Buletinul Ştiinţific al Universităţii "POLITEHNICA" din Timişoara

Seria HIDROTEHNICA

TRANSACTIONS on HYDROTECHNICS

Tom 57(71), Fascicola 1, 2012

Up-to-date hydrodynamic and hydrochemical state of the Fratesti deep aquifer system in the Bucharest area

Ivan Irina Maria [1] Popa Iulian [1]

Abstract: The aim of this paper is to assess the current hydrodynamic and hydrochemical state of the Fratesti confined aquifer system in the Bucharest city area. In past decades, the Fratesti deep hydrostructure was heavily exploited, resulting in a significant depression of the piezometric surface, with a maximum value in 1981. In 2011, a field campaign for piezometric level measurements in deep wells was conducted. The current piezometric map of the Fratesti A aquifer, built using geostatistical methods, shows an increase in the piezometric level by up to 25 m. The paper also presents the concentration distribution of ammonium in the groundwater, parameter of which the maximum permissible concentration is exceeded.

Keywords: aquifer system, piezometric map, geostatistical methods, ammonium concentration.

1. INTRODUCTION

The Fratesti deep aquifer system is considered a strategic source of water supply for the Bucharest area. It has been widely exploited in the past, with a total flow rate of 1593 l/s in 1981, in the city area [1]. Presently, the city is supplied mainly from surface waters. The groundwater abstraction rate for the aquifer system in this area is about 333.96 l/s (70.06 l/s for household consumption and 263.9 l/s for industry and other purposes). Currently, there are 597 exploitation deep wells in the Bucharest area (according to the National Institute of Hydrology and Water Management, NIHWM, for the year 2010).

The objective of this paper is to assess the current hydrodynamic and hydrochemical state (NH_4^+ ion concentration) of the Fratesti aquifer system in the Bucharest area, in particular of its uppermost unit (the Fratesti A aquifer). The necessity of hydrodynamic evaluation is due to the changing exploitation regime of the aquifer system after 1990s. Although numerous local studies have been conducted, there is no regional study with actual data on this aquifer system in the last 15 years. Ammonium content evaluation is needed because the RoAg13-Bucharest groundwater body (within the Fratesti Formation) was declared water body at qualitative risk regarding NH_4^+ and NO_2^- indicators in 2003 [5].

The investigated region is the area within the Ring Road of Bucharest (about 390 km^2) (Fig. 1).

Evaluation of the actual hydrodynamic and hydrochemical state (ammonium content) relies on the information from 66 deep wells (Fig. 1). In 2011, a field campaign for piezometric measurements was conducted. Chemistry data was obtained from the deep wells users. In data processing, geostatistical methodology was used (spatial variability analysis, kriging interpolation).

Assessment of the aquifer state is the base for numerical modeling, which is the next step in the aquifer system analysis.

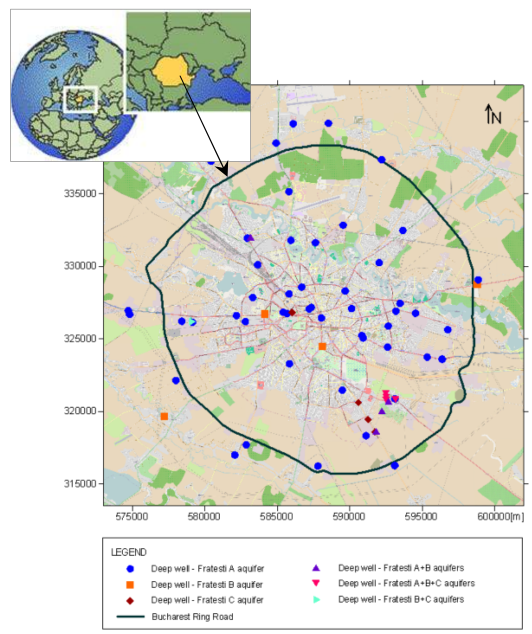

Fig. 1 Study area (background map: Google Maps image)

2. HYDROGEOLOGICAL SETTING

Study area is located in a plain region, crossed by the Colentina and Dambovita rivers. The altitudes range between 55-95 m.

