A GEOPHYSICAL APPROACH FOR MAPPING OF ABANDONED MINING WORKINGS AND UNCONSOLIDATED ZONES IN COAL MINING AREAS

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ABSTRACT. Coal mining is the cause of significant changes in the geotechnical and hydrogeological conditions in the subsurface areas affected by it. This creates serious problems with the ground stability, rapid rise of groundwater level and concentrated or scattered water surface inflows. The proposed geophysical approach for mapping of abandoned mining workings and unconsolidated zones in the problem areas is based on the application of electrical resistivity tomography (ERT). This approach is approbated during the localization of abandoned mining workings (galleries, collapsed zones, cracked areas and pillars) developed throughout the many years of coal mining in the region of Pernik northern neighborhoods. The presented results confirm the applicability of the proposed methodology of field data measurement, analysis and interpretation.

Keywords: electrical resistivity tomography, abandoned mining workings, unconsolidated zones

ГЕОФИЗИЧЕН ПОДХОД ЗА КАРТИРАНЕ НА СТАРИ МИННИ ИЗРАБОТКИ И РАЗУПЛЪТНЕНИ ЗОНИ ВЪВ ВЪГЛЕДОБИВНИ РАЙОНИ

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РЕЗЮМЕ. Подземният въгледобив е причина за значителни промени в геотехническите и хидрогеоложките условия в засегнатите от него части от подповърхностното пространство. Това създава сериозни проблеми с устойчивостта на земната основа, бързо покачване на подземните води и съсредоточени или разсеяни водопроявления на земната повърхност. Предложеният геофизичен подход за картиране на стари минни изработки и разуплътнени зони в проблемните участъци се базира на прилагането на електротомографски изследвания. Подходът е апробиран при картирането на отработените пространства (галерии, обрушени зони, напукани зони и целици) по време на многогодишния подземен въгледобив в района на северните квартали на гр. Перник. Представените резултати потвърждават приложимостта на методиката на измерване, анализ и интерпретация на данните.

Ключови думи: електротомографски изследвания, стари минни изработки, разуплътнени зони

Introduction

The mining activities in the Pernik coal basin are the cause of significant changes in the geotechnical and hydrogeological conditions in the subsurface areas affected by it. They create serious problems with the ground stability, rapid rise of groundwater level and concentrated or scattered water surface inflows. Some of the most affected areas in the region are Pernik northern neighborhoods Rudnichar, Dimova mahala, Beli breg (Figs. 1 and 2).

Geophysical methods can be successfully applied for the detailed study of the near-surface geological section (Dimovski et al., 2007). They fulfil the results from the borehole investigations and allow correct interpolation of the general behavior of the present formations. Electrical resistivity methods have wide application for the detailed mapping of the near-surface section. Their geological efficiency is connected to the rocks differentiation according to electrical resistivity. For a precise geoelectrical section the rocks electrical resistivity is tied to the existing preconditions for presence of ionic conductivity (Dimovski et al., 2008; Shanov et al., 2009).

The main task of the performed geophysical studies is to detail the near-surface hydrogeological section in the studied area down to a depth of 40-50 m. More specifically, the results have to provide the possibility to outline, with sufficient reliability, the spatial boundaries of layers and zones characterized by different lithological and grain-size characteristics, as well as by different degree of water-permeability and water-saturation. It is also necessary to establish the potential presence and to define the extent of unconsolidated zones and cavities in the subsurface section.

The main objectives of the geophysical research are to map the spatial boundaries of the determined low-rank hydrogeological units (HGU) in the affected by the coal mining parts of the Paleogene coal bearing complex and to determine the boundary between the unsaturated zone (zone of aeration) and the water-saturated zone.

