

Application of Groundwater modeling for designing a dewatering system: Case study of the Buvač Open Cast Mine, Bosnia and Herzegovina



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ABSTRACT

This paper presents groundwater management based on the results of groundwater modeling. Model used to simulate the effects of the operation of three dewatering system scenarios of the Buvač open cast mine. Several aquifers exist within the region of the Buvač limonite ore deposit, which puts ore exploitation at risk due to water ingress. Groundwater modeling was used to understand the groundwater regime within these aquifers. A previous numerical model (2007) was completed for the state of the groundwater regime prior to the opening of the open-cast mine. In the last five years, development of the open cast mine and associated activities have drastically modified the flow field. The model was modified for the altered conditions on site, and with new data from monitoring both the ground and surface water regimes. The existing system of protection of the cast mine from groundwater encompasses drainage of both the alluvial and ore body aquifers. This paper analyzes three scenarios for protecting the opencast mine from groundwater between 2013 – 2024. The new model was used to simulate the effects of operating the three proposed dewatering systems. Differences in the operating effects of the scenarios were quantified through the conditions of groundwater levels and water budget. Recommendations have also been given for performing prediction calculations in the case of the existence of drainage wells, with the most effective dewatering system determined from a hydrodynamic aspect. The results presented may be used for developing an effective dewatering system.

Keywords: numerical modeling, groundwater management, mine dewatering, Bosnia and Herzegovina

1. INTRODUCTION

Groundwater ingress into a mine during its operative life is one of the most important mining concerns. It is therefore necessary to quantify groundwater inflow into the mine and the effectiveness of the dewatering system in operation. Prior to the development of computational numerical modeling methods, groundwater impacts were predicted by analytical and empirical methods, or hard-won experience. Many analytical solutions for predicting water inflow into mine excavations can be found in the literature (HANNA et al., 1994; MARINELLI & NICCOLI, 2000; SHEVENELL,

2000; LI et al., 2014). These solutions were often developed based on simplified assumptions and boundary conditions that restrict their applicability in real world mining situations. Numerical modeling codes such as Modflow (HARBAUGH et al., 2000) enable finding solutions to significant regional groundwater problems and are very important for the design of dewatering systems for open cast mines. Numerical models do not have the limitations of analytical solutions and are suitable for the simulation of all aquifer conditions (RAPANTOVA et al., 2007; POLOMČIĆ et al., 2013b). For example, BOSKIDISA et al. (2012) describe the use of Modflow to examine several alternative scenarios for

groundwater extraction from two aquifers, and describe how the calibrated model allowed for better management of groundwater resources. MYLOPOULOSA et al. (2007) described an integrated water resources management plan wherein a numerical groundwater model of a deep aquifer system was used to develop alternative exploitation plans for the deeper aquifer.

Dewatering systems should also be designed and constructed to fully protect groundwater and surface water from mining impacts, to enable the sustainable extraction of ore. The new age of numerical analysis has enabled modeling of increasingly complex hydrogeological regimes and inclusion of components such as dewatering systems, drainage wells, and cut-off walls (STRZODKA & FISCHER, 1988; ŠUBARANOVIĆ et al., 2013). Numerical models are most often used for open cast mines in order to determine the inflow of water into the mine workings (BRAWNER, 1982), for assistance in designing dewatering systems (STRUZINA et al., 2011; BAHRAMI et al., 2014) or in order to analyze the effects and optimization of operating several possible dewatering systems (WU et al., 2010; JIANG et al., 2013). They are also used to analyze the environmental impact of mining activities (WU et al. 2000, QIAO et al., 2011; MARRANDI et al., 2013) or to predict groundwater mounding after ore exploitation and dewatering system operation ends (BANKS et al., 2010; GÖDEKE, 2011).

The study area encompasses the wider region of the Buvač open cast mine. In order to design a dewatering system, a numerical model of the open cast mine (POLOMČIĆ et al., 2013a) was constructed when the mine was opened in 2007, with input data from the period 1971-1973. The use of data available from the beginning of the 1970s decreased the model's reliability; however, these were the only data available at the time of model construction. From October 2010 to October 2012, new hydrogeological research and groundwater monitoring was conducted. In the meantime, from 2008, ore exploitation commenced at the open cast mine. As one of the measures of protection of the open cast mine from groundwater and surface water, the Rivers Gomjenica and Bistrica were diverted into the new river bed of the River Gomjenica, to the north of the mine (Figure 1). The first numerical model was corrected and adjusted to the new conditions in the study area. New data regarding the site have enabled certain improvements to be made in assigning boundary conditions in the model. The model was supplemented with a set of the new registered data on the groundwater and surface water regimes. A new recalibrated model was used to simulate the operational effects of the dewatering systems from 2013 - 2024, i.e. until the end of ore exploitation. In total, three scenarios operating different dewatering systems were analyzed. The most efficient system, from a hydrodynamic perspective, was chosen by comparing the predicted operational effects.

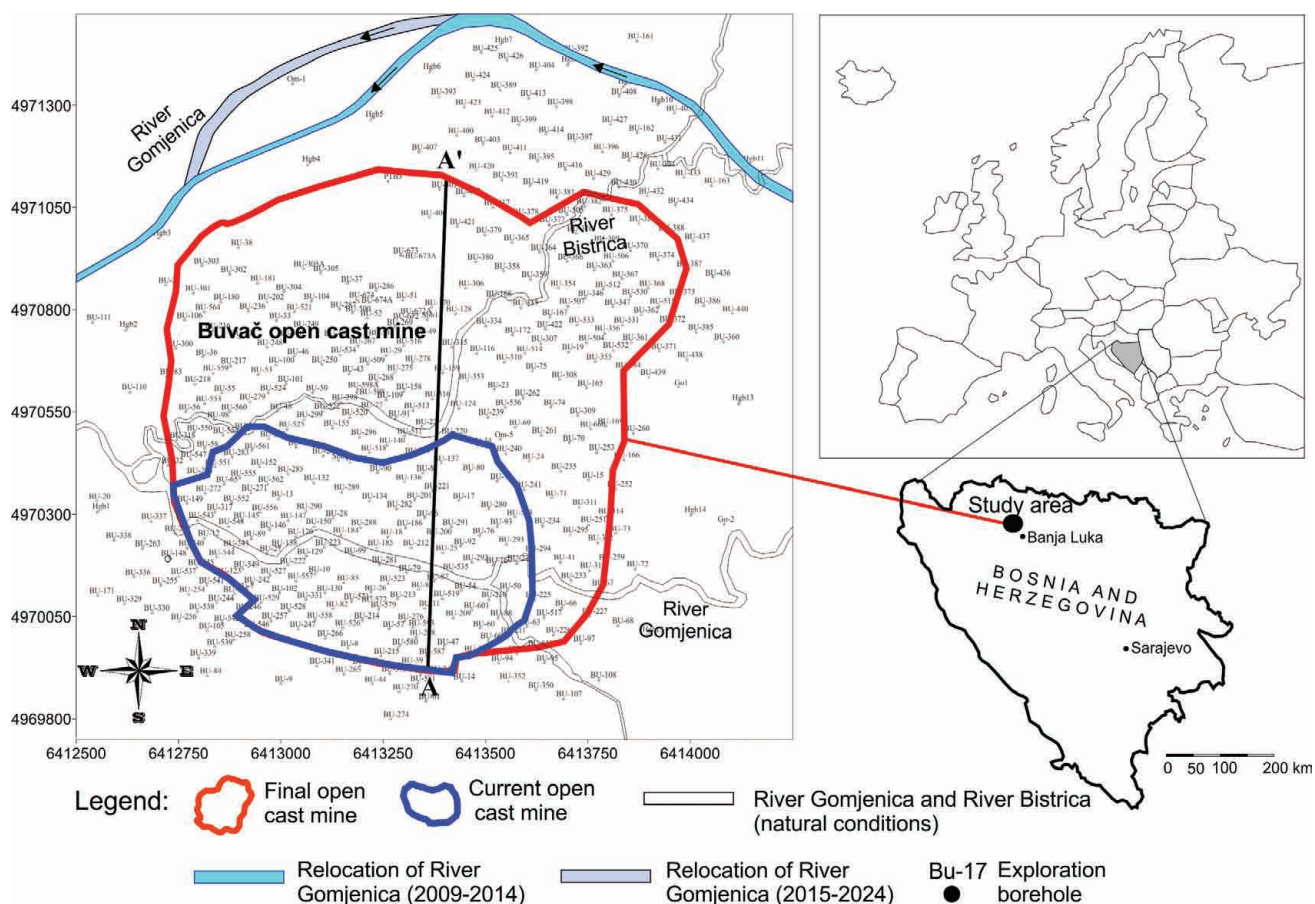


Figure 1: Location and test borehole map of the study area.

