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Professional paper

A HYDROGEOLOGICAL MODEL OF THE OPEN-CAST MINE TAMNAVA-WEST FIELD (KOLUBARA COAL BASIN, SERBIA)

HIDROGEOLOŠKI MODEL POVRŠINSKOG KOPA „TAMNAVA - ZAPADNO POLJE“ (RUDARSKI BASEN „KOLUBARA“)

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Abstract: The Kolubara Coal Basin is the largest coal-producing area in Serbia. It is administratively comprised of several open-cast mines: Field A, Field B, Field C, Field D, Field E, Field F, Field G, Veliki Crljeni, Šopić-Lazarevac, Tamnava - West Field, Tamnava – East Field, Radljevo, Zvizdar, Ruklade, and Trlić. The paper focuses on the largest active open-cast mine: Tamnava - West Field. A study and conclusions about the hydrogeologic functions of the lithologic strata, and insight into their spatial interactions, are extremely important for hydrogeologic modeling of a given area. The main purpose of a hydrogeologic model is to derive conclusions about the spread of the aquifers in the study area, their interactions, and groundwater flow conditions. Based on geologic and hydrogeologic exploration, and analysis and synthesis of the collected data, the paper describes hydrogeologic modeling of the open-cast mine Tamnava – West Field. The software used in the research provides a portrayal of the 3D distribution of the aquifers present in the study area. As such, the hydrogeologic model constitutes a basis for developing a hydrodynamic (mathematical) model of the groundwater regime.

Keywords: hydrogeologic (conceptual) model, aquifer, model layers, hydrogeologic parameters

Apstrakt: Kolubarski ugljonosni basen najveći je basen uglja u Republici Srbiji. U basenu je administrativnom podelom okontureno više površinskih kopova: „Polje A“, „Polje B“, „Polje C“, „Polje D“, „Polje E“, „Polje F“, „Polje G“, „Veliki Crljeni“, „Šopić-Lazarevac“, „Tamnava - Zapadno polje“, „Tamnava Istočno polje“, „Radljevo“, „Zvizdar“, „Ruklade“ i „Trlić“. U ovom radu, istražni prostor obuhvata najveći aktivni površinski kop „Tamnava - Zapadno polje“. Analiza i izvođenje određenih zaključaka o hidrogeološkoj funkciji prisutnih litoloških članova na nekom istražnom području kao i sagledavanje njihovih prostornih odnosa od izuzetnog su značaja kod formiranja hidrogeološkog modela nekog područja. Osnovna namena hidrogeološkog modela je izvođenje zaključaka o

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prostiranju zastupljenih tipova izdani na istražnom području, njihovim međusobnim odnosima, kao i uslovima kretanja podzemnih voda. Na osnovu geoloških i hidrogeoloških istraživanja i analizom i sintezom dobijenih podataka, u radu je prikazano formiranje hidrogeološkog modela površinskog kopa „Tamnava - Zapadno polje“. Primenjenim softverskim paketom prikazan je 3D raspored prisutnih izdani na ovom istražnom području. Kao takav, hidrogeološki model predstavlja osnovu za nadgradnju - izradu hidrodinamičkog (matematičkog) modela režima podzemnih voda.

Ključne reči: konceptualni model, izdan, modelski slojevi, hidrogeološki parametri

1. INTRODUCTION

Kolubara Coal Basin (KCB) is the strongest link of the Electric Power Industry of Serbia. Since World War II, it has produced more than 580,000,000 tons of coal. Every other kilowatt in Serbia comes from KCB's lignite (brown coal). A daily extraction rate of as much as 100,000 tons of coal ensures reliable operation of the thermal power plants Nikola Tesla and Veliki Crljeni.

KCB has been the object of extensive research, the most important being the studies conducted by: Jagodić Krunić and Jovičić, 2007; Polomčić and Bajić, 2011; Buhač et al. 2012; Bajić and Polomčić, 2012; Polomčić et al. 2012; Stevanović Petrović et al. 2013; Polomčić et al. 2013a; Polomčić et al. 2013b; Polomčić et al. 2014; Šubaranović et al. 2013).

KCB'S Tamnava - West Field is the largest and most modern open-cast lignite mine in Serbia. In 2015, its total output was 11,600,000 tons of coal, or about 15.5% more than the annual budget.

