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IZRADA NUMERIČKOG MODELA STRUJANJA PODZEMNIH VODA U ZONI UTICAJA RUDNIKA RTB-a KORIŠĆENJEM SOFTVERSKOG PAKETA SPRING**

Izvod

Numerički model strujanja podzemnih voda razvijen je za borsku oblast u cilju utvrđivanja potencijalnog uticaja odloženog rudničkog otpada iz pogona RTB Bor (kopovska odlagališta i flotacijska jalovišta u okolini Bora) na kvalitet podzemnih voda. Svi parametri i prostorno-vremenska dinamika uzimanja uzoraka podzemnih voda definisani su standardom ISO 5667-11, kojim se utvrđuje program uzimanja uzoraka i rukovanje uzorcima za fizičko i hemijsko ispitivanje istih.

Ključne reči: *podzemne vode, SPRING softver, rudnička jalovina, zagađenje*

UVOD

Zagađenje voda u Republici Srbiji potiče od različitih privrednih grana (industrija, energetika, poljoprivreda, saobraćaj, rudarstvo itd.), kao i od neprečišćenih komunalnih otpadnih voda. Na pogoršanje kvaliteta vode u Republici Srbiji utiču, pored komunalnih i industrijskih i poljoprivredne aktivnosti, rečni saobraćaj, poplave, kao i prekogranično zagađenje. Značajno mesto u zagađenju voda zauzimaju prostori deponovane jalovine nastale u procesu rudarsko – prerađivačke industrije (flotacijska jalovišta Bora, Majdapeka, Rudnika, Velikog Majdana, Zajače, Raške, Vranja i dr.), deponije nastale pri metalurškoj preradi mineralnih sirovina i deponije pepela nastale pri energetsko-toplotnoj proizvodnji (termoelektrane).

HIDROGEOLOŠKI MODEL TRANSPORTA

Numerički model strujanja podzemnih voda razvijen je za borsku oblast, u cilju procene potencijalnog priliva podzemnih voda u oblasti površinskih kopova i jame

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Bor, kao i u cilju utvrđivanja potencijalnog uticaja kopovskih odlagališta i flotacijskih jališta RTB Bor koja su u okruženju, na kvalitet podzemnih voda.

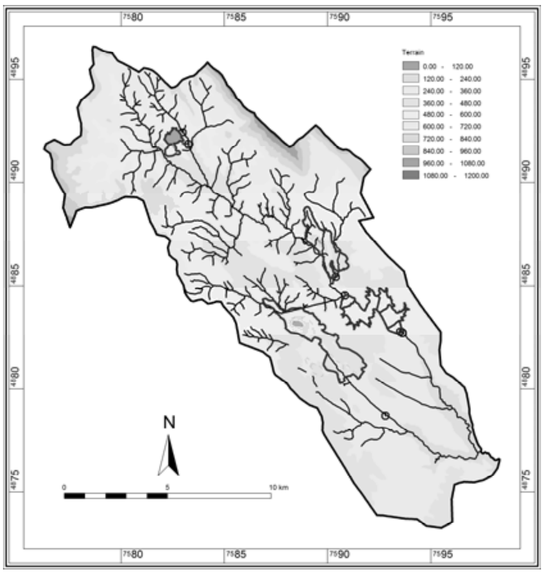
Izbor softverskog modela

Konceptualni model podzemnih voda preveden je u numerički model strujanja podzemnih voda, u cilju procene vrednosti brzine i pravca strujanja podzemnih vode. Izabran softverski paket "SPRING" za 3D numeričko modeliranje strujanja podzemnih voda, zasnovan na metodi konačnih elemenata, razvijen od strane Delta h Ingenieurgesellschaft mbH, Germany (König 2010). Program je prvi put objavljen 1970. godine i od tada je prošao kroz nekoliko revizija. "SPRING" je široko prihvaćen softverski program od strane naučnika iz oblasti zaštite životne sredine i naučnih udruženja. Ovaj softverski paket koristi metodu konačnih elemenata prilikom rešavanja jednačina kojom je prikazano strujanja podzemnih voda. To znači da je domen modela predstavljen brojem čvorova i elemenata.

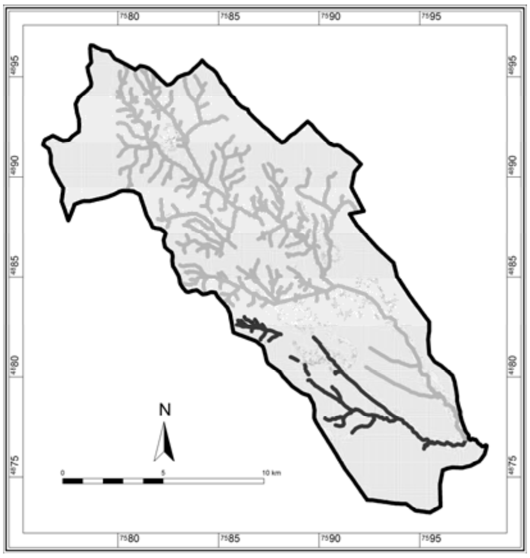
Hidrauličke osobine, svojstva ovih čvorova, elemenata i jednačina, razvijaju se za svaki čvor, a na osnovu susednih čvorova. Niz iteracija je zatim pokrenuto za rešavanje sistema diferencijalnih jednačina matričkom metodom. Model je pokazao da ima "konvergentne" rezultate, kada se greške smanjuju do prihvatljivog opsega. "SPRING" je u stanju da simulira stacionarno i nestacionarno strujanje podzemnih voda u izdani nepravilnih dimenzija, kao i prilikom zatvorenog ili otvorenog strujanja, ili kombinacije ova dva. Mogući su različiti modeli slojeva podzemnih voda različitih debljina.

