SIMULATION OF PUMPING AND ARTIFICIAL RECHARGE IN A PHREATIC AQUIFER NEAR BUCHAREST, ROMANIA

by

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ABSTRACT: Bucharest's water supply is provided by three major water-treatment plants. These plants are supplied with surface water from the Arges and Dambovita Rivers (80 percent), and with groundwater from aquifers near Bucharest. However, due to the high proportion of surface water used, some problems with water quantity are periodically encountered at the end of summer or after long periods of intense freezing. It would thus be desirable to increase the proportion of groundwater usage and, among other solutions, to support increased pumping rates in the shallow phreatic aquifer by artificial recharge.

Because the study area covers about 540 km^2, groundwater flow was modeled on a regional scale and, because of the low density of data, the horizontal discretization consists of a network of 30 x 100 cells of dimension 600 x 300 m. After consideration of the complex interlayering of the lithologic units, three vertical model layers were adopted. The two important rivers, Arges and Dambovita, represent two lateral limits of the studied zone.

After calibration of the model against a map of observed potentiometric heads, convective travel times and streamlines were assessed in the context of artificial recharge of the aquifer. According to the results of the simulation, artificial recharge options warrant further study, because the travel time between the recharge and pumping areas is simulated to be more than five years.

RÉSUMÉ: L'alimentation en eau de la ville de Bucarest est assurée via trois stations de traitement principales. Ces stations sont alimentées à 80 pour-cent en eaux de surface par les captages dans les rivières Arges et Dambovita, et pour le reste par des pompages dans les aquifères situés à proximité de Bucarest. A cause de la proportion importante d'eau de surface utilisée, des problèmes périodiques de quantité d'eau sont enregistrés à la fin de l'été ou après de longues périodes de gel intense. Il est donc souhaitable d'augmenter la proportion d'eau souterraine, et parmi les solutions envisagées, de rendre possible l'augmentation des pompages par une intensification de la recharge dans les aquifères superficiels.

La zone étudiée couvre une superficie de 540 km^2; l'écoulement souterrain a été modélisé à une échelle régionale et, vu la relativement faible densité de données, la discrétisation horizontale consiste en un maillage de 30 x 100 cellules de dimensions 600 x 300 m. Pour tenir compte le mieux possible des variations lithologiques verticales, un modèle composé de trois couches a été adopté. Latéralement, les deux rivières, Arges et Dambovita, constituent les limites de la zone étudiée.

Après calibration du modèle sur une carte piézométrique mesurée, les temps de transfert convectif et les lignes de courant ont été estimées dans le contexte de l'étude de la recharge artificielle de l'aquifère. Selon les résultats de la simulation, l'option de cette recharge artificielle mérite des études ultérieures, car le temps de transfert entre le point de réinjection et celui de pompage est évalué actuellement à plus de cinq ans.

RESUMEN: **La ciudad de Bucarest está abastecida de agua por medio de tres grandes plantas depuradoras. Estas plantas están suministradas, a su vez, por aguas superficiales de los ríos Arges y Dambovita (el 80 %), y por aguas subterráneas procedentes de acuíferos cercanos a Bucarest. Sin embargo, y debido a la alta proporción de aguas superficiales usadas, periódicamente se presentan algunos problemas de suministro, coincidiendo con el final del verano o después de un largo periodo de intensas heladas. Sería, por tanto, deseable incrementar la proporción de agua subterránea, lo que supone, entre otras soluciones, la posibilidad de mantener en el acuífero libre superficial unos caudales bombeables mayores, mediante la utilización de recarga artificial.**

Dado que el área de estudio comprende unos 540 km^2, el flujo de agua subterránea se modeló a escala regional, y, dada la baja densidad de datos, la discretización horizontal consiste en una red de 30 x 100 celdas de dimensión 600 x 300 m. Tras considerar la gran complejidad de las variaciones litológicas verticales, se adoptó un modelo formado por tres capas en vertical. Los dos ríos, Arges y Dambovita, constituyen dos de los límites laterales de la zona de estudio.

El modelo se calibró a partir de un mapa de medidas piezométricas y se utilizó para evaluar tiempos de tránsito y líneas de corriente en el contexto de la recarga artificial del acuífero. Según los resultados del modelo, la recarga artificial es una opción que debe estudiarse en más profundidad en el futuro, ya que el tiempo de tránsito calculado entre el punto de recarga y el área de extracción es de más de cinco años.

INTRODUCTION

Bucharest's water is supplied by two systems, one for drinking water and the other for industrial water. The drinking-water supply system includes surface-water sources, such as the Arges, Dambovita, and Ilfov Rivers; groundwater wells; treatment units; and transport pipes, storage tanks, and distribution installations.

The drinking water of Bucharest is supplied from the two large water-treatment plants at Arcuda and Rosu. Another water-treatment plant is being built at Ogrezeni. Eighty percent of the water for these plants is supplied from two rivers (Arges and Dambovita). The rest is supplied from aquifers near Bucharest.

Current requirements for potable water result in the system working at its maximum capacity. Taking this fact into account, artificial recharge of the shallow aquifer could provide a solution to the problem of continuously increasing water demand. Recharge of the aquifer using treated river water would be made by direct injection.

Before any kind of geochemical study is attempted to assess the possible effects of the recharge water not being in physico-chemical equilibrium with the aquifer, simulations of the groundwater flow conditions and convective transport need to be completed.

The purpose of this study was to evaluate the feasibility of various artificial-recharge management alternatives for the shallow aquifer near Bucharest. The approach was to develop and apply a numerical model of groundwater flow and transport. Figure 1 shows the location of Bucharest and the study area.