Among the major recent hydrogeologic exploration activities at Tamnava - West Field are those reported in Polomčić et al. (2016) and Đinđić et al. (2016).

With regard to the topic of this paper, many researchers worldwide have addressed hydrogeologic systems of ore deposits, groundwater flow and processes that affect the hydrogeology of mining sites, including: Dimitrakopoulos et al. 2000; Rapantova et al. 2007; Kamkar-Rouhani, 2008; Rühaak et al. 2009; Niedbalska et al. 2011; Wels et al. 2012; Brown and Trott, 2012.

2. STUDY AREA

KBC occupies a land area of about 600 km^2. It is located some 50 km southwest of the capital Belgrade (Fig. 1) and encompasses the area around the middle and lower courses of the Kolubara River and its tributaries: the Tamnava (left) and the Peštan (right). Tamnava – West Field falls within the municipalities of Lajkovac and Ub, near the villages of Kalenić, Mali Borak, Radljevo and Skobalj. To the west and south, the mine borders on the exploratory field Radljevo, and to the east on Tamnava - East Field. The northern boundary is natural, where the coal bed lenses out.

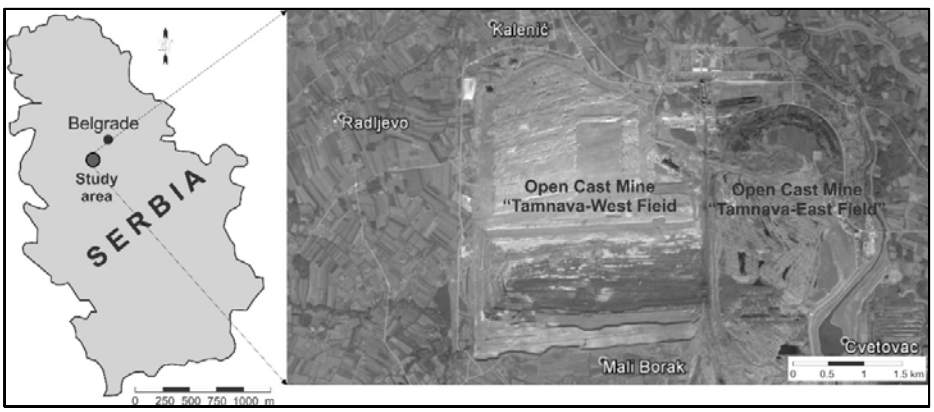

Figure 1 Geographic location of the study area

The geologic framework of Tamnava - West Field is comprised of Paleozoic and Mesozoic sediments within the paleo-relief. The coal basin is built up of Quaternary and Tertiary (Neogene/Pliocene) strata. In the extended zone of the study area (Fig. 2), these deposits contain alluvial and terrace riverine-lacustrine sediments made up of medium-grain gravels and sandy gravels (river terraces and alluvial plains - riverbed sediments of the Kolubara, the Kladnica, the Turija and the Peštan). There are also other deposits, such as diluvial/proluvial and oxbow sediments - silty clays and local bog clays (alluvial plains). Quaternary sediments lie discordantly over Pontian strata. The coal seams of Tamnava - West Field are underlain by quartz sands. In addition to the coal beds, the complex coal-bearing sequence comprises sand and coaly-clay interbeds. Upper Pontian and Quaternary sediments make up the ceiling of the coal sequence.