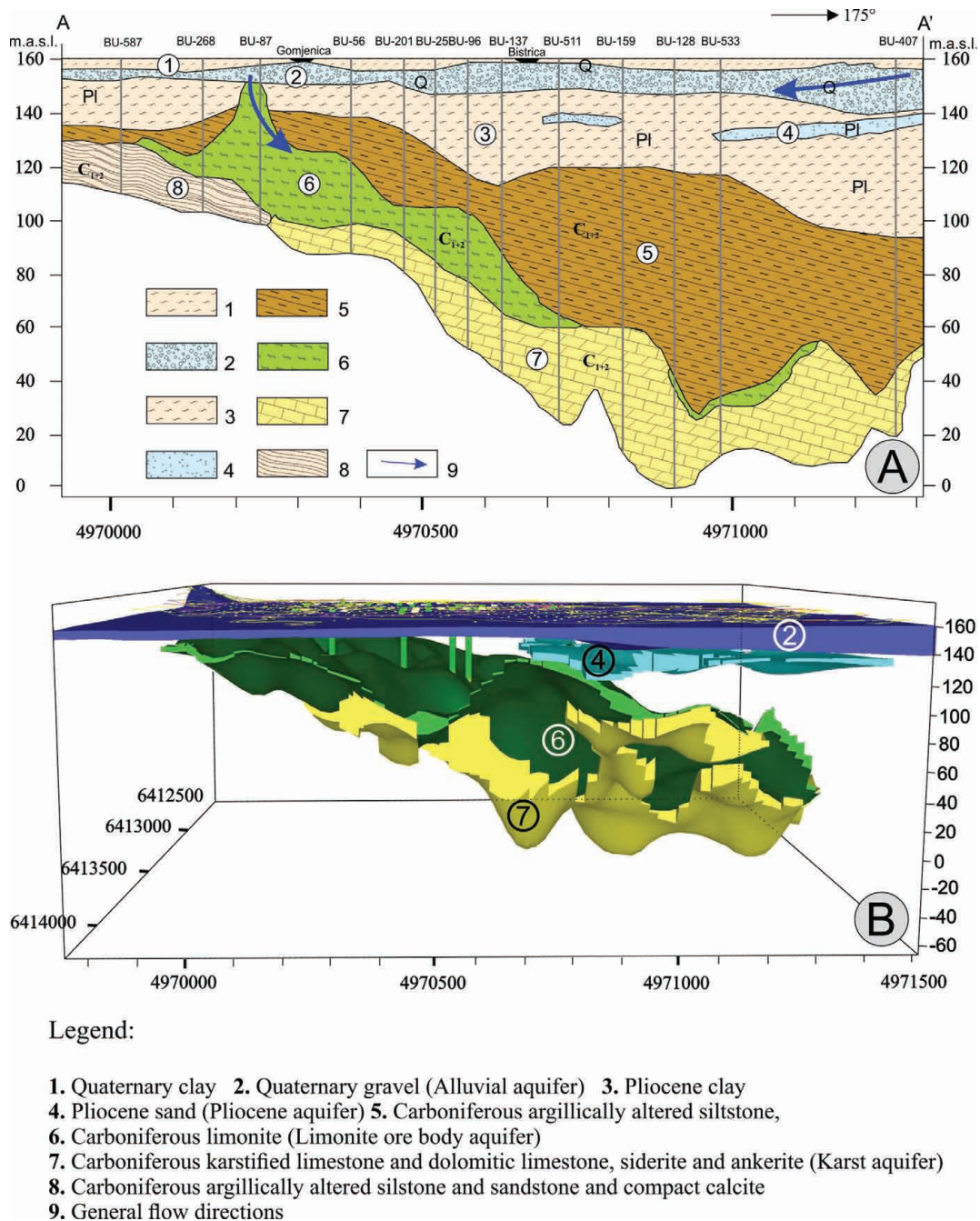


Figure 2: a) Hydrogeological cross-section A-A' (profile line in Fig. 1) and b) 3D aquifer model in the study area.

Due to the changed conditions in exploration area, because of the mine dewatering and the beginning of mining, recalibrating of the first model was done (POLOMČIĆ et al., 2013). Additional advantages of the recalibrated model, compared to the first model, arise from the following facts:

- more recent detailed exploration, which included expansion of the observation network of piezometers, resulted in a better understanding of the groundwater regime
- the model was calibrated both manually and automatically, using PEST (DOHERTY & HUNT, 2010) soft-

ware, and the hydraulic properties which constituted model inputs were thus optimized.

This contributed to a more efficient and more reliable approach to groundwater modeling and, as a result, recalibration of the new model was implemented at a higher level than that of the first model (POLOMČIĆ et al., 2013a).

2. THE HYDROGEOLOGICAL SETTING OF THE STUDY AREA

The Buvač limonite ore deposit (Figure 1) is located in Bosnia and Herzegovina. It belongs to the northeastern part of

the Ljubija Metallogenic Province and occupies the south-eastern peripheral area of the Omarska mineral ore deposits which, in addition to the Buvač mine, comprise the open cast mines of Jezero and Mamuze, (separated by about 500 m). The Omarska ore deposits lie in a morphological depression of the Omarska-Prijedor field, which trends SE-NW and is about 5 - 10 km wide and about 20 km long. The slopes of Mt. Kozara, which separates the Prijedor Gorge from the Sava Valley and the lower end of the Pannonian Basin, constitute the northern boundary of the Omarska-Prijedor field. Along the southern, southwestern and northern perimeters, the terrain continuously rises gradually to Mt. Grmeč, on the left bank of the Sana River, and Mt. Menjača on the right bank of the Sana river. The terrain is open to the north. The deposit is of Carboniferous age and extends over an area of about 3000 m² with an average thickness of about 20 m. The ore body is oriented northeast-southwest with a dip towards the northeast. It lies very close to the surface on the southwest side, while on the northeast side it is located at a depth of about 170 m (Figure 2a). The lithological characteristics were determined based on core logging in more than 550 boreholes (Figure 1). From a hydrogeological perspective, the basic characteristic of the study area is the variability of hydraulic conductivity with depth. Within the study area, there are four types of aquifers: a Quaternary alluvial aquifer, another in Pliocene sands, an aquifer within the limonite ore body, and a confined karst aquifer located at the bottom of the ore body. The interrelationship between these aquifers is shown in the hydrogeological cross-section A-A' (Figure 2a) and in the 3D aquifer model (Figure 2b).

The alluvial aquifer is formed in alluvial sediments (Quaternary gravels) of the River Gomjenica and its tributaries. This aquifer is unconfined, and there is good evidence that it is connected hydraulically with the river, as shown in fluctuations in the Gomjenica stages and the water table of the alluvial aquifer (POLOMČIĆ et al., 2013a, Fig. 6). Groundwater recharge of the alluvial aquifer takes place through infiltration of precipitation and river water. The Pliocene sands aquifer is mostly confined and receives recharge from outside of the boundaries of the ore body, on the northern edge of the study area. The ore body aquifer was formed in limonites which are characterized by significant porosity and water content. Besides the alluvial aquifer, this is the most significant aquifer in the study area in terms of dewatering. The hydraulic link between the ore body aquifer and the River Gomjenica was shown by POLOMČIĆ et al., (2013a, Fig. 7). Groundwater in the limonite ore body is indirectly recharged by groundwater from the alluvial deposits, where they come into contact, and also from the karst aquifer at the bottom of the ore body. The hydraulic link between the ore body aquifer and the alluvial aquifer is shown in Figure 3. The correlation coefficients between groundwater levels of alluvial aquifer and ore body aquifer indicate a very strong link ($R^2=0.95$). The Karst aquifer is a confined aquifer (POLOMČIĆ et al., 2013a) and formed in Carboniferous limestones and dolomites. It is not significantly water bearing and discharges directly into the limonite ore body

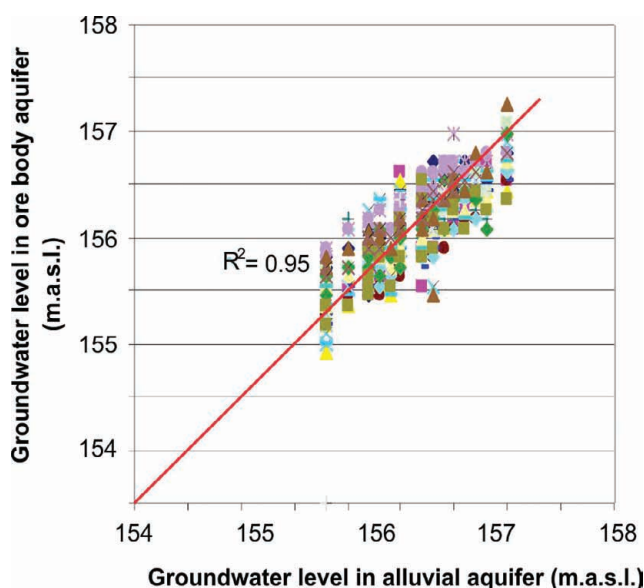


Figure 3: Correlation dependence between groundwater levels of alluvial aquifer (a) and ore body aquifer (b)

in places where these two aquifers are in direct hydraulic contact (BAJIĆ & POLOMČIĆ, 2008).

