GROUNDWATER RESOURCES AND RESERVES EVALUATION IN THE SOUTHERN PART OF SUHARD MOUNTAINS

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Abstract: *The evaluation of groundwater resources and reserves was performed in Ousorul – Livada hydrostructure, located in the southern part of Suhard Mountains, by using a site-specific algorithm, specially developed for this purpose. The general evaluation of groundwater potential was completed by basic climate and hydrological studies. Therefore, the specific groundwater discharge was extracted from river hydrographs while the value of yearly evopotranspiration was calculated from climate data. The conceptual model of the hydrostructure, developed in a previous phase of the research work, was further completed with hydrogeological parameters, calculated from pumping tests performed in four boreholes, by graphic-analytical methods*
Key words: *evapotranspiration, specific groundwater discharge, pumping tests, resources and reserves*

1. Introduction

The objective of this scientific paper is to calculate the groundwater resources and reserves in a study area from the south part of Suhard Mountains. The studied perimeters is bordered to the South by Dorna river, to West by Cosna rivers, to North by the water divide between Catariga and Ciotina valleys until Livezii peak (1,389 m), continued to Ousorul crest (1,638 m), and the water divide towards Haju peak (1,238 m), and to the East by the water divide between Haju and Selesvar rivers. The perimeter was such selected to overlay the hydrographic basins.

2. Methods

The field works were conducted based on a research contract for groundwater resources, while the data processing and interpretation were realized as part of doctoral thesis proposed by Valentin-Ion Boian "*Complex hydrogeological research in flysch area of Carpathian orogen*". The conceptual model was developed by the authors as part of the same doctoral program, and the results were published in Revista Minelor, 2019, Vol. 25, Issue 4, p24-28.

2.1. Climate works

Considering that groundwater recharge is done by surface infiltration (rain, snow melting, morning dew), the research program included weather monitoring, by using the automatic digital Davis station, WeatherLink model, with continuous data storing. The weather station was located in Dealu Floreni area, STEREO70 coordinates: X = 517,255, Y = 652,104, at an altitude of 890 m, consisting of weathervane for wind speed and direction, temperature sensor, and pluviometer for rain measurement, with reading frequency of 2h and continuous data storage of 1 month. The weather monitoring was extended continuously during August 2005 – October 2009.

Starting from the general water balance equation:

$$P = E + R + I,$$

where: *P = total precipitation, E = evapotranspiration, R = surface runoff, I = groundwater infiltration*,

we can calculate the yearly value of evapotranspiration, by using Turc formula, as described by Roberto Chetoni in *Acque Minerali e Termali, Italgrafica Segale Segrate, 2000, chapter 9.7.17*:

$$E_r = \frac{P}{\sqrt{0.9+\frac{P^2}{L^2}}}; L = 300 + 15T + 0.05T^3$$

where: *Er = real evapotranspiration, in mm/yr, P = yearly precipitation in mm/yr, L = evaporation capacity, T = yearly mean air temperature, in °C*

2.2. Hydrological research

The hydrological study was conducted in the following steps:

- Mapping of hydrographic basins out of the level curves exported from satellite images SRTM (Satellite Radio Topographic Mission);
- Hydraulic measurements on the downstream section of all collectors from the study area, in order to calculate the limnimetric keys;
- Flow monitoring of all collectors, during June 2008 – May 2010;
- Calculation of river flow rates at to 5% and 80% probability from the time series, corresponding to storm events and minimum discharge values;
- Calculation of main hydro-morphological parameters for each hydrographic basin.

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The hydrographic basins were mapped according to geomorphological rules, by digitizing the topographical map. For the main river collector of each hydrographic basin, the morphology and flow rate were measured *in situ*, in order to calculate the limnimetric keys. In parallel with the measurements for the limnimetric keys, there was implemented a weekly monitoring program for the water level, during June 2008 – June 2010.