Geometrijska struktura

Za mapiranje slivova relevantnih voda i kvantifikaciju uticaja ovih voda na situaciju podzemnih voda u borskoj oblasti, kreiran je regionalni dvodimenzionalni model. Prilikom formiranja mreže uzeti su u obzir: geološka struktura, nadmorska visina (Slika 1), površinske vode (Slika 2) sa svojim nivoima vode, bušotine izrađene u prethodnom periodu u cilju geoloških istraživanja i lokacija pijezometara za monitoring podzemnih voda.



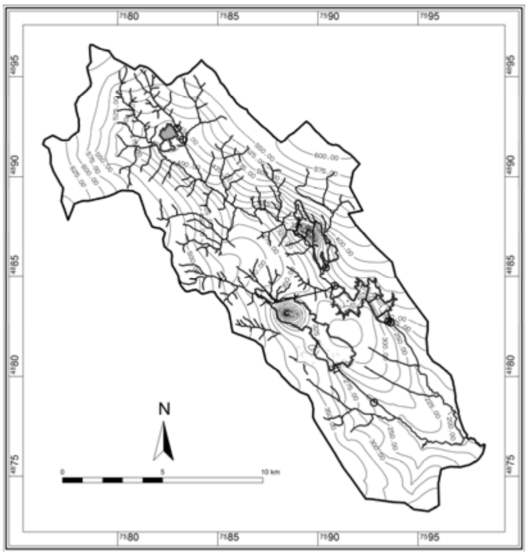
Sl. 1. *Visina površine terena čitave oblasti modeliranja*



Sl. 2. *Tok površinskih voda u domenu modela*

Pravac kretanja podzemnih voda

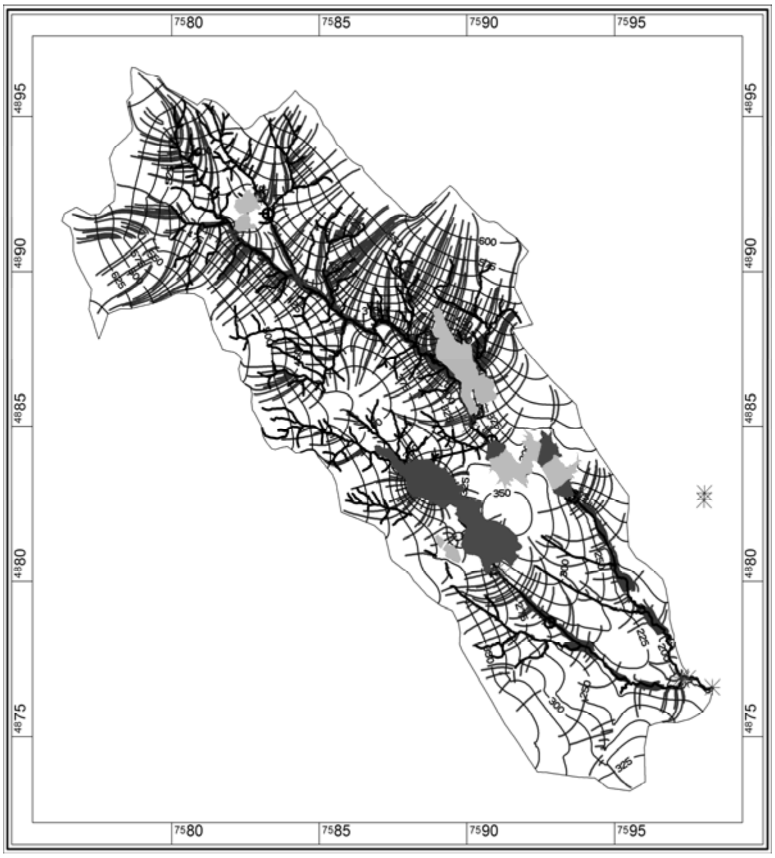
Po modelu kontura lokalnih podzemnih voda, jasno se vidi da je veliki uticaj rudnika bakra, flotacijskih jalovišta i odlagališta rudničke jalovine. Konture regionalnih stacionarnih podzemnih voda su, kao što se očekuje, u bliskoj vezi sa topografijom. Podzemne vode teku od viših ka nižim terenima, gde se pojavljuju kao izvorišta od kojih nastaju potoci i reke (Sl.3).