Based on the above, it can be concluded that there is a hydraulic link between all the aquifers. Additionally, the objective of chemical analyses (BAJIĆ & POLOMČIĆ, 2008) was to provide evidence of such a link between all aquifers in the Buvač mine area. These analyses also indicated that the groundwater in the study area belongs to the hydrocarbonate class, Ca type.

The aquitards are dominated by Quaternary sandy clays, Pliocene Clays and Carboniferous altered siltstone, sandstone and compact calcite. Sandy clays make up the northern periphery of the Omarska-Prijedor field, above an altitude of 160 m. They constitute the first and second palaeoterraces of the Gomjenica river and overlie Pliocene strata. The Pliocene clays along the southern and northern edges of the field are extensive and lie directly on top of Palaeozoic sediments. The thickness of these clays range from 10 - 60 m. Pliocene clays also constitute a large proportion of the mining field, apart from the dominant Carboniferous altered siltstone. These impermeable layers are lateral barriers to the groundwater in limestones. The floor of the ore body is also made up of impermeable rocks – Carboniferous altered siltstone, sandstone and compact calcite (Figure 2a).

The beginning of ore exploitation in the Buvač mine in 2008 had permanently and irreversibly altered the original hydrogeological and hydrological conditions in the study area. Between 2008–2012 the dewatering system for protection of the open cast mine from groundwater inflow consisted of 8 wells in the alluvial aquifer and 7 wells in the ore body aquifer. There is also a significant number of piezometers – more than 20 which provide data on the groundwater heads. In 2009, the river beds of the River Gomjenica and River Bistrica were diverted into a new river bed with a length of 2,919 m, a width of 20 m with a bank inclination of 1:2. The

river bed elevations range from 156.3 to 153.63 m.a.s.l., and the general river bed slope is $i=0.0011\%$. The diverted river bed is designed for 100 year maximum water levels, and a protective levee was constructed on the left bank which is 1 m higher than the 100 year water level. The new river bed and the natural river beds of the River Gomjenica and River Bistrica are shown in Figure 1.

3. NUMERICAL MODEL (METHODOLOGY)

The conceptual model is based on the geological information obtained from boreholes (Figure 1) and water-level data from observation wells. The model schematization includes a surface clay layer and a basal argillic siltstone of low permeability and an interbedded sequence of aquitards and four aquifers (POLOMČIĆ et al. 2013a). The system is modeled using eight layers. The model layer characteristics are given in Table 1. Except for the overlying clays and alluvial gravels and sands, there is no lithological unit with continuous distribution in one model layer. Table 1 shows lithological units which are present in each of the model layers. The hydraulic characteristics shown were derived from numerous research works and used in designing the first model (POLOMČIĆ et al. 2013a).

The three-dimensional finite-difference numerical model for this study was developed using Modflow (HARBAUGH, 2000) with Groundwater Vistas as a graphical user interface (RUMBAUGH & RUMBAUGH, 2011). The model domain is 2260×2040 , and 175 m in depth. The domain is oriented north-south and discretized into 102 rows, 113 columns, and

8 layers, with 85.425 active cells. The cell size of the flow field discretization in plan is $20 \text{ m} \times 20 \text{ m}$ this was deemed a reasonable size given the number and quality of available data. The hydraulic characteristics of the model layers were assigned based on the hydraulic conductivity and specific storage values (Table 1) that were previously determined during well testing in the open cast mine (POLOMČIĆ et al., 2013a).

The previous numerical model of the Buvač open cast mine was updated to reflect the current condition of the mining works and the diversion of the River Gomjenica, and supplemented with new data of the groundwater regime from October 2010 – October 2012.

3.1. Boundary and Initial Conditions

A head-dependent flux boundary condition (Cauchy's or mixed boundary condition) and a boundary of prescribed flux (Neumann boundary condition) were used in the model. The effect of the diverted course of the river was simulated with the head-dependent flux boundary. In the ModFlow code, this simulation was performed using the river boundary condition and it was assigned in the first and second model layer (Figure 4a) with water level values for the period from 1 October 2010 to 15 October 2012 (Figure 5a). All geometric characteristics of the new river bed of the River Gomjenica were incorporated into this type of boundary condition. The initial thickness of the sediment on the river bed bottom was assigned a value of 0.1 m, with an initial value of the hydraulic coefficient of the river sediment

Table 1: Model layers and initial values of hydraulic parameters.

Model layer	Lithostratigraphic unit	Hydraulic conductivity (at x,y-axis) (m/s)	Hydraulic conductivity (at z-axis) (m/s)	Specific storage (1/m)	Specific yield
1	Clay overburden	$8.50 \times 10^{-7} - 1.00 \times 10^{-6}$	1.00×10^{-6}	0.001	0.037
2	Alluvial gravel and sandy gravel	$1.40 \times 10^{-4} - 3.80 \times 10^{-4}$	1.00×10^{-4}	2.25×10^{-5}	0.225
3	Clay and sandy clay	$6.20 \times 10^{-6} - 2.00 \times 10^{-5}$	1.00×10^{-6}	5.00×10^{-5}	0.06
	Part of ore body	2.30×10^{-4}	–	6.00×10^{-5}	0.06
4	Clay and sandy clay	5.00×10^{-6}	1.00×10^{-6}	5.00×10^{-5}	0.06
	Sand and gravel	$1.00 \times 10^{-4} - 1.40 \times 10^{-4}$	1.00×10^{-4}	2.25×10^{-5}	0.23
5	Part of ore body	2.3×10^{-4}	1.00×10^{-4}	6.00×10^{-5}	0.06
	Clay and sandy clay	4.0×10^{-6}	1.00×10^{-6}	5.00×10^{-5}	0.06
6	Part of ore body	2.3×10^{-4}	1.00×10^{-4}	6.00×10^{-5}	0.06
	Argillic siltstone and sandstone	1.00×10^{-6}	1.00×10^{-6}	6.30×10^{-5}	0.06
7	Part of ore body	2.3×10^{-4}	1.00×10^{-4}	6.00×10^{-5}	0.06
	Limonite and fine limonite	$5.0 \times 10^{-5} - 2.40 \times 10^{-4}$	1.00×10^{-6}	5.00×10^{-5}	0.06
8	Argillic siltstone and sandstone	1.5×10^{-5}	1.00×10^{-6}	6.30×10^{-5}	0.06
	Limonite ore body	2.3×10^{-4}	1.00×10^{-4}	6.00×10^{-5}	0.06
8	Limestone and dolomitic limestone, siderite and ankerite in argillic siltstone and siltstone	$3.52 \times 10^{-4} - 4.70 \times 10^{-4}$	2.50×10^{-4}	6.30×10^{-5}	0.06
	Argillically altered siltstone and sandstone and compact calcite	1.00×10^{-7}	1.00×10^{-7}	6.30×10^{-5}	0.06

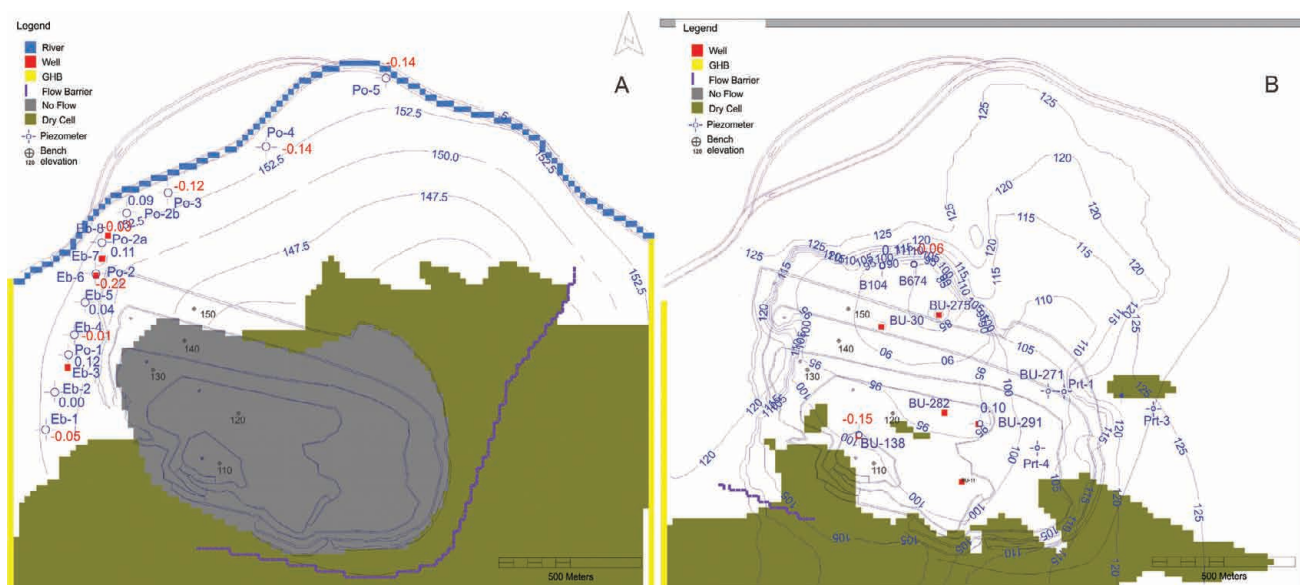


Figure 4: Distribution map of piezometric levels (15 Oct. 2012) in the alluvial aquifer (a) and levels in the ore body (b) and the boundary conditions in the open cast mine “Buvač”.