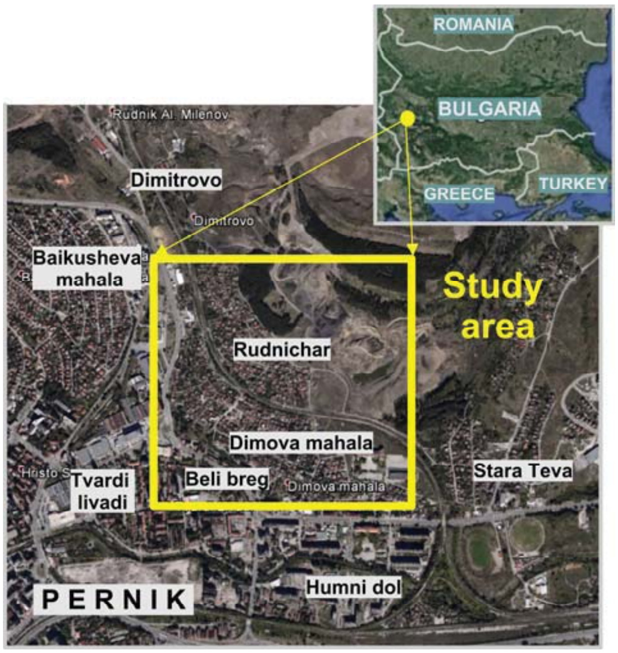

Fig. 1. Location of the study area in the region of Pernik – neighborhoods Rudnichar, Dimova mahala, Beli breg

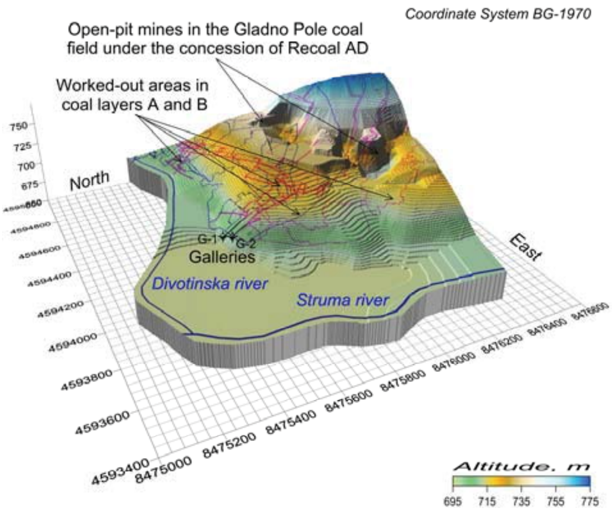

Fig. 2. Geomorphologic map with the location of the abandoned mining workings in the region of Pernik – neighborhoods Rudnichar, Dimova mahala, Beli breg

Basic elements of the electrical tomography surveying technique

Electrical resistivity tomography (ERT) is a new and rapidly evolving technology for the non-invasive imaging of the near-surface section. This method, based on the use of modern equipment, optimal measuring techniques (Griffiths et al., 1990), and computer processing of acquired data (Loke, 1999). From a series of electrodes, low frequency electrical current is injected into the subsurface, and the resulting potential distribution is measured. A large variety of different source and receiver positions are used to sample the target section (Griffiths and Barker, 1993).

The true resistivities in the subsurface area are determined by the computer program RES2DINV (Loke, 2001). For this purpose, the resistivity values measured by the field equipment in different points (having particular electrodes location) have to be transferred into apparent resistivity values after taking into consideration the array geometry. The computer program uses as input data the information about the electrodes location on the surface and the apparent resistivity values in each measured point. On this basis the program automatically divides the subsurface area into a given number of rectangular blocks. Then, applying the least-squares method, the resistivity of each block is determined in such a way that the calculated apparent resistivity values for the composed model fit in the best possible way the measured electric field.

The so determined geoelectrical model can be transformed into a geological one on the base of:

- General information of the geological and hydrogeological conditions in the studied region.
- Reference data for the electrical resistivity of different rock types (Keller and Frischknecht, 1966; Daniels and Alberty, 1966).
- Data from the drilled boreholes.

Surveying results, analysis and interpretation

When planning the number, length and location of the geophysical lines, the available archive data for the coal mining accomplished in the past (maps, schemes, plans and mine surveys), as well as data from the drilling activities performed in 2012-2015 are taken into account. The lines cover comparatively evenly the territory of the Pernik neighborhood Rudnichar, which is a prerequisite for a better determination of the spatial boundaries of the low-rank HGU in the Paleogene coal bearing complex.