The hydro-morphological parameters calculated are the surface of hydrographic basins, flow rate at 5% and 80% return rate, specific groundwater discharge, and the contribution of groundwater discharge to total flow rate. The hydro-morphological calculation followed the methodology described by *Ugo Maione* in *Le Piene Fluviale, 2nd Edition, La Goliardica Pavese, 1999*. In this handbook, the author describes the various possibilities to extract the groundwater discharge value from the storm events hydrographs or from multiannual hydrographs computed for large basins. And the most straightforward method consists in integrating the area underneath the minimum flow rate curve. For the current paper, the 5% and 80% return rates were selected to calculate the reference flow rates for storm events and groundwater discharge, as probability of corresponding flow rate in the time series.

The specific groundwater discharge, expressed in L/s/km^2, as mean value for the hydrographic basin, is calculated by dividing the groundwater discharge (which corresponds to the 80% return rate of the river flow rate in the time series) to the basin area. This parameter is very valuable to understand the groundwater potential. Practically, by multiplying the specific groundwater discharge with the estimated depression cone are of the pumping boreholes, one can understand the potential exploitation flow rate.

2.3. Pumping tests

The hydraulic properties of aquifers (transmissivity, hydraulic conductivity, storage coefficient) were determined by graphical-analytical processing of pumping tests, performed in the research boreholes, without piezometers. In the study area, there were 5 boreholes drilled.

In borehole F1, the pumping tests couldn't be performed, considering there was only limited infeed of groundwater from the clay-marly formations. The pumping test data was collected on-site in hard-copy documentation, and subsequently converted in electronic format and processed in InfinitExtent and StepMaster software.

The pumping tests data processing follows the detailed methodology described by *Antonio di Molfeta*, in *Ingegneria degli Acquiferi, Politeko, Torino, 2002, chapter 6.2.2.1*, out of which we retain the summary table with the diffusivity equation solutions, the computed parameters and type of diagram used in the graphical plotting of pumping tests data.

Tipul de acvifer	Metoda	Principiul de interpretare	Ecuația	Parametrii ce se pot determina	Diagrama s vs. t
Sub presiune	Theis	Curba experimentală	$s=\frac{Q}{4\pi T}W(u)$	T, S, K_r	log-log
	Jacob	Linearizare	$s=\frac{Q}{4\pi T}ln2.25\frac{tT}{Sr^2}$	T, S, K_r	semilog
Parțial sub presiune	Walton	Curba experimentală	$s=\frac{Q}{4\pi T}W(u,\frac{r}{B})$	T, S, B, K_r	log-log
	Hantush	Punct de inflexiune	$s=\frac{Q}{4\pi T}W(u,\frac{r}{B})$	T, S, B, K_r	semilog
Cu nivel liber	Neuman	Curba experimentală	$s=\frac{Q}{4\pi T}W(u_a,u_b,\beta)$	T, S, n_e, K_r, K_v	log-log
	Jacob	Linearizare	$s=\frac{Q}{4\pi T}ln2.25\frac{tT}{n_e r^2}$	T, n_e, K_r	semilog

Fig. 1. *Main methods for pumping test data processing, constant flow rate, transitory regime*

where: *s = drawdown, Q = pumping flow rate, T = transmissivity, S = storage coefficient, r = radius of depression cone, t = time,* $W(u_a,u_b,\beta)$ *= Theiss function,* n_e *= efficient porosity, K = hydraulic conductivity, B = leakage factor*

3. Results

3.1. Computation of yearly evapotranspiration value

The main advection of atmospheric masses is made from the W-WNW and NE directions, determining the character of temperate climate - continental, with oceanic and boreal nuances. The dominance of westerly winds stands out as an essential characteristic of the Dornelor basin climate, imposed by the regional atmospheric circulation, and favored by the orographic opening represented by the low area of Bârgăului mountains (to the west), in contrast to the Suhard and Călimani mountains (towards NW, E, SW).

