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Management perspectives on a deep aquifer system for rural water supply in Olt and Vàlcea counties, Romania

Irina Dinu,[1]* Marius Albu,[1] Victor Moldoveanu,[2] Alain Dassargues[3] and Philippe Olive[4]

[1]Faculty of Geology and Geophysics, University of Bucharest, 6 Traian Vuia, 70139 Bucharest 1, Romania, [2]PROED (Studies and Design Institute for Public Works), 21 Tudor Arghezi, Bucharest 2, Romania, [3]Laboratories de Géologie de l'Ingénieur, d'Hydrogéologie et de Prospection Géophysique, University of Liège, B19 Sart Tilman, 4000 Liège, Belgium and [4]Centre de Recherches Géodynamiques, University of Paris VI, 47 Avenue de Corzent, BP510, 74203 Thonon, France

Abstract

The water supply in the Romanian counties of Olt and Vàlcea is mainly from groundwater from a deep aquifer system in Pliocene formations. Isotope analyses have been used to establish the supply area of the deep aquifer system. The age of the groundwater has been estimated for two samples by using ^{14}C analysis. A simplified numerical model for a north–south cross-section has provided global values for the hydraulic conductivity and effective porosity of the aquifer system. The groundwater from permeable horizons deeper than 120–140 m is highly mineralised and is, therefore, inappropriate for use as a water supply. Because groundwater resources are limited, the water supply for industry and domestic use in urban regions cannot increase too much. Thus, the deep aquifer system could also be used as a water supply for rural regions.

Key words

aquifers, groundwater resources, isotopes, transit times.

HYDROGEOLOGICAL CONDITIONS

The study area, covering an area of approximately 6600 km^2, is in the southern part of Romania, on the lower course of the River Olt, which is a tributary of the Danube (Fig. 1). The water-supply of the cities of Slatina (Olt County) and Drăgăşani (Vàlcea County) comes mainly from groundwater from an aquifer system in Pliocene and Pleistocene formations.

The aquifer system consists of two aquifers separated by an aquitard. The first is a shallow aquifer that develops in the flood plain and terraces of the River Olt. This shallow aquifer is up to 20 m in thickness and consists of Pleistocene sands and gravels. The second component of the aquifer system is a confined (deep) aquifer complex, comprising several Pliocene sandy horizons separated by discontinuous clay intercalations (Moldoveanu 1995).

The River Olt is polluted by wastes from two chemical plants in the city of Ràmnicu-Vàlcea. Consequently, pollution occurs downstream and the shallow aquifer becomes progressively more contaminated by sodium and chloride. Moreover, there are storage lakes on the river course, which have modified the natural conditions of the aquifer system. The storage lakes, and especially the artificial canals along them, allowed the pollutants to penetrate into the shallow aquifer instead of being carried away by the river water. Chemical analyses have found a high chloride content (more than 200 mg L^{-1}) at some points in the shallow aquifer. Because of agricultural activities, the presence of nitrates and nitrites has been locally detected in the shallow aquifer. During the last few years, contamination also extended to the confined aquifer because of leakage; chemical analyses found local chloride concentrations of more than 60 mg L^{-1} (Albu *et al.* 1996).

As groundwater from the shallow aquifer is of poor quality, it is usually mixed with groundwater from deeper layers. Thus, the confined aquifer provides the main water supply for urban and rural regions, both municipal and industrial. There are four main wellfields near the city of Slatina. For this region, it has been proven that the groundwater from permeable horizons deeper than 120–140 m is highly mineralised and it is inappropriate for use as a water supply. Thus, one can expect that there is a boundary at a certain depth, where the transition from fresh water to highly mineralised water occurs.

The confined aquifer system extends toward the north and the outcrop zone of the Pliocene deposits is in the

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*Corresponding author. Email: dinui@gg.unibuc.ro

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Fig. 1. Map of Romania showing the location of the study area.

sub-Carpathians. The outcrop zone is considered to be the main recharge area of the confined aquifer.

ISOTOPE ANALYSES (^{3}H, ^{18}O)

Isotope analyses (^{3}H and ^{18}O) were carried out on several samples at Centre de Recherches Géodynamiques, Thonon, France. Four samples were taken from surface waters, three from wells in the shallow aquifer and nine from wells in the confined aquifer. The locations of the sampling sites for isotope analysis are shown on Fig. 2.

Tritium analysis

Tritium (^{3}H) can be considered as a water-dating element. The half-life of tritium is 12.43 ± 0.05 years (Unterwegger *et al.* 1980). A tritium unit (TU) corresponds to one tritium atom for 10^{18} hydrogen atoms.

