ANALYSIS OF GROUNDWATER FLOWS IN THE AREA OF THE DESIGNED PSPP VRILO LOWER BALANCING RESERVOIR

Stručni rad/Professional paper
Primljen/Received: 23. 10. 2018.
Prihvaćen/Accepted: 30. 11. 2018.

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Abstract: This paper gives an overview of the research conducted as part of the graduation thesis titled: "The hydraulic study of groundwater flows in the area of the lower PSPP Vrilo balancing reservoir", which was developed and successfully defended at the Faculty of Civil Engineering University of Mostar in 2018. The task was to develop a spatial model of steady groundwater flows in the area of the designed lower balancing reservoir of the Vrilo pumped-storage power plant, based on field investigation data and data from the PSPP Vrilo preliminary design.

Key words: lower balancing reservoir, Vrilo pumped-storage power plant, groundwater flow, DHI WASY FEFLOW 7.0, numerical model

ANALIZA STRUJANJA PODZEMNIH VODA NA PODRUČJU PROJEKTIRANOG DONJEG KOMPENZACIJSKOG BAZENA CHE VRILO

Sažetak: Ovaj rad daje prikaz istraživanja urađenoga u sklopu izrade diplomskoga rada pod naslovom: „Hidraulička studija strujanja podzemnih voda na području donjeg kompenzacijskog bazena CHE Vrilo“, a koji je urađen i uspješno obranjen na Građevinskom fakultetu Sveučilišta u Mostaru 2018. godine. Zadatak je bio formirati prostorni model ustaljenog strujanja podzemnih voda na području projektiranoga donjeg kompenzacijskog bazena crpne hidroelektrane Vrilo, temeljem podataka istraživanja na terenu i podataka iz idejnog projekta CHE Vrilo.

Ključne riječi: donji kompenzacijski bazen, crpna hidroelektrana Vrilo, strujanje podzemnih voda, DHI WASY FEFLOW 7.0, numerički model

1. INTRODUCTION

This paper gives an overview of the research conducted as part of the graduation thesis titled: "The hydraulic study of groundwater flows in the area of the lower PSPP Vrilo balancing reservoir", which was developed and successfully defended at the Faculty of Civil Engineering University of Mostar in 2018. The task was to develop a spatial model of steady groundwater flows in the area of the designed lower balancing reservoir of the Vrilo pumped-storage power plant, based on field investigation data and data from the PSPP Vrilo preliminary design.

The location of the designed Vrilo pumped-storage power plant is in the Tomislavgrad municipality area and it is planned to use the water potential of the Upper Cetina basin, more precisely of the Šuica River. This power plant will offer an additional peak power generation to the power system and will help reduce harmful gas pollution by an amount of about 230,000.00 t CO_2/year. At the same time, this power plant contributes to flood control and irrigation of the Duvno field for the purposes of intensive agricultural production, having a positive effect on the environment,[1].

The paper gives a brief summary of the results of conducted field investigations and data from the existing project documentation, as well as a description of the developed spatial model of steady groundwater flows in the area of the lower balancing reservoir of the designed PSPP Vrilo.

2. STUDY AREA

The PSPP Vrilo power plant uses a gross head of about 155 m from Duvno Field to Buško Lake. It is planned to use this potential by a reversible pumped-storage power plant which, in addition to using the water of Duvno Field and Šuica River during reduced inflows in Duvno Field and excess power in the system, it also pumps water from Buško Blato (lower balancing reservoir) to the reservoir space in Duvno Field (upper balancing reservoir), in order to be able to use it when power is insufficient in the system.