The Fratesti deep aquifer system is part of the Candesti-Fratesti hydrostructure, having regional development in the southern part of Romania and representing the most important drinking water source in this area [6]. This corresponds to the RoAg12-Eastern Wallachian Depression deep groundwater

[1]University of Bucharest, Faculty of Geology and Geophysics, Department of Geological Engineering, 6 Traian Vuia Street, Sector 2, 020956 Bucharest, Romania, irina.ivan@ymail.com, iulian.popa@g.unibuc.ro.

body, from which the RoAg13-Bucharest groundwater body was delimited. Deep groundwater bodies studied in the Bucharest area are assigned to the Arges-Vedea Water Basin Administration (AVWBA) [5] (Fig. 2).

In the study area, several Quaternary aquifer formations underlain by the Fratesti Formation were previously described [1]; [5]; [6]; [7] (Fig. 3):

- Colentina Gravels (part of the Formation Deposited by the Actual Rivers [3]) – Upper Pleistocene gravels and sands, situated at depths of 15-20 m, with thickness of 5-15 m and depth to piezometric level of 5-10 m.
- Mostistea Formation – Middle Pleistocene medium-fine sands, situated at depths of 20-42 m, with thickness up to 30 m and depth to piezometric level of about 12 m.
- Coconi Formation – sand layers within a 40-150 m thick clayey or clayey-marly formation, aged Lower-Middle Pleistocene; these sands do not allow accumulation of large water amounts.

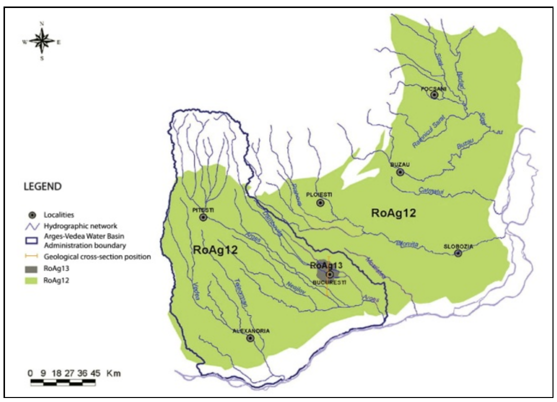

Fig. 2 Deep groundwater bodies assigned to the AVWBA (modified after AVWBA, 2008)

Lower Pleistocene Fratesti Formation (Lower Sands and Gravels Horizon [4], Fratesti Strata, Liteanu, 1953 or Lower Danube Subformation, Enciu, 2000, 2007 in [3]) contains a succession of upfinning sedimentary rhythms. Each one includes coarse-grained sand, sometimes sand and gravel, medium and fine-grained sand and clay. The sand layers (locally sand and gravel) have the greatest thickness (Enciu *et al.,* 1995, in [3]).

In the study area, the Fratesti aquifer system is confined, multi-layered, including A, B and C aquifers [4], separated by continuous clay intercalations. The aquifer system top depth ranges from 60 m (southern part of the investigated area) to 250 m (northern part) and the bottom depth varies between 130 m (south) and 420 m (north) [1]. From a structural point of view, there is a gradual lifting of the aquifer system from north to south (Fig. 3).

Average thickness of the aquifers in the investigated area is about 25-30 m (A aquifer), 20-25 m (B aquifer) and 25-30 m (C aquifer). South of Bucharest, due to the structural uplifting, the Fratesti Formation comes into contact with the alluvium of the Arges and Neajlov rivers valley [1].

The main hydrogeological parameters of the Fratesti aquifer system are transmissivity, ranging between 350-1200 m^2/day, and storage coefficient, varying from 10^{-4} to $5x10^{-4}$ [2]. A detailed research of these parameters will be undertaken using a database that includes 840 deep wells, drilled between the years 1900-2011.