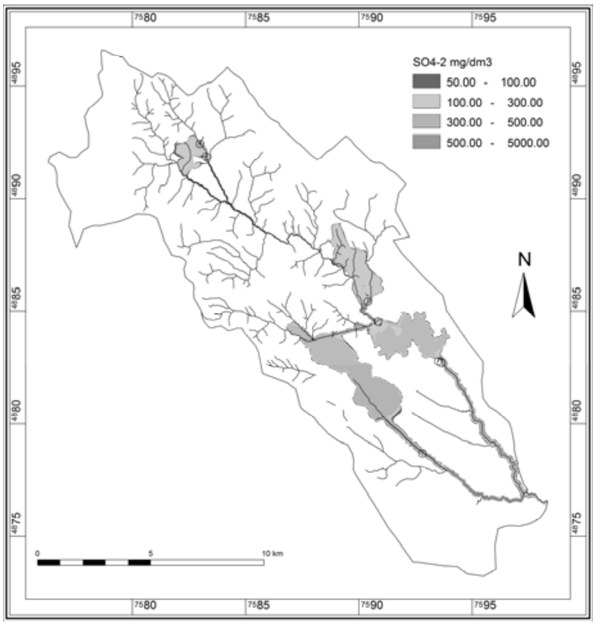
Sl. 3. *Model kontura podzemnih voda za čitavu oblast modeliranja*

Zagađenje u podzemnim vodama

3D model stacionarnih podzemnih voda korišćen je kao osnova za transportni model primenom "SPRING"-a. Jalovišta, deponije i površinski kopovi su smatrani kao potencijalni izvori zagađenja i ubačeni su u domen modela kao oblasti dreniranja sa izvorom konstantne koncentracije. U ovom tekstu se razmatra samo, transport potencijalnih zagađivača pretpostavljen kao advekcioni - disperzivni (longitudinalna disperzivnost 50 m) bez zadržavanja ili transformacija. Uticaji potencijalnih izvora zagađenja na kvalitet podzemnih voda su stoga ograničeni. Slike 4 i 5 pokazuju proračunate koncentracije SO_4^{-2} [mg/dm³] u borskoj oblasti u podzemnim i površinskim vodama.

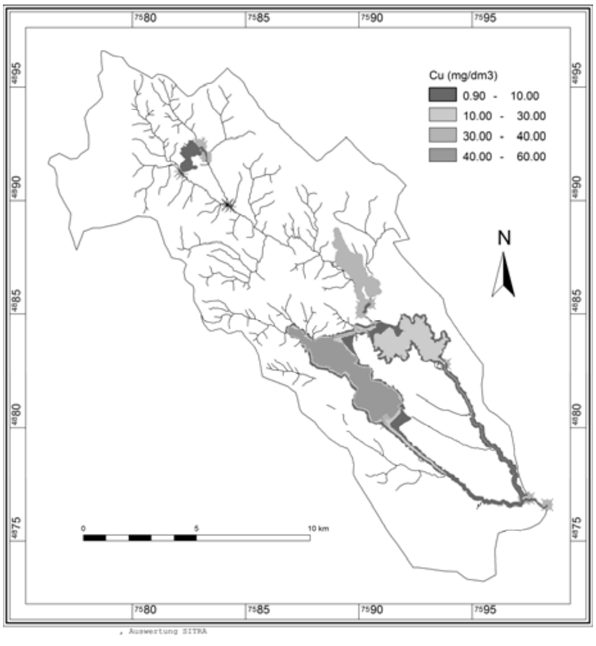


Sl. 4. *Proračunate linije pravca kretanja*



Sl. 5. *Proračunate koncentracije* SO_4^{-2} *[mg/dm³]*

Slika 6 pokazuje proračunate koncentracije Cu [mg/dm³] u borskoj oblasti u površinskim i podzemnim vodama.



Sl. 6. *Proračunata koncentracija Cu [mg/dm³]*

Uzorkovanje i ispitivanje kvaliteta podzemnih voda

Svi parametri i prostorno-vremenska dinamika uzimanja uzoraka podzemnih voda definisani su standardom ISO 5667-11, kojim se utvrđuje program uzimanja uzoraka i rukovanje uzorcima za fizičko i hemijsko ispitivanje istih (Tabela 1).

***Tabela 1**. Uzimanje uzoraka podzemnih voda, terenska osmatranja i merenja*

Opis aktivnosti	Metoda/Standard	Prostorno-vremenska dinamika
Uzimanje uzoraka	ISO 5667-11:1997 Water quality -- Sampling -- Part 11: Guidance on sampling of groundwaaters	7 lokaliteta: na području RBB Bor; Dinamika: april-juni 2012.

REZULTATI I DISKUSIJA

Fizičko-hemijsko ispitivanje podzemnih voda na području borskog rudnika je uključivalo određivanje sledećih elemenata: hroma, selena, gvožđa, bakra, olova, nikla, kadmijuma, cinka, arsena, sadržaja suspendovanih materija i sulfata. Rezultati fizičko hemijskih ispitivanja uzoraka podzemnih voda prikazani su u Tabelama 2a i 2b.