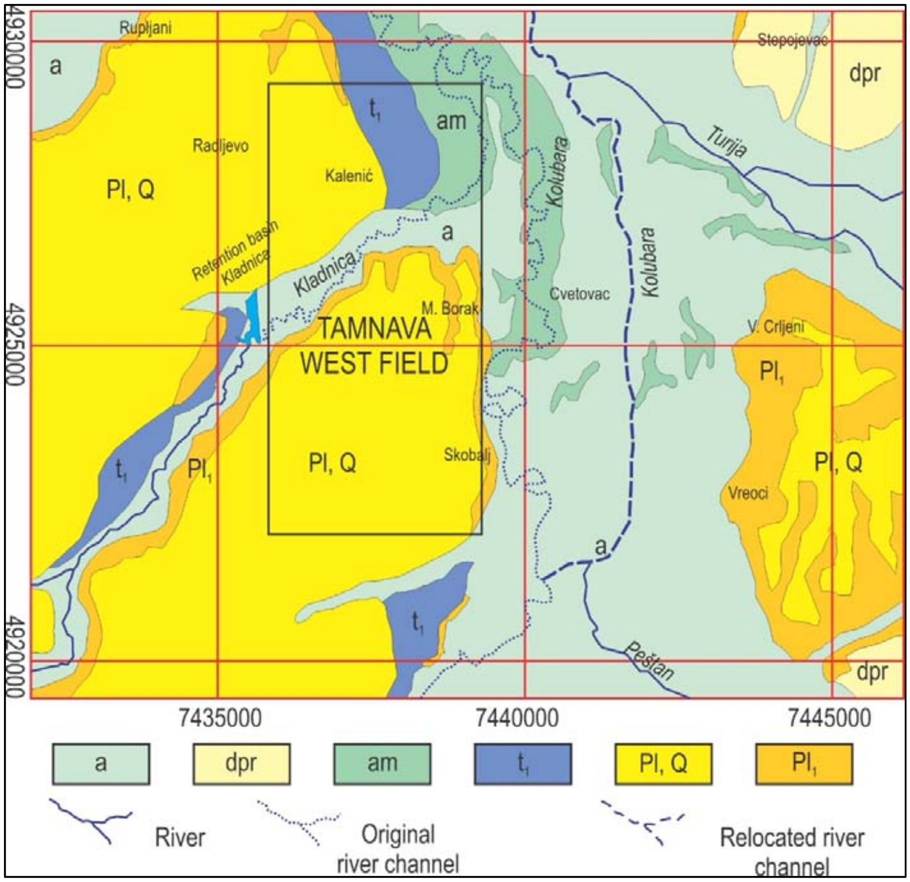

Figure 2 Geological map of the extended area of the open-cast mine Tamnava - West Field (According to the National geological map of Serbia, scale 1:100,000, Obrenovac section (Filipović et al. 1976))

Legend: a - riverbed sediments (gravel, sand and clay); dpr - diluvial/proluvial sediments; am - oxbow sediments (mud and clay); t_1 - lower river terrace; Q, Pl - riverine-lacustrine terrace; Pl_1 - sand and clay (marly and coaly)

There is a triple aquifer system in the extended zone of the study area: upper, intermediate and lower. The three aquifers are all confined and feature a subartesian groundwater level.

The upper aquifer at Tamnava - West Field is largely comprised of alluvial and riverine/lacustrine terrace sediments - terrace gravels of various grain sizes in both vertical and horizontal directions. Well pumping tests have been conducted and the hydraulic conductivity found to range from $6x10^{-5}$ m/s to $6x10^{-4}$ m/s.

The intermediate aquifer comprised of sands is found in the extended area of Tamnava - West Field, in a part where deposited sands lie between two coal beds. These sands extend beyond the mine to the northwest, where they join the sands of the lower aquifer. The grain-size distribution of the intermediate aquifer is relatively homogeneous in both vertical and horizontal directions, the sands are fine-grain and medium-grain, and the hydraulic conductivity is about $1x10^{-5}$ m/s. The intermediate aquifer is overlain and underlain by coal beds. In the northern part of the mine the overlying layer is integrated into the upper aquifer.

The lower aquifer at Tamnava - West Field is comprised of Lower Pontian sediments, represented by quartz sands. These sands extend beyond the mine and reach the edges of the Kolubara Coal Basin. The sands within Tamnava - West Field are very homogenous. Their values of hydraulic conductivity is (1.3 to 2.5) x 10^{-5} m/s and transmissivity T = (2.5 to 6.0) x 10^{-3} m^2/s. The aquifer floor comprises coal beds, fine Miocene sands, silt and clay.

3. METHODOLOGY

A hydrogeologic model is an interpretation of the dynamic and physical properties of a hydrogeologic system (American Society for Testing and Materials, 2014). According to Polomčić (2001), a hydrologic system is determined by: input elements, characteristics of the medium, processes that take place in the medium, and output elements, where the input and output elements are inter-dependent. The characteristics of a hydrogeologic system are its geometry (i.e. spatial distribution of water-bearing media) and filtration properties. Hydrogeologic modeling is schematization of the hydrogeologic system, due to the hydrogeologic and hydrodynamic complexity of the conditions, and includes modeling of the (Polomčić, 2002):

- flow field (aquifer geometry),
- filtration characteristics of the porous medium and hydrodynamic state of aquifer flow,
- aquifer regime, which is determined by certain laws, phenomena and distribution of factors,
- water balance components,
- boundary conditions (inflow into and outflow from the model), and
- initial conditions, determined by the piezometric head at a certain initial time.