of 1×10^{-6} m/s. By assigning head-dependent flux boundary conditions, the model simulates groundwater inflow and outflow into the model. In the Modflow code, this was represented with a general head boundary (GHB). In the alluvial aquifer to the east and west, this boundary condition simulates the outflow or inflow into the model which also generally follows the River Gomjenica outside of the study area (Figures 4 and 6). The ore body during the development of the mine had the role of a local base level of erosion towards which the surrounding groundwater gravitates. Based on earlier research, and as a result of the first model (POLOMČIĆ et al., 2013a), the existence of impermeable rocks in the south was determined, and the absence of significant inflow into the study area from the north. In the seventh model layer with the largest distribution of the ore body in the east and west, a general head boundary was assigned (Figure 4b and Figure 6). According to the layers shown in Figure 2, in the

Karst aquifer (7) and the Pliocene aquifer (4), the inflow into the model was assigned only in the northern contour of the study area. Also, the GHB hydraulic conditions were taken from the first model (Figure 6). The Pliocene aquifer is much larger north of the model domain. The effect of that aquifer on the edges of the Pliocene sands included in the model was specified via the GHB boundary condition, simulating inflow while keeping in mind the hypsometric positions of the recharge zone of this aquifer along the southern slopes of Mt. Kozara (north of the model domain). The karst aquifer was handled in a similar manner in the 8th model layer (Table 1), which is represented in the central part of the model domain, while in the northernmost part it extends beyond the model domain. It was also assumed that it was part of a larger aquifer to the west, as it was detected in open cast mines west of study area. An additional problem was a lack of data as there are no piezometers in the Pliocene and karst aquifers.

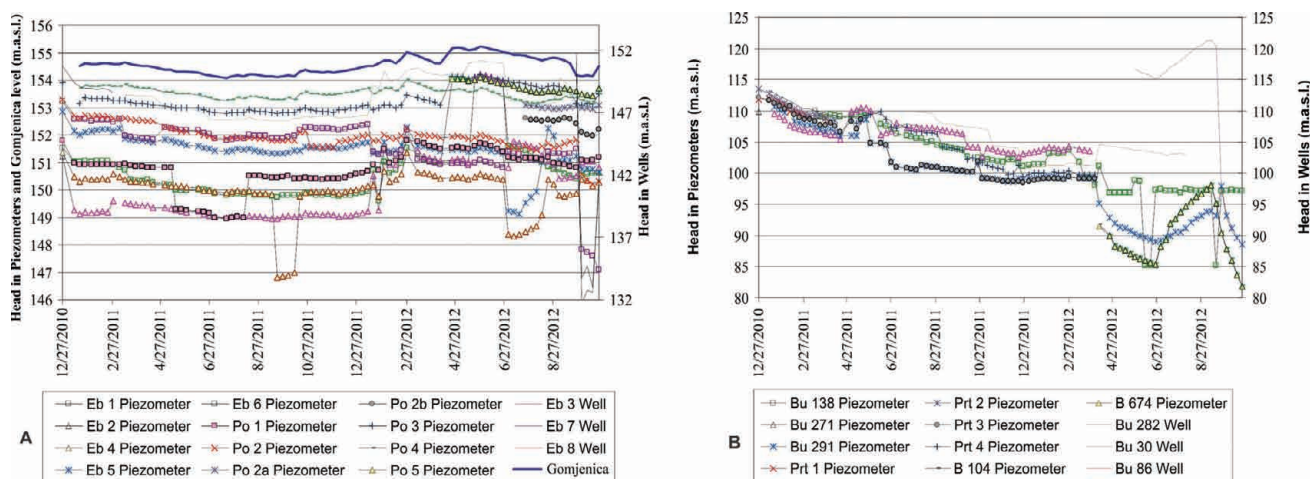


Figure 5: An overview of groundwater levels: a) in the alluvial aquifer and b) in the limonite ore body in the period 1 October 2010 – 15 October 2012.

The outer contours of the impermeable units (Layers 3 – 8) are represented by a no-flow boundary condition (Figure 6). Initial heads for the karst aquifer and the Pliocene aquifer, as there is no exact data, were based on the results of calibration of the first model (POLOMČIĆ et al., 2013a). Unpublished data were used for the initial heads of these aquifers in the first model, which were collected during the course of designing urban and rural water supply systems, at 10 km and 18 km northwest of the study area, respectively. Based on the regional extent of the Pliocene and karst aquifers, their hypsometric positions and the activities relating to the nearby water supply projects, the conclusion was that these aquifers are slightly pressurized.

A total of 8 drainage wells were in operation in the Buvač open cast mine from 1 October 2010 – 15 October

Recharge is simulated by selecting the prescribed flux boundary condition in the first model layer only. This creates an influx as the difference between the total recharge and evapotranspiration. According to the 2007 model (POLOMČIĆ et al., 2013a), the average infiltration was 15% of total precipitation; this value was used as an initial condition applied to precipitation for the period 1 October 2010 – 15 October 2012. The existing cut-off wall on the south and east side of the ore body (Figure 4), and a new one, which was modeled in a number of the predictive option models as discussed later, is assumed to be composed of a cement-bentonite fill with a thickness of 1 m and hydraulic conductivity of 1×10^{-8} m/s. This feature was simulated with a prescribed flux boundary condition (Neumann boundary condition), i.e. “wall” (flow barrier) in the Modflow code.

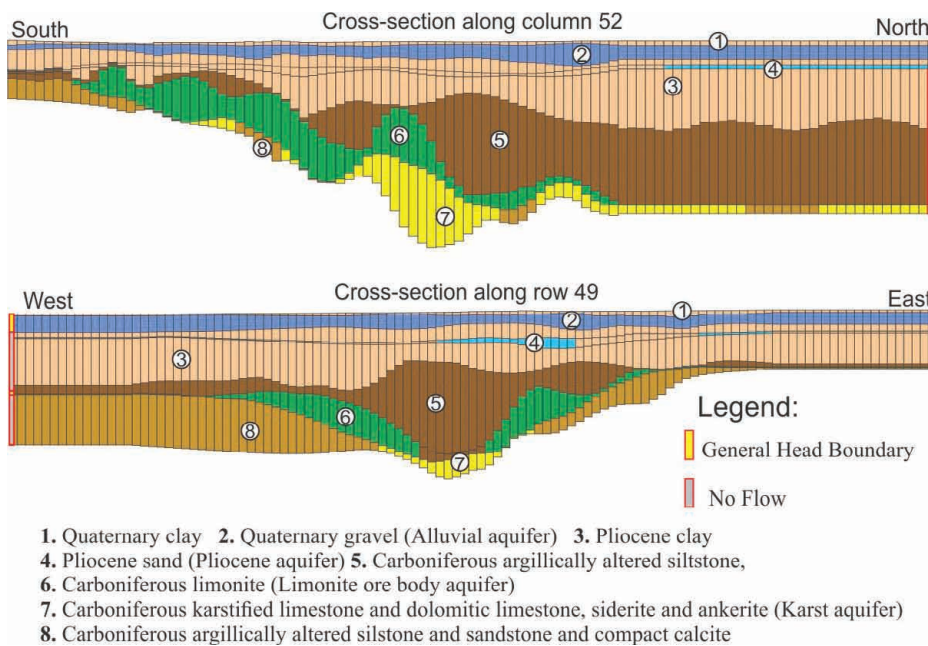


Figure 6: Column (south-north) and row (west-east) cross section.