In the study area, general groundwater flow direction is west to east in all three aquifers (A, B and C). Piezometric levels are different for the three aquifers, with similarities between the B and C aquifers [1].

The piezometric levels of the Fratesti aquifer system were recorded in deep wells drilled over time. In one of the first deep wells drilled in Bucharest (Cotroceni deep well, built between 1865-1870 at 253 m depth), the piezometric level of the B aquifer was +73 m above sea level (asl). In the Ciurel deep well (1902), the piezometric level was +68 m asl for the A aquifer and +72 m asl for the C aquifer [4]. Both wells were situated in the central-western part of Bucharest.

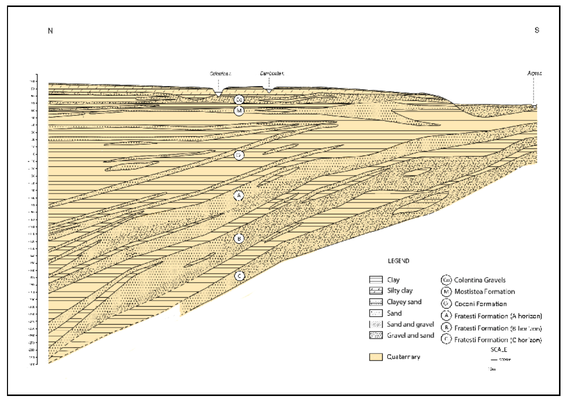

Fig. 3 N-S geological cross-section (modified after Cineti *et al.,* 1990)

By the early 1990s, deep wells indicated piezometric level lowering with increasing aquifer system exploitation, especially in the case of the A aquifer. It has been emphasized the existence of a depression cone in the A aquifer piezometric surface, in the central-eastern part of the study area (Fig. 4). The +12.5 m asl minimum piezometric level was a consequence of the A aquifer exploitation with 1183 l/s in the Bucharest area (October 1981) [1].

During 2000-2010, due to the decrease in water abstraction from the Fratesti aquifer system, the existing operating wells in the study area recorded an increase in the piezometric levels for all three aquifers. According to our database, the maximum increase was of 25 m in the piezometric level of the A aquifer in 2010, compared to the one in 1981.

3. MEASUREMENTS AND DATA

Assessment of the current hydrodynamic and hydrochemical state of the Fratesti aquifer system was based upon data from 66 deep wells (80-275 m depth); data is stored in the archives of the NIHWM, *Prodac Ltd.*, *Geo Aqua Consult Ltd*. or local users.

Drilling data refers to: borehole depth and year of execution, lithology, open aquifer layers, piezometric level at the execution moment, flow rate, screen diameter and position. The wells geographical coordinates X and Y (in the Stereo 1970 coordinate system) and the corresponding terrain elevations were added using ArcMap 9 software, by point extraction from georeferenced maps and digital elevation models, respectively.

In the summer of 2011, piezometric measurements in 30 deep wells were undertaken. There have been performed 25 measurements for the A aquifer, two for the B aquifer, one for the C aquifer, one for A+B aquifers and one for B+C aquifers.

Piezometric level measurements were performed using a *Solinst Model 101* water level meter and the geographical position was achieved with a *Geonaute SiRFstarIII* GPS device.

Ammonium content in groundwater was determined in 46 deep wells as follows: 33 values for the A aquifer, three for the B aquifer, three for the C aquifer, three for A+B aquifers and 4 values for A+B+C aquifers.

In order to assess the current contamination risk of the aquifer system from surface waters, two water samples from the Neajlov and Arges rivers were collected (Fig. 5).