The tritium content in precipitation was approximately 5 TU in the medium latitudes of the Northern Hemisphere before 1952 (Roether 1967). After aerial thermonuclear tests that were carried out between 1952 and 1963, the tritium content reached thousands of TU, followed by an exponential decrease. Since 1980, the aerial thermonuclear tests have ceased and the tritium content in precipitation is between 10 and 30 TU, being influenced only by the civil nuclear industry (Létolle & Olive 1983; Pally *et al.* 1993).

Most of the samples from the confined aquifer have a tritium content of less than 0.8 TU (Table 1). This could be explained by a groundwater transit time of 1000–2000 years or by light contamination with surface waters, which have a tritium content of approximately 15 TU. This contamination could have occurred because of damaged wells or leakage after over-exploitation of the aquifer (Olive *et al.* 1996). The second possibility is more likely because many wells are damaged in this way.

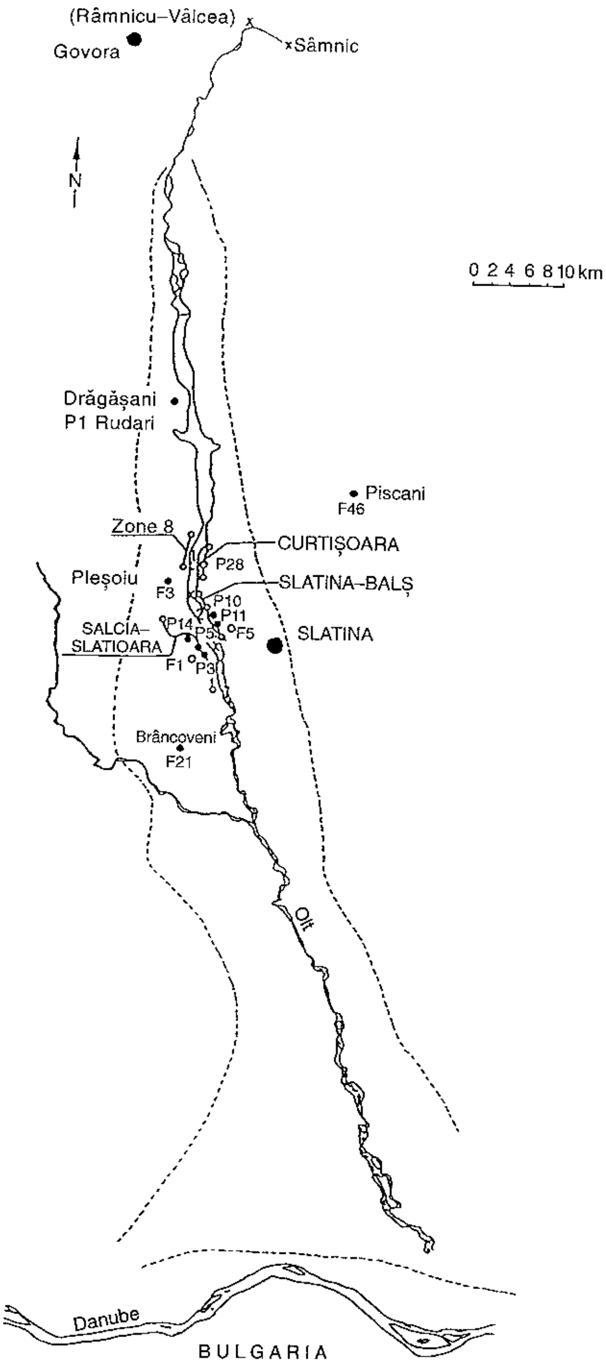

Fig. 2. Map of the sampling sites for the isotope analyses. (- - -), Extension of the shallow aquifer; (O—O), wellfield; 1, Arcesti Lake; 2, Slatina Lake. Sample from: (O), shallow aquifer; (●), confined aquifer; (×), surface water.

Samples from the shallow aquifer had a tritium content of between 10 and 20 TU (Table 1). One can conclude that this is recent groundwater in which the transit time varies between 5 and 10 years, and which has been influenced by the peak in 1963 (Olive *et al.* 1996). These samples have a tritium content close to that of surface waters.