2012. The individual capacities of the wells ranged from 1-50 L/s, with a total capacity of 158 L/s. The locations of the wells in the area included in the model are shown in Figure 4. The wells only drain the alluvial aquifer and the ore body aquifer. The wells were assigned a “prescribed flux” boundary condition. With this type of boundary condition, the case of no flow is also assigned ($q=0$), i.e. selected cells can be designated “no-flow” cells in the Modflow code. These no flow cells represented zones where material has been excavated as a consequence of mining (Figures 4). In nature, these zones are practically impermeable. The exception is a part of the excavated ore body the active surface of which is relatively small and continually changes with the dynamics of ore exploitation. Along the working benches of the mine there are drainage canals that direct precipitation to a water collector and from there transfer the water by pumps into the River Gomjenica, so the working area for ore exploitation is not at risk from run off.

The proposed cut-off wall (Figure 4), will extend through the entire alluvium layer down to 1 metre in clayey sediments, its geometric characteristics, as well as the characteristics of the infilling were assigned in the first and second model layer.

3.2. Model recalibration

The model was recalibrated under transient flow conditions, with a time step of one day (a total of 654 steps) for the period 1 October 2010 – 15 October 2012, which in the lower level of iteration was divided into 10 parts, of unequal duration (factor 1.2). Measured piezometric levels in the alluvial aquifer (Figure 5a) and in the limonite ore body aquifer (Figure 5b) were used as calibration targets. Figure 4 shows the plan location of the measuring points and the distribution of the piezometric levels in the alluvial aquifer and in the ore body as of 15 October 2012. Gradually, over time, a certain

Table 2: Groundwater balance (15 October 2012).

Aquifer	Boundary condition	Inflow to model (L/s)	Outflow from model (L/s)
Alluvial aquifer and aquifer in pliocene sands	Effective infiltration	15.2	
	Gomjenica river	97.4	
	GHB – east	2.3	
	GHB – west	9.7	
	Drainage wells		22
	Migration into the ore body aquifer		26.8
The limonite ore body aquifer	GHB – east	36.7	
	GHB – west	24.1	
	Drainage wells		136
Karst aquifer	GHB – east		8.3
	GHB – north	7.9	
	Sum	193.3	193.1

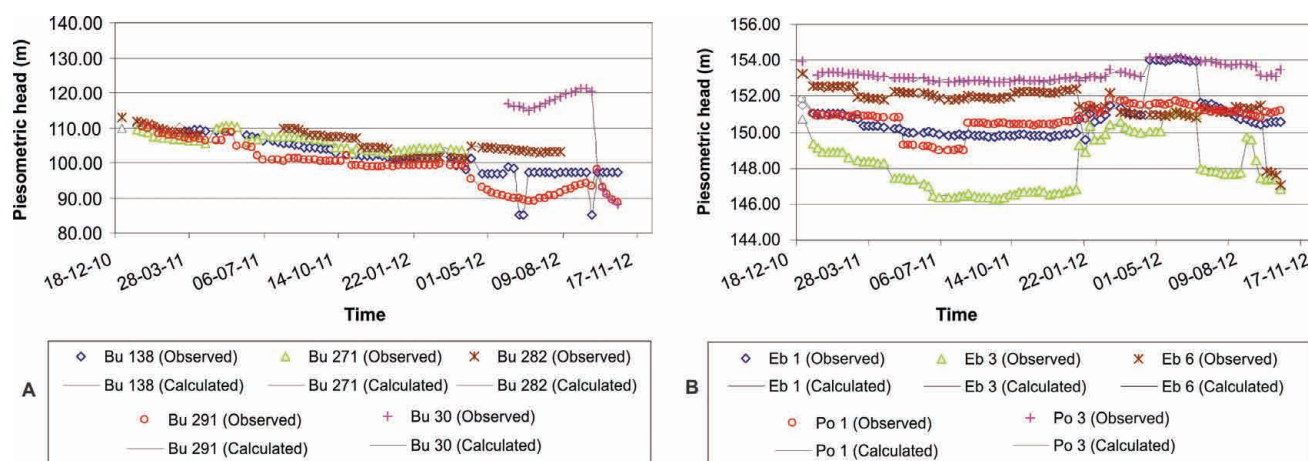
number of piezometers and wells (Figure 5) were unusable due to the lowering of groundwater levels below their maximum depth. As a confirmation of the quality of the performed recalibration of the model, Figure 7 shows the time series and calibration graph. Results of the mathematical simulation of the groundwater regime, in relation to the registered groundwater levels, are in good agreement. The statistical indicators of the quality of model recalibration are: Residual Mean: -0.03, Residual Standard Deviation: 0.09, Absolute Residual Mean: 0.08; Residual Sum of Squares: 0.15; RMS Error: 0.10; Normalized RMS 5.84%; Minimum Residual: -0.22; Maximum Residual: 0.12.

Under the operating conditions of the dewatering wells system in the mine, a change in the flow conditions occurred i.e. intensified three-dimensional groundwater flow as a result of the diversion of the River Gomjenica into a new river bed and the development of the mine. Table 2 gives an overview of the basic elements of the groundwater water balance after model recalibration. In the alluvial aquifer, the predominant mode of recharge is water infiltration from the River Gomjenica (78.17%). In relation to the first model (POLOMČIĆ

et al., 2013a) which was calibrated to conditions prevailing in 1973, river water recharge to the alluvial aquifer has increased due to the operation of drainage wells which have a total discharge of 158 L/s. The flow between the existing aquifers in the mine has also changed since 1973. Model predicted inflows to the ore body from the alluvial aquifer and from the karst aquifer are 26.8 L/s and 8.3 L/s respectively. Inflow to the ore body is greatest from the east, with less from the west. The total inflow into the ore body decreased by 40.1 L/s in relation to the quantities of water captured by wells, which confirms the successful drainage of the ore body up to this point (Figure 5b). The balance of the Pliocene aquifer is not significant for the total groundwater balance in the study area. Inflow from the Karst aquifer to the ore body aquifer is partially replenished by groundwater inflow from the north.

3.3 Management Scenarios

The recalibrated groundwater model was used to evaluate options for water management for 2013–2024. Calculations were based on sequential time steps; the result at the end of

**Figure 7:** Time series and calibration graph for the analyzed period (1 October 2010 – 15 October 2012): a) alluvial aquifer b) ore body aquifer.

one time interval representing the initial condition for calculation in the next. The calculations were performed in a transient flow regime, using a month as the basic time interval for the calculation within one year. At the end of each year, in prognostic calculations, there has been increase in area of “no flow” cells as a result of the yearly advancement of the mining works – excavating the spoil and extracting the ore, and the development of analyzed dewatering systems. Three groundwater management scenarios were modeled, as described later, and Figure 8 shows the elements of the dewatering system in the „Buvač“ open cast mine: on the day of recalibration of the hydrodynamic model (a), the dewatering system according to variant 1 (b), variant 2 (c), and variant 3 (d). All three scenarios were identical during 2013 and 2014, while for 2015 scenarios 2 and 3 are identical. From 2016, all scenarios are different and develop independently. For all three scenarios, the open cast development follows the planned mining activities until the end of 2024.

All three management scenarios included the following features:

- 8 existing drainage wells in the west that drain the alluvial aquifer,
- the existing drainage channel DU-4 in the alluvial aquifer;
- starting from 01.01.2015 the Gomjenica river is partly relocated to the new riverbed north of the mine;
- the River Gomjenica diversion;
- the locations, initial capacities, and length of operation of drainage wells that primarily drain the ore body, and
- the main mining criterion is that the groundwater level should be at least 15 metres below the working bench in the ore body.

The drainage channel DU-4 is assumed to be excavated to the bottom of the alluvial sands and gravels in the northern part of the mine, ahead of the mining. The channel will intercept groundwater which is not extracted by the wells. The water from the drainage channel flows to the water collector and is then returned to the River Gomjenica.

At the beginning of prognostic calculations, seven drainage wells are assumed in the ore body each with a capacity of 8-50 L/s, for a total capacity of 126 L/s.

Scenario 1

According to Scenario 1, 33 additional wells in the alluvial aquifer to the north of the open cast will start on 1 January 2015, will increase the protection from river water seepage based on the 8 existing wells. The initial well capacities range from 2 L/s to 7 L/s (with a sum of 107 L/s) and are assumed to operate continually during the entire life of the mine, i.e. until the end of 2024. Figure 8b shows the dewatering system according to variant 1.

Scenario 2

In Scenario 2, instead of the 33 drainage wells, a dewatering system in the alluvial aquifer comprises a cut-off wall, almost 2000 m long and extending 1m into the clayey silty

sediments below the alluvial sediments. The cut-off wall is assumed to be completed on 1 January 2016. Figure 8c shows the dewatering system according to variant 2.