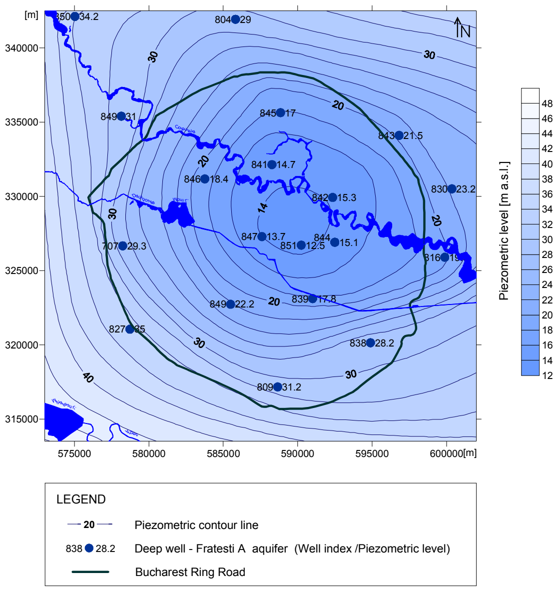

Fig. 4 Piezometric map of the Fratesti A aquifer referred to 1981 (re-drawn after [1])

Fig. 5 Surface water sampling points (2011)

4. METHODOLOGY

Hydrodynamic and hydrochemical state of the Fratesti A aquifer have been evaluated using the piezometric map and the concentration map of ammonium, selected as a water quality parameter of which the maximum permissible concentration (MPC) of 0.5 mg/L was exceeded.

The maps were obtained by universal punctual kriging (case of the piezometric level) and ordinary punctual kriging (case of the NH_4^+ ion content) [9]; [10]. This method was chosen because of the high variability of the piezometric levels and ammonium content. Kriging application was preceded by the anisotropy analysis of the studied parameters [10].

Anisotropy analysis was performed using as main tool the variogram function:

$$\gamma(\vec{d}) = \frac{1}{2 \cdot N(\vec{d})} \sum_{(i,j)|d_{ij}=\vec{d}}^{N(\vec{d})} (v_i - v_j)^2 \qquad (1)$$

where:

$N(\vec{d})$ – set of observation pairs situated at distance $\vec{d}$;

$\vec{d}$ – distance between the points i and j for which v_i and v_j are determined.

Calculation of the anisotropy parameters (anisotropy ellipse orientation θ and anisotropy ratio $\eta = \frac{R}{r}$) was performed using the variogram surface for the studied parameters.

Estimation of NH_4^+ content and piezometric level was based on minimizing the variance of estimation errors, summarized in the kriging systems:

a. for ordinary kriging:

$$\begin{cases} \sum_{j=1}^{n} w_i \cdot \tilde{\gamma}_{ij} + \mu = \tilde{\gamma}_{i0}, \forall i = 1,2,\ldots,n \\ \sum_{i=1}^{n} w_i = 1 \end{cases} \qquad (2)$$

b. for universal kriging:

$$\begin{cases} \sum_{j=1}^{n} w_j \cdot \tilde{\gamma}_{ij} + \sum_{l=1}^{k} \mu_l \cdot f_l(p_i) = \gamma_{i_0},\ i = 1,2,\ldots,n \\ \sum_{i=1}^{n} w_i \cdot f_l(p_i) = f_l(p_0),\ l = 1,2,\ldots,k \end{cases} \qquad (3)$$

where:

$\tilde{\gamma}_{ij}$ – value of the variogram model;
w_i – v_i weight;
μ – Lagrange parameter;
f_l – regional trend function in the observation points p_i ($i = 1,2,...,n$);
n – number of observation points.

Values of the two parameters (NH_4^+ content and piezometric level) were estimated using the following relationship:

$$v_{p_0}^{*} = \sum_{i=1}^{n} w_i \cdot v_i \qquad (4)$$

For the minimum variance of the estimation errors, the following relationships were used:

a. for ordinary kriging:

$$\widetilde{\sigma}_R^2 = \sum_{i=1}^{n} w_i \cdot \widetilde{\gamma}_{i0} + \mu \qquad (5)$$

b. for universal kriging:

$$\widetilde{\sigma}_R^2 = \sum_{i=1}^{n} w_i \cdot \widetilde{\gamma}_{i0} + \sum_{j=1}^{k} \mu_j \cdot f_j(p_0) \qquad (6)$$

5. HYDRODYNAMIC MODEL

In the study area, the hydrodynamic model of the Fratesti A aquifer shows an anisotropic distribution of the piezometric level with minimum variability direction NW-SE and maximum variability direction SW-NE (Fig. 6). There is a regional trend of decreasing piezometric level along SW-NE direction.

