validation of the model initial conditions were taken from BÖCKER and MÜLLER [1958-1974], who reported water level data in the karstic aquifer every year.

As boundary conditions two types are considered /Fig. 4/:

a./ erosion basis of the main karstic aquifer that is, springs and infiltration along the boundary as constant pressure points;

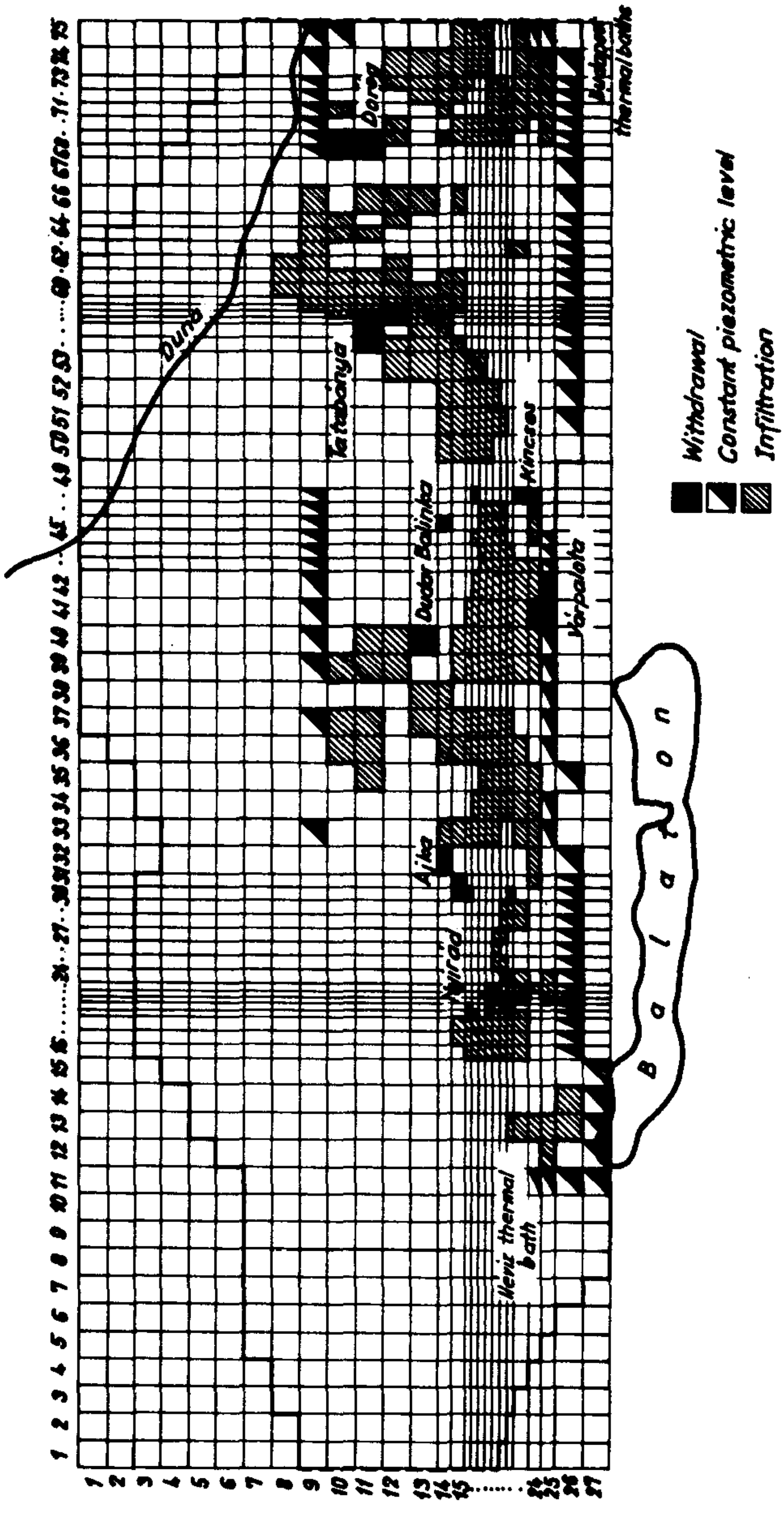
b./ other parts of the boundary are closed.