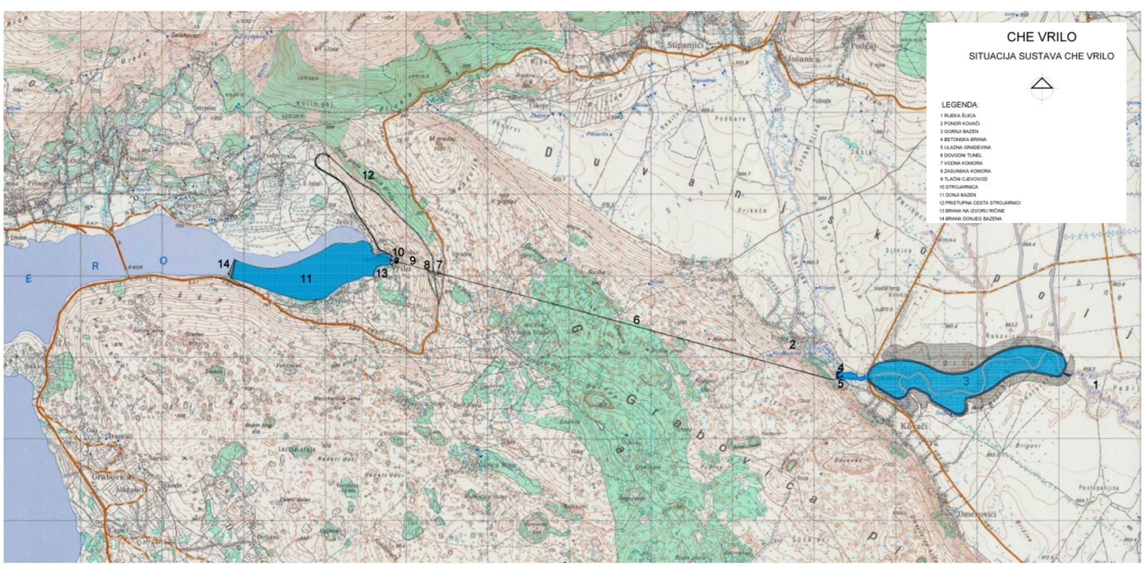

Figure 1. Situation view of the PSPP Vrilo facilities, [1]

The selected solution of PSPP Vrilo consists of:

- Upper reservoir of usable storage capacity of 1.8 million m^3, which is realized by constructing a concrete dam approx. 400 m downstream of the bridge over which the Posušje - Tomislavgrad road crosses the Šuica watercourse.
- Intake structure of the headrace tunnel.
- Headrace tunnel 5207 m in length and 4.6 m in diameter.
- Relief well and valve chamber.
- Penstock 450 m in length and 3.8 m in diameter.
- Turbine hall with tailrace tunnel and outlet structure, and plateau and switching station.
- Lower reservoir of usable storage capacity of 1.9 million m^3, which is realized by constructing a rock fill dam approx. 1.4 km downstream of the turbine hall and concrete dam near the Ričina spring, [1].

Investigations required for the development of the PSPP Vrilo conceptual design comprised:

- Geodetic surveying with development of the geodetic survey report for project development needs and maps for preparation of the land acquisition study.
- Engineering geological investigations.
- Seismological, seismotectonic and engineering seismological investigations.
- Geophysical investigations.
- Geotechnical investigations and laboratory tests of materials.
- Additional hydrological analyses related to the lower balancing reservoir and existing Buško Blato Lake.
- Investigations for the purpose of developing the environmental impact study.
- Investigations for the project of connecting the Power Plant to the EPS.

The primary purpose of the investigations and analyses was to obtain relevant data for determining the size and position of the upper and lower reservoir, position and technical solutions of dams for formation of the reservoirs, position and technical solution of the turbine hall, and position and technical solution of the conduit and ancillary structures. Results of the research were elaborated into a range of professional studies.

The investigations were divided into four lots and were thus elaborated:
LOT-1: Geodetic measurements, DMTGmbH CO.KG Essen;
LOT-2: Geological, engineering geological and hydrogeological investigations, GEO MARIĆ Mostar d.o.o., Mostar;
LOT-3: Exploratory boring with in situ measurements, “Geotehnika '94”, geotechnical and special construction works, Mostar;
LOT-4: Geophysical investigations, Moho d.o.o., Zagreb;
Hydrological, meteorological and hydrogeological data were used from the project Hydrological study of the Upper Cetina basin, Elektroprojekt- Zagreb, FHMZ-Sarajevo, 2006, [1].