HYDROGEOLOGY

Hydrogeological studies (Cineti, 1994) concluded that, in the extensive Romanian Plain, the main hydrogeologic formations are as follows (oldest to youngest):

- Lower Jurassic - Cretaceous-age strata, containing fissured limestone aquifers;
- Lower Romanian - Pleistocene-age strata, containing the gravelly Candesti aquifer and the more sandy Fratesti aquifer;

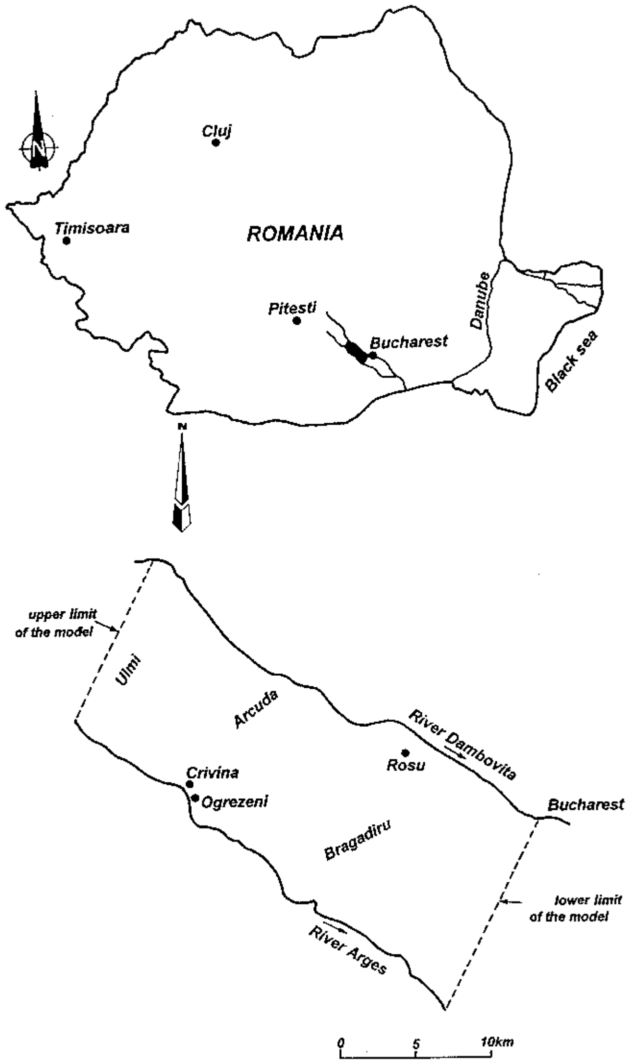


Figure 1. Locations of Romania (top) and study area (bottom).

- An upper aquifer system of Pleistocene age, containing the sandy Mostistea aquifer, together with the more gravelly Colentina aquifer.

This large tabular plain, also known as the Central Baragan Plain, has a fluvio-lacustrine origin and a gentle topographic gradient from north to south and from east to west. On the surface of this plain, eolian loess dunes occur with a NNW-SSE trend. In the northeastern part of the plain, several lakes occur in depressions among the dunes.

In the Pleistocene-age strata, the regional aquifers are composed of medium-to-fine sand, silty sand, and silt, and these are occasionally interlayered with thin clay layers. Potentiometric levels have small seasonal variations and also longer-period multi-annual rhythms, reflecting water-storage and discharge conditions in the aquifer. Generally, groundwater recharge is the result of rainfall during the cold period of the year (October to April). The amplitude and the rate of the potentiometric-level variations depend strongly on the length of the precipitation period and on the infiltrated quantity. Factors that control the quantity of infiltration include air temperature, vegetative cover, water content of the aerated zone, and depth to water table.

River/aquifer interactions can result in either recharge or discharge conditions, depending on the water levels that are maintained in the rivers (Drobot and Dimache, 1994).

NUMERICAL MODEL AND DISCRETIZATION

The finite-difference method was adopted for this study, using a multi-layer regional network of cells. MODFLOW (McDonald and Harbaugh, 1988), together with the PM processor (Chiang and Kinzelbach, 1992), was coupled with the MODPATH program (Pollock, 1989) for simulation of pollutant transport. Convective travel times of pollutant particles were calculated. The results are strongly dependent on the values of effective porosity that are introduced in the model.

At this stage, due to the lack of reliable data, processes related to mechanical dispersion, molecular diffusion, 'immobile' water effects, adsorption/ desorption, and density effects were not considered. However, because the hydraulic-conductivity values are high (generally greater than 25 m/d), a convective regime dominates. The convective transport simulations realised with MODPATH were assumed to yield the mean position of any simulated contaminant plume. This approach provided a very good approximation of solute-transport behaviour in the aquifers.

In the construction of the model, the first stage was to define the modeled area and boundary conditions in accordance with natural physical features or limits.

The three layers of the model represent the whole Upper Pleistocene aquifer system, containing the Mostistea and Colentina aquifers. The complex interlayering of the lithologic units is described as accurately as possible, using the full three-dimensional capabilities of the finite-difference code.

The two principal rivers (the Arges and the Dambovita) form, respectively, the southwestern and northeastern boundaries of the modeled zone (fig. 1). The rivers represent the natural lateral boundaries and are modeled with prescribed-head conditions (Dirichlet condition). These conditions imply a hydraulic continuity between the groundwater and the river, numerically translated by a potentiometric level in the aquifer equal to the water level in the rivers. Consequently, the model calculated the flows at these boundaries, and these values correspond either to infiltration from the rivers into the aquifer or vice-versa (Stefanescu, 1994).

Imposed potentiometric-head conditions were also selected at the upstream boundary of the model. The distance between this upstream limit and the main pumping area was chosen to be large enough for the boundary to lie outside the influence area of the pumping.

At the base of the model, a clay layer underlying the main sandy aquifer limits the possible upward flow from the Fratesti aquifer (Bretotean et al., 1994). Vertical leakage from or into this layer is assumed to be minimal when compared to the other stresses imposed on the aquifer (e.g., rainfall recharge or artificial recharge).

In general, the degree of heterogeneity, the aquifer behaviour type (confined or not), and the infiltration conditions are strongly influenced by the geometries of the geologic formations. Therefore, the space discretization and the distribution of the hydrogeological parameters were allocated with known heterogeneous and/or anisotropic conditions in mind.