A hydrogeologic model is the first step in groundwater modeling and precedes a hydrodynamic model. If the hydrogeologic model is not properly defined, the hydrodynamic model will not be realistic. In hydrogeologic exploration of open-cast mines (Morton and van Mekrek, 1993), the hydrogeologic model can be developed in two stages, so-called "conceptualization phases".

In the first phase, the hydrogeologic model is created using collected data from prior investigations and, as such, it constitutes a basis for determining which data are "critical". The second phase is elaboration, founded upon the outcomes of additional, more recent geological and hydrogeological research.

In essence, the hydrogeologic model shows the types of rocks, from a hydrogeological perspective, and their geometry. The focus is on aquifers and their spatial relationships. Groundwater levels, directions of groundwater flow, and recharge and discharge zones of the hydrogeologic system can also be depicted.

Such a hydrogeologic model constitutes the groundwork for the next step - conversion of the hydrogeologic model into a hydrodynamic model via model geometry (i.e. spatial distribution of hydrostratigraphic units) and hydrogeologic parameters of the porous medium, followed by specifying initial and boundary conditions and selecting the numerical method to be applied (Krešić, 2006; Krešić and Mikszewski, 2012).

4. RESULTS

The software used in this research, to create the conceptual hydrogeologic model, was Groundwater Vistas Advanced, version 64-Bit 6.74 b.24 (Rumbaugh and Rumbaugh, 2011).

The contours of the modeled layers were determined on the basis of data collected from numerous exploration boreholes, distributed across the study area. According to the "Report on Lignite Reserves at Tamnava - West Field of the Kolubara Coal Basin as on 31 December 2009" (Kitanović, 2010), there were 796 exploration boreholes from contour 172.5 to contour 100, whose total depth was 48,449.05 m. Based on those field explorations and an assessment of the lithologic members and their hydrogeologic functions, a total of eight layers were identified along the vertical, four of which were water-bearing layers: upper aquifer (Layer 2), intermediate aquifer (Layer 5) and lower aquifer (Layers 7 and 8). The real geometry of the layers was represented by their real areal spread in both planform and elevation. Given the natural depths and positions of the geologic members, the hydrogeologic model was specified with different areal spreads in planform and different, real thicknesses of the layers. The layers, from a hydrogeological perspective, viewed from the ground surface, are listed in Table 1.

Table 1 Modeled flow field: lithologic members of the modeled layers

Model layer	Lithologic members
1st isolating layer	Quaternary sands and heterogeneous dumped material in the northern part of the study area
2nd water-bearing /	Sands and gravels of the upper aquifer
isolating layer	and heterogeneous dumped material in the northern part of the study area
3rd isolating layer	Silt and heterogeneous dumped material in the northern part of the study area
4th isolating layer	First coal bed
5th water-bearing /	Sands of the intermediate aquifer in the western and central parts before the mine contour,
isolating layer	heterogeneous dumped material in the northern part of the study area, clays in the northeastern part, and coal in the eastern and southern parts
6th isolating layer	Second coal bed
7th water - bearing layer	Sands of the lower aquifer, good filtration characteristics
8th water - bearing layer	Sands of the lower aquifer, poor filtration characteristics

An aquifer's water balance assessment involves the determination of input and output components, and then the establishment of certain correlations between them. Polomčić et al. (2016) presented a quantitative 2013 groundwater balance of Tamnava - West Field, and also determined aquifer recharge and discharge in the form of model inflow and outflow. Given that there is a groundwater control system in place, the rate of groundwater extraction is greater than the rate of aquifer recharge (422.78 l/s vs 452.15 l/s). Analysis of the boundary conditions of the hydrogeologic system included effective infiltration and boundary conditions: river, general head boundary, drainage, specified discharge - drainage wells, specified discharge - "no flow" cells, and flow barrier. Among the so-called initial conditions, which characterize the piezometric head at a certain initial time, groundwater levels of the observation network comprised of 116 piezometers (of which 54 in the upper aquifer, 22 in the intermediate aquifer, and 40 in the lower aquifer) were measured and analyzed. Both the initial and boundary conditions are also examined in detail in Polomčić et al. (2016).