***Tabela 2a i 2b.** Rezultati fizičko-hemijskih ispitivanja uzoraka podzemnih voda iz posmatranih pijezometara koji su uzorkovani 18.05.2012. godine*

Parametar	T (^oC) vazduha	T (^oC) vode	Boja/miris	El.provod. µS/cm	pH	Cu (mg/dm^3)	Pb (mg/dm^3)	Zn (mg/dm^3)
P1	20	13.7	mutna/bez	3452	**5.82**	<0.1	<0.1	0.5
P2	20	11.9	mutna/bez	3812	6.15	<0.1	<0.1	**16.1**
P3	20	12.7	mutna/bez	5858	**4.45**	**3.6**	<0.1	**1.1**
P4	20	16.0	mutna/bez	1777	**5.21**	**5.1**	<0.1	**2.9**
P5	23	14.4	mutna/bez	2751	6.83	<0.1	<0.1	0.73
P8	23	17.8	mutna/bez	3032	6.67	<0.1	<0.1	<0.1
B3	22	17	mutna/bez	3081	7.39	<0.1	<0.1	<0.1

Parametar	Cd (mg/dm^3)	Ni (mg/dm^3)	Cr (mg/dm^3)	Se (mg/dm^3)	As (mg/dm^3)	Fe-uk (mg/dm^3)	Sus.mater. (mg/dm^3)	SO_4^{-2} (mg/dm^3)
P1	<0.1	<0.1	<0.1	<0.2	<0.1	**132.7**	363.0	2837.2
P2	<0.1	<0.1	<0.1	<0.2	<0.1	**64.4**	1977.0	2806.3
P3	<0.1	**0.5**	<0.1	<0.2	<0.1	<0.1	2225.0	3392.8
P4	<0.1	**0.37**	<0.1	<0.2	<0.1	**36.9**	899.0	1204.3
P5	<0.1	<0.1	<0.1	<0.2	<0.1	0.1	2264.0	1641.1
P8	<0.1	<0.1	<0.1	<0.2	<0.1	**2.1**	6770.0	1276.0
B3	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	62.0	1944.8

Tabele 2a i 2b - Lokacije posmatranih pijezometara

P1 *- Desna obala Valja Luterice – drenažna šahta;*
P2 - *Desna obala Valja Luterice – drenažno jezero;*
P3 - *Podnožje odlagališta Saraka potok;*
P4 *- Borska reka uzvodno od Slatine;*
P5 *- Kriveljska reka posle izlaza iz tunela;*
P8 *- Telo brane III;*
B2 *- Ulaz u tunel Kriveljske reke*

Pravilnik koji propisuje maksimalno dozvoljenu količinu opasnih i štetnih materija u zemljištu i vodi koje mogu da oštete ili promene proizvodnu sposobnost zemljišta i koje dolaze ispuštanjem iz fabrika i izlivanjem iz deponija, dat je u Službenom listu Socijalističke Republike Srbije br. 23/94. U tabeli 3 prikazani su podaci o maksimalno dozvoljenim količinama opasnih i štetnih materija u vodi.

Tabela 3. *Maksimalno dozvoljena količina opasnih i štetnih materija*

Broj	Parametar	MDK u vodi (mg/L)
1.	Kadmijum	Do 0.01
2.	Olovo	Do 0. 1
3.	Živa	Do 0.001
4.	Arsen	Do 0.05
5.	Hrom	Do 0.5
6.	Nikl	Do 0. 1
7.	Fluor	Do 1.5
8.	Bakar	Do 0.1
9.	Cink	Do 1.0
10.	Bor	Do 1.0

Opasne materije, u smislu ovog pravilnika su: kadmijum, olovo, živa, arsen, hrom, nikl i fluor, a štetne materije su: bakar, cink i bor.

Za analizu kvaliteta podzemnih voda u zoni uticaja rudnika i odložene jalovine RTB Bor, uzeti su kao hemijski parametri prvenstveno teški metali i pH vrednost.

Smanjena pH vrednost odnosno povećana kiselost ispod donje granice od 6 pH jedinica, u posmatranom periodu uočena je na mernim mestima P1, P3 i P4, pri čemu je najniža izmerena pH vrednost iznosila 4,45 u zoni odlagališta Saraka (pijezometar P3).

U Tabeli 2a i 2b boldirane su sve vrednosti onih elemenata čije se koncentracije nalaze iznad dozvoljenih granica. Povećane sadržaje imaju bakar, cink, gvožđe i nikl. Sadržaj bakra u posmatranom periodu se kretao od 3.6 mg/dm^3 (P3) do

5,1 mg/dm^3 (P4), cinka od 1,1 mg/dm^3 (P3) do 16,1 mg/dm^3 (P2), gvožđa 2,1 mg/dm^3 (P8) do 132,7 mg/dm^3 (P1) i nikla od 0,37 mg/dm^3 (P4) do 0,5 mg/dm^3 (P3). Ukoliko uporedimo izmerene koncentracije i maksimalno dozvoljene koncentracije (MDK) uočavamo da su one kod nekih elemenata višestruko povećane, na primer za bakar 51 put, za cink 16 puta, za gvožđe 132 puta i za nikl do 5 puta. Sadržaj hroma, kadmijuma, selena i arsena se u posmatranom periodu kretao ispod MDK.