The 3D model composed of three layers was adopted to conform most precisely to the geometry of the actual geology, as shown in figure 2. An area of more than 540 km^2 was discretized as a 30 x 100 cell network for each layer. Because each layer is not strictly horizontal, local heterogeneities were taken into account by varying the values of the parameters, as indicated in figure 3. Reference axes were chosen parallel to the general direction of the rivers, which also corresponds to the main local groundwater gradients. Some cells outside the studied area, lying between the Arges and the Dambovita Rivers, were deactivated. In figure 4, only the active cells of the network are shown.

Layer 2 of the model represents the main sandy aquifer. The top layer and the bottom layer locally contain more silt and clay.

The main input parameters of the model are: 1) recharge due to effective infiltration and artificial recharge, 2) pumping, and 3) interactions with the rivers. All these are time-dependent, but because no time-variant data exist for the calibration of this model, only a steady-state solution was considered in the calculations.

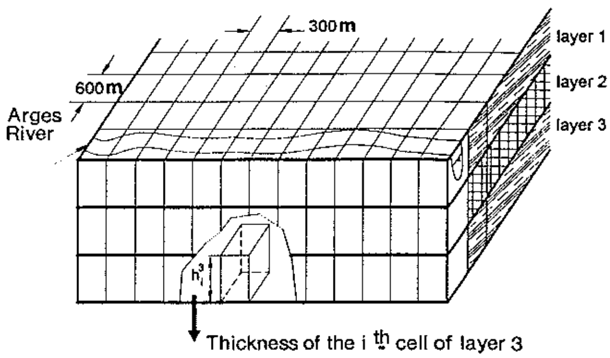


Figure 2. Diagram of vertical meshing network.

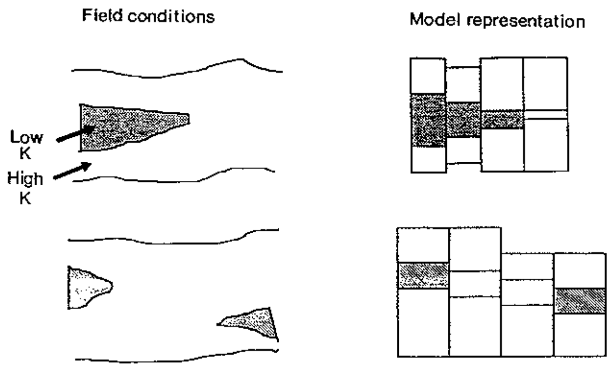


Figure 3. Discretization of local heterogeneities.

Data from the Romanian Meteorological and Hydrologic National Institute suggest that the aquifer can be considered a water-table aquifer, even though a semi-confined behaviour is locally observed. The position of the free surface is thus itself a part of the model solution. This non-linear problem can be very CPU time-consuming in transient conditions; it can be solved by many different methods (Dassargues, 1991, 1993). In this study, steady-state conditions were chosen and, using MODFLOW, the problem was solved by an internal cycle, computing the new transmissivity in the cell on the basis of the last computed potentiometric level (McDonald and Harbaugh, 1988).

The main pumping areas of Ulmi (in the upstream part of the study area) and Bragadiru (downstream part of the area) are shown in figure 4, together with three simulated possible locations of artificial recharge.