3. RESULTS OF FIELD INVESTIGATIONS - SHORT SUMMARY

The area of the lower balancing reservoir is situated on the part of the plateau from the bridge over Ričina in the west, up to the spring caves and Dolac cove in the east. Its longer axis is oriented in the east-west direction and is about 2.5 km long, while its width is variable and is about 500 m. The following field investigations were conducted in this area:
- 4 exploratory boreholes (DB-1, DB-2, DB-3 and DB-4) each up to 40 m in depth;
- 4 geophysical profiles (RF-6a, RF-8, RF-9 and RF-11) in different parts of the area;
- 2 geoelectrical profiles (GE-11 and GE-9) immediately downstream of the bridge on Ričina and
- engineering geological and hydrogeological mapping of the terrain.

It should be emphasized that all field investigations had to be postponed until withdrawal of high water, which persisted exceptionally long in the hydrological cycle in which the investigations were conducted, which had undesirable consequences on the dynamics and scope of field investigations [2].

Figure 2. The lower reservoir area, [2]

Figure 3. The upper reservoir area – dry period, [2]

Exploratory drilling works in the lower basin area defined the basic geological structure, thickness and characteristics of the surface cover, as well as the quality of bedrock. Two boreholes DB-2 and DB-3 were equipped with piezometers for monitoring groundwater levels.

The borehole DB-1 has a thin surface cover 0.00 - 4.60 m. It is made of cohesionless clayey limestone detritus underlain by medium fractured to compact stratified limestones with local occurrences of more intensely fragmented and cavernous limestone.

The exploratory borehole DB-2 has colluvial surface deposits 0.00 – 4.40 m. They are made of highly clayey limestone detritus underlain by weakly fractured to compact limestones established by drilling down to the bottom of the borehole (39.40 m).

The exploratory borehole DB-3 is located in the left limestone side above the secondary spring. Medium to highly fragmented Upper Cretaceous limestones were extracted. A more intensely fractured zone is in the interval 24.00 – 29.00 m.

The exploratory borehole DB-4 is located in the wider area of turbine hall. The drilling established colluvial deposits in the interval 0.00 - 6.80 m, made of dark brown clays and clayey limestone detritus, under which light gray to white low to medium fractured rudist limestones were found down to a depth of 35.50 m. A cavern filled with light brown clay and rare limestone fragments was found at the depth 35.50 down to the end of the borehole (40.30 m).

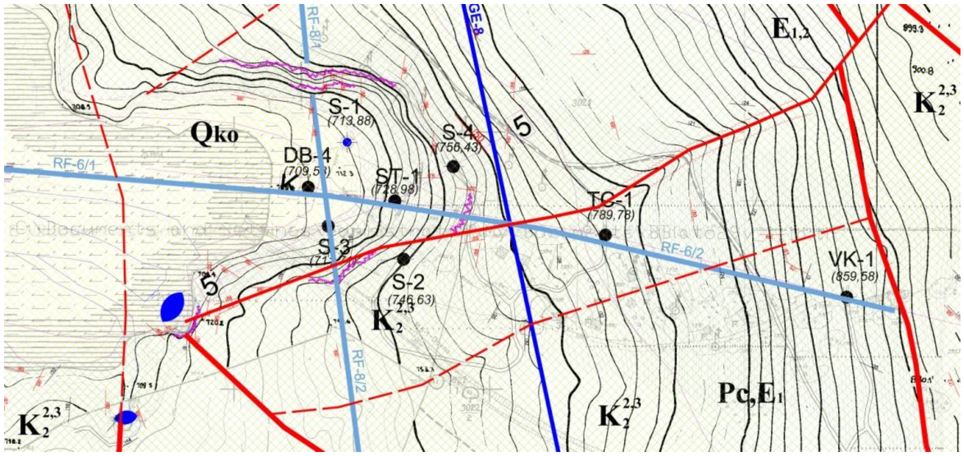

Figure 4. Layout of exploratory boreholes and profiles on a part of LBR of PSPP Vrilo

In terms of engineering geological characteristics, four units were identified in the area of the lower balancing reservoir:
1. technogenic formations (embankments at the foot of the bridge on the far western part of the area);
2. surface cover (formations of Quaternary age);
3. upper weathering zone of the bedrock massif and
4. intact rock mass (Upper Cretaceous carbonate formations).