ZAKLJUČAK

Ogromne količine odloženog rudničkog otpada u opštini Bor nastalog tokom vekovne eksploatacije i prerade rude bakra, konstantno zagađuje kako površinske tako i podzemne vodotokove. Kao krajnji rezultat i posledica zagađenja imamo neupotrebljive vodotokove Borske i Kriveljske reke koji se ne mogu koristiti čak ni za navodnjavanje poljoprivrednog zemljišta, jer je kvalitet vode u njima van svake kategorije. Ono što je takođe veoma ozbiljno je da su i posledice po podzemne vode u zoni uticaja rudničkog otpada RTB Bor katastrofalne. Svi bunari i izvorišta u selima Veliki i Mali Krivelj, Slatina i Oštrelj, koji se nalaze u bližoj okolini Kriveljske i Borske reke su veoma zagađeni i ne mogu se koristiti, kako za piće tako i za napajanje domaćih životinja. Ovo isto važi i za bunare i izvorišta u bližoj okolini odlagališta kopovske raskrivke i flotacijske jalovine. Numeričko modeliranje ima za cilj da nam omogući kvalitetan grafički prikaz uticaja zagađenja kako na podzemne tako i na površinske vodotokove, sa definisanim zonama rasprostiranja zagađenja i njihovom krajnjem dometu. Na taj način se u potpunosti može sagledati sveobuhvatan uticaj koje zagađenja generisana rudničkim otpadom imaju na površinske i podzemne vode u njihovom okruženju.

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DEVELOPMENT THE NUMERICAL MODEL OF GROUND WATER FLOW IN THE IMPACT ZONE OF RTB MINE USING THE SOFTWARE PACKAGE SPRING**

Abstract

The numerical model of ground water flow was developed for the Bor area in order to determine the potential impact of disposed mine waste from the site of RTB Bor (open pit and flotation tailing dumps in the vicinity of Bor) on the ground water quality. All parameters and spatial-temporal dynamics of ground water sampling are defined by the Standard ISO 5667-11, which establishes a program of sampling and handling of samples for physical and chemical analysis the same.

Keywords: *ground water, SPRING software of mine waste, pollution*

INTRODUCTION

Water pollution in the Republic of Serbia comes from various economic sectors (industry, energy, agriculture, transportation, mining, etc.), as well as from untreated municipal wastewater. The deterioration of water quality in the Republic of Serbia is influenced, in addition to the municipal and industrial activities and agricultural activities, by the water transport, floods, and cross-border pollution. An important place in the water pollution is occupied by the areas of deposited tailings produced in the process of mining - processing industry (flotation tailing dumps of Bor, Majdanpek, Mine, Veliki Majdan, Zajača, Raška, Vranje, etc.), the waste dumps incurred in the metallurgical treatment of mineral resources and ash landfills resulting from the energy-thermal production (thermal power plants).

HYDROGEOLOGICAL MODEL OF TRANSPORTATION

Numerical ground water flow model was developed for the Bor area in order to assess the potential groundwater inflow in

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the area of open pits and pit Bor, as well as to determine the potential impact of open pit dumps and flotation tailing dumps of RTB Bor, which are in the environment, on the ground water quality.

Selection of software model

A conceptual model of ground water has been translated into a numerical model of ground water flow in order to assess the value of speed and direction of ground water flow. The selected software package SPRING for 3D numerical modeling of ground water flow, based on the finite element method, was developed by the delta h Ingenieurgesellschaft mbH, Germany (König 2010). The program was first published in the 1970 and since then it has gone through several revisions. SPRING is a software program widely accepted by scientists in the field of environmental protection and scientific societies. This software package uses the finite element method in solving the equation that shows the flow of ground water. This means that the model domain is represented by the number of nodes and elements.

Hydraulic characteristics, properties of these nodes, elements and equations, are developed for each node, based on the neighboring nodes. A series of iterations was then run to solve the system of differential equations using the matrix method. Model showed that it has the "convergence" results when the errors are reduced to an acceptable range. SPRING is able to simulate steady and unsteady flow of ground water in the aquifers of irregular sizes, as well as in the closed or opened flow, or a combination of these two. There may be different models of ground water layers of different thicknesses.

Geometric structure

To map the relevant water basins and quantify the impact of this water on the ground water situation in the Bor area, a regional two-dimensional model was created. During formation the network, the followings are taken into account: geological structure, altitude (Figure 1), surface water (Figure 2) with their levels of water, drill holes made in the previous period for geological explorations and locations of piezometers for ground water monitoring.