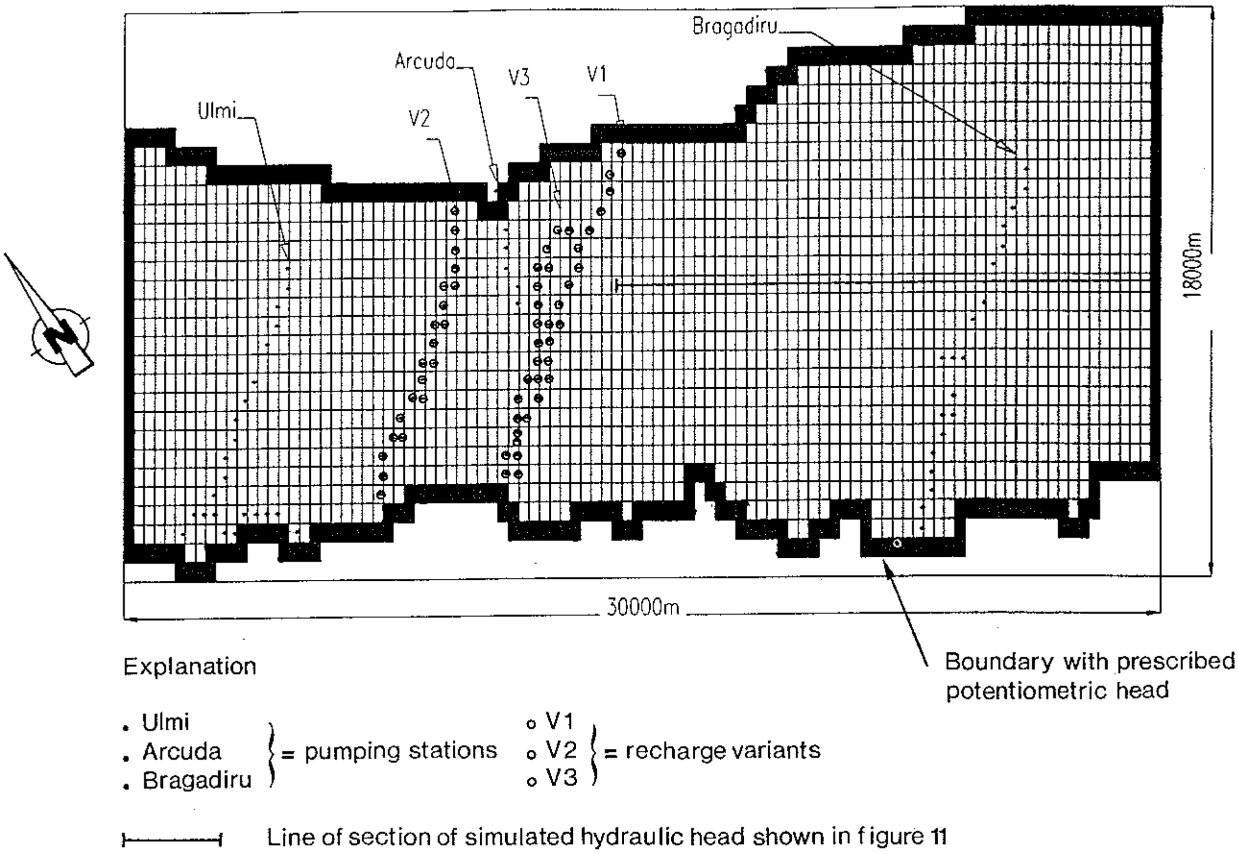


Figure 4. Horizontal network and locations of pumping and recharge areas.

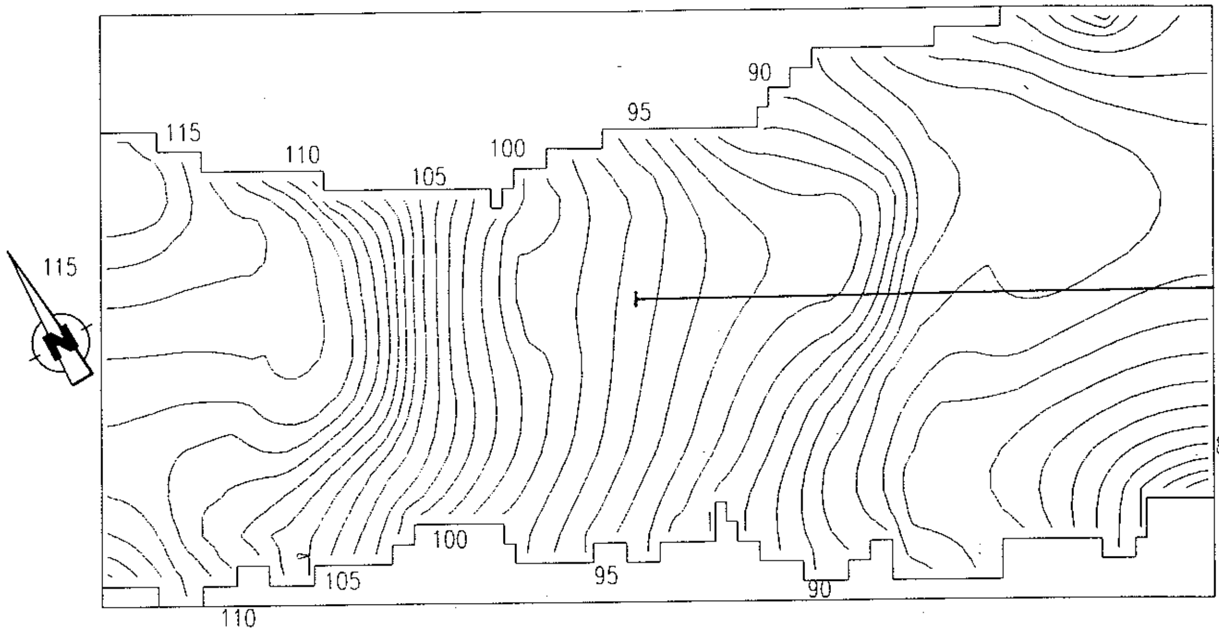
CALIBRATION OF THE MODEL

In order to identify any possible problems due to the chosen discretization, it is always better to proceed from the simple to the complex during the calibration stage. The first step of the calibration procedure was made using hydraulic-conductivity values that were deduced from pumping-test results provided by the Meteorological and Hydrologic National Institute. The computed results of the first runs of the model showed that the main trends of the potentiometric gradients were already well represented.

As a second step of this calibration, using a trial-and-error approach, more localized zones of different hydraulic conductivity values were introduced. By this means, more accurate geological knowledge about the different layers was progressively introduced. This optimization process continued until it became difficult to significantly improve the calibration. In view of the available data, the calibration was stopped after this stage, because the differences between the measured and modeled potentiometric heads were generally smaller than 0.5 m.

For comparison between the calibration results and the measured potentiometric levels, maps of potentiometric heads from the second layer were mainly used. Most of the available piezometers are screened at this level. Because this second layer is also the main aquifer, the principal calibration was focussed on parameters pertaining to this layer; only in small areas could parameters in the third layer be effectively calibrated, due to lack of data. No calibration could be performed on the parameters of the first layer, which is often dewatered. Figure 5 shows the calibrated computed potentiometric map for layer 2.

Figures 6 and 7 show the hydraulic-conductivity maps for layers 2 and 3 after calibration of the model. Not many variables were considered during the calibration. At this stage, however, it was assumed that as long as the model accurately reproduces the observed behaviour of the system, it can be used to make predictions (de Marsily et al., 1992). The future



Explanation

Line of equal potentiometric head, layer2, following model calibrations, in meters above mean sea level, contour interval 1m

Line of section of simulated hydraulic head shown in figure 11

Figure 5. Potentiometric surface, layer 2, following model calibration.