In the lower reservoir area there are no Quaternary deposits, which are insulators, or media that would represent significant barriers to groundwater flow, as is known from the conducted investigations [2].

The Quaternary cover has a heterogeneous composition. The surface interval along the bed and in the zone of frequent flooding is of a silty-clayey composition. This part significantly reduces the permeability of lower Quaternary sediments, and even of the entire system. Retention of water in some isolated areas of the terrain even after the level of Buško Blato has lowered is a consequence of the existence of this surface layer.

Monitoring of groundwater condition during the investigations was conducted at three piezometers (DB-2, DB-3 and S-1) during 2009. Their measurements are presented in the following table.

Table 1. GWL measurements in piezometers S-1, DB-3 and DB-2 [2]

	S-1			DB-3			DB-2		
Date	**GWL [-m]**	**GWL**	**Difference [m]**	**GWL [-m]**	**GWL**	**Difference [m]**	**GWL [-m]**	**GWL**	**Difference [m]**
17.07.09.							7.48	705.47	0.00
10.08.09.	8.10	706.19	0.00	6.53	706.18	0.00	5.85	704.37	-1.10
19.08.09.	9.25	705.04	-1.15	7.64	705.07	-1.11	7.28	702.94	-1.43
24.08.09.	9.50	704.79	-0.25	7.99	704.72	-0.35			
26.08.09.	10.95	703.34	-1.45						
16.09.09.	12.86	701.43	-1.91	9.36	703.35	-1.37	11.46	698.76	-4.18
01.10.09.	23.00	691.29	-10.14	20.55	692.16	-11.19	25.50	684.72	-14.04
		Total:	**-14.90**			**-14.02**			**-20.75**

Lowering of groundwater levels ranging from 14.02 m (DB-3) to 20.75 m (DB-2) in the period from 10 August 2009 to 1 October 2009 can be observed by analyzing these results.

These data are indicative of the constantly higher groundwater levels in the piezometer DB-3, which corroborates the previously defined direction of underground flow toward Buško Blato, or at times of minimums toward the springs in the Cetina basin. The registered low water levels are certainly not extreme values. The water levels at the piezometer DB-2 indicate that the registered groundwater level at a minimum (684.72 m a.s.l.) was significantly below the normal top water level of the Buško Lake, whose water table is formed not far from this piezometer at the altitude of about 703 m a.s.l. The piezometer S-1 shows that the groundwater level is above the planned turbine hall foundation levels also during the minimum. Besides, all this suggests that Ričina springs (main spring, secondary spring and the spring near the borehole DB-3) are large in size and probably represent branched underground systems which, during low and minimum water (when they dry out) assume the function of conditional sinkholes if the normal top water level of the lower reservoir is higher than them, [2].

4. CONCEPTUAL NUMERICAL MODEL

For the purpose of defining the distribution of accumulation and transport characteristics of the medium, a three-dimensional model of the lower balancing reservoir of PSPP Vrilo was created. Project documentation and data borrowed from JP Elektroprivreda HZ H-B Mostar for preparation of the graduation thesis were available for model development.