Scenario 3

Scenario 3 represents a combination of the previous two scenarios. In the northwest part of the mine, where the open cast is closest to the river, a 1000 m long cut-off wall is assumed, similar to that described in scenario 2. The cut off starts near the existing well Eb-8, and is assumed to be complete on 1 January 2016. Continuing from the wall, 13 drainage wells are assumed to be constructed with the same characteristics and initial capacities as in scenario 1, for a total capacity of 65 L/s. The wells begin operation on 1 January 2017, and operate until the end of mining (2024). Figure 8d illustrate this scenario.

4. RESULTS AND DISCUSSION

Before analyzing the results of the simulation of different variants of the dewatering system, it should be noted that in Bosnia and Herzegovina, it is usual for projected mining works to be presented on a yearly state (31 December) during the first five years, and subsequently on a 5-year level with a projected final contour of the mine at the end of ore exploitation. The most significant change in the flow pattern in the wider area of the mine depends on the construction dynamics of the advancing excavation contour, given in 1-year time steps (at the end of the calendar year, 31 December). It is realistic for the mine advancement to be a linear continuous process. This applies especially to the overview of derived results per time interval viewed in 2022 (a five-year step of 2017-2022) and 2024 (a two-year step: 2022-2024). It is also necessary to provide an explanation, regarding the correct interpretation of the calculated results, which relates to the operation of drainage wells. The wells were assigned in the model using their discharge, for which the initial values represent one of the results of the prognostic calculations. The results of the calculations proved to be very sensitive to changes in initial well capacities, which must gradually decrease over time. Otherwise, there is an excessive decrease in the piezometric head in the wells. If too large initial capacity were given, this would result in shutting down of the well. These facts primarily apply to the hydraulic characteristics of porous media. In the other hand, these are the consequences of the limits of the MODFLOW finite difference model. First is, that it is a quasi 3D flow model. Second, the hydraulic conductivity tensor is represented only with three principal components K_{xx} , K_{yy} and K_{zz} perpendicular to the faces of the finite difference cells (horizontally rectangular). All of this is not representing in the best possible way 3D problems which occur in the vicinity of the pumping wells. The piezometric heads in the alluvial aquifer obtained for each scenario are shown in figures 9 (a, b) and 10 (a, b, c) and the piezometric heads in the ore body are shown in figures 9c and 10d, at the end of 2015 and 2024. Over time, the operation of the drainage system, excavation of overburden and of the ore body, will lead to a

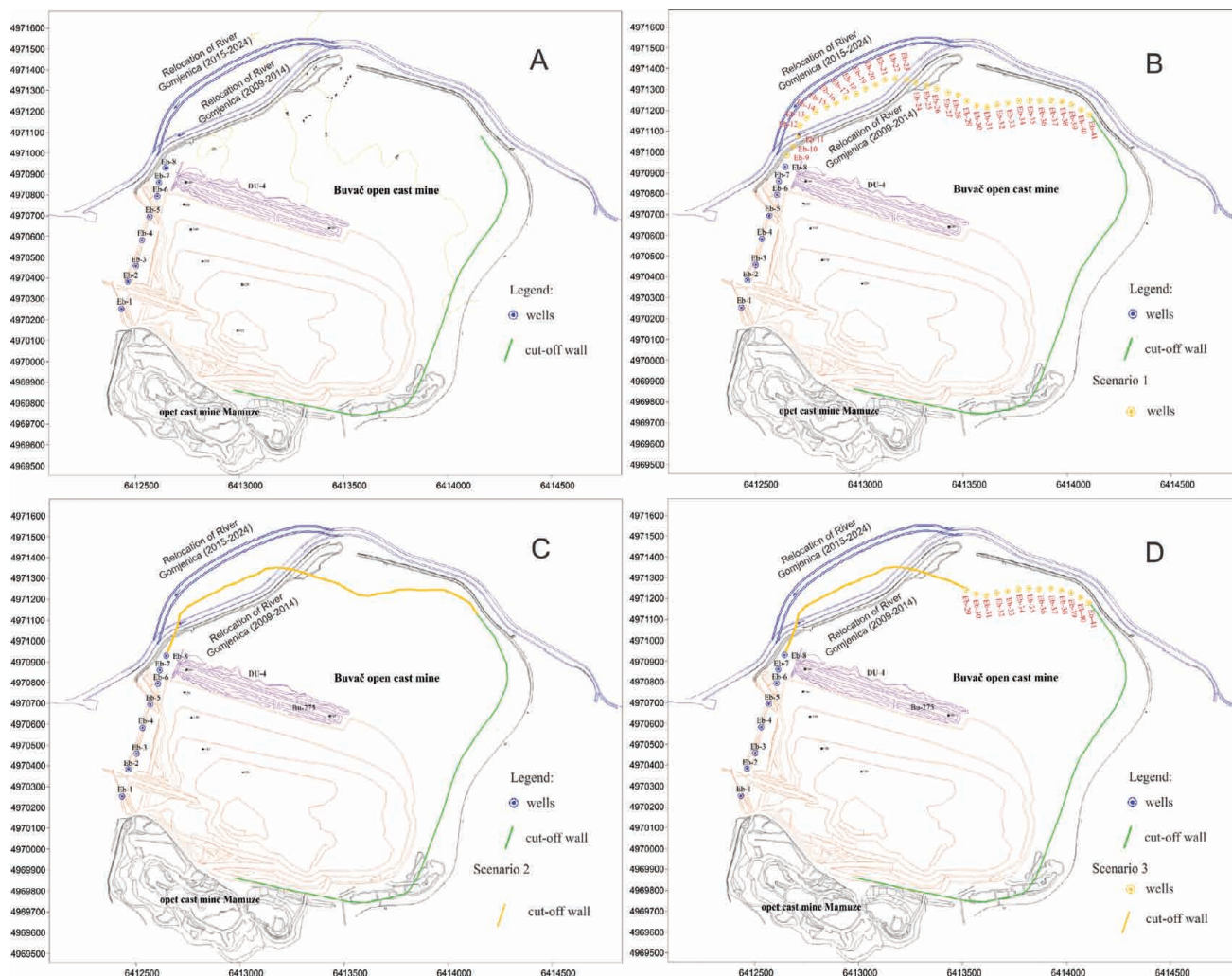


Figure 8: Elements of the dewatering system in open pit mine „Buvač“: on the day of re-calibration of the hydrodynamic model (a), the dewatering system according to variant 1 (b), variant 2 (c), and variant 3 (d).

gradual lowering of the regional piezometric heads. During one years simulated operation of the drainage system, besides the “no flow” cells, (which are primarily a consequence of mining), “dry cells” appear in the model and expand in time due to the operation of the system.

The protective influence of the system on groundwater ingress to the open cast mine is manifested by different gradients of hydraulic head both within and outwith the outer contours of the drainage system. In relation to 2013 and 2014, when the system in the alluvial aquifer consists only of the DU-4 drainage channel (Figures 9 and 10), there begins in 2015 or 2016, a significant change in the flow pattern for each of the three simulated dewatering systems.

According to the first simulated scenario (Figures 9a and 10a) for protection of the open cast mine, a total of 41 fully penetrating wells together with with the drainage channel DU-4, compose the drainage system. The first scenario is the least effective, and results in the smallest decrease in groundwater levels ahead of mining. The second scenario (Figures 9b and 10b) with a cut-off wall which prevents groundwater

inflow through the alluvial sediments from the direction of the River Gomjenica, very quickly results in dewatering of the alluvial deposits ahead of mine development, and causes the DU-4 drainage channel to cease surface flow relatively quickly. Over time, the “dried” surface spreads, while in the north-east of the mine a narrow zone remains along which there is inflow into the open cast mine, as the result of the flow of uncaptured groundwater between wells Eb-1 to Eb-8. According to the achieved protective effects, this variant represents the most efficient defense from the inflow of groundwater into the open cast mine through the alluvial deposits. The third scenario (Figures 9b and 10c) simulates the operation of the open cast mine protection system which is composed of the existing drainage wells Eb-1 to Eb-8 in the west, a cut-off wall in front of the open cast mine where the river bed of the River Gomjenica is closest, the drainage wells Eb-29 to Eb-41 continuing after the wall in the north, as well as the DU-4 drainage channel. The third scenario is a combination of the first and second scenarios and the impact on groundwater flow is intermediate between scenarios 1 and 2.

In terms of drainage of the ore body, an almost identical decrease in groundwater levels is predicted for all three of the analyzed scenarios (Figures 9c and 10d), due to the identical drainage system in the ore body for each scenario. The obtained differences per scenario are only related to the capacities of the individual wells (Figure 11). The decrease of groundwater levels in the ore body is, for all variants and for each analyzed year, below the working bench levels in the assigned values (a minimum of 15 metres below).