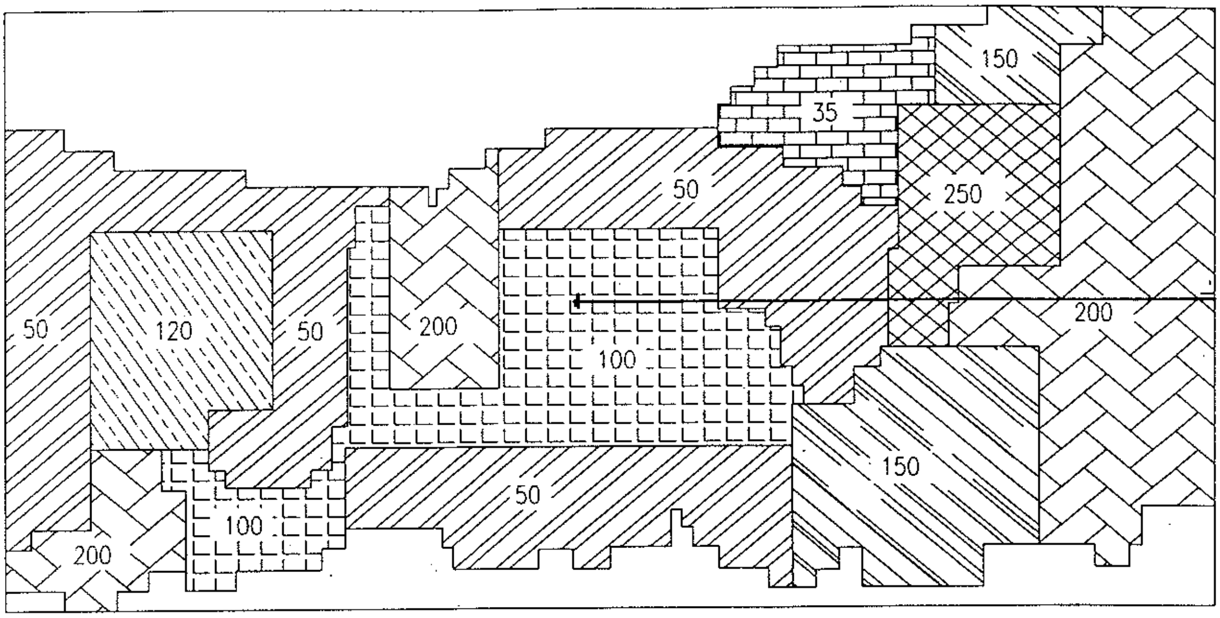
incorporation of new data and an assessment of the model's performance in simulating future conditions should increase confidence in the model's validity.

SIMULATIONS AND PREDICTIONS

The region chosen for the injection of recharge water is near the Arcuda pumping installations (fig. 4), near the two treatment stations of Crivina and Arcuda. The location was selected on the basis of the following points: 1) proximity to treatment stations ensures a standard quality of water without long-distance transport; 2) the distance to the Bragadiru pumping area (fig. 4) (12 km from V1, 15 km from V2) and to the individual Bucharest wells is sufficient to offer the possibility of using the aquifer as a large reservoir and, moreover, the travel time of groundwater would be great enough to ensure effective attenuation of any contaminants in the recharge water (Stefanescu, 1994).

As mentioned above, three variants of the artificial recharge were analysed and refined: the injected flow and the position and number of wells (and hence the injection flow rate in each well). The characteristics of the three tested solutions are presented in the table 1. Figures 8, 9, and 10 present potentiometric maps for simulations of each solution (V1, V2, and V3; fig. 4).

The total recharge of 0.5 m^3/s (500 L/s) produced a modification of the potentiometric contours both upstream and downstream of the injection zone. An increase of 1-3 m in head was estimated over only a very short distance upstream (figs. 8, 9, and 10), although no effect was observed at the Ulmi pumping zone (fig. 4). Downstream, the difference between simulated potentiometric heads with and without recharge occurs over a greater distance, as far as the Bragadiru pumping area. As an example, figure 11 illustrates the longitudinal potentiometric profile as far as the Bragadiru pumping zone (16-30 km). Because the potentiometric level on the lateral boundaries is



Explanation

120 Hydraulic conductivity, layer 2, following model calibration, in m/d
Line of section of simulated hydraulic head shown in figure 11

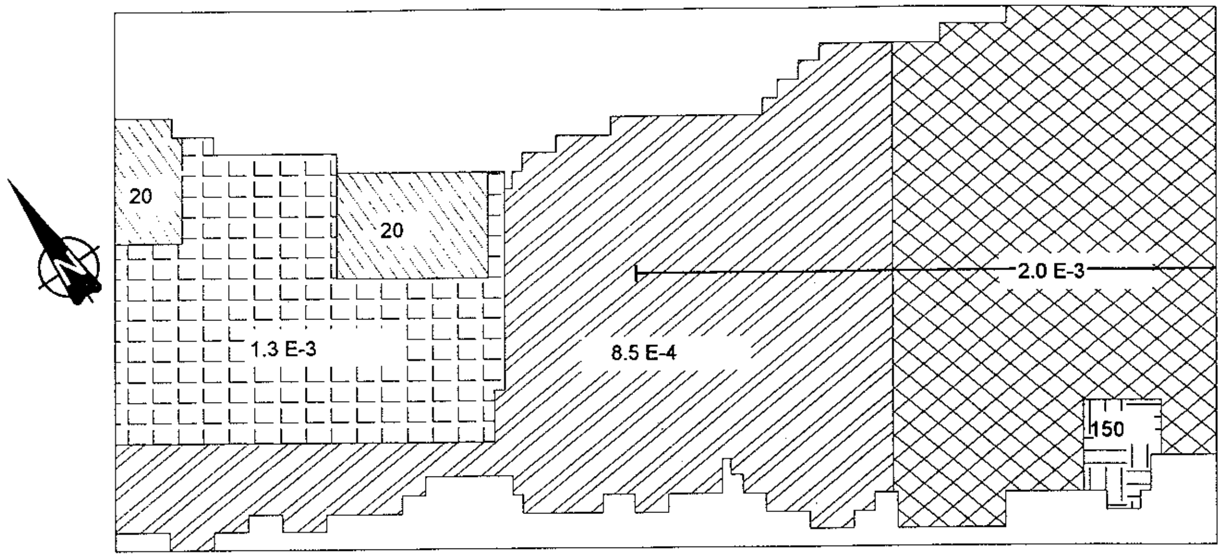
Figure 6. Hydraulic conductivity, layer 2, following model calibration.

prescribed, additional flow is computed from the aquifer into the rivers.