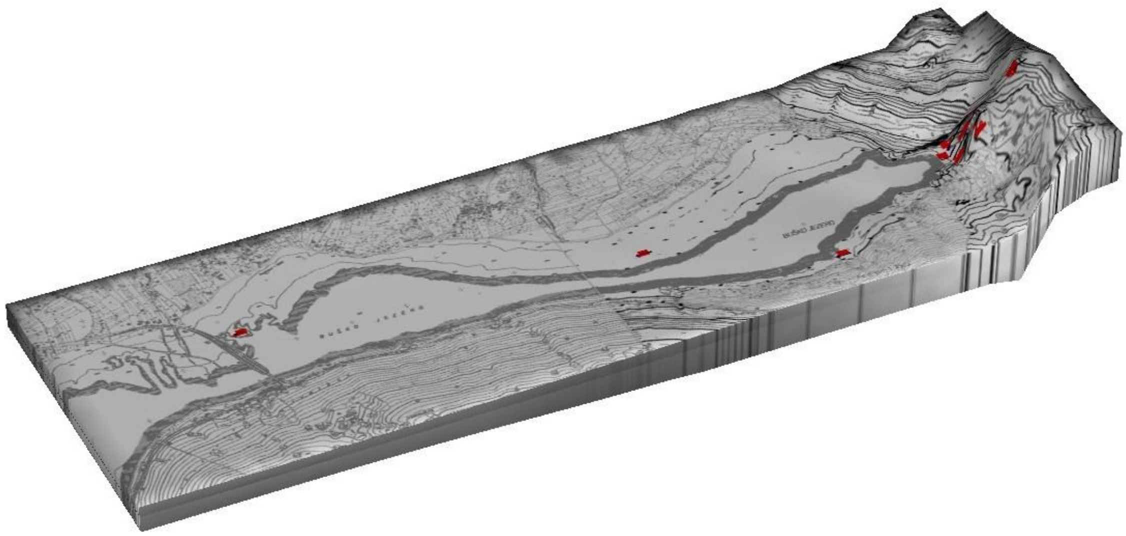

Figure 5. Position of the considered PSPP Vrilo area

The analysis of filtration flows with determination of variant disposition effects was performed by the computer program DHI WASY FEFLOW 7.0.

In order to obtain the necessary information on groundwater levels, groundwater levels were calculated in an area about 4500 m in length and about 1500 m in width. A three-dimensional stationary mathematical model was created. By setting Darcy's filtration law and continuity equation for each prism element, an expression was obtained for groundwater level at one point, depending on the levels at all adjacent points - centers of prism elements.

The first step in developing the model was to extract an area of interest for modeling from the whole of the area. The area covers the space of the designed LBR of PSPP Vrilo, as well as the area of the designed PSPP Vrilo turbine hall.

The selected area is discretized by a mesh of triangular finite elements. The third dimension of the model is defined by adding three different layers of material. Each layer is

assigned a certain filtration coefficient. The interaction between ignored and modeled area is substituted by initial and boundary conditions.
The area is discretized by triangular prismatic finite elements. The number of nodes per element is six. The total number of finite elements within the domain of spatial model is 10010, and the total number of nodes is 2653.

Stationary flow in a saturated aquifer with free surface was analyzed. Boundary conditions were set as the absolute value of the Buško Lake level and water level at the Kovači gauging station.