Usually, the tritium content of the confined aquifer complex is quite different to that of the shallow aquifer and surface waters. Even so, there are two samples from the

Table 1. Results of ^{3}H and ^{18}O isotope analyses

Sample	Origin	Sampling date	^{3}H (TU)	$\delta^{18}O$(‰)
Slatina Lake	Surface	04 Feb. 1997	14.3 ± 0.5	−10.8
River Olt (near Râmnicu Vâlcea)	Surface	20 Mar. 1997	13.2 ± 0.5	−9.9
Sâmnic Creek	Surface	20 Mar. 1997	4.1 ± 0.4	−10.4
Arcesti Lake	Surface	11 June 1997	14.7 ± 0.5	−11.5
P28 Curtisoara wellfield	Shallow aquifer	04 Feb. 1997	13.6 ± 0.5	−10.3
F5 Domestic well	Shallow aquifer	04 Feb. 1997	11.8 ± 0.5	−10.7
F1 Domestic well	Shallow aquifer	04 Feb. 1997	18.0 ± 0.6	−10.2
P5 Salcia-Slatioara wellfield	Deep aquifer	04 Feb. 1997	14.4 ± 0.5	−10.9
P3 Salcia-Slatioara wellfield	Deep aquifer	04 Feb. 1997	≤0.8	−12.4
P10 Slatina-Bals wellfield	Deep aquifer	04 Feb. 1997	≤0.8	−11.8
P11 Slatina-Bals wellfield	Deep aquifer	04 Feb. 1997	≤0.8	−12.6
F3 Han Plesoiu	Deep aquifer	05 Feb. 1997	≤0.8	−11.7
F46 Piscani	Deep aquifer	05 Feb. 1997	≤0.8	−10.0
F21 Brancoveni	Deep aquifer	05 Feb. 1997	26.5 ± 0.6	−10.5
Dràgàaşani (P1 Rudari)	Deep aquifer	20 Mar. 1997	≤0.8	−11.0
		11 June 1997	≤0.8	−12.1
P14 Salcia-Slatioara wellfield	Deep aquifer	11 June 1997	≤0.8	−13.3

TU, tritium units. $\delta^{18}O$ values (±0.1‰) are the difference in isotopic ratios between the sample and the Vienna Standard Mean Ocean Water.

confined aquifer that had a higher tritium content: P5 from the Salçia-Slatioara wellfield (14.4 TU) and F21 Brancoveni (26.5 TU). These values usually represent recent, not very deep groundwater, with a transit time of between 50 and 100 years (for confined aquifers). The 1996 and 1997 chemical analyses that were carried out on samples from these two wells reveal high chloride concentrations (170 mg L^{-1} for P5 and 71 mg L^{-1} for F21), of the same order as those of the shallow aquifer. It is assumed that local contamination by surface water is occurring.

^{18}O analysis

The ^{18}O content of a sample (S) is given by the difference in isotopic ratios between the sample and the standard V-SMOW (Vienna Standard Mean Ocean Water):

$$\delta^{18}O\ (‰) = [(R_S/R_{V\text{-}SMOW}) - 1] \times 1000,$$

where R_S and R_{VSMOW} are the isotopic ratios of the sample and the standard, respectively. An isotopic ratio is defined as follows:

$$R\ (light/heavy) = {}^{18}O/{}^{16}O.$$

If $\delta > 0$, then the sample is enriched in the heavy isotope compared to the standard and if $\delta < 0$, it is depleted. The ^{18}O content depends on the air temperature in the infiltration zone. Because temperature decreases with altitude, $\delta^{18}O$ depends on the altitude of the supply zone. Thus, a sample more depleted in ^{18}O comes from water having a higher supply zone.

Water samples from the confined aquifer system are usually more depleted in ^{18}O (Table 1). Their average ^{18}O content is −11.6‰. The average ^{18}O content of the samples from the shallow aquifer is −10.4‰. Thus, the ^{18}O analyses show that the supply zone of the confined aquifer is higher than that of the shallow aquifer. This was expected, as the outcrop zone of the Pliocene deposits is in the north of the study area.

The two samples from the confined aquifer that had a higher tritium content than the others (P5 Salcia-Slatioara and F21 Brancoveni) have ^{18}O values similar to the samples from the shallow aquifer and surface waters (Table 1), which confirms that there is local contamination with surface water.

However, there was one sample from the confined aquifer (F46 Piscani) that was more enriched in ^{18}O ($\delta^{18}O = -10‰$) than others with the same tritium content (0.8 TU). This could be explained by local contamination with surface waters coming from an altitude lower than the outcrop zone of the Pliocene deposits.

The samples from surface waters in the outcrop zone were more enriched in ^{18}O (average $\delta^{18}O = -10.1‰$) than those from the confined aquifer (average $\delta^{18}O = -11.6‰$). This leads to the hypothesis that the altitude of the supply zone of the deep aquifer system is higher than the water-table elevation of the River Olt near Ràmnicu-Vàlcea and of the

Sâmnic Creek (which is approximately 250 m a.s.l.). Recharge could come from the sub-Carpathians, where altitudes of up to 600 m are reached to the north of the outcrop zone of the Pliocene deposits.

