THE DEVELOPMENT OF A "DRIVE-IN" FILTERS DEWATERING SYSTEM IN THE VELENJE COAL MINE USING FINITE-ELEMENT MODELLING

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abstract

During the mining operations at the Velenje coal mine, groundwater has been presenting a constant threat to underground works. The hydrogeological setup is so complex that a lot of structural drilling and well-logging operations were needed in the past to clarify it. Above the lignite seam is a Pliocene and Pleisticene multilayer aquifer system, composed mainly of permeable sand layers and impermeable clay layers. In 1981 the Pliocene aquifers were divided into three packages. Based on the water-table data of each aquifer, pumping tests, chemical analyses of the groundwater and the geophysical properties the Pliocene aquifers directly above the seam, together with impermeable layers, were divided into: a) the first water-bearing sands (Pl1), b) the aquifers 2080 m above the coal seam (Pl2) and c) the upper Pliocene aquifers (Pl3). For the mining operations the most important aquifer of saturated sands is Pl1. The hydraulic pressure of the groundwater in these sands directly affects the safety of the mining. These aquifers are mostly affected by the dewatering activities, too. However, the dewatering wells are constructed in such a way as to capture the whole Pl2 and, somewhere, even a part of the Pl3 complex, too. The water pressure in this multilayer aquifer can reach over 35 bars, so a massive program of drawdown activities has been needed and is still in place to decrease the water table in the area related to the mining operations. Special, multilevel observation wells are used to monitor the water level. A number of 3D finite-difference models (FDMs) were used to estimate the regional groundwater drawdown. It was observed that the FDMs performed well when predicting the regional situation, but the model-predicted drawdown was lower than the observed values at observation points in the area where the dewatering operations using "drive-in" filters have taken place in the past. This is a well-known problem of the FDM: the drawdown being rather a function of the cell size than of the flow net. The risk of water inrushes will increase, especially after 2012 and 2017, when a series of surface-drilled wells, connected into the mine's pumping-line batteries, will be abandoned due to excavation works and mining-subsidence effects. Consequently, the dewatering schemes had to be completely reviewed. The destroyed, first-order dewatering structures will have to be replaced by a series of "drive-in" filters, drilled from the mine roadways in the area of the planned longwall face operations. For the drive-in filter-system design the FDM does not seem to be appropriate. This is especially so if the error in the drawdown and pumping flow prediction is taken into account. That led, in 2007, to the selection of the finite-element method (FEM) for the prediction of the groundwater drawdown and the water pumping rates in the areas were the underground works will encounter the risk of a water inrush. Based on the FEM prediction the sizing and the layout pattern of the "drive-in" filters were made.

Keywords

drive-in filters, groundwater mathematical modelling, mining water, mining hydrology, geophysical well login & solid modelling

1 INTRODUCTION

The Velenje coal mine is one of the largest and most modern collieries in Europe. It is situated in the north-eastern part of central Slovenia in the Šaleška Valley tectonic depression, filled up with more than 1000 m of Pliocene and Pleistocene sediments (Fig. 1). The sediment material represents the complete sedimentation cycle of the terrestrial, swamp and lake phases in both directions. This sequence is sometimes interrupted with fluvial sediments transported from the northern and north-western side [7].

Coal extraction in the Velenje coal mine has been uninterrupted since the end of the 19th century, during which time several stopping methods for the excavation of wide coal seams have been tested. In the first half of the 20th century the room-and-pillar method as well as block caving were used. Since 1947, however, the longwall mining method with improvements has been practiced; this is known as the Velenje longwall method[9]. The Velenje coal mine is producing lignite from a coal seam that has huge dimensions. The coal seam is a more or less continuous body: 8.3 km long, 2.5 km wide and more than 160 meters thick. The depth to the seam varies from 200 to 500 meters. In the central part, the exploitable seam is up to 168 m thick. In the central part the seam is the most deeply buried (approximately 450 m) and in the marginal parts it is closer to the surface (approximately 100 m) (Fig. 2). In the lower part of the coal seam the ash content gradually increases, while the upper margin is very sharp. The coal seam is covered by marl with fossil snail shells, followed by mudstone, sometimes laminated or massive (Fig. 2). Within this mudstone, intercalations of water-bearing sands and gravel of changeable thickness appear.

This impermeable layer between the coal seam and the first sands on top of it is called the isolation or the protective layer. This isolation prevents water and mud inrushes into the mine openings [9]. However, large spaces are opened during the mining works, leading to a failure of the protecting layer, which allows the lowest sand and gravel layers of the hanging wall multi-aquifer system to come into contact with the lignite seam.