4.3. Model parameters
Determination of aquifer properties - conductivity and storage coefficient - for equation 1 means one of the most critical phases in such problems. Initial values of these parameters for different locations have been estimated on the basis of past mining withdrawal observations, numerous pumping tests and hydraulic analyses [SCHMIEDER, 1975]. Initial values were gradually improved during calibration.

4.4. Model solution and output
A finite difference method was used to solve equation 1 [HEINEMANN and SZILÁGYI, 1976]. Variable grid and a time step of 1 year was used. Solution yields for any time piezometric levels in the grid points, and system outflows along the boundary. The grid system shown in Fig. 4 has been gradually developed and contains 2025 blocks. First, smaller parts of the system was modelled [HEINEMANN and SZILÁGYI, 1976] and using that experiences the model was enlarged. In that present form of the modelled system such areas are also included which are, and probably will be undisturbed from mining interventions. The reason of such enlarging is that boundary conditions for the present system can be more truly modelled than for the smaller one.

4.5. Model calibration
Differences between model results - from different 1 year runs - and observations were reduced to $\pm 10$ meters by iterative corrections of conductivity values. Over the best-explored areas, covering the vicinity of mine withdrawals, these corrections were relatively slight, less than one order of magnitude. However, in the northern part of the region, at some locations corrections of two orders of magnitude became necessary.

Not only corrections in conductivity values were required during the calibration process but modifications of inputs and boundary




*Boundary conditions and inputs of the model*

*Fig. 4.*

conditions were also necessary at some points, by
- transferring points with constant piezometric level along the boundary;
- changing inner impervious zones, and
- increasing infiltration surfaces.

4.6. Model validation

After the calibration with 1 year runs a further 20 year period was simulated and compared with observations. During this period already heavy mining withdrawals have been occurring. It was concluded that
- calculated values simulate the observed values in tendency fairly well,
- there are still considerable deviations at some places, and
- a quasi-steady state is reached with the calculated outflows equalling those determined by other methods.