Between August 2005 - October 2009, there was a decreasing trend in the amount of precipitation falling annually, as well as a decrease in the maximums in the rainiest period of the year, May - August. This trend is due to the changes in the general circulation of the atmosphere, registering in recent years the increasing participation of western air masses, compared to the north-northeast, boreal. If in 2005, the atmospheric circulation in the strictly Western direction had an incidence of about 15%, in the following years it increases to 16%, 18%, 25%, and 20% respectively in 2009. The western air masses carrying significant amounts of humidity in the formation areas, reach the area of the Dornelor basin after strongly discharging on the Western frame of the Western Carpathians and then a second time on the Western slope of the Rodna mountains, giving rise to increased nebulosity, but lacking significant precipitation in the Dornelor depression. If in the months I - X of 2006 there were 832 mm of rainfall, this amount decreased progressively, to 709 mm, 710 mm, reaching 563 mm in 2009. In terms of the distribution of the amount of annual rainfall, there is a cyclicality, in the sense that in 2006 and 2009 a unimodal distribution of the amount of precipitation is specific, which falls especially in the summer months of May - August, while in 2007 and 2008, the amount of precipitation is distributed much more evenly, in cycles of every two to three months, this favoring the ground infiltration, leading to increased aquifer flows.

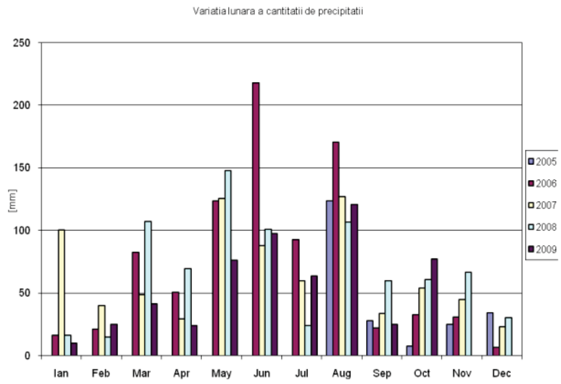

Fig. 2. *Monthly precipitation*

As a consequence of the decrease in the amount of annual precipitation, the thermal inertia of the soil and implicitly the atmospheric one decreased, in 2009 there were increasing atmospheric and soil thermal amplitudes. Due to the lack of water in the soil, the thermal energy from solar radiation is transferred to the mineral skeleton, which has a lower caloric potential than water, resulting in high temperatures during the day and low at night, stimulating the evapotranspiration process, which for example reached of 100 mm only in May of 2009, the period when the thermal amplitude of the soil had values of about 20°C. The strongest trend of continentalization of the climate is noticeable in 2009, by increasing the difference between soil and atmospheric temperature, constantly registering values between 1.5 and 2°C, between May and September.

Analyzing from a statistical point of view the time series regarding the monthly atmospheric thermal amplitude, the monthly soil thermal amplitude and the monthly soil-air thermal amplitude, by drawing a tendency curve that respects a polynomial equation of degree 5, the same continentalization trend is found.

Based on Turc's formula, the value of evapotranspiration is equal to 366 mm/year, considering the total amount of precipitation 1,250 mm/year (in the case of the Ouşorul-Livada hydrostructure) at an average annual temperature of 5°C.

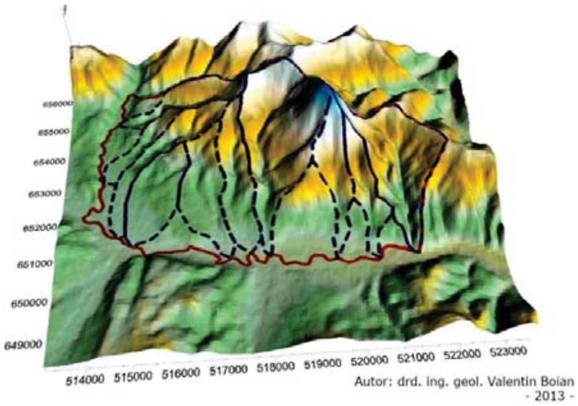

Fig. 3. *Hydrographic basins – 3D view*

3.2. Computation of hydro-morphological parameters

The Dorna River, the main surface water collector in the area, has a fan-shaped hydrographic network and has a south-north flow direction on the upper course, while after Podu Cosnei the direction of flow will be oriented to the east. The Dorna river basin has an area of 595 km2, and the length of the river is 46 km. Among the tributaries of Dorna river, most important ones are Cosna, Teşna and Dornişoara.

The Catariga, Pârâul Alb and Haju basins reach the northern interfluve, occupying its entire length in the studied perimeter. These are in fact the only river basins with a typical dentricular shape. The rest of the river basins are smaller, interspersed between the three listed above.