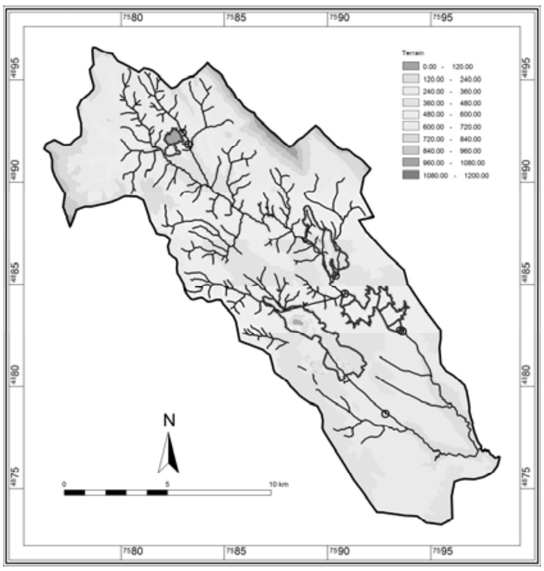

Fig. 1. *Field surface height of the entire modeling area*

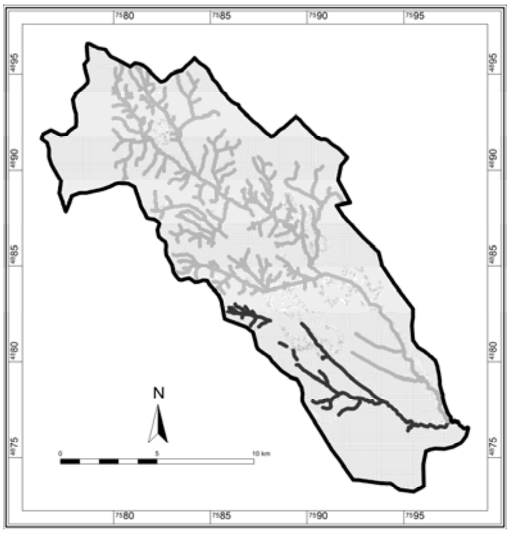

Fig. 2. *Surface water floe in the area of model*

Ground water directions

According to the model local ground water contours, it is clear that the copper mine, flotation tailing dumps and mine waste dumps have the major impact. The contours of regional stationary ground water, as it is expected, are closely related to the topography. Ground water flows from higher to lower terrains where they appear as sources which crate streams and rivers (Figure 3).

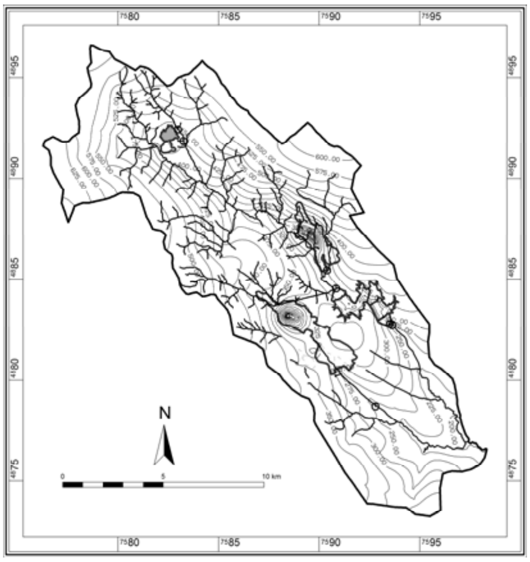

Fig. 3. *Model of ground water contours for the entire area of modeling*

Pollution of groundwater

3D model of stationary ground water was used as the basis for the transport model using SPRING. Tailing dumps, landfills and open pits are considered as potential sources of pollution and they are inserted into the model domain as drainage areas with a source of constant concentration. This paper discusses only the transport of potential pollutants assumed to advection-dispersion (longitudinal dispersion 50 m) without stopping or transformation. The effects of potential pollution sources to the ground water quality are therefore limited. Figures 4 and 5 show the calculated concentration of SO_4^{-2} [mg/dm³] in the Bor area in the ground and surface water.