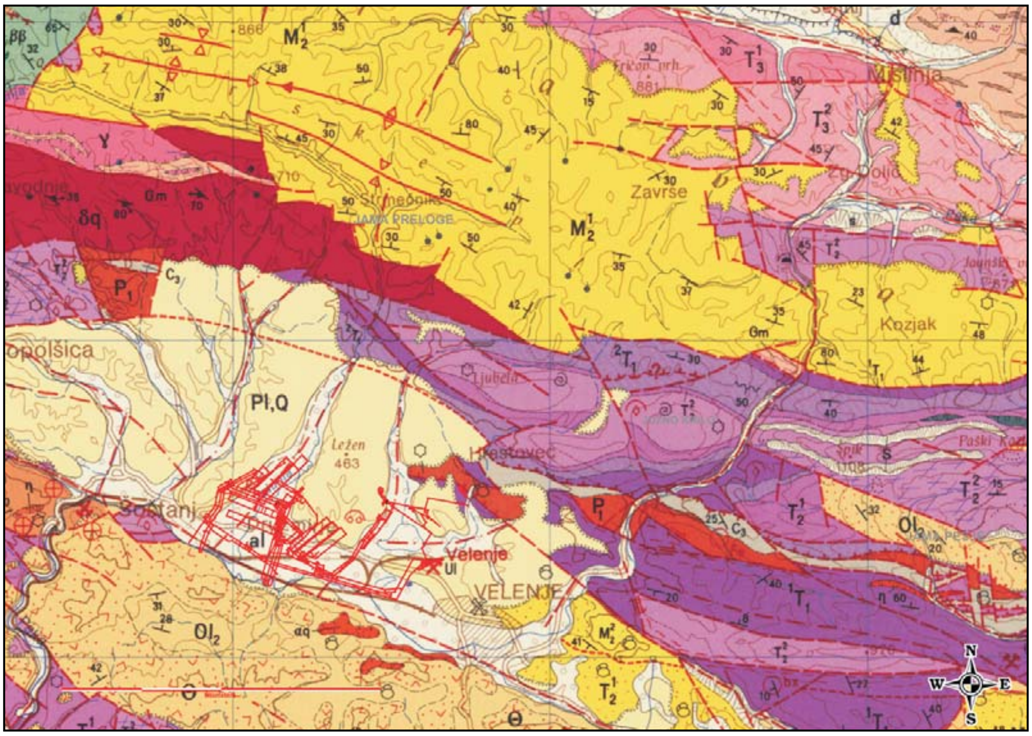


Figure 1. Geological map of the surrounding area of the Velenje lignite mine underground works. The red lines representing the coal mine's active mine roadways.

Because of this, the groundwater pressure in these aquifers, as the most relevant part of the hanging-wall multi-aquifer system, has to be constantly monitored [10] and groundwater modelling has to be used to predict the underground hydrological state. In the past, FDM numerical models were used.

The most successful predictions until now were made with Visual ModFlow. Even though Visual ModFlow has been the best prediction tool and it is widely used in Velenje, its limitations were impeding its use in predicting the hydrological state on a short scale [8]. This problem has been very well known for a long time and different approaches need to be found. The main problem is that the FDM produces groundwater drawdown, which is more a function of the cell size than of the flow net [2] [3].

2 HYDROGEOLOGICAL SETTING

In general, in the Velenje coal mine three hydrogeological systems can be distinguished [12]. The upper one is a Quaternary system, which lies on the Pliocene aquifers. These Pliocene aquifers lying over the coal seam are the most important for mining safety. It was in 1981 that the roof aquifers were divided into the Pliocene and quaternary aquifers [12]. The division was based on water-table data in a single aquifer, pumping tests, chemical analyses of the water and the geophysical properties [15]. The Pliocene aquifers were then further divided into three packages. The aquifers directly above the seam and isolative layer, the first water-bearing sands (Pl1), the aquifers placed 20–80 m above the coal seam (Pl2) and the upper Pliocene aquifers (Pl3) [7]. From the point of view of safety criteria, the first and second sand layers (P11 & Pl2) are the most important. The high water pressure in the sands can directly affect the underground works below. The bottom elevation of the first sands (Pl1) in the years before the excavations is presented in Fig. 3.

There are some difficulties in determining the aquifer thickness. The first problem is the heterogeneity of the whole aquifer complex, consisting of sand, gravel, mudstone, clay, and the various mixture layers [7]. Overall, the vertical and lateral permeability is, therefore, low. The second problem is to delineate the part of the complex affected by the dewatering operations, and the third one is the insufficient amount of data in the area of the missing coal seam [7].