Calculations were then made by increasing the withdrawal in the pumping zones by 10 percent. Simulations V2b and V3b correspond to this pumping regime and to V2 and V3 recharge variants. The calculated potentiometric results showed only a very slight influence caused by the extra pumping (Stefanescu, 1994).

MODPATH allows the calculation of both convective transport paths and convective travel times. The effective convection velocity is equal to the Darcy velocity (or specific discharge) divided by the effective porosity. No accurate data were available concerning the values of effective porosity; therefore, multiple simulations were performed, each with a different assumed value of effective porosity. For example, figure 12 shows the convective transport for particles injected in the second layer with the recharge variant V3. A uniform effective porosity (n_e = 0.15) was chosen. Only the convective travel time estimate is affected by this choice, because the pathlines themselves can be computed for steady-state conditions. On the basis of local water-balance calculations and inspection of the computed results in figure 12, it is observed that;

1) A substantial part (about 0.165 m^3/s) of the water injected in the northern part of the recharge area is flowing to the northeast to reach the Dambovita River;
2) Similarly, about 0.121 m^3/s of the water injected in the southern part of the recharge area is flowing to the southwest to reach the Arges River;
3) About 0.040 m^3/s of the water injected in the northern and central parts of the recharge area is flowing directly to the northwest toward the Arcuda pumping zone;
4) About 0.168 m^3/s of the injected water is flowing to the southeast and is being abstracted by the Bragadiru pumping zone; and



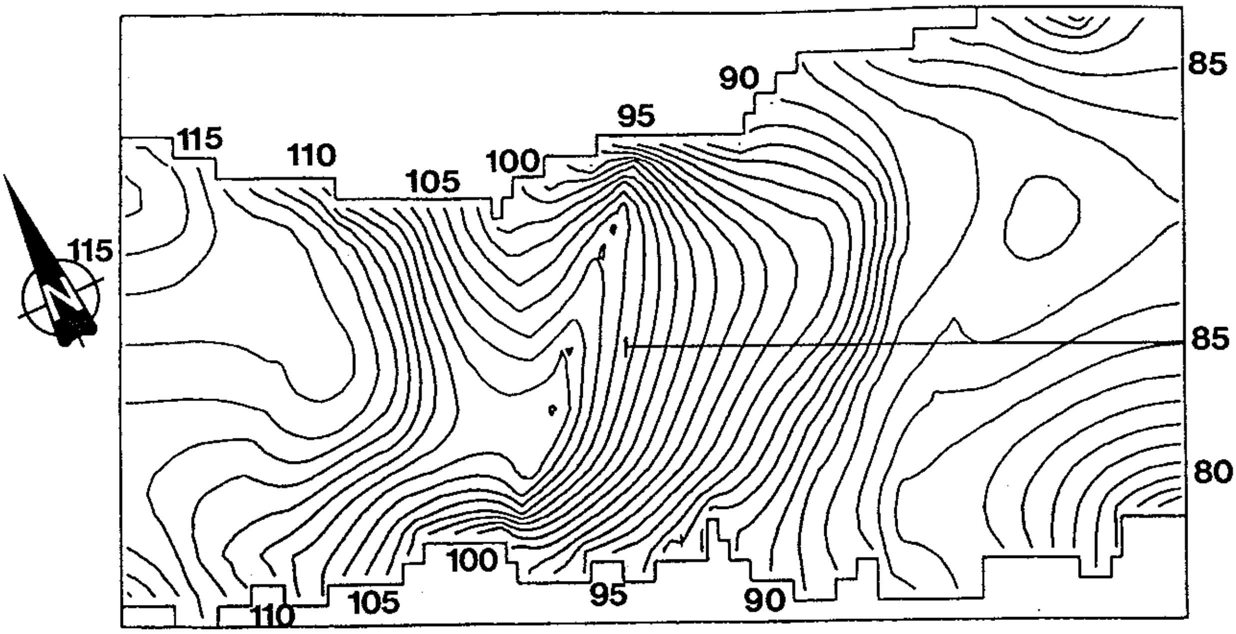
Explanation

1.3E-3 Horizontal hydraulic conductivity, layer 3, following model calibration, in m/d
Line of section of simulated hydraulic head shown in figure 11

Figure 7. Horizontal hydraulic conductivity, layer 3, following calibration.

Table 1. Description of artificial-recharge variants.

Variant	Injection rate in each well (m^3/s)	Injection wells		
		Total number of wells	Distance between wells (m)	Position in relation to Arcuda pumping station
V1	0.00625	80	150	Downstream
V2	0.00625	80	150	Upstream
V3	0.01000	50	200	Downstream