The schematization described above enabled the development of the hydrogeologic model of Tamnava - West Field. Supported by suitable software, the model made it possible to distinguish and show individual lithologic members and provide an unlimited number of hydrogeologic cross-sections. By way of illustration, Fig. 3 shows the spatial distribution of the upper, intermediate and lower aquifers from different angles.

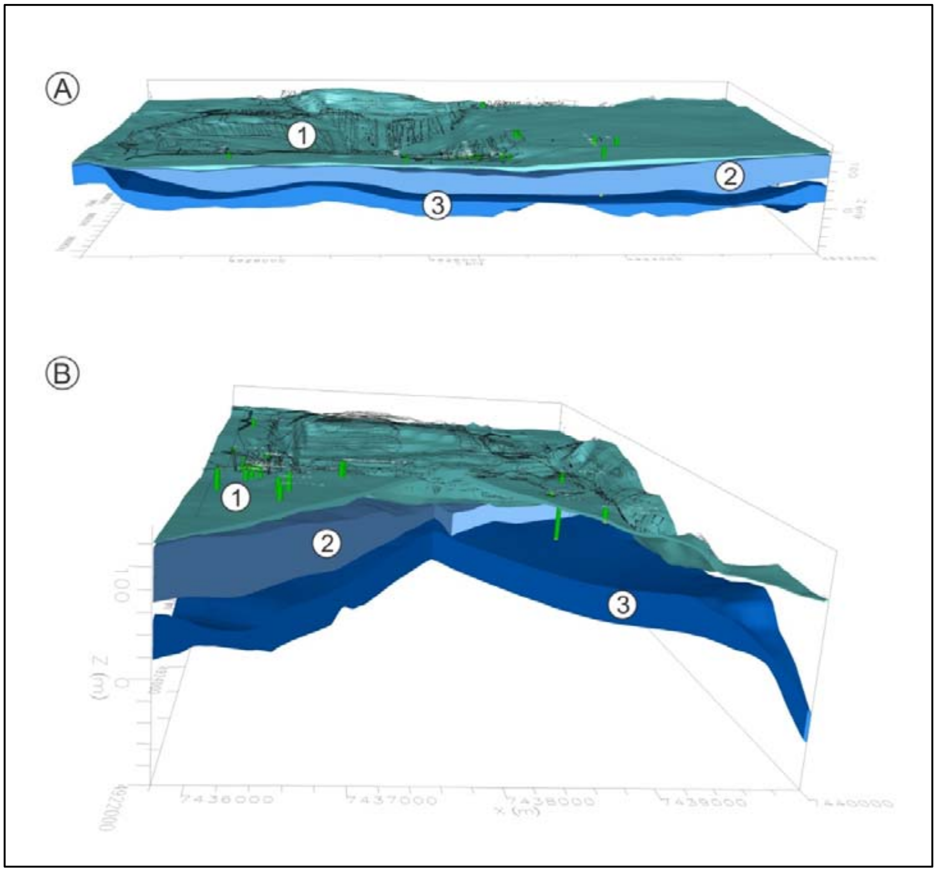

Figure 3 3D representation of the triple aquifer system (1 - upper, 2 - intermediate, and 3 - lower): a) south-north cross-section, and b) view from the south.

5. CONCLUSION

The geologic and hydrogeologic conditions of the origin of the lithologic members in the study area have determined the geologic framework and sediment structure, as well as the hydrogeologic relationships between the lithologic members.

Distinct spatial (3D) groundwater flow has been noted in the zones of contact of the alluvial sand-and-gravel sediments with the sands of the intermediate aquifer and further down with the sands of the lower aquifer, where there is vertical lithologic stratification and non-uniform horizontal spread of the lithologic members. This affected the selection of the main characteristics of the hydrogeologic model, which was comprised of eight layers along the vertical.

The developed hydrogeologic model constitutes unavoidable groundwork for the creation of a hydrodynamic model of groundwater flow, which will support a hydrodynamic analysis of the conditions for ensuring protection of the open-cast mine Tamnava - West Field from groundwater, as well as the selection of an optimal dewatering system.

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REFERENCES

BAJIĆ, D. and POLOMČIĆ, D. (2012) A conceptual hydrogeological model for open pit mine „Polje E“ (Kolubara coal basin, Serbia). In: RŮŽIČKA, J. and RŮŽIČKOVÁ, K. (eds.) *Proceedings of the GIS Ostrava 2012 - Surface models for geosciences symposium. Ostrava, Czech Republic, 23-25 January 2012.* Ostrava: Vysoká škola báňská - Technical University of Ostrava, pp 1-12.