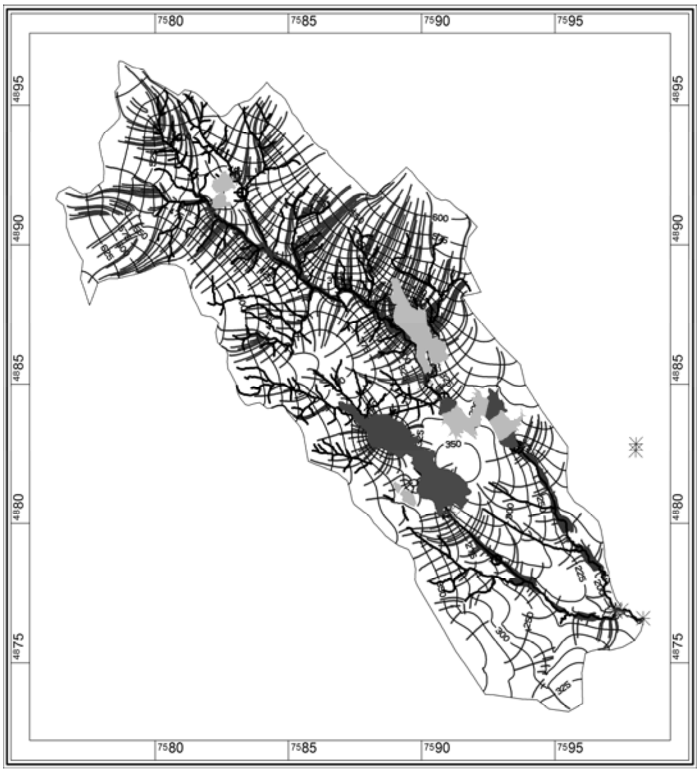

Fig. 4. *Calculated lines of movement direction*

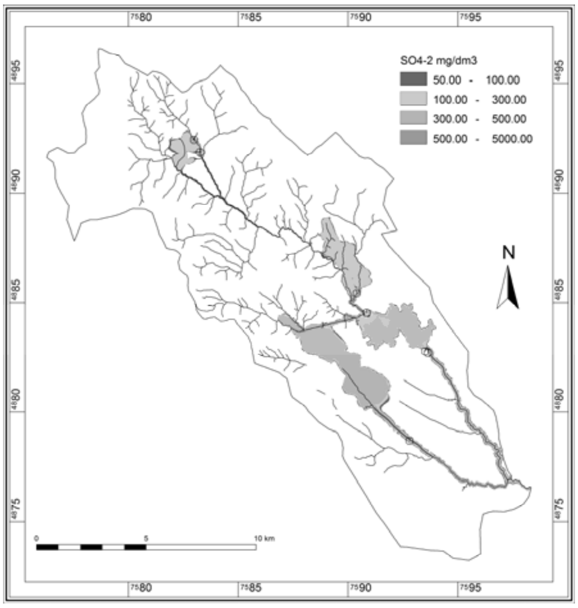

Fig. 5. *Calculated concentrations of* SO_4^{-2} *[mg/dm³]*

Figure 6 shows calculated concentrations of Cu [mg/dm³] in the Bor area in the ground and surface water.

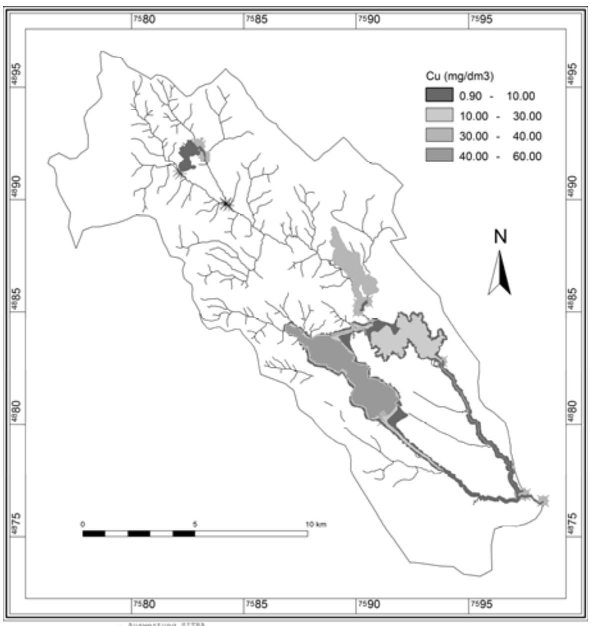

Fig. 6. *Calculated concentration of Cu [mg/dm³]*

Sampling and testing the groundwater quality

All parameters and spatial-temporal dynamics of ground water sampling are defined by the Standard ISO 5667-11, which establishes a program of sampling and handling of samples for physical and chemical analysis of the same (Table 1).

Table 1. *Groundwater sampling, field observations and measuring*

Activity description	Method/Standard	Prostorno-vremenska dinamika
Sampling	ISO 5667-11:1997 Water quality -- Sampling -- Part 11: Guidance on Sampling of Ground Water	7 locaities: in the area of RBB Bor; Dynamics: April-June 2012

RESULTS AND DISCUSSION

Physical-chemical testing of ground water in the area of Bor mine included determining the following elements: chromium, selenium, iron, copper, lead, nickel, cadmium, zinc, arsenic, content of suspended solids and sulfates. The results of physical and chemical testing of ground water samples are present in Tables 2a and 2b.