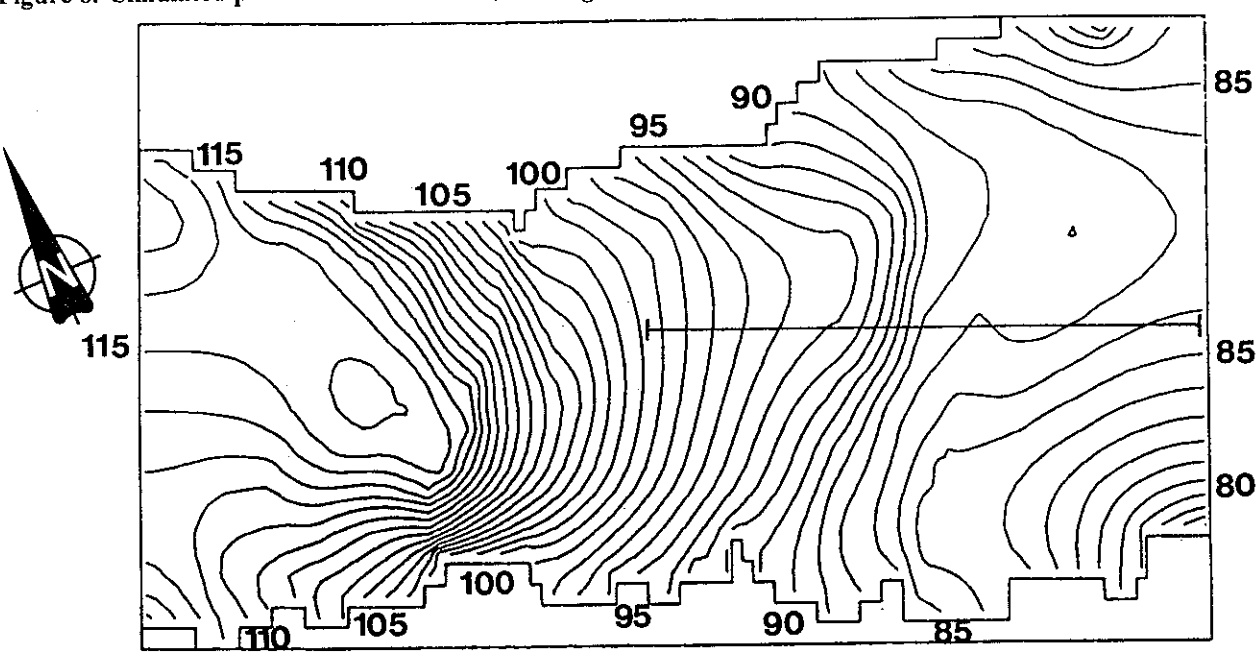


Explanation

~110~ Line of equal simulated potentiometric head, recharge variant V1, in meters above mean sea level. Contour interval 1m.

├──┤ Line of section of simulated hydraulic head shown in figure 11.

Figure 8. Simulated potentiometric surface, recharge variant V1.



Explanation

~110~ Line of equal simulated potentiometric head, recharge variant V2, in meters above mean sea level. Contour interval 1m.

├──┤ Line of section of simulated hydraulic head shown in figure 11

Figure 9. Simulated potentiometric surface, recharge variant V2.

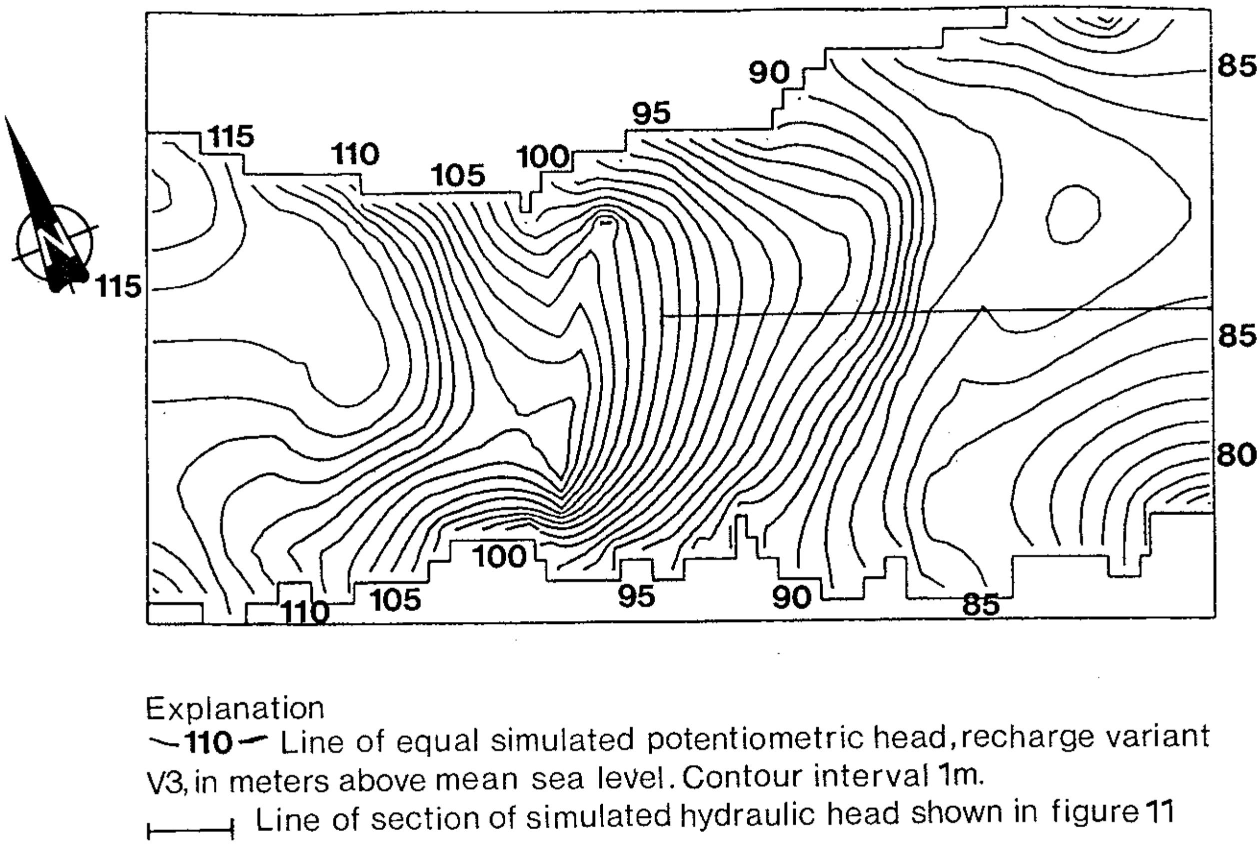


Figure 10. Simulated potentiometric surface, recharge variant V3.