^{14}C-BASED GROUNDWATER AGES AND TRANSIT TIMES

Two other samples were taken for ^{14}C analyses, one from a well in the Slatina region (P14 Salcia-Slatioara) and the other from a well in the Drăgăşani region (P1 Rudari), to determine the age of groundwater in the confined aquifer system. The ^{14}C-based groundwater age has been calculated with the following formula:

$$\text{Age (years)} = \frac{5730}{\ln 2} \times \ln \frac{A_0}{A_t}$$

where 5730 is the half-life of ^{14}C in years, A_0 is the original ^{14}C activity of the total dissolved mineral carbon (percentage of modern carbon) and A_t is the residual ^{14}C activity of the total dissolved mineral carbon at the moment of sampling (percentage of modern carbon).

The age (or residence time) of the groundwater represents the time between infiltration and sampling. The ages of the two samples from the confined aquifer system are shown in Table 2.

The transit time between the outcrop zone of the Pliocene deposits and the Drăgăşani region is 6000 ± 1000 years, a value that is approximated by the ^{14}C-based age of the groundwater sample from the well at P1 Rudari. The transit time between the outcrop zone of the Pliocene deposits and the Slatina region is 24900 ± 2500 years, a value that is approximated by the ^{14}C-based age of the groundwater sample from the well at the P14 Salcia-Slatioara wellfield.

MODEL FOR A NORTH–SOUTH CROSS-SECTION

A simplified 2D vertical model for a north–south cross-section has been created in order to obtain groundwater transit times in the deep aquifer system that are compatible to those calculated by means of the ^{14}C-based groundwater ages. The model was created using MODFLOW (McDonald & Harbaugh 1988).

The model consists of one layer with 88 columns and two rows of cells with horizontal dimensions of 1000 m × 0.5 m and 500 m × 0.5 m in the region of the Slatina wellfields. The cross-section extends 74 km from the outcrop zone of the Pliocene deposits (north) to the Slatina wellfields region (south). The thickness of the layer is usually equal to the difference between the top of the confined aquifer system and the bottom of the lower permeable horizon that is exploited by the wellfields.

Effective infiltration was considered only in the northern part of the model (only in the first three cells), in the outcrop region of the Pliocene deposits. As lateral groundwater flow was disregarded and the model was calibrated on transit times, prescribed piezometric heads were imposed at locations where they have been measured. For the same reason, the wells were introduced in the model by their dynamic piezometric heads (not by their abstraction rates, as is usually the case). The values of hydraulic conductivity and effective porosity were adjusted during calibration. They represent global values that are representative of the layers of sands and clays of the deep aquifer system.

The model allows the calculation of transit times from the outcrop zone of the Pliocene deposits to the Drăgăşani and Slatina regions, which are compared to the ^{14}C-based groundwater ages.

Two hypotheses were considered concerning the inflow from the north in the deep aquifer system:

1. The northern boundary of the model is impervious and the aquifer system is supplied only from effective infiltration.
2. Both lateral inflow across the northern boundary and effective infiltration enter the aquifer system.

Each hypothesis has been tested on the model by an analysis of the sensitivity to recharge rates from effective infiltration. Therefore, in each case, recharge values of 50, 100 and 200 mm per year were used in the model, to analyse their effects on the global effective porosity and transit times.

The results of the sensitivity analysis are shown in Tables 3,4 and 5. As Tables 3 and 4 show, the hypothesis of a northern no-flow boundary leads to high values of global effective porosity toward the outcrop zone. In the first case (recharge of 50 mm per year), if the effective porosity is lower than 15% in zone 1, the transit time from

Table 2. ^{14}C-based groundwater ages

Well	Sampling date	A_0 (pmc)	A_t (pmc)	Age (years)
P1 Rudari (Drăgăşani)	15 Apr. 1997	46.26	22.39	6000 ± 1000
P14 Salcia-Slatioara wellfield	15 Apr. 1997	46.95	2.31	24 900 ± 2500

A_0, ^{14}C activity of the total dissolved mineral carbon (percentage of modern carbon); A_t, residual ^{14}C activity of the total dissolved mineral carbon at the moment of sampling (pmc, percentage of modern carbon).

the outcrop zone to the Drăgăşani region will be less than 5000 years (the lower limit of the ^{14}C-based groundwater age). Even so, a value of 15% for the global effective porosity seems unreasonable, taking into account that the aquifer system consists of several layers of sands and clays. At the same time, the piezometric head of the aquifer in the North should not be higher than the water-table of the surface water (approximately 250 m a.s.l.). If the recharge increases to 100 mm per year, the results are obviously unreasonable, therefore, this hypothesis is rejected.