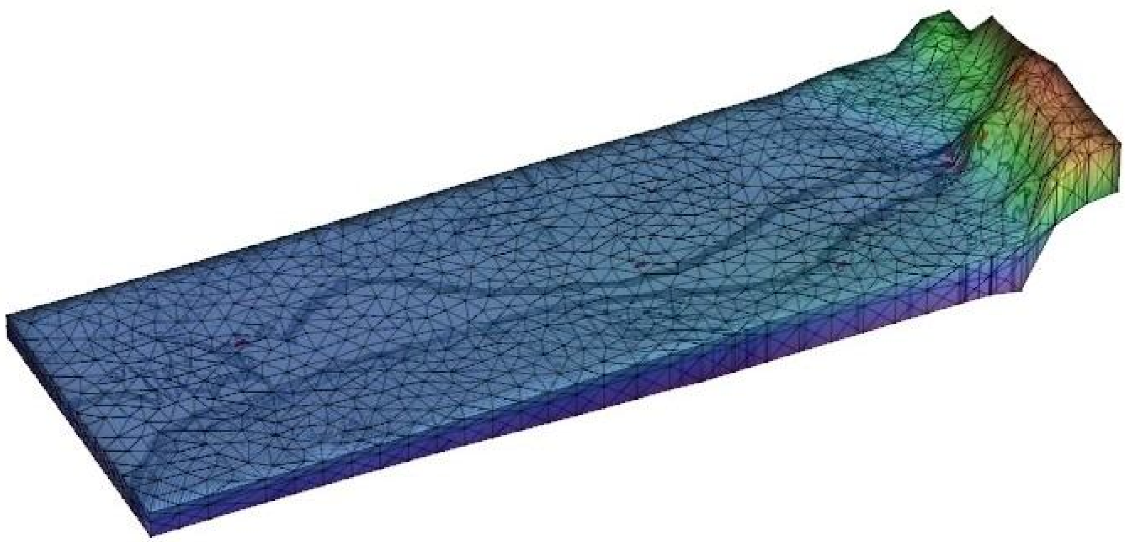

Figure 6. Triangular finite element mesh on the spatial model of the PSPP Vrilo area.

The third dimension of the model is determined by defining 3 layers of material at 10 boreholes (nodes) distributed throughout the area. There is a detailed description of geological profiles for these boreholes [3]. Based on these data, the entire area is interpolated by the Kriging regionalization method. The values of the filtration coefficients are qualitatively assigned to certain layers and/or boreholes based on an analysis of geological investigations in the area.

Table 2. Materials on geological profiles

LAYER MARK	LITHOLOGICAL COMPOSITION	COEFFICIENT OF FILTRATION [m/s]
1	Very heavily and heavily fractured limestones.	$K_{xx} = K_{yy} = 1.04*10^{-3}$ $K_{zz} = 1.04*10^{-4}$
2	Medium fractured limestones.	$K_{xx} = K_{yy} = 2.00*10^{-4}$ $K_{zz} = 2.00*10^{-5}$
3	Very weakly and weakly fractured limestones of good quality.	$K_{xx} = K_{yy} = 3.21*10^{-5}$ $K_{zz} = 3.21*10^{-6}$

Control points (nodes) aimed at validating the model are marked within the model area. The piezometric state is known at these points for the set boundary conditions and these points are used to compare the results obtained by modeling and the GWL value measured at the piezometer. The simulations were run until satisfactory results were obtained.

Considering the problems of the area, hydraulic relationships in the observed area were analyzed based on existing available data. The analysis consisted of the following:

- Development of the spatial stationary mathematical model for analysis of the area and intensity of groundwater flow in the area of the designed LBR of PSPP Vrilo. Everything was done for a specific number of characteristic cross sections for which hydrogeological data are available.
- Coefficients of filtration were qualitatively assigned according to the description of hydrogeological characteristics of the boreholes. GWLs in known boreholes were used to verify the model.

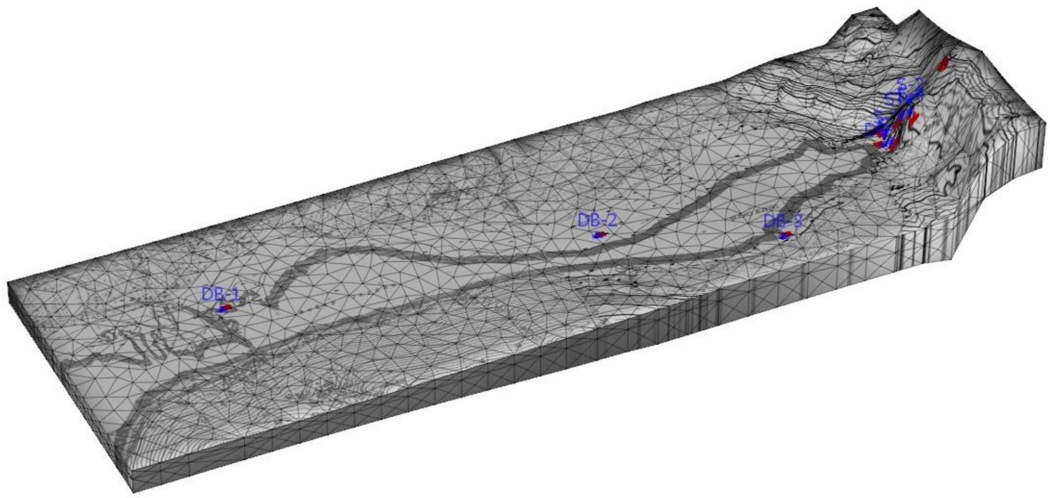

Figure 7. Positions of control points

After defining the spatial model coverage area, characteristics of soil layers and initial and boundary conditions, simulation of the model was started for steady flow in unbounded free aquifer. Figure 8 shows the distribution of groundwater levels in the modeled area.