Tables 2a and 2b. *Results of physical- chemical testing of ground water samples from the observed piezometers, sampled on May 18, 2012*

Parameter	T (^{o}C) air	T (^{o}C) water	Colour/smell	El.conduct. μS/cm	pH	Cu mg/dm^3	Pb mg/dm^3	Zn mg/dm^3
P1	20	13.7	muddy / without	3452	**5.82**	<0.1	<0.1	0.5
P2	20	11.9	muddy / without	3812	6.15	<0.1	<0.1	**16.1**
P3	20	12.7	muddy / without	5858	**4.45**	**3.6**	<0.1	**1.1**
P4	20	16.0	muddy / without	1777	**5.21**	**5.1**	<0.1	**2.9**
P5	23	14.4	muddy / without	2751	6.83	<0.1	<0.1	0.73
P8	23	17.8	muddy / without	3032	6.67	<0.1	<0.1	<0.1
B3	22	17	muddy / without	3081	7.39	<0.1	<0.1	<0.1

Parameter	Cd (mg/dm³)	Ni (mg/dm³)	Cr (mg/dm³)	Se (mg/dm³)	As (mg/dm³)	Fe-total (mg/dm³)	Suspended matters (mg/dm³)	SO_4^{-2} (mg/dm³)
P1	<0.1	<0.1	<0.1	<0.2	<0.1	**132.7**	363.0	2837.2
P2	<0.1	<0.1	<0.1	<0.2	<0.1	**64.4**	1977.0	2806.3
P3	<0.1	**0.5**	<0.1	<0.2	<0.1	<0.1	2225.0	3392.8
P4	<0.1	**0.37**	<0.1	<0.2	<0.1	**36.9**	899.0	1204.3
P5	<0.1	<0.1	<0.1	<0.2	<0.1	0.1	2264.0	1641.1
P8	<0.1	<0.1	<0.1	<0.2	<0.1	**2.1**	6770.0	1276.0
B3	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	62.0	1944.8

Tables 2a and 2b – Locations of the observed piezometers

P1 *- The right bank of Valja Luterica - drainage manhole;*
P2 *- The right bank of Valja Luterica - drainage lake;*
P3 *- Bottom of the waste dump Saraka Stream;*
P4 *- The Bor River upstream from Slatina;*
P5 *- The Krivelj River after exit of the tunnel;*
P8 *- The body of Dam III;*
B2 *- The entrance into the tunnel of the Krivelj river.*

The Rulebook that prescribes maximum allowable quantity of hazardous and harmful substances in soil and water that might damage or change the production capacity of soil and that come from factory discharges and spillages from land fills, is given in the Official Gazette of the Socialist Republic of Serbia No. 23/94. Table 3 presents the data on maximum allowable quantities of hazardous and harmful substances in water.

Table 3. *Maximum allowable quantities of hazardous and harmful substances*

No.	Parameter	MDK in water (mg/L)
1.	Cadmium	Up to 0.01
2.	Lead	Up to 0. 1
3.	Mercury	Up to 0.001
4.	Arsenic	Up to 0.05
5.	Chrome	Up to 0.5
6.	Nickel	Up to 0. 1
7.	Fluorine	Up to 1.5
8.	Copper	Up to 0.1
9.	Zinc	Up to 1.0
10.	Boron	Up to 1.0

Hazardous substances, in terms of this regulation are: cadmium, lead, mercury, arsenic, chromium, nickel and fluorine, and harmful substances are: copper, zinc and boron.

For the analysis of ground water quality in the area of impacts the mine and disposed tailings of RTB Bor, primarily heavy metals and pH value were taken as chemical parameters.

Decreased pH value and increased acidity below the lower limit of 6 pH units in the reporting period was observed at the measuring points P1, P3, and P4, with the lowest measured pH value of 4.45 in the area of Saraka landfill (piezometer P3).

Table 2a and 2b present the bolded all values of those elements whose concentrations are above the permissible limits. Copper, zinc, iron and nickel have the increased contents. Content of copper in the observed period ranged from 3.6 mg/dm^3 (P3) to 5.1 mg/dm^3 (P4), zinc from 1.1 mg/dm^3 (P3) to 16.1 mg/dm^3 (P2), iron from 2.1 mg/dm^3 (P8) to 132.7 mg/dm^3 (P1) and nickel from 0.37 mg/dm^3 (P4) to 0.5 mg/dm^3 (P3). If the measured concentrations and maximum permissible concentrations (MPC) are compared, it is seen that they are several times increased in some elements, for example 51 times for copper, 16 times for zinc, 132 times for iron and up to 5 times for nickel. Content of chromium, cadmium, selenium and arsenic in the observed period was under MPC.

CONCLUSION

Huge amounts of disposed mine waste in the municipality of Bor, created during centuries of mining and processing of copper ore, constantly pollute both surface and ground waterways. As the final result and consequence of pollution, there are unusable waterways of the Bor and Krivelj River that cannot be used even for irrigation of agricultural land, because the water quality in them is out of any category. It is also very serious that the consequences for ground water in the impact zone of mine waste of RTB Bor are disastrous. All wells and springs in the villages of Veliki and Mali Krivelj, Slatina and Oštrelj, which are located in the vicinity of the Krivelj and Bor River are heavily polluted and they can be used both for drinking and watering of domestic animals. This is also true for wells and springs in the vicinity of the open pit overburden and tailing dump. Numerical modeling is intended to allow a high quality graphic display of the pollution impact both on ground water and surface water courses, with defined areas of pollution spreading and their ultimate range. In this way, a completely comprehensive impact can be seen of pollution, generated by mine waste on the surface and ground water in their environment.

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