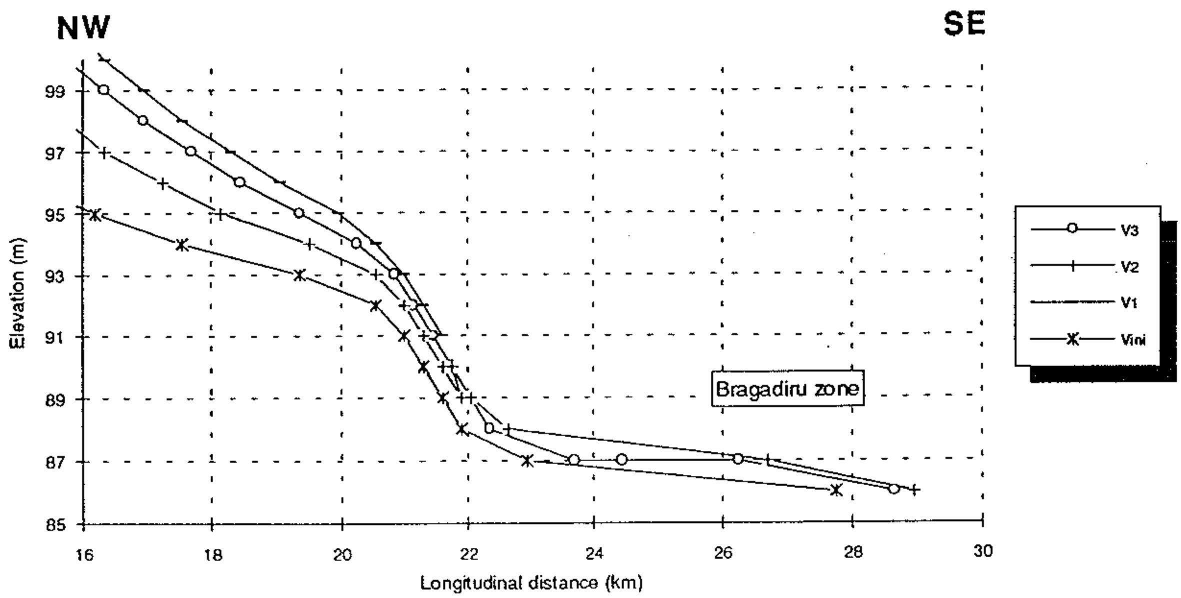


Figure 11. Longitudinal potentiometric profiles, recharge variants V1, V2, and V3, and initial conditions (Vini).

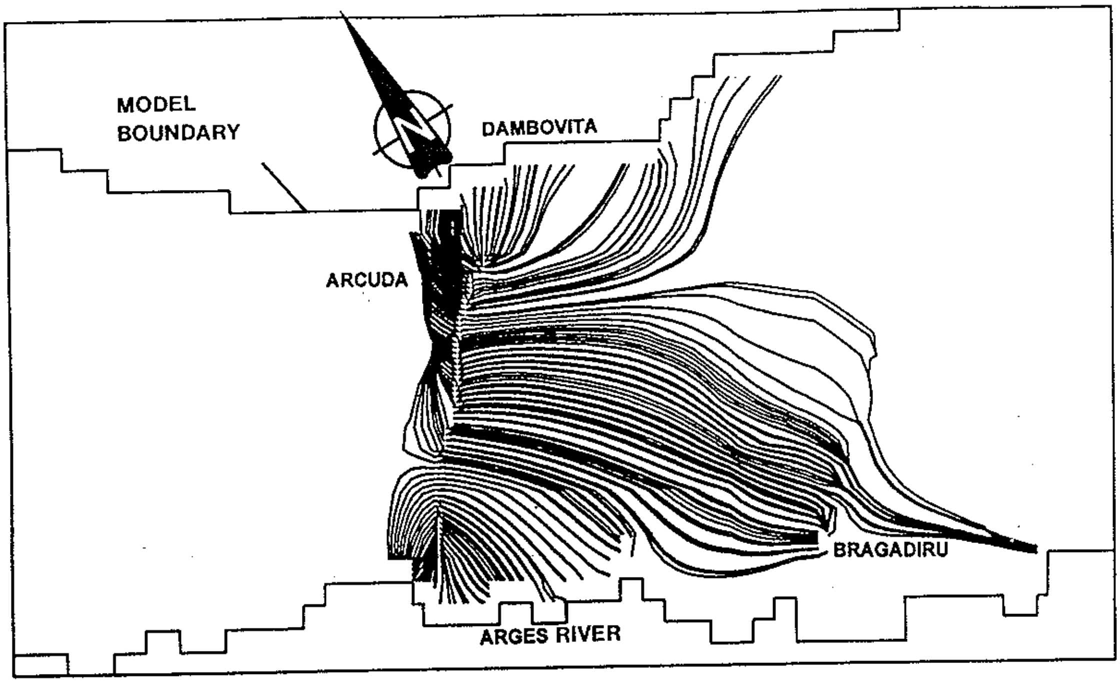


Figure 12. Computed pathlines from the recharge area, variant V3.

5) Only a very small amount of additional recharge water (about 0.006 m^3/s) is flowing through the Bragadiru pumping zone to reach the Arges River.

The computed travel time depends strongly on the value selected for effective porosity. For example, for n_e = 0.15, about 18 years would be necessary for an injected solute particle to reach the Bragadiru pumping zone, whereas for n_e = 0.05, only six years would be required.

CONCLUSIONS

This work provides new understanding regarding the hydrogeologic conditions of the phreatic aquifers near Bucharest and about their eventual capacity to supply the water demand in this city. The new information is synthesised in a 3D hydrogeological model that permits the calculation of groundwater flow and convective solute transport in the aquifer concerned. This integrated model can be used to simulate different options for the management of both water quantity and quality in the aquifer. For example, artificial recharge of the aquifer by injected surface water can be optimised with regard to location and rate of recharge. For each simulated situation, the pro- portions of recharge water reaching the rivers and the main pumping zones can be calculated. The travel time of particles between the recharge area and the pumping zones can also be estimated if effective porosity values are known.

On the basis of initial results, the phreatic aquifer probably could be used as a buffer reservoir for the Bucharest water supply. The fact that the aquifer provides a very long residence time for the water between recharge and abstraction means that the abstracted water should be of satisfactory biological quality.

When more accurate data for effective porosity values and hydrodynamic dispersion parameters become available, more detailed simulations are expected to provide increasingly accurate results.

ACKNOWLEDGMENT

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