The Coşna - Dorna confluence area, developed on a syncline that induces a sinking of the structure and implicitly of the landscape, has a strong impact in the form of hydrographic basins, in the sense of their curvature towards the confluence point. The Şarul Negru, Batca Cofii, Pârâul Negru, Batcilor, Dulcani, Jgheabul Ouşorului and Jgheabul Strugurelului basins are simple creek courses bordered by long interfluves, without having developed a network of tributaries.

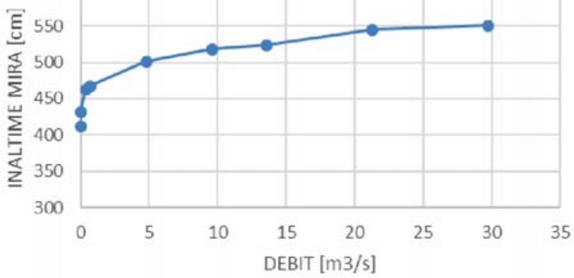

Fig. 4. *Cheie limnimetrică Pârâul Alb aval*

The hydrometric measurements allowed the creation of the limnimetric keys on the downstream sections of all streams in the area, and the monitoring during June 2008 - May 2010 allowed the creation of the flow hydrograph and implicitly the extraction of the groundwater discharge, as statistical value from the series of measurements, at 80% return rate.

From a geological point of view, the most atypical river basin is Haju, as it is developed entirely in crystalline schist. Therefore, the hydrological interpretations of the resulted values for this basin are particular compared to the rest of the basins:

- The specific groundwater discharge of 1.19 L/s/km2, falls into a middle-upper class in the whole perimeter;
- Following the hydrogeological mapping, a low permeability of these rocks was highlighted, the only groundwater flows being those developed in the alteration zone;
- In the upper area of the river basin there is a spring line at the border with the sedimentary formations, through which significant volumes of water are discharged from the suspended structure Oușorul - Livada;

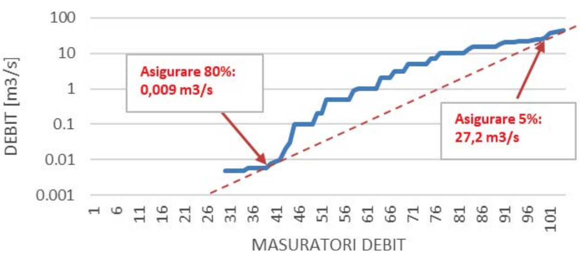

Fig. 5. *Flow rate series on Pârâul Alb downstream*

Denumire rau	Suprafata bazin	Debit 5%	Debit 80%	Scurgere subterana specifica	Participare scurgere subterana
	[m2]	[m3/s]	[m3/s]	[L/s/km2]	[%]
Haju	4.202.422	22,3	0,005	1,19	0,02
Jgheabul Strugurelului	1.260.838	9,77	0,002	1,59	0,02
Jgheabul Ousorului	1.289.129	9,0	0,002	1,55	0,02
Paraul Alb	5.526.362	27,2	0,009	1,63	0,03
Paraul Dulcani	2.345.028	14,2	0,002	0,85	0,01
Paraul Batcilor	2.590.609	16,3	0,002	0,77	0,01
Paraul Negru	2.690.525	13,4	0,002	0,74	0,01
Paraul Floreni (Batca Cofii)	2.270.541	13,8	0,002	0,88	0,01
Sarul Negru	1.128.903	7,17	0,001	0,89	0,01
Catariga	1.966.555	13,0	0,003	1,53	0,02

Fig. 6. *Hydro-morphological parameters*

Pârâul Alb basin is highlighted as the most productive in terms of groundwater discharge, with values of 1.63 L/s/km2, and with a participation of 0.03% in the total flow, this being the smallest gap between the 5% and the 80% return rate flows, which shows an increased storage capacity.

Immediately lower values are recorded at the Catariga creek, whose upper course, and in fact the entire river basin, are extended, as in the case of the Paraul Alb, in deposits of Pg2 age. High values of groundwater discharge are also recorded in the Jgheabul Strugurelului and Jgheabul Oușorului, being also correlated with the outcrop of Pg2 deposits.