Anisotropy parameters are the following:

- anisotropy ratio $\eta = \frac{R}{r} = 1.53$;

- anisotropy angle $\hat{\theta} = 119^0$.

The variogram model is a power-type model [8], with exponent λ = 1.9, scale C = 1.1 and length A = 3500 m (Fig. 7). Relative errors of the piezometric distribution evaluation, induced by the variogram model, are about ±5%; these values were obtained by variogram model cross-validation.

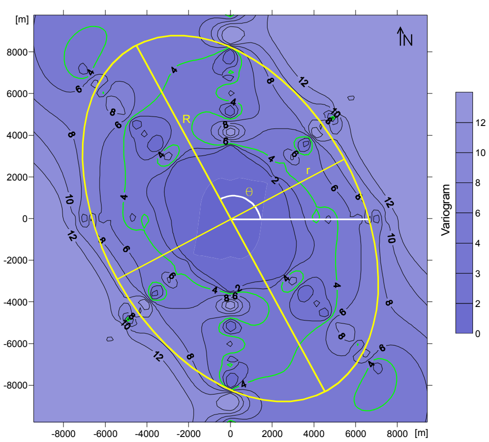

Fig. 6 Variogram surface of the piezometric level forthe Fratesti A aquifer (2011)

Assessment of the groundwater flow net was based on universal kriging, which allows removal of the regional trend negative effect.

Current piezometric map of the A aquifer (Fig. 8) was built using Surfer 8 by *Golden Software*. By comparison with the piezometric level measured in 1981 (Fig. 4), it can be noticed a current increase of about 15-20 m, with a maximum value of about 25 m (in the central-eastern part of the study area). This is due to a significant decline in groundwater abstraction. Piezometric levels of the Fratesti A aquifer in the study area decrease from west to east, from +51 m asl to +35 m asl.

The general groundwater flow direction in the A aquifer is west-east, with components from both northwest and southwest. Hydraulic gradients range from 0.45 to 2.90‰, with average of about 1.4-1.5‰.

Based on sparse piezometric measurements for the B and C aquifers, we observed the following:
- an increase of 11.7 m in the piezometric level of 2011 compared to the one of 1978 for the case of the B aquifer (in the eastern part of the study area);
- an increase of 14.7 m between the piezometric level of 1979 and the one of 2011 for the case of the C aquifer (in the central-western part of the study area).

These variations can be explained by less exploitation rates of the B and C aquifers compared to the A aquifer [1]; [2].

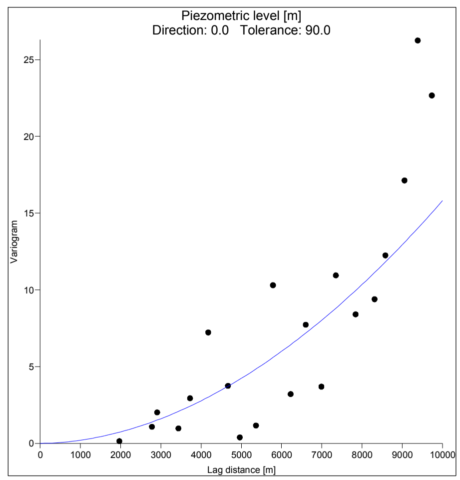

Fig. 7 Omnidirectional variogram model of the piezometric level for the Fratesti A aquifer (2011)