BROWN, K., TROTT, S. and NABI, A. (2012) An alternative approach to managing dewatering in an open pit mine. In: MCCULLOUGH, C.D., LUND, M.A., and WYSE, L. (eds.) *Proceedings of the International Mine Water Association Symposium. Bunbury, Australia, 2012*. Bunbury: IMWA, pp. 557-567.

BUHAČ, D. et al. (2012) Designe solution of open pit „South Field” dewatering from surface and underground water, coal basin Kolubara. In: PAVLOVIĆ V. (ed.) *Proceedings of the X International Opencast Mining Conference OMC 2012*. Belgrade: Yugoslav Opencast Mining Committee, pp. 19-32.

DIMITRAKOPOULOS, D., GRIGORAKOU, E. and KOUMANTAKIS, J. (2000) Groundwater modelling of the South lignite field, West Macedonia, Greece. In: *Proceedings of the 7th International Mine Water Association Congress. Ustron, Poland, 2000*. Ustron: IMWA, pp. 519-529.

ĐINĐIĆ, I. et al. (2016) The impact of dewatering of open pit mine „Tamnava“ on groundwater regime of groundwater source „Kalenić“. In: VRANJEŠ, A. and VUKIĆEVIĆ, M. (eds.) *Proceedings of the XV Serbian Symposium on Hydrogeology, Kopaonik, Serbia, 14-17 September, 2016*. Belgrade: University of Belgrade - Faculty of mining and geology, pp 173-178.

FILIPOVIĆ, I. et al. (1976) *National geological map of Serbia, scale 1:100,000, Obrenovac section (L 34-125)*. Belgrade: Geological, Hydrogeological, Geophysical and Geotechnical Research Institute - Geozavod.

JAGODIĆ KRUNIĆ, D. and JOVIČIĆ, V. (2007) Shifting of the Kolubara in terms of dynamic development mining proceeding and opening new open pits in the central part of Kolubara's coal basin. In: PAVLOVIĆ, V. (ed.) *Proceedings of the VIII International conference of Surface Mining OMC 2007. Vrujci Spa, Serbia, 17-20 October, 2007*. Belgrade: Yugoslav Opencast Mining Committee: pp. 67-74.

KAMKAR-ROUHANI, A. (2008) A Finite Difference Groundwater Modelling and Comparison of the Results with Those Obtained Using Finite element modelling approach. In: RAPANTOVA, N. and HRKAL, Z. (eds.) *Proceedings of the 10th International Mine Water Association Congress: Mine Water and the Environment. Ostrava, Czech Republic, 2008*. Ostrava: IMWA, pp. 449-452.

KITANOVIĆ, Z. (2010) *Report on Lignite Reserves at Tamnava - West Field of the Kolubara Coal Basin as on 31 December 2009*. Kalenić: RB Kolubara.

KREŠIĆ, N. (2006) *Hydrogeology and Groundwater Modeling*. London: CRC Press.

KREŠIĆ, N. & MIKSZEWSKI, A. (2012) *Hydrogeological conceptual site models; data analysis and visualisation*. London: CRC Press.

MORTON, K.L., VAN MEKERK, F.A. (1993) A phased approach to mine dewatering. *Mine Water and Environment*, 12 (1), pp. 27-33.

NIEDBALSKA, K. et al. (2011) Modelling of changes of hydrodynamic conditions in the aquatic environment of the Maczki-Bór sand pit due to the fact of planned closure of mining operations (NE part of Upper Silesian Coal Basin - Poland). In: RÜDE R. T., FREUND A. and WOLKERSDORFER, CH. (eds.) *Proceedings of the 11th International Mine Water Association Congress: Mine Water - Managing the Challenges*. *Aachen, Germany, 2011*. Aachen: IMWA, pp 231-235.

POLOMČIĆ, D. (2001). *Hydrodynamic research, opening and management of groundwater sources in intergranular porous media*. Belgrade: University of Belgrade, Faculty of Mining and Geology.

POLOMČIĆ, D. (2002). Schematization types of hydrogeological system for setting up the hydrodynamic model. In: *Proceedings of the XIII Yugoslav symposium of hydrogeology and engineering geology*. *Herceg Novi, Montenegro, 2002.* Herceg Novi: pp 389-396.