The lowest values of groundwater contribution to surface flow rate are found in the streams from the central area, which on the one hand don't have favorable infiltration conditions, being short courses, and on the other hand due to the bedrock, mainly of marly-clayey rocks.

From the water balance equation, knowing the values of the total precipitation of 1,250 mm/year, and of the evapotranspiration of 366 mm/year (determined in the previous chapter for the Oușorul - Livada structure), results a difference of 884 mm/year. This value is practically the volume of water available for surface and groundwater discharge. From the analysis of Paraul Alb hydrograph, if we use the 80% return rate as specific to the groundwater discharge, results a value of 707 mm/year available for aquifer recharge, and the difference of 176 mm/year represents exclusively the direct surface runoff.

3.3. Computation of hydraulic conductivity

The hydrodynamic tests - with constant flow, short and long term, or efficiency - have been processed by several methods, with the aim of calculating the hydraulic transmissivity and conductivity, and the storage coefficient. If for the storage coefficient, the values can be assimilated with the results of the laboratory determination of porosity (accepted relationship in the case of non-confined aquifers), the results of hydraulic conductivity differ greatly, as the pumping test leads to the calculation of a specific value of the entire aquifer thickness opened by the drilled borehole. The hydraulic transmissivity determined by the graphic-analytical calculation cannot be considered representative as the thickness of the aquifer depends on the piezometric level in the case of non-confined aquifers.

In conclusion, the results of these processes will retain the average values of hydraulic conductivity, as an essential parameter in the hydrodynamic calculation, as well as the values of the storage coefficient.

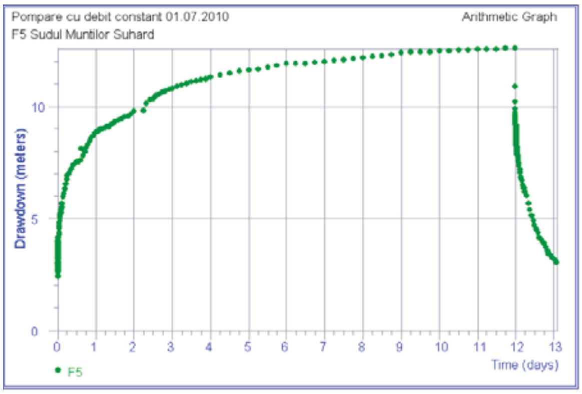

Fig. 7. *Pumping test data, F5, constant flowrate*

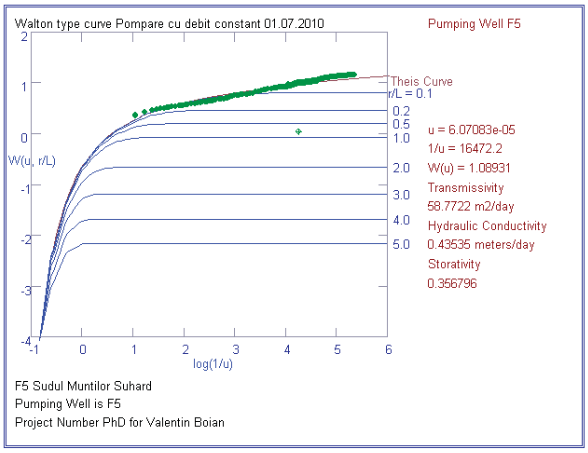

Fig. 8. *Processing F5 pumping test data*

For F5 drilling, we performed a pump test with a flow rate of 7.8 L/s for 12 days, a pump test with a flow rate of 6.99 L/ s for 160 days, and an efficiency test, with eight pumping stages for 8 hours. The borehole was drilled in a limestone flysch formation, associated with the Lutetian - Priabonian interval on the entire intercepted thickness. The mapping of core samples and geophysical well measurements reveals several groundwater infeed depths, and a potentially high flow rate. For these reasons, the testing program associated with this drilling was the most extensive.