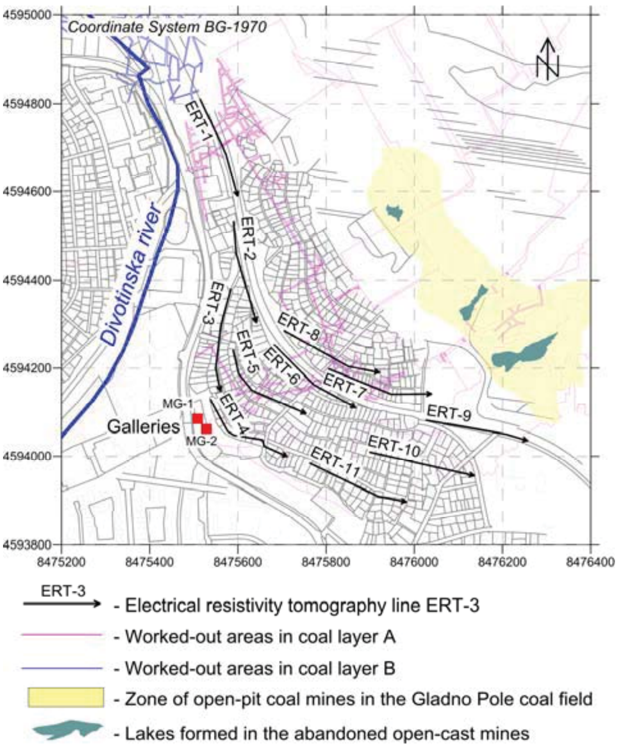

Fig. 3. Cadastral plan with the location of the geophysical surveying lines in the region of Pernik northern neighborhoods

The field measurements were performed along eleven lines having a total length of 2530 m (each ERT line has a length of 230 m). The location of the geophysical surveying lines in the area under study is illustrated in Figure 3. The four-electrode Wenner-Schlumberger array was applied. The measurements were performed applying Terrameter SAS 1000, a resistivity and IP instrument produced by ABEM. The processing of the acquired data and the interpretation of the obtained results are performed by members of the Departments of Applied Geophysics and Hydrogeology and Engineering Geology, University of Mining and Geology "St. Ivan Rilski", Sofia. A case of water surface inflow and moments from the field measurements are illustrated in Figure 4 and Figure 5.

Fig. 4. Water surface inflow through the exit of mining gallery MG-1 in the region of Pernik neighborhood Dimova mahala

Fig. 5. Moments from the field measurements in the region of Pernik neighborhood Rudnichar

The analysis of the results is in accordance with the geological sections recorded in the drilled boreholes and the available information about the past coal mining activities in the area.

The electrical resistivity sections obtained along the eleven studied lines are illustrated in Figure 6, Figure 7, and Figure 8. The performed analysis gives reason the following conclusions to be made:

1. The geoelectrical section along all lines is consistent regarding the electrical resistivity distribution in depth.

2. The electrical resistivity of the varieties composing the studied near-surface section changes in a relatively narrow range – from about 30 Ωm up to more than 120 Ωm.

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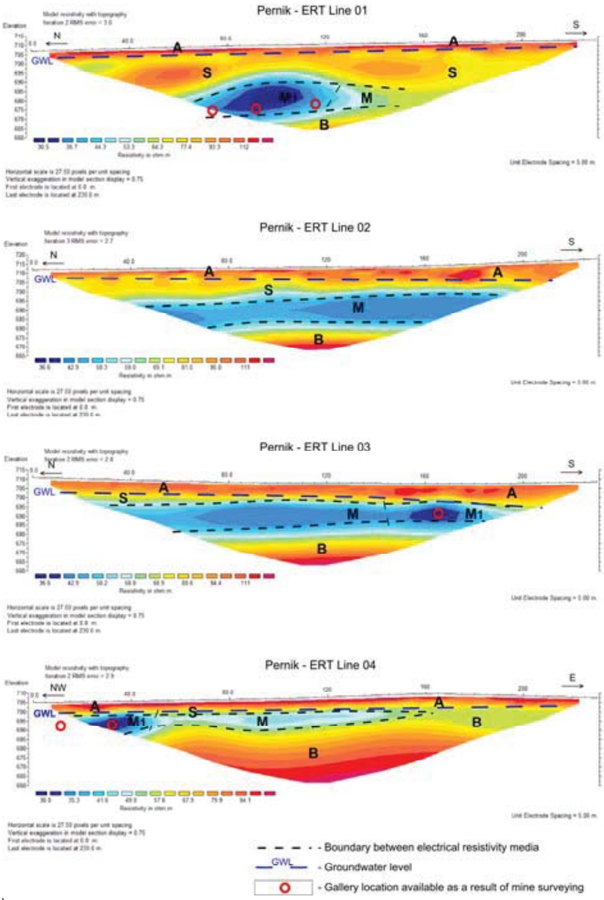