Table 3. Calibration parameters in the Dràgàaşani and Slatina regions

Zones	K/n_e (m s^{-1})	K (m s^{-1})	n_e (%)
1	3×10^{-4}	4.5×10^{-5}	15
2	1.25×10^{-5}	5×10^{-7}	4
3	10^{-3}	7×10^{-5}	7

K, Global hydraulic conductivity of the confined aquifer system; n_e, effective porosity.

The hypothesis of lateral inflow across the northern boundary allows a prescribed head of 250 m. Figures 3, 4 and 5 show piezometric heads in the north–south cross-section for each of the recharge values. Figure 6 shows the zones of different global values of hydraulic conductivity and effective porosity in cross-section. The inflow across 1 m of the northern boundary has been calculated for each recharge value (Table 5). Moreover, the hypothesis of lateral inflow from the north in the deep aquifer system is in agreement with the results of ^{18}O analyses, which assume that infiltration occurs at an altitude higher than 250 m. Therefore, the real groundwater ages are

Table 4. Simulated groundwater ages (transit times; years) in the Dràgàaşani and Slatina regions for different values of recharge (northern no-flow boundary)

	Recharge (mm year^{-1})		
	50	100	200
Drăgăşani region	5031	< 5000	< 5000
Slatina region	23 102	< 22 400	< 22 400
	Lower K/n_e leads to higher piezometric head in the northern zone	Piezometric head too high in the northern zone (280 m)	Piezometric head too high in the northern zone (280 m)
	n_e < 15% in zone 1 leads to transit times of less than 5000 years	To increase the transit time: Reduce K (leads to higher piezometric heads) Increase n_e (unrealistic)	To increase the transit time: Reduce K (leads to higher piezometric heads) Increase n_e (unrealistic)

K, Global hydraulic conductivity of the confined aquifer system (m s^{-1}); n_e, effective porosity (%).

Table 5. Calibration parameters and simulated groundwater ages (transit times) in the Drăgăşani and Slatina regions for different values of recharge (inflow through the northern boundary)

					Groundwater age (years)		
Recharge (mm year^{-1})		Zone 1	Zone 2	Zone 3	Drăgăşani region	Slatina region	Inflow (m^3 day^{-1})
50	K/n_e	2.5×10^{-4}	1.25×10^{-5}	10^{-3}	5057	23 147	0.154
	K	1.25×10^{-5}	5×10^{-7}	7×10^{-5}			
	n_e	5	4	7			
100	K/n_e	2×10^{-4}	1.25×10^{-5}	10^{-3}	5779	23 877	0.443
	K	10^{-5}	5×10^{-7}	7×10^{-5}			
	n_e	5	4	7			
200	K/n_e	2×10^{-4}	1.25×10^{-5}	10^{-3}	5059	23 157	0.975
	K	10^{-5}	5×10^{-7}	7×10^{-5}			
	n_e	5	4	7			

K, Global hydraulic conductivity of the confined aquifer system (m s^{-1}); n_e, effective porosity (%).

higher than those calculated by means of the 2D vertical model.

The 2D vertical model provided global values of hydraulic conductivity and effective porosity for the confined aquifer system in the northern part of the study area. The low hydraulic conductivity value between the Drăgăşani and Slatina regions (Fig. 6) is justified by the geological structure. Figure 7 represents a simplified north–south cross-section on the left bank of the River Olt, which shows that in the Drăgăşani region, the exploited layers belong to Upper Romanian deposits, while in the Slatina region they belong to Dacian–Lower Romanian deposits. The layers are approximately parallel to the Dacian/Pontian stratigraphic limit that is lower in the Drăgăşani region than in the Slatina region. Thus, there are clay layers with the same tendency, which results in a low horizontal hydraulic conductivity and,