As recognized by surface geological and hydrogeological research, the Lt + Pr range is notable for good permeability, being the main structure favorable to groundwater accumulations, as evidenced by the values of hydraulic conductivity, 0.4 m/day.

j	Tip test	Durata	Debit	Metoda	Transmisivitate hidraulica	Conductivitate hidraulica	Inmagazinare
			[L/s]		[m2/zi]	[m/zi]	[-]
	Debit constant	12 zile	7,8	Theis recuperare faza 1	22,57	-	-
				Theis recuperare faza 2	65,41	-	-
				Theis recuperare faza 3	86,70	-	-
				Theis	58,77	0,43	0,35
				Walton	58,77	0,43	0,35
				Hantush	58,77	0,43	0,35
				Neuman	44,00	0,32	2,49
	Eficienta	8 h	1,25	Eden-Hazel pas 1	70,91	-	-
			2,04	Eden-Hazel pas 2	70,91	-	-
			3,00	Eden-Hazel pas 3	70,91	-	-
			4,00	Eden-Hazel pas 4	70,91	-	-
			5,00	Eden-Hazel pas 5	70,91	-	-
			6,00	Eden-Hazel pas 6	70,91	-	-
			7,00	Eden-Hazel pas 7	70,91	-	-
			10,00	Eden-Hazel pas 8	70,91	-	-
	Debit constant	160 zile	6,99	Theis	40,50	0,30	0,14
				Walton	40,50	0,30	0,14
				Hantush	40,50	0,30	0,14
				Neuman	34,21	0,25	0,49

Fig. 9. *Summary table with hydrogeological parameters of F5*

4. Evaluation of resources and reserves

A unitary approach and an exhaustive definition of groundwater resources and reserves are presented by *Marin Palcu et al*, in the article *Theoretical Aspects Concerning Groundwater Reserves and Resources Assessment and Administration, Geo-Eco-Marina 15/2009*, a scientific paper that reveals the principles of analytical calculation of resources and reserves starting the unitary volume water balance.

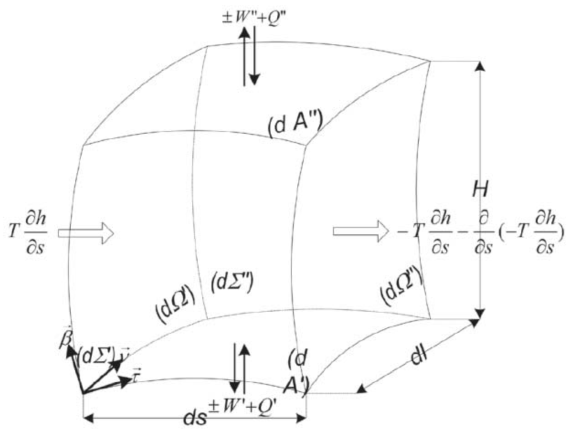

Fig. 10. *Water flows in a representative unit volume*

$$S\frac{\partial h}{\partial t}dA + \frac{\partial}{\partial s}\left(-T\frac{\partial h}{\partial s}\right)dA \pm wdA \pm Q = 0\ ,$$

where: S = *storage coefficient*, h = *piezometric head*, t = *time*, A = *recharge area*, s = *horizontal distance*, w = *infiltration module*, Q = *flow rate*

The above-mentioned authors define the water reserve as the volume of water contained in an aquifer structures. In the case of a non-confined aquifer, similar to the Ouşorul-Livada structure, the equation describing the groundwater reserve is:

$$W = \sum_{i=1}^{n} m\Omega H,$$

where: *W = groundwater reserve, m = porosity, Ω = surface, H = piezometric head.*

In the same article, the groundwater resource is defined as the water flow through the wet cross-section of the aquifer, based on the following formula:

$$Q_{ni} = \int \vartheta d\Omega,$$

where: *Q = groundwater resource, v = velocity, Ω = cross-section area*

The hydrodynamic model used further on falls into the family of analytical models, for which the author proposes a new method, developed especially for the investigated hydrostructure.