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Fig. 6. Electrical resistivity sections obtained along lines ERT-1, ERT-2, ERT-3 and ERT-4

3. It can be summarized that the studied geoelectrical section is represented by five electrical resistivity media, mapping five zones and two sub-zones, each characterized by different degree of unconsolidation, water-saturation and water-permeability. Most probably, these zones are mapping the spatial boundaries of the low-rank HGU determined down to a depth of 50 m in the range of the affected by the coal mining parts of the Paleogene coal bearing complex.

4. The differentiated electrical resistivity media, zones and sub-zones in the sections along the eleven studied lines are the following:

The first electrical resistivity media (Zone A) is located in the upper part of the near-surface sections along all lines. It is characterized by the highest values of the electrical resistivity for the studied geoelectrical section – in the range from 75 Ωm up to more than 120 Ωm. It most likely maps the spread of the unsaturated zone (zone of aeration) in the consolidated near-surface part of the Paleogene coal bearing complex.

The second electrical resistivity media (Zone S) is situated just underneath *Zone A* in the range of the affected by the underground coal mining parts of the Paleogene complex. It is characterized by a little bit lower values of the electrical resistivity – in the range from 55 Ωm up to 80 Ωm. *Zone S* probably shows the spread of the partially unconsolidated water-saturated areas above the abandoned mining workings that comprise the low-rank HGU *upper anthropogenic complex 2 – Anthr cmx - up*$_2$.

<u>The third electrical resistivity media (Zone M_1)</u> is determined in the depth interval from 16 m down to 35 m in the sections along lines ERT-1, ERT-5, ERT-6, ERT-7, ERT-8, and along lines ERT-3 and ERT-4 – in the depth interval from 7 m down to 20 m. The values of the electrical resistivity in this zone are the lowest for the studied geoelectrical section – in the range from 30 Ωm up to 50 Ωm, sometimes a little bit higher. Most probably *Zone* M_1 denotes the location of the galleries and the worked-out area in coal layers A and B. The galleries locations available as a result of mine surveying in the past are illustrated by red circles on the presented geoelectrical sections (Figs. 4 and 6). This media is water-saturated. In the scope of *Zone* M_1 enter two low-rank HGU – *lower anthropogenic complex 2 (Anthr cmx - l*$_2$*)* and *lower anthropogenic complex 4 (Anthr cmx - l*$_4$*)*.

In the section along line ERT-5, in the upper part of the third electrical resistivity media, a high-ohmic region *(Sub-zone* $^aM_1$*)* is established. It is characterized by values of the electrical resistivity in the range from 45 Ωm up to 70 Ωm (Fig. 7). *Sub-zone* $^aM_1$ most probably maps the unsaturated part of *Zone* M_1 that is located above groundwater level.