POLOMČIĆ, D. and BAJIĆ, D. (2011). 3D Hydrodinamic model of open pit mine "Polje E" (Kolubara coal basin). In: PAVLOVIĆ, V. (ed.) *Proceedings of the V International Conference "Coal 2011". Zlatibor, Serbia, 19-22 October, 2011.* Belgrade: Yugoslav Opencast Mining Committee, pp. 320-330.

POLOMČIĆ, D., BAJIĆ, D. and RISTIĆ-VAKANJAC, V. (2012) Groundwater balance, natural recharge and drainage zones at open pit mine „Polje E" of Kolubara Coal Basin (Republic of Serbia). In: BAN, M., et al. (eds.) *CD Proceedings of the 7th Conference on Sustainable Development of Energy Water and Environmental Systems. Ohrid, Republic of Macedonia, 01-07 July, 2012.* Zagreb: Faculty of Mechanical Engineering and Naval Architecture, pp. 236-237.

POLOMČIĆ, D. et al. (2013a) Multiannual effects of Peštan source operation in the function of predewatering the future Kolubara basin opencast mines. In: PAVLOVIĆ, V. (ed.) *Proceedings of the VI International Conference "Coal 2013". Zlatibor, Serbia, 02-05 October, 2013*. Belgrade: Yugoslav Opencast Mining Committee, pp. 259-266.

POLOMČIĆ, D. et al. (2013b) Hydrodynamic characteristics of water supply source „Peštan" (Lazarevac, Serbia). *Vodoprivreda*, 45, pp. 55-68.

POLOMČIĆ, D., BAJIĆ, D. and ILIĆ, Z. (2014) Implementation of alternative forecasting hydrodynamic during designing of mines defense system against groundwater on opencast mine field C example. In: PAVLOVIĆ, V. (ed.) *Proceedings of the 11th International Opencast Mining Conference. Zlatibor, Serbia, 15-18 October 2014*. Belgrade: Yugoslav Opencast Mining Committee, pp. 321-338.

POLOMČIĆ, D. et al. (2016) Groundwater balance and its components at Tamnava West field open-pit coal mine. In: VRANJEŠ, A., VUKIĆEVIĆ, M. (eds.) *Proceedings of the XV Serbian Symposium on Hydrogeology. Kopaonik, Serbia, 14-17 September, 2016.* Belgrade: University of Belgrade - Faculty of mining and geology, pp. 483-487.

RAPANTOVA, N. et al. (2007) Ground Water Flow Modelling Applications in Mining Hydrogeology. *Mine Water and the Environment*, 26 (4), pp. 264-270.

RÜHAAK, W., LUO, J. and DIERSCH, H.-J.G. (2009) 3D Modelling of Brine Flow - A Case Study for a Flooded Salt Mine. In: *Proceedings of the International Mine Water Conference*. *Pretoria, South Africa*, *2009*. Pretoria: IMWA, pp 688-694.

RUMBAUGH, J.O. and RUMBAUGH, D.B. (2011) *Guide to using Groundwater Vistas: version 6*. New York: Environmental Simulations.

STEVANOVIĆ PETROVIĆ, N., STOJANOVIĆ, S. and COJIĆ, M. (2013) Peštan riverbed replacing for opening phase of new open pit "E" - Kolubara coal basin. In: PAVLOVIĆ, V. (ed.) *Proceedings of the VI International Conference "Coal 2013"*. Belgrade: Yugoslav Opencast Mining Committee, pp. 293-300.

THE AMERICAN SOCIETY FOR TESTING AND MATERIALS (2016) Available from: http://www.astm.org/DATABASE.CART/WITHDRAWN/D5447.htm [Acessed 23/11/16].

ŠUBARANOVIĆ, T., PAVLOVIĆ, V. and POLOMČIĆ, D. (2013) Influence on environment of sealing screen at lignite opencast mines. *Metalurgia International,* 18 (5), pp. 169-175.

WELS, C., FERGUSON, P.R. and FAWCETT, M. (2012) Numerical groundwater flow modelling at the historic Rum Jungle mine site, northern Australia. In: MCCULLOUGH, C.D., LUND, M.A., and WYSE, L. (eds.) *Proceedings of the International Mine Water Association Symposium*. *Bunbury, Australia, 2012*. Bunbury: IMWA, pp 309-315.