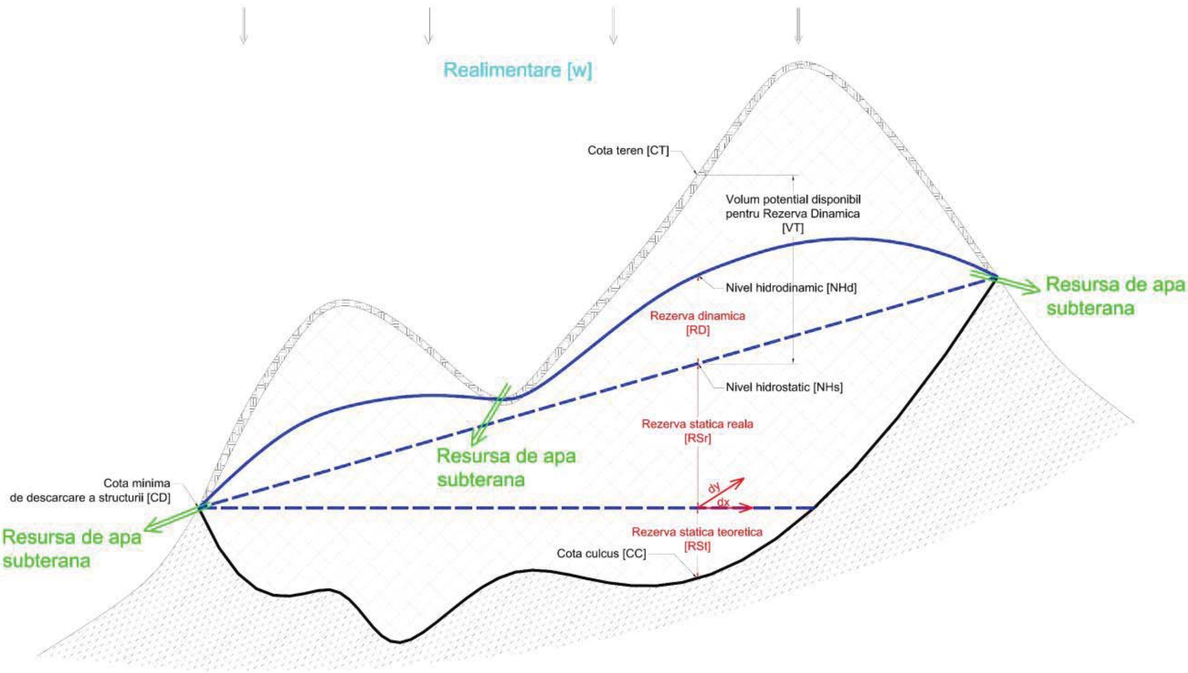

Fig. 11. *Calculation elements of the analytical model*

The working hypotheses used derive from the conceptual model, namely:

- Non-confined aquifer: impermeable bed represented by the marly-sandstone formation Pg1-2, while model top is represented by the topographic profile;
- Constant piezometric head on the model border takes over the head values from the topographical map;
- Recharge exclusively by net precipitation: calculated at 700 mm/year;
- Homogeneous and isotropic porosity of 5%;
- The piezometric surface follows the topographic profile, and varies depending on the recharge value;

In a theoretical cross-section of the structure, we can define the following geometric elements:

- Land elevation: **CT**
- Dynamic piezometric head: **NHD**, representing the free surface of the aquifer, as it is naturally generated by the effect of topography, recharge value and hydraulic conductivity
- Static piezometric head: **NHS**, representing the interpolated surface of the contour points
- Lowest discharge point of the structure: **CD**
- Bed level: **CC**
- Theoretical static reserve: **RST**
- Real static reserve: **RSR**
- Dynamic reserve: **RD**
- Total potential volume available for dynamic reserve: **VT**
- Surface of the hydrogeological basin: **SB**
- Recharge factor: **w**
- Grid size: **dx dy**
- Porosity: **n**

The analytical calculation is performed in a grid of 5,418 cells with dimensions of dx = 35.07 m and dy = 34.92 m.

The **static reserve** is given by the volume of water stored in the aquifer, up to the minimum natural discharge level of the structure. Thus, at the discharge elevation 1,026 m, represented in the field by the exit point of the Paraul Alb stream from the hydrogeological basin, we have a free horizontal plane surface (extended to the intersection with the contour of the structure) of 6,635,515 m2, and a volume of groundwater stored of 7,463,252 m3, considering the general porosity of the aquifer of 5%. This volume can also be called the **theoretical static reserve**, since in the multiannual hydrogeological regime it is not possible to reach the complete discharge of the structure up to the minimum level.