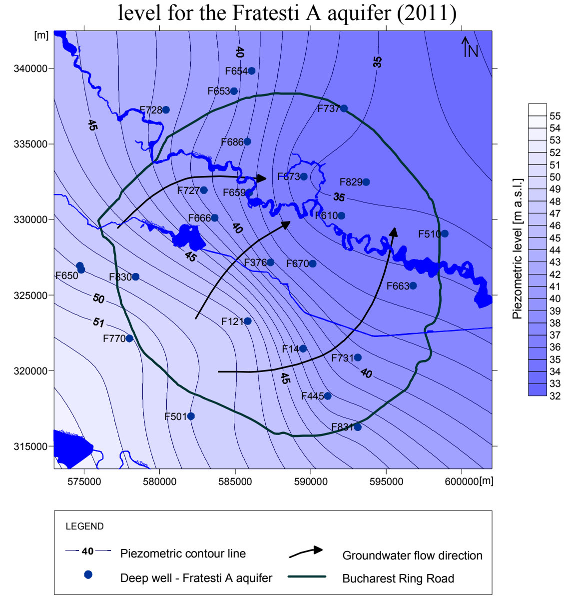

Fig. 8 Piezometric map of the Fratesti A aquifer (2011)

The hydrodynamic model we obtained might be affected by uncertainties when determining elevation values. Validation of the hydrodynamic model will be performed within the further mathematical modeling of the Fratesti aquifer system.

6. HYDROCHEMICAL MODEL

The hydrochemical model of the Fratesti A aquifer has an anisotropic content distribution with minimum variability direction WNW-ESE and maximum variability direction NNE-SSW (Fig. 9).

Anisotropy parameters are the following:

- anisotropy ratio $\eta = \frac{R}{r} = 1.52;$

- anisotropy angle $\hat{\theta} = 167^0.$

Variogram model is a power-type model [8], with exponent λ = 1.4, scale C = 0.12 and length A = 9000 m (Fig. 10).

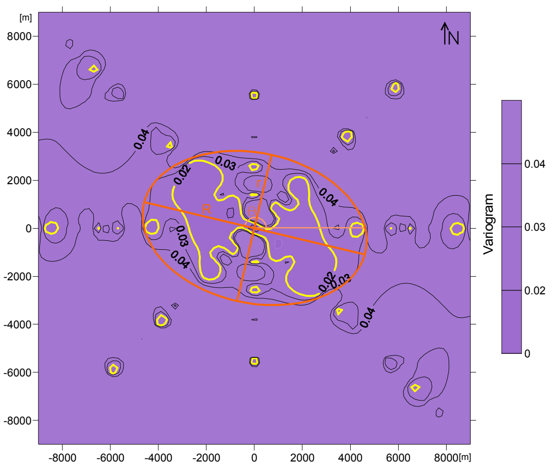

Fig. 9 Variogram surface of ammonium concentration for the Fratesti A aquifer (2011)

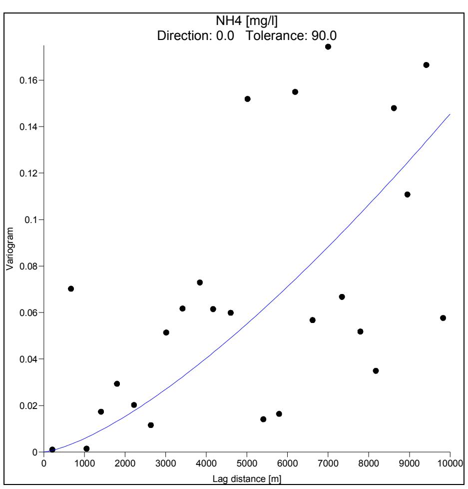

Fig. 10 Omnidirectional variogram model of ammonium concentration for the Fratesti A aquifer (2011)

Concentration map of ammonium in groundwater (Fratesti A aquifer) was built using the information from 33 deep wells (Fig. 11). Estimation errors have values of 0.1 in areas with high density of deep wells, such as the central, southern, eastern and southeastern part of the study area, exceeding 0.2 in the northern, northwestern, western-southwestern and central-southern parts (Fig. 12).