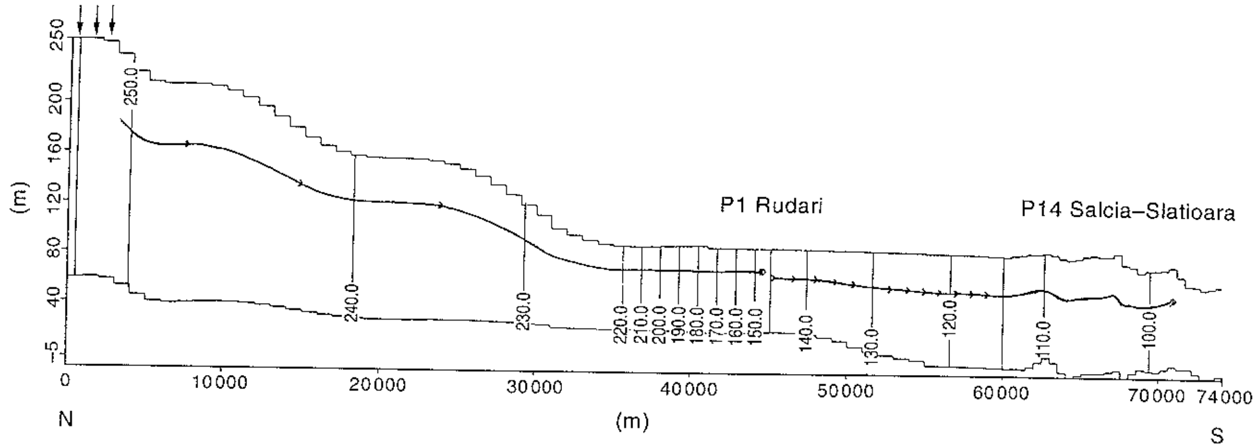

Fig. 3. Cross-section model for a recharge of 50 mm $year^{-1}$ with the distribution of piezometric heads. Arrows indicate the recharge area.

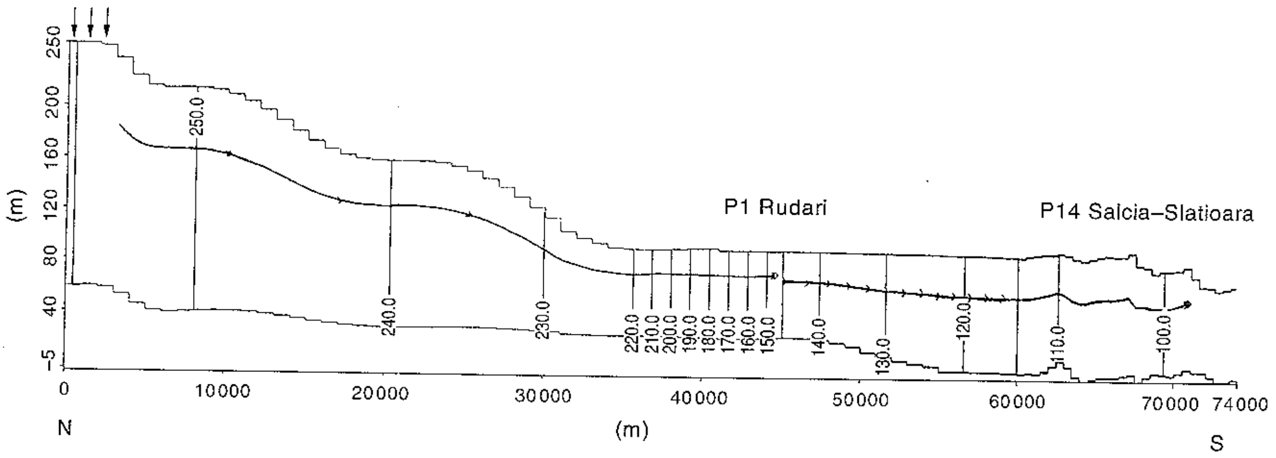

Fig. 4. Cross-section model for a recharge of 100 mm $year^{-1}$ with the distribution of piezometric heads. Arrows indicate the recharge area.

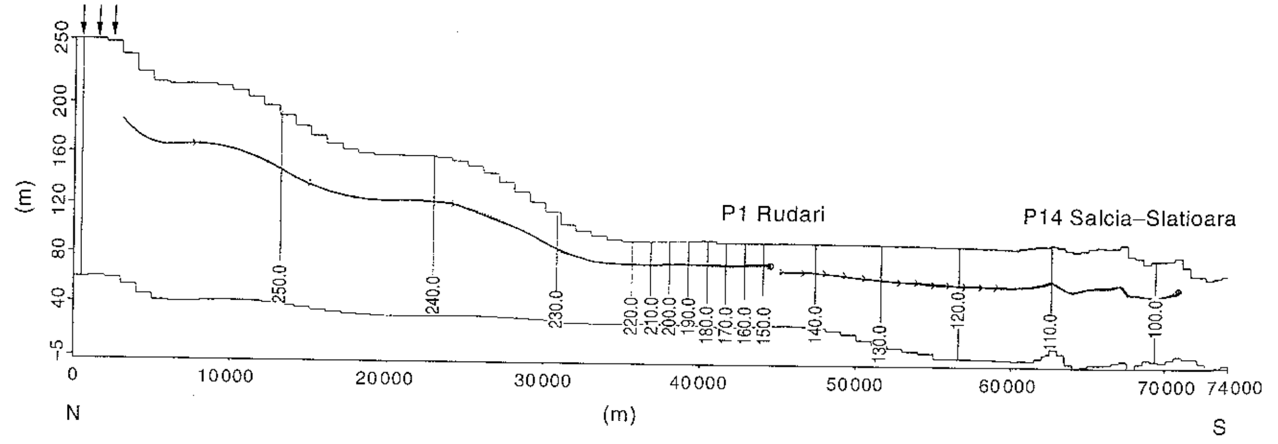

Fig. 5. Cross-section model for a recharge of 200 mm $year^{-1}$ with the distribution of piezometric heads. Arrows indicate the recharge area.

furthermore, in a longer transit time between the Drăgăşani and Slatina regions.