The **dynamic reserve** is calculated in two stages:

- By interpolating the constant head points from the border, resulting a surface with a general NE-SW slope; the volume of water stored in the aquifer up to this level can be considered the **real static reserve**, having a calculated value of 75,602,153 m3 (it also includes the value of the theoretical static reserve)
- By recharge input over the real static reserve, the final hydrodynamic piezometric surface is reached, thus resulting in the value of the **dynamic reserve**, 4,644,860 m3

On the total aquifer structure, we have a ratio between the dynamic reserve and the total potential volume available for the dynamic reserve of 0.24:

$$\frac{RD}{VT} = \frac{SB\, w}{(CT - NHs)\, n\, dxdy} = \frac{6.635.515\, m^2 x\, 0{,}7\, m/an}{18.868.615\, m3} = 0{,}24$$

The resulting ratio will be used to determine the share of the dynamic piezometric level, following the variation of the topographic profile, based on the formula demonstrated as follows on a representative unit volume:

$$\frac{dx\, dy\, (NHd - NHs)\, n}{dx\, dy\, (CT - NHs)\, n} = 0{,}24$$

$$NHd = NHs + 0{,}24\, (CT - NHs)$$

The **groundwater resource** is given by the groundwater flow through the wet cross-section of the aquifer. Thus, on a total cross-section of 12,670 m2, on the entire border of the hydrogeological basin, a water flow of 21.12 L/s is drained naturally, through the hydraulic gradient.

- Discharge surface on the hydrogeological model border: 12,670 m2;
- Hydraulic conductivity: 0.4 m/day;
- Hydraulic gradient: 0.36

$$Q = 12.670\, m2\, x\, 0{,}4\, m/zi\, x\, 0{,}36 = 21{,}12\, L/s$$

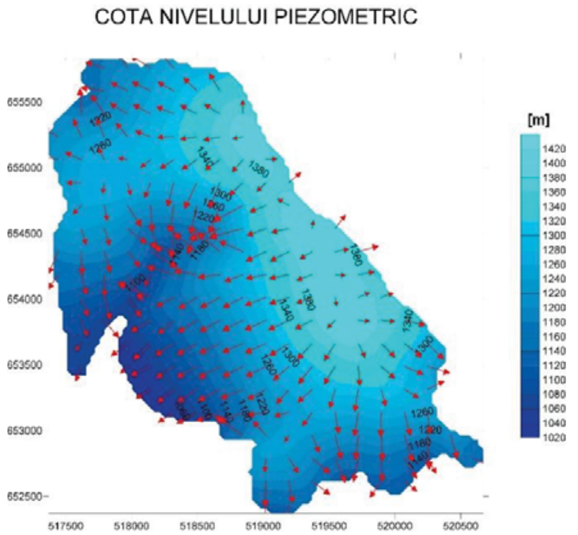

Fig. 12. *Piezometric head map*

5. Conclusions

The climatological study carried out in the area reveals the continentalization trend, which determines the reduction of groundwater infiltration, due to the concentration of precipitation in short periods of the year, and the increase of the average annual temperature. However, the orography and the geological constitution of the Oușorul - Livada structure contributes to the development of the most productive aquifer in the studied area, a conclusion noted since the preliminary results provided by the hydrological study. The specific groundwater discharge, with a value of 1.63 L/s/km2, double compared to other river basins in the area, determined the continuation of hydrogeological studies in this structure, by computing the characteristics of the aquifer and the evaluation of resources and reserves.

Thus, by developing an analytical model specific to this hydrostructure, it was possible to determine both the static reserve of the aquifer and the dynamic reserve (this one being practically available for sustainable exploitation) at a value of 4,644,860 m3, considering the general porosity of the aquifer of 5%.

The interpretation of the pumping tests led to the determination of the hydraulic conductivity of the aquifer by various graphic-analytical processing methods, at a value of 0.4 m/day, which was further used for the calculation of the groundwater resource on the total discharge area on the border of the structure, at a value of 21.12 L/s.

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