We can observe an irregular distribution of ammonium content in the study area (Fig. 11). In the northern half, values generally lies below the MPC, except for the east, with content greater than
0.7 mg/L. In the southern half, except for the southernmost part, the MPC is exceeded by a maximum content greater than 1.3 mg/L.

In the case of the B aquifer, NH_4^+ concentration is about 1.38 mg/L in central-southern part of the study area and 2.61 mg/L in the central-western part. In the case of the C aquifer, NH_4^+ concentration values increase to 7.34-10.07 mg/L (in southeast). MPC exceeding is also recorded for A+B and A+B+C aquifers (mixed waters).

We can state that NH_4^+ content increases from the A aquifer to the C aquifer, exceeding 20 times the MPC within the C aquifer, at least in southeast.

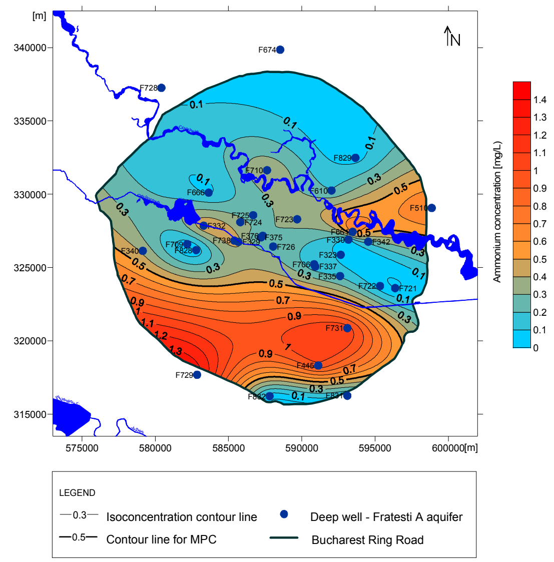

Fig. 11 Map of ammonium concentration for the Fratesti A aquifer (2011)

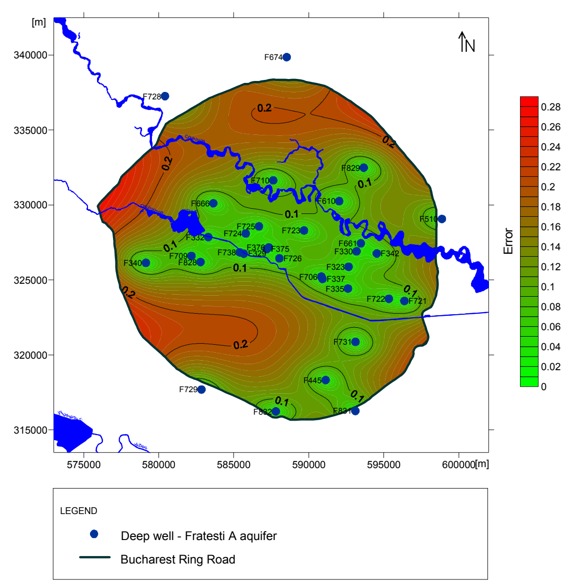

Fig. 12 Error map of ammonium concentration estimation for the Fratesti A aquifer (2011)

These values are consistent with the exceeding of the MPC for NH_4^+ mentioned in previous studies [1]; [5]. In 2007, groundwater quality in the RoAg13-Bucharest water body was monitored by 8 observation points. It was considered that this water body had a good qualitative status. However, the monitoring network had not enclosed the entire city area (missing observation points in south) (AVWBA, 2008).

In previous research, it was assumed that nitrogen compounds (NH_4^+ and NO_2^-) were transferred into the Fratesti aquifer system from the Neajlov and Arges alluvium, due to partial recharge of the aquifer system in this area [2].

Analysis of the two water samples from the Neajlov and Arges rivers in 2011 revealed concentration values below 0.06 mg/L for NH_4^+ (and below 0.09 mg/L for NO_2^-), indicating that there was no pollution of the aquifer system from the mentioned rivers at the sampling moment. However, these values are temporarily, but the effect of a previous transfer of the compounds into the aquifer system from surface waters should not be neglected.