The effects of the three scenarios are analyzed for the alluvial aquifer and for the ore body (Figure 11) through comparisons of the predicted flow of the drainage wells. All three analyzed scenarios include a line of wells (Eb-1 do Eb-8) in the west. In the first scenario, these wells have greater predicted flow than in scenarios 2 and 3, due to the absence of the cut-off wall. The maximum well capacity will be reached at the beginning of 2015 (158 L/s) and towards the end of the simulated period will decrease by 14%. In scenarios 2 and 3, the greatest differences in well flow occur in

those wells closest to the cut-off wall, due to the restricted inflow of water to the wells. In scenarios 2 and 3, the predicted flows from wells in the west are 40% less at the end of the calculation period, in comparison to scenario 1. There is a similar occurrence in other wells close to the cut-off wall in scenario 3 (wells Eb-29 and Eb-30). In wells Eb-38 to Eb-41 in variant 3, the proximity of the cut-off wall does not affect a significant decrease in the capacity of these wells, due to the proximity of the diverted river bed of the River Gornjenica, and the small initial capacities of the wells. Drainage channel DU-4 is likely to be most effective in the first operational years of the model with an inflow of 38 L/s, where, apart from the drainage channel and drainage wells, there are no other facilities to protect the mine from groundwater inflow through the alluvium. The inflow into the channel varies between scenarios with the smallest flow predicted for scenario 2 (no inflow until January 2016) and the largest flow for scenario 1 (16 L/s in January 2016 to 5 L/s in September 2017).

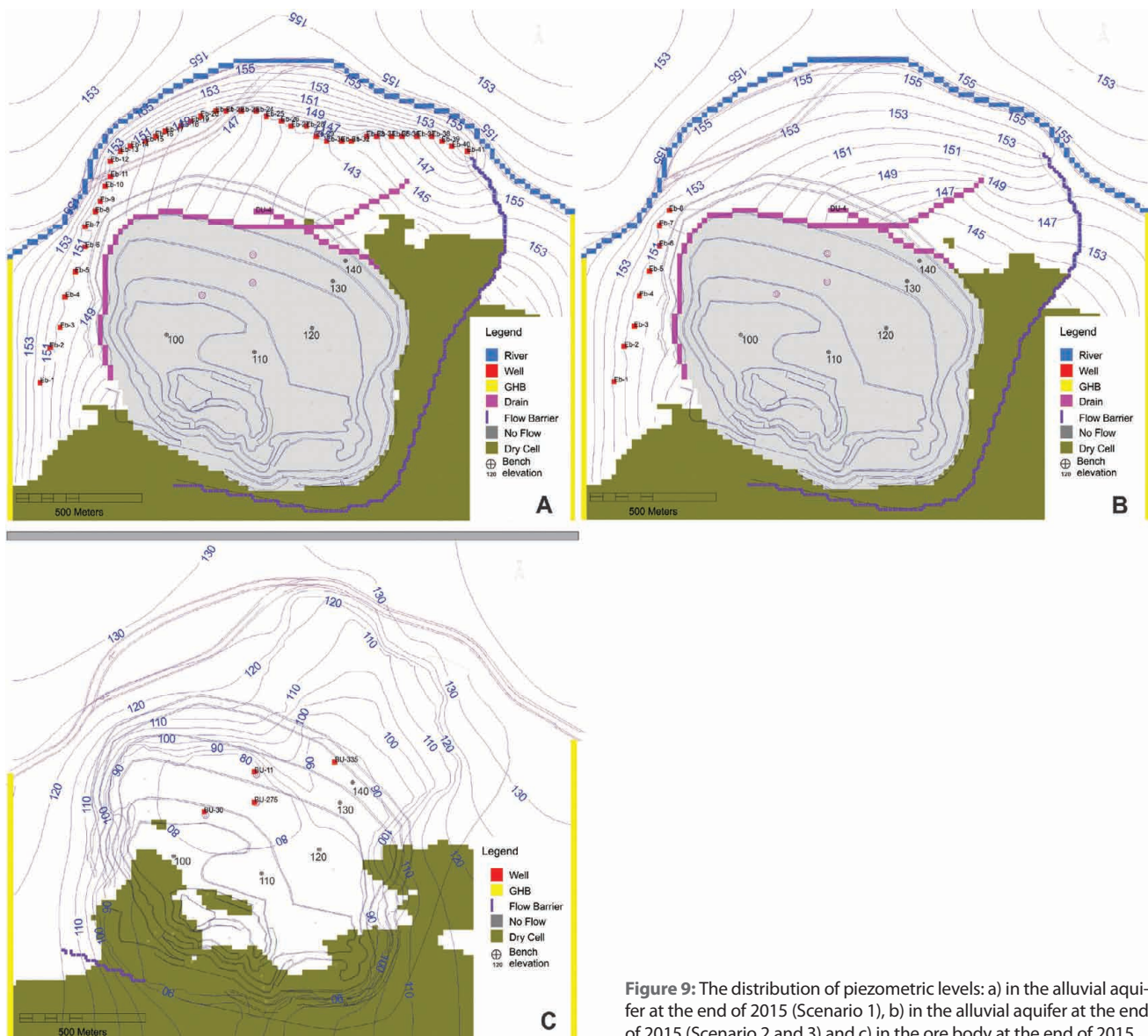


Figure 9: The distribution of piezometric levels: a) in the alluvial aquifer at the end of 2015 (Scenario 1), b) in the alluvial aquifer at the end of 2015 (Scenario 2 and 3) and c) in the ore body at the end of 2015.

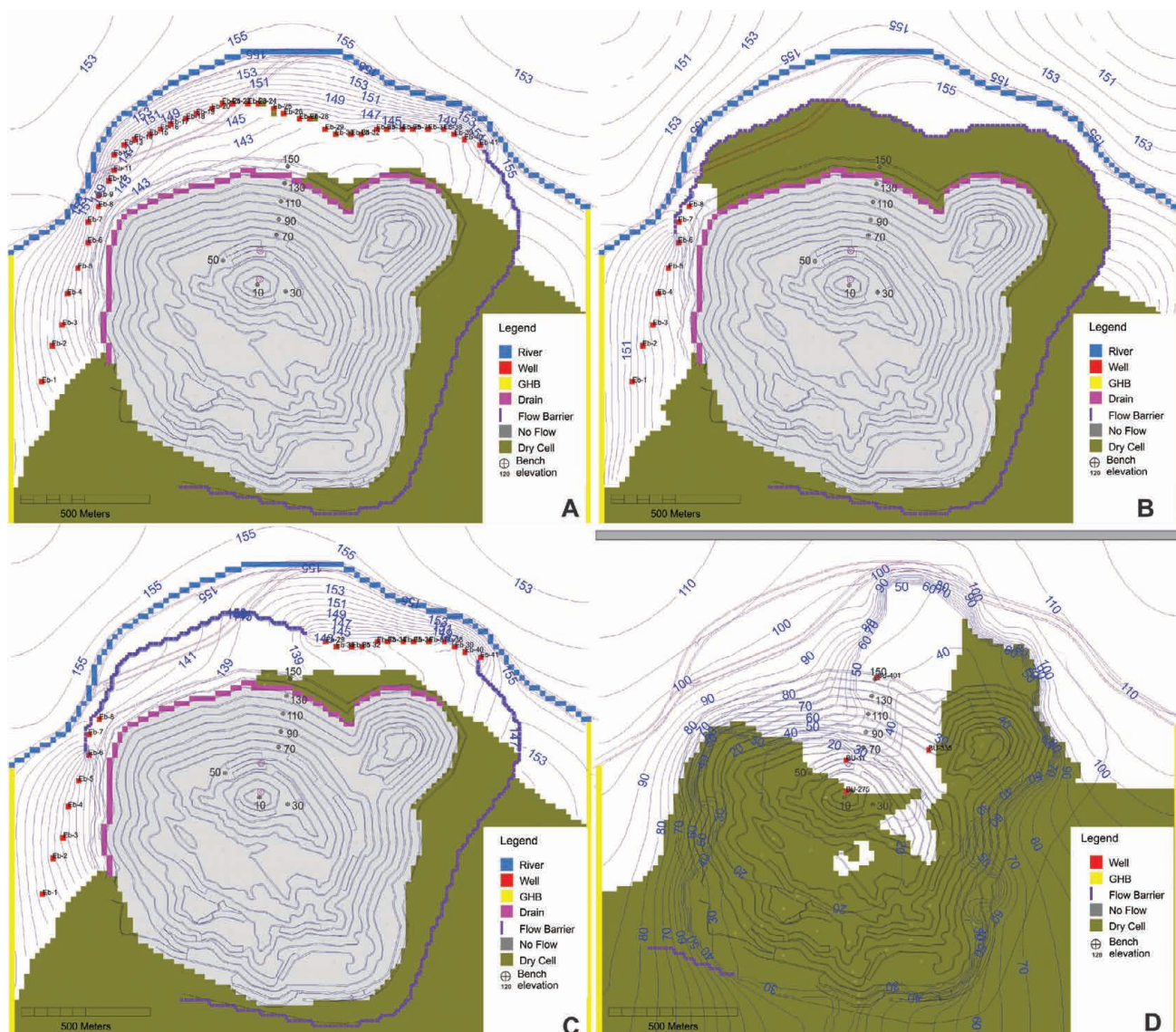


Figure 10: The distribution of piezometric levels: a) in the alluvial aquifer at the end of 2024 (Scenario 1), b) in the alluvial aquifer at the end of 2024 (Scenario 2), c) in the alluvial aquifer at the end of 2024 (Scenario 3) and d) in the ore body at the end of 2024.