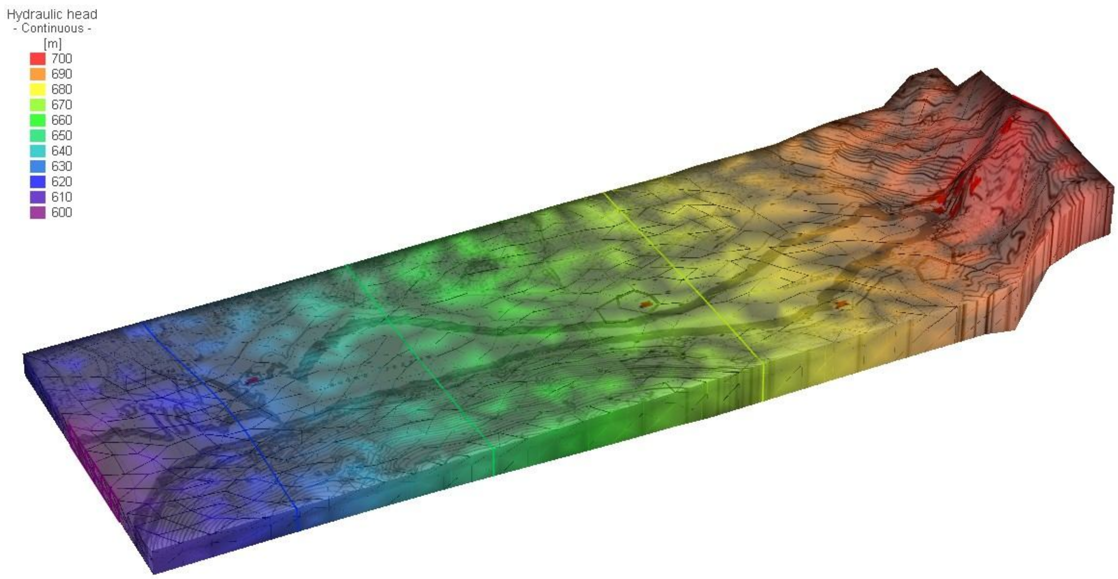

Figure 8. GWL distribution - spatial view

Control points of known spatial coordinates were used to compare the results of groundwater levels in the area of the designed LBR of PSPP Vrilo. These points were input into the finite element mesh to obtain the values of potentials at them and to compare them with the values measured in the field. Larger deviations can be observed at the control points for the rainy period. These deviations were due to the insufficient number of input data for the spatial stationary flow model, and because the author did not have precipitation data at disposal for the analyzed period [4].

5. CONCLUSION

The modeling conducted on the spatial stationary mathematical model of the designed lower balancing reservoir of PSPP Vrilo made it possible to qualitatively analyze the impact of the designed power plant facilities on filtration conditions in the examined area.

Taking into account the pronounced inhomogeneity of the considered area, as well as complex boundary conditions, the selected method of mathematical modeling using the software solution DHI WASY FEFLOW 7.0 proved to be very practical for the analysis of groundwater flows.

With precisely defined geometry of the area, as well as thoroughly processed available geological data from a large number of boreholes in the area, it is possible to get a good perception of groundwater conditions.

Making it possible for this type of hydrodynamic model to be the basis for future analyses requires a finer grid of observations in the existing project area. This particularly concerns the area of the lower balancing reservoir of the pumped-storage power plant Vrilo, all with the aim of as accurate determination of water retentivity as possible. The recommendation is to regularly monitor the existing piezometers and to implement new ones for the purpose of collecting data on groundwater flows and the relation between flows and hydrological conditions.

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