ESTIMATED GROUNDWATER RESOURCES FOR THE WATER SUPPLY

Taking into account the regional scale and the simplicity of the 2D vertical model, the extrapolation of the hydraulic conductivity and effective porosity values to a larger area is risky. However, a very simple calculation could be made to estimate the lateral groundwater inflow in the confined aquifer system, on the basis of the available data from several wells in the Olt and Vâlcea counties. The main lateral inflow comes from the north, however, inflows also come from the west, north-west, north-east and east. The average thickness of the aquifer system with renewable groundwater is considered to be 150 m. Inflow through a boundary (Q) is calculated as follows:

$$Q\ (\mathrm{m^3\,day^{-1}}) = K \times M \times i \times l$$

where K is the global hydraulic conductivity of the confined aquifer system ($\mathrm{m\,day^{-1}}$); M is the average thickness of the aquifer system (m); i is the hydraulic gradient (dimensionless); and l is the length of the recharge boundary (m).

The sum of lateral inflows (Table 6) is 12 735–52 200 $\mathrm{m^3}$ per day. The current total abstraction rate at the Slatina wellfields is approximately 33 260 $\mathrm{m^3}$ per day (Albu *et al.* 1996). After reconditioning works it is expected that the Slatina wellfields will provide a total abstraction rate of almost 51 235 $\mathrm{m^3}$ per day (Albu *et al.* 1996; Dinu *et al.* 1997). The abstraction rate of the wellfields from Drăgăşani is approximately 15 000 $\mathrm{m^3}$ per day (Baciu 1987). This means that a total abstraction rate of 66 235 $\mathrm{m^3}$ per day is required to ensure the water supply that is taken from the main wellfields only. This value is more than the sum of lateral inflows (52 200 $\mathrm{m^3}$ per day). Moreover, there are other wells, for which the abstraction rates were not included.

The confined aquifer is also supplied by leakage from the shallow aquifer. Inflow by leakage was not taken into account here. An initial numerical model of the whole aquifer system (comprising the shallow aquifer and the confined aquifer) in the region of the Slatina wellfields provided a total leakage inflow of 15 777 $\mathrm{m^3}$ per day over approximately 110 $\mathrm{km^2}$ (Dinu *et al.* 1997). Therefore, leakage is assumed to be rather important, but occurs especially in the area of the wellfields, due to the decrease of the piezometric heads in the confined aquifer. Leakage of the same order of magnitude cannot be expected outside the area of the wellfields.