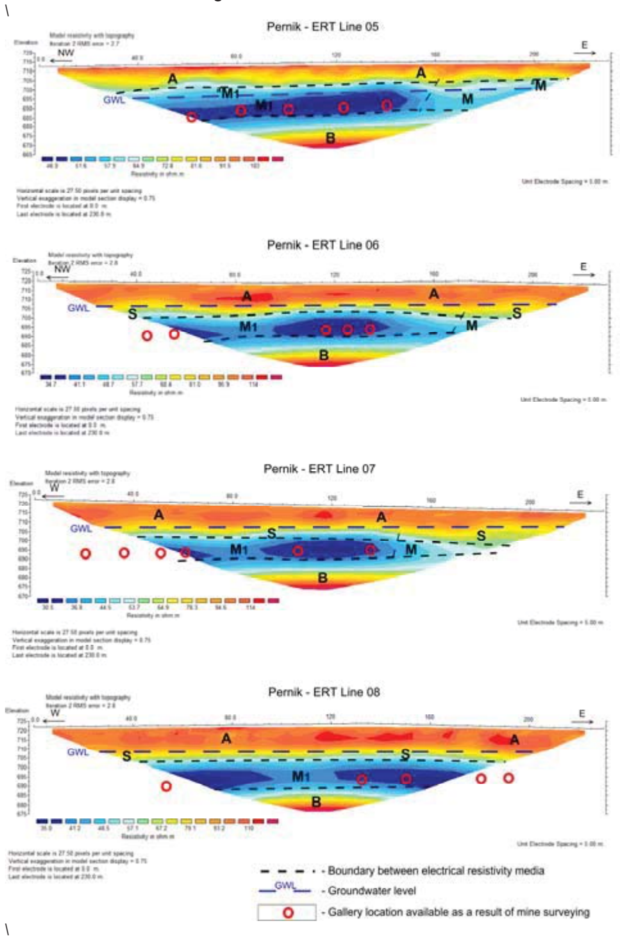

Fig. 7. Electrical resistivity sections obtained along lines ERT-5, ERT-6, ERT-7 and ERT-8

<u>The forth electrical resistivity media (Zone M)</u> is expressed in the sections along all lines (with the exception of line ERT-8) in a fairly wide range – in the depth interval from 3 m down to 32 m, most frequently in the interval from 5 m down to 25 m. It has a little bit higher values of the electrical resistivity than the ones characteristic for *Zone* M_1 – in the range from 50 Ωm up to 70 Ωm, however in separate regions outside these limits. This zone includes the water-saturated parts of the worked-out areas in coal layers A and B (mining workings, collapsed zones, cracked areas and pillars) that comprise two low-rank HGU – *lower anthropogenic complex 1 (Anthr cmx – l*$_1$*)* and *lower anthropogenic complex 3 (Anthr cmx – l*$_3$*)*.

In the eastern end of the section along line ERT-5, in the upper part of the forth electrical resistivity media, a high-ohmic region *(Sub-zone* ^aM*)* is established. It is characterized by values of the electrical resistivity in the range from 50 Ωm up to 80 Ωm (Fig. 7). In this case, *Sub-zone* ^aM probably reveals the spread of the unsaturated part of *Zone M* that is located above groundwater level.

<u>The fifth electrical resistivity media (Zone B)</u> maps the deep parts, in some cases also the periphery, of the sections along all lines. It is characterized by comparatively high values of the electrical resistivity – in the range from 75 Ωm up to more than 120 Ωm. Most probably *Zone B* denotes the relatively stable, unaffected by the coal mining, parts of the Paleogene coal bearing complex. This zone comprises the low-rank HGU *Paleogene coal bearing complex in natural state – Pg cmx.*

5. The groundwater level in the sections along all lines (with the exception of line ERT-5) is marked by the boundary between Zone A and Zone S. At some locations in the sections along lines ERT-4, ERT-9, ERT-10 and ERT-11, the groundwater level is mapped by the boundary between Zone A and Zone B, and in the section along lines ERT-5 – by the lower of boundaries of Sub-zone $^aM_1$ and Sub-zone ^aM. The groundwater level is presented by a dotted blue line on the presented geoelectrical sections (Figs. 6, 7, 8).

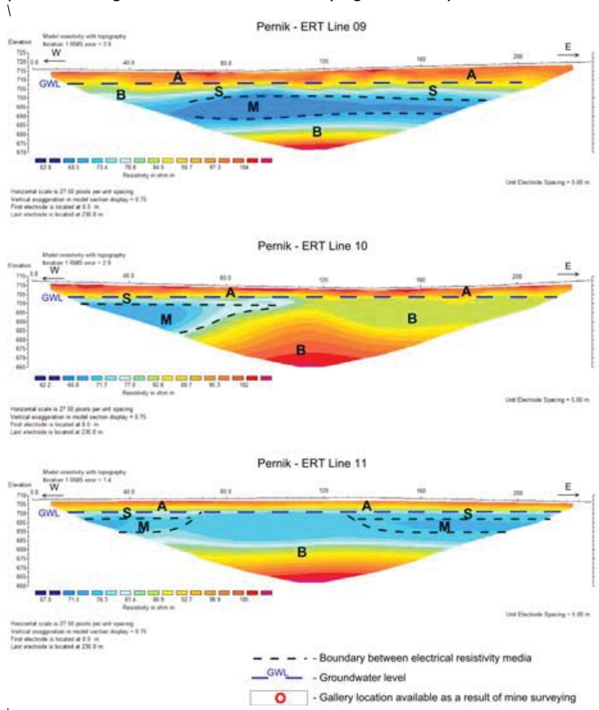

Fig. 8. Electrical resistivity sections obtained along lines ERT-9, ERT-10 and ERT-11