5. EXPERIENCES AND CONCLUSIONS OF SM APPLICATION

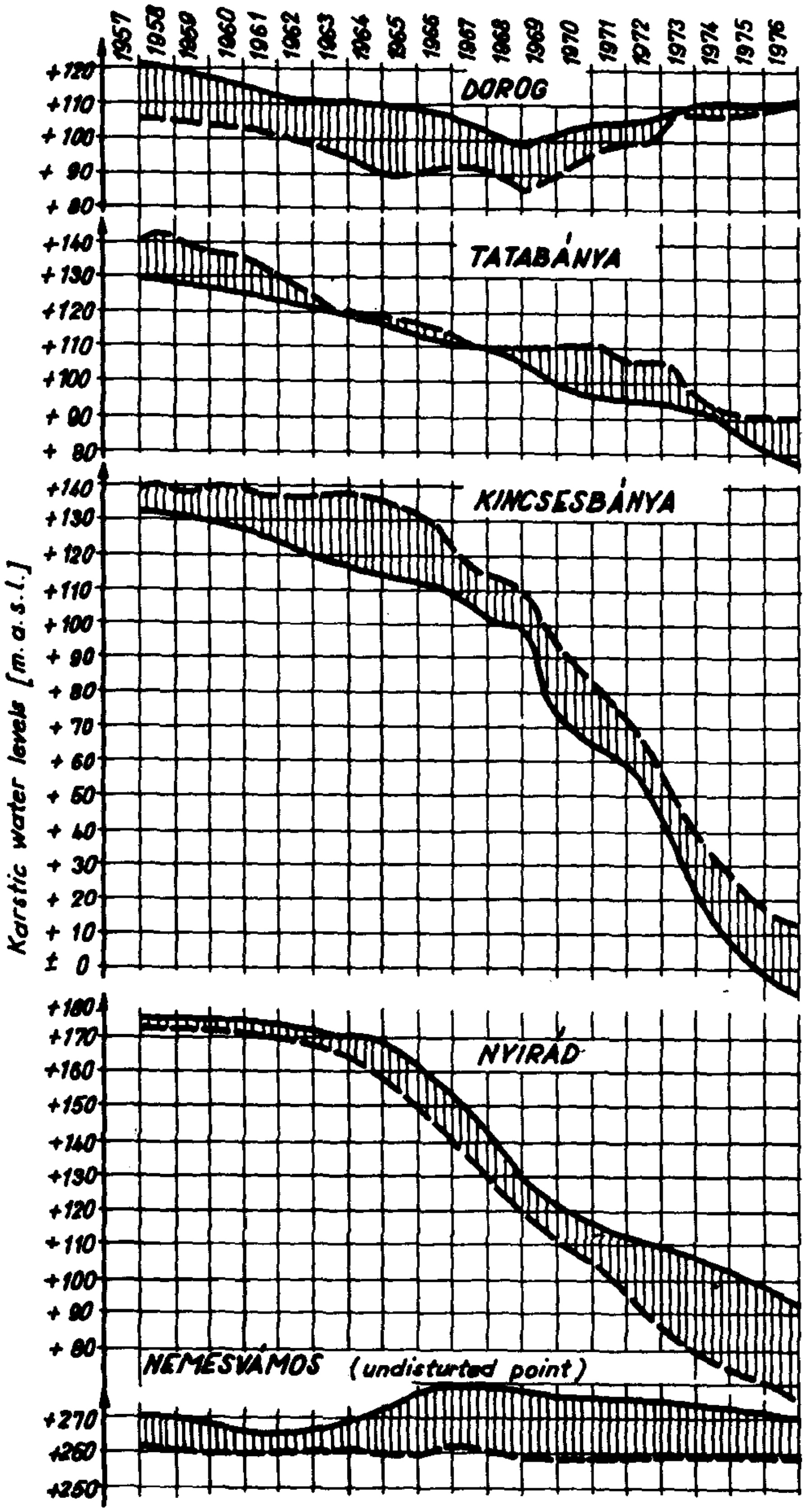
Results of the first application of SM are illustrated in Figs. 5 and 6. Direct check is possible when measured and calculated karstic water levels are compared. On the other hand, a part of outflows cannot be observed /lateral seepage, communication with the Danube/ but can be estimated by water-budget methods [SZILÁGYI, 1976; KOVÁCS, 1977]. As a result, comparison with the SM values is relative in these cases. An other part of outflows can be observed as discharge of springs and thermal wells.

Figs. 5 and 6 show that there are differences between calculated and observed or derived values. These differences are caused by model uncertainties and parameter uncertainties. Model uncertainties involve the inaccuracy of finite difference scheme /size of mesh/, and the modelled initial and boundary conditions. Parameter uncertainties involve the input error, mostly in rainfall infiltration, and the errors in rock properties. Further improvement in model accuracy can be expected if - in addition to the subjective calibration outlined - a calibration algorithm is used to estimate - in a sense at least - optimal initial and boundary conditions, inputs and rock parameters.

Finally, the implication of SM with MDM is briefly discussed. There are two possibilities to connect SM with MDM:

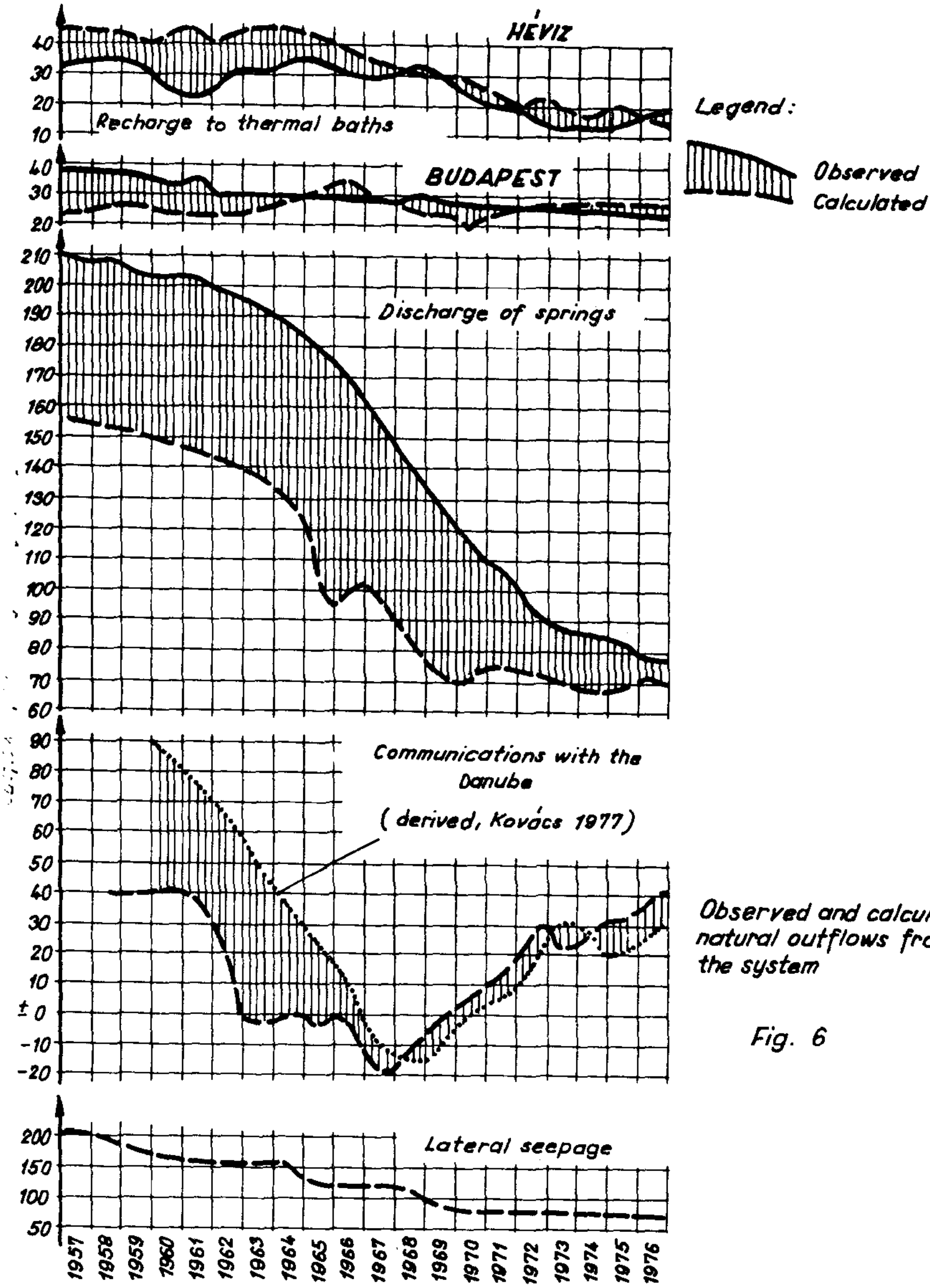
a./ For each decision alternative /amount of withdrawals and artificial recharges/ a system output /e.g. the amount of natural recharge toward thermal baths/ is calculated by the help of SM. Since MDM solution requires a number of such calculations, some efficient interactive operation of the SM is necessary as in HELWEG and LABADIE [1977].

b./ A regression model f is constructed by the help of a suffucient number of SM runs:




***Observed and calculated Karstic water levels in specific points***

***Fig. 5***




Observed and calculated natural outflows from the system

Fig. 6

$$y = f\left(x_1 . x_2, \ldots x_n\right) + \underset{\sim}{\xi}$$

where $x_1, x_2, \ldots, x_n$ are values of the decision variables /withdrawals and artificial recharges/;
y is the system output in question, and
$\xi$ is the random error of the regression.
Then this regression equation can be directly inbedded into MDM as in DUCKSTEIN et al. [1978]. In that case there is no use to run SM in an interactive way with MDM, however the error $\xi$ can be quite high unless a great number of SM runs is used for the estimation of regression model f. Also, the type of f - if it is not linear - may aggravete MDM solution.

In summarizing, the following conclusions can be drawn:
a./ In a regional aquifer, if several different objectives are present, a satisfactory water resources utilization policy can be found by the conjunctive use of an SM and a MDM.

b./ It is shown that an operational SM in this karstic aquifer can be based on the unsteady seepage equation elaborated for porous media.

c./ Due to model uncertainties and parameter uncertainties there are differences between observations and SM calculations, even after a proper calibration - on a subjective basis - and validation.

d./ SM can be connected to MDM by a direct interactive way or by the help of a regression model.

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