The differences between the scenarios in terms of water balance in the ore body are practically negligible and a single conclusion may be drawn for all three. A number of “BU wells”, even after a periodic reduction, are withdrawn from operation, due to the overall decrease in groundwater levels (Figure 11). From the beginning of 2013 to the end of 2015, the total capacity of the wells in the ore body (BU wells) decreased by 13% (from 121 L/s to 105 L/s). A certain increase in the predicted flow (Figure 11) of the wells in the ore body is due to the introduction of new wells (January 2016). From 2016 when the dewatering system in the ore body reaches the maximum capacity of 124 L/s, to the end of the prognostic period, there is a continual decline in well capacity as well as in mining activities, and the deactivation of a number of wells. At the end of 2024, the total well capacity is decreased by 68%.

In the first three years the model predicts similar groundwater discharge into the pit of about 10–14 L/s with all scenarios showing similar inflow. The inflow reduces over the modeled period to about 6 - 10 L/s for scenario 1 and 3 - 6 L/s for scenario 2 with scenario 3 inflows being intermediate between the scenario 1 and scenario 2 inflows.

5. CONCLUSION

The exploitation of the limonite ore in the open cast mine Buvač began at the end of 2008. New hydrogeological research and monitoring of the groundwater regime were performed to assist in the selection of groundwater management schemes for protection of the Buvač open cast mine from groundwater inflow until the end of ore exploitation (2024). The numerical model provides a tool for predictive calcula-

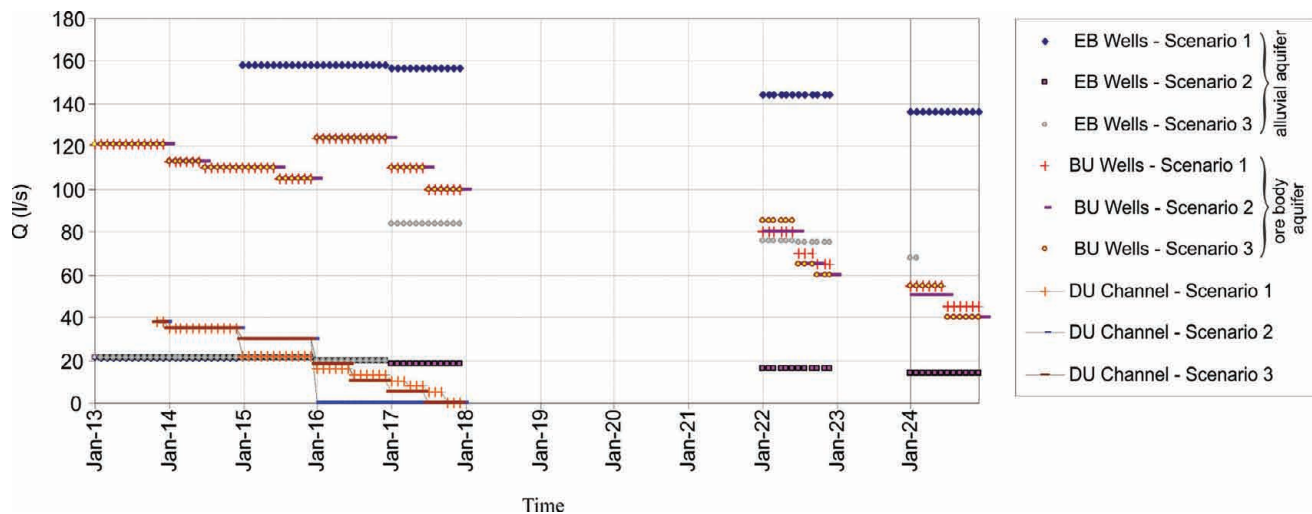


Figure 11: A comparative diagram of the predicted total flow of drainage wells and in the DU-4 channel (January 2013 – December 2024) for all scenarios where EB wells are in the alluvial aquifer and BU wells are in the ore body.

tions to compare options for protection of the open cast mine from groundwater inflow. Three groundwater management scenarios were modeled for the period from 2013 to 2024. The scenarios mainly differ in the methods of management of groundwater flow in the alluvial aquifer. In all of the analyzed scenarios of the dewatering system, the required drop of groundwater levels to more than 15 metres below the working bench in the ore body, has been achieved for every year in the prognostic calculations.

All the facilities protecting the open cast mine from water ingress via the diverted river bed of the River Gomjenica are positioned parallel to the river course, north of the mine. Scenario 1 models management of the alluvial flows by the use of a line of wells, while scenarios 2 and 3 include different numbers of wells and variable lengths of cut-off wall. The design and sequence of construction of the drainage wells in the ore body is the same for all options. All options show that groundwater inflow to the pit, and flow through the alluvial aquifer decreases as a consequence of the dewatering systems.

The projected open cast mine contours are the primary basis for the analysis of the different dewatering systems. In Bosnia and Herzegovina, and in some of the former Yugoslav states, it is usual to present projected mining works on a yearly state (year end) for the first five-year period, and then on a 5-year interval level, with a projected final open cast mine contour at the end of ore exploitation. Likewise, after each five-year period of ore exploitation, the prognoses of the dewatering system operation are verified or corrected. The most significant change in the flow pattern in the wider area of the mine is influenced by the construction dynamics of the excavation contour advancement, which is presented with a time step of a minimum of one year, which differs from the real conditions when advancement of the mine is linear in process. As a reference position, the prognostic calculations adopted the condition of

the mine contour at the end of the year (31 December) which is kept during the entire following year of calculations. More significant differences appear in 2022 (after five years) and in 2024 (after two years). Besides this, in all the analyzed dewatering systems, the drainage wells have a significant role. During the calculations, the results proved to be very sensitive to changes in the initial values of well capacities, which must decrease gradually over time. Otherwise, there is an excessive decrease in piezometric heads in the wells which results in wells either being shut down or showing an insufficient level of reduction in the wider area of the wells. Therefore an especially sensitive task during prognostic calculations was assigning the discharge of the drainage wells, where several criteria and limits had to be kept in mind:

- The initial well capacities should not be too large, as the dewatering effect which is aimed at will not be achieved – even with a steep decrease in the groundwater levels in a well, a corresponding drawdown does not form in the surrounding area. This is a not only a result of the hydraulic characteristics of the media (alluvial sediments and the limonite ore body), but also their variable thickness.
- The life span of the wells which are located in the course of the mine advancement front, depends on the dynamics of the advancement of spoil excavation. Over time, with the advancement of the spoil benches, the well gradually shortens and its capacity decreases, until the final shut down, i.e. destruction of the well.
- The well discharge decreases correspondingly and simultaneously with the gradual drainage and decreasing groundwater levels. It is necessary to create a balance between the well discharge and level reduction, in the well itself and its immediate surroundings, as well as in the wider zone of the well.

- A proportion of the wells in the ore body are not destroyed, remaining permanently in operation, and their capacities decrease over time.
- A number of wells are removed from operation over time due to the decrease in groundwater levels below the elevation of the well screen construction.

From a hydrodynamic aspect, Scenario 2 which includes a cut-off wall ahead of mining of the north wall of the open cast mine provides the best protection from the inflow of groundwater from the alluvial aquifer from the direction of the diverted river bed of the River Gomjenica. Scenario 3 is a combination of the first and second scenarios, with a dewatering system composed of a shorter cut-off wall and drainage wells, and this is the second most effective option. A techno-economic analysis is required to select the best of the analyzed scenarios for protection of the open cast mine "Buvač" from groundwater inflow.

Finally, it is concluded that the application of groundwater modeling has proven very useful in comparing methods for protection of the open cast mine from groundwater inflow. The hydrodynamic model of the aquifer regime and management scenarios for protection from groundwater inflow in the open cast mine "Buvač" opens the way toward system optimization and sustainable economic development.

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