In accordance with one of the main objectives of the performed study, on the base of the derived electrical resistivity sections along the eleven surveyed lines and the detected geoelectrical borders, structural maps are developed concerning the top and the bottom of the areas affected by coal mining (*Zone* M_1 and *Zone M*) – Figure 9 and Figure 10. These surfaces are revealing the spatial boundaries of the four determined low-rank HGU of the lower anthropogenic complex: *Anthr cmx – l1, Anthr cmx – l2, Anthr cmx – l3* and *Anthr cmx – l4*.

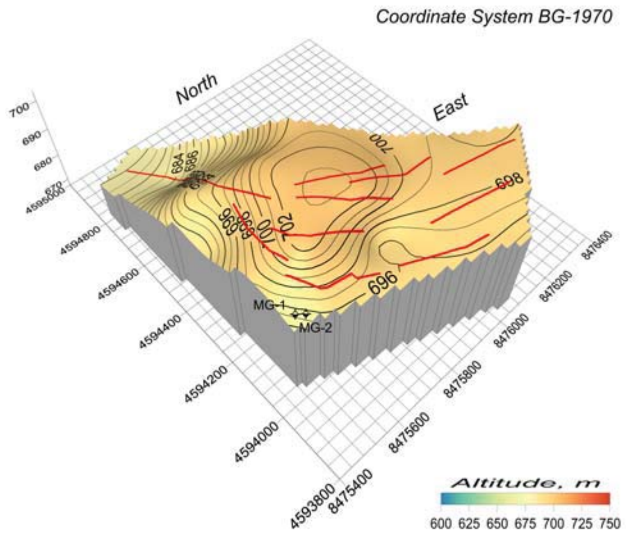

Fig. 9. Structural map of the top of low-rank HGU of the lower anthropogenic complex – *Anthr cmx – l1, Anthr cmx – l2, Anthr cmx – l3* and *Anthr cmx – l4*

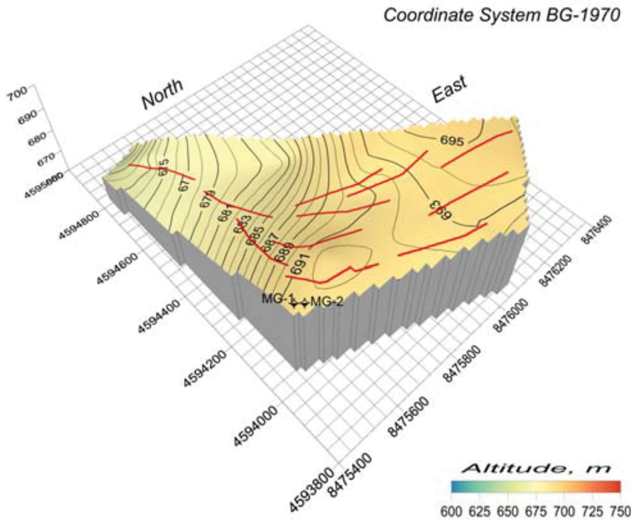

Fig. 10. Structural map of the bottom of low-rank HGU of the lower anthropogenic complex – *Anthr cmx – l1, Anthr cmx – l2, Anthr cmx – l3* and *Anthr cmx – l4*

The determined spatial boundaries of the low-rank HGU in the range of the affected by the coal mining parts of the Paleogene coal bearing complex are implemented in the development of a numerical 3-D hydrogeological model. This model is applied for estimating the changes in the hydrogeological conditions, the rise of groundwater level and the quantity of groundwater drained by concentrated or scattered water surface inflows.

Conclusions

The achieved practical results are confirming the geological effectiveness of the discussed approach for data acquiring, analysis and interpretation.

Five zones and two sub-zones, each characterized by different degree of unconsolidation, water-saturation and water-permeability are separated. These zones map the spatial boundaries of the low-rank HGU determined down to a depth of 50 m in the range of the affected by the coal mining parts of the Paleogene coal bearing complex.

The obtained results are implemented in the development of a numerical 3-D hydrogeological model that is applied for estimating the changes in the hydrogeological conditions, the rise of groundwater level and the quantity of groundwater drained by concentrated or scattered water surface inflows.

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