Hypothesis of a possible endogenous nature of the NH_4^+ ion, as an alternative for its anthropic/exogenous origin, needs to be studied through extensive research. Studies will consider correlations of ammonium content with aquifers depth, physical-chemical properties of groundwater (electrical conductivity, pH, alkalinity, Na^+ content), as well as with the presence of organic matter (coal/bituminous intercalations) into the aquifer system.

7. CONCLUSIONS

The Fratesti deep aquifer system research has been conducted during a field campaign for measuring the piezometric level in 30 deep wells, in the year of 2011. Also, the values of ammonium concentration measured in 46 deep wells have been used.

Piezometric map of the Fratesti A aquifer referred to 2011 was built using geostatistical methods. In the study area, the hydrodynamic model has an anisotropy with maximum variability direction SW-NE of the piezometric level. It was revealed an increase of about 15-20 m (with a maximum value of 25 m in the central-eastern area) in the piezometric level of 2011, compared to the piezometric level measured in 1981. For the B and C aquifers, sparse measurements also indicated increases in the piezometric level of 2011, compared to the piezometric level of 1978-1979.

Concentration map of the NH_4^+ ion in the groundwater of the Fratesti A aquifer (in 2011) displayed exceeding of the MPC in the eastern part and the southern half of the study area, with a maximum greater than 1.3 mg/L in southwest.

Analysis of water samples from the other two aquifers (B, C) showed greater NH_4^+ contents, exceeding 20 times the MPC value within the C aquifer, in southeast. Hypothesis of endogenous origin of ammonium ion needs to be studied by correlations with other physical-chemical groundwater parameters.

Validation of the hydrodynamic and hydrochemical elements will be performed during further research of the Fratesti deep aquifer system.

ACKNOWLEDGMENTS

This work was partially supported by the POSDRU/88/1.5/S/61150 *Doctoral Studies in the field of life and Earth sciences* project, co-financed through Sectorial Operational Program for the Development of Human Resources 2007-2013 from the European Social Fund.

REFERENCES

[1] *M., Bretotean,* Underground aquifer systems analysis by mathematical modeling for water resources assessment, University of Bucharest, 1996.

[2] *M., Bretotean, G., Stanescu*, Pollution risk of the Fratesti Strata strategic aquifer in the Bucharest exploitation area and its combating, *Hidrotehnica*, no. 3, vol. 52, Bucharest, 2007.

[3] *R., Lacatusu, N., Anastasiu, M., Popescu, P., Enciu*, Bucharest City Geo-Atlas, Estfalia Publishing, Bucharest, 2008.

[4] *E., Liteanu,* Geology of the city of Bucharest, Research and Exploration of the Underground Resources Committee, Bucharest, 1952.

[5] *R., Macalet, M., Badescu, M. N., Minciuna*, Considerations about groundwater bodies from southern part of Romania, *Geo-Eco-Marina* no. 14 – supplement no. 1, Bucharest, 2008.

[6] *M. C., Melinte et al.,* Scientific fundamentation, conceptual and numerical modeling of the aquifer structures for the protection and sustainable development of the groundwater resources from southern part of Romania, PNCDI II Project, Bucharest, 2007.

[7] *M., Palcu, M. C., Melinte, A., Iurkiewicz, Gh., Witek, A., Rotaru.* Preliminary inventory of the aquifer structures from southern part of Romania, *Geo-Eco-Marina* no. 14 – supplement no. 1, Bucharest, 2008.

[8] *Y., Pannatier,* Variowin: Software for spatial data analysis in 2D, Springer Verlag, New York, 1996.

[9] *D., Scradeanu, G., Mihnea,* L'étude des variations spatiales des grandeurs hydrogéologiques a l'aide du krigeage, University of Bucharest Annals, 1987.

[10] *D., Scradeanu, R., Popa*, Applied Geostatistics, Spatial structures estimation, University of Bucharest Publishing, 2003.