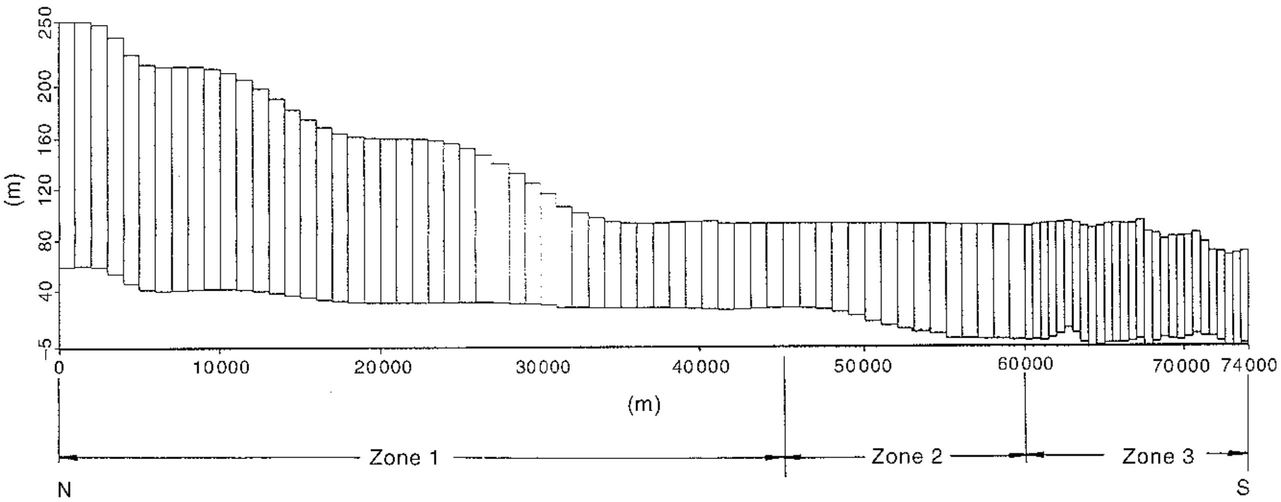

Fig. 6. Cross-section model showing the zones for calibration parameters. Zone 1: $K/n_e = 2.5 \times 10^{-4}\ \mathrm{m\,s^{-1}}$; $K = 1.25 \times 10^{-5}\ \mathrm{m\,s^{-1}}$; $n_e = 5\%$. Zone 2: $K/n_e = 1.25 \times 10^{-5}\ \mathrm{m\,s^{-1}}$; $K = 5 \times 10^{-7}\ \mathrm{m\,s^{-1}}$; $n_e = 4\%$. Zone 3: $K/n_e = 10^{-3}\ \mathrm{m\,s^{-1}}$; $K = 7 \times 10^{-5}\ \mathrm{m\,s^{-1}}$; $n_e = 7\%$. K, Global hydraulic conductivity of the confined aquifer system; n_e, effective porosity.

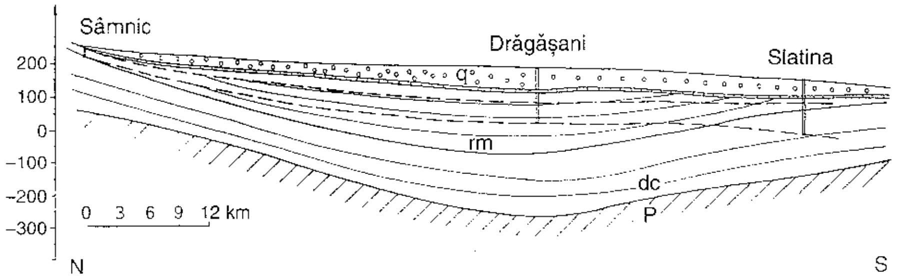

Fig. 7. Cross-section of the left bank of the River Olt. q, Quaternary (terrace deposits: sands, gravels, clays, marls); rm, Romanian (sands, clays, marls); dc, Dacian (sands, clays); P, Pontian (marls); (——), stratigraphic limit; (——), lithological limit; (||||), aquitard below the Quaternary deposits; (- - -), exploited interval in the confined aquifer system.

Table 6. Estimated lateral inflows through the recharge lateral boundaries of the confined aquifer system

Inflow direction	K (m day^{-1})	M (m)	i	l (km)	Q (m^3 day^{-1})
North	0.8–4	150	$(1.3–2) \times 10^{-3}$	30	4680–36 000
North–west	0.2	150	1×10^{-3}	15	450
North–east	0.1–0.4	150	$(3.8–4) \times 10^{-3}$	15	855–3600
East	0.3–1	150	$(3–4.5) \times 10^{-3}$	10	1350–6750
West	1.5	150	1.2×10^{-3}	20	5400

K, global hydraulic conductivity of the confined aquifer system; M, average thickness of the aquifer system; i, hydraulic gradient (dimensionless); l, length of the recharge boundary; Q, inflow through boundary.

The conclusion of this simplified calculation is that the groundwater resources of the confined aquifer system are limited. Therefore, the water supply for human use and industrial activities in the urban region should not increase without restrictions. The groundwater resources should also be used for the water supply of the rural regions of both the Olt and Vàlcea counties.

CONCLUSIONS

The isotope analyses of the samples from the deep aquifer, the shallow aquifer and the surface waters in the lower basin of the River Olt confirmed the hypothesis of local water interference in a regional aquifer system. It is rather difficult to demarcate the limits of the aquifer system both in space and in thickness.

The tritium contents in the two aquifers are usually well differentiated. The ^{18}O analyses show that the supply zone of the confined aquifer is higher than that of the shallow aquifer. The ^{14}C-based groundwater ages of the confined aquifer made possible the calibration of a 2D vertical model for calculated transit times. Through calibration, the model provided global values of hydraulic conductivity and effective porosity of the confined aquifer system for a north–south cross-section. The model also provided a better representation of the supply of the deep aquifer system in the northern part of the study area.

Because of the contamination of surface waters and the shallow aquifers, the confined aquifer system is the main source of the water supply in the Olt and Vàlcea counties. As the groundwater resources of the confined aquifer are limited, adequate management should be carried out, in order to guarantee a water supply for both human and industrial uses in the urban region, as well as for the rural region. A more detailed study on groundwater resources is highly recommended, which should be the background for any extension of the water supply.

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