The coefficient values were acquired through numerous pumping tests performed on the dewatering and observation wells. For the area where no wells were drilled, no values exist. Based on pumping test data, different zones of hydraulic conductivity could be established (Fig. 6). As can be seen, the hydraulic conductivity coefficient values are in range from $k = 1.74 \times 10^{-7}$ m/s up to $k = 2.88 \times 10^{-6}$ m/s (Fig. 6). Regarding the specific yield, only a few values are given. For modelling purposes a representative value of the specific storage $S_0 = 5 \times 10^{-5}$ m^{-1} for the whole area was chosen. Because there were no data available for the effective porosity, we had to adopt an assumed value of $n_{ef} = 5\%$. According to the references this is the value for dense, silty sands [6]. However, this value can be lower in the zones where more silt is present [7].

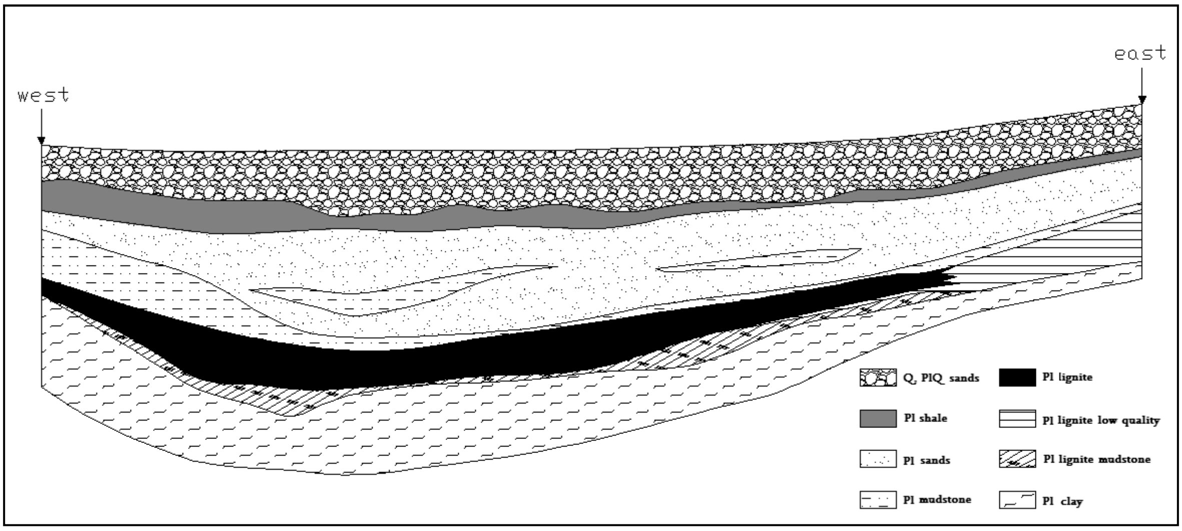


Figure 2. Geological cross-section (west-east) of the Velenje lignite mine. The multilayer aquifer system is composed of sand strata lying directly on the lignite seam [9].

3 TIME EFFECTS OF MINING WORKS ON THE AQUIFERS

Underground works will increase the open spaces, which are to be filled in with the material lying over the coal seam. The basic concept of excavating coal by the longwall method is that the affected area of exploitation extends above the supported roof coal of the face, thus enhancing the natural forces that break and crush the coal and/or assist the natural process. The excavation face is divided into the lower-excavation part and the upper-excavation part. The lower part is 3–4 m high and is protected by a hydraulic shield support, thus enabling mechanized coal production with shearers and haulage using chain conveyors. The upper-excavation part is 7–17m high and is exposed to dynamic stresses, which, in combination with blasting, cause the coal to disintegrate and crumble onto the conveyor. The direct roof crumbles into the cavity and consolidates over time, so the excavation of the lower panel is enabled. The winning of the upper part can be continuous or time delayed [9].

The mining operations will also affect the pumping rates. The pumping wells shown in the red rectangles in Fig. 3 & 4 will be disused in 2012 as a result of the coal-excavation operations affecting these wells (Fig. 3). As a consequence, the bottom-wall elevation of the sands Pl1 will change from that given in Fig. 3 to the state presented on the elevation contour map in Fig. 4.

As has already been pointed out, the groundwater pressure in the sands Pl1 & Pl2 is the most important issue. From the measurement data using multilevel piezometers it was possible to reproduce the groundwater table (Fig 5). It is obvious, however, that the groundwater depression cone is the result of long-term dewatering in the pumping wells. To keep the effects of the pumping well battery abandoning at a minimum, the so-called "drive-in" filters, i.e., the pumping wells drilled vertically from underground roadways into the roof aquifers, will be applied (Fig. 5.). The emplacement and operation of "drive-in" filters will not start simultaneously, but their start and stop times will depend on the excavating processes with the longwall method. In Table 1 the start and stop times of the "drive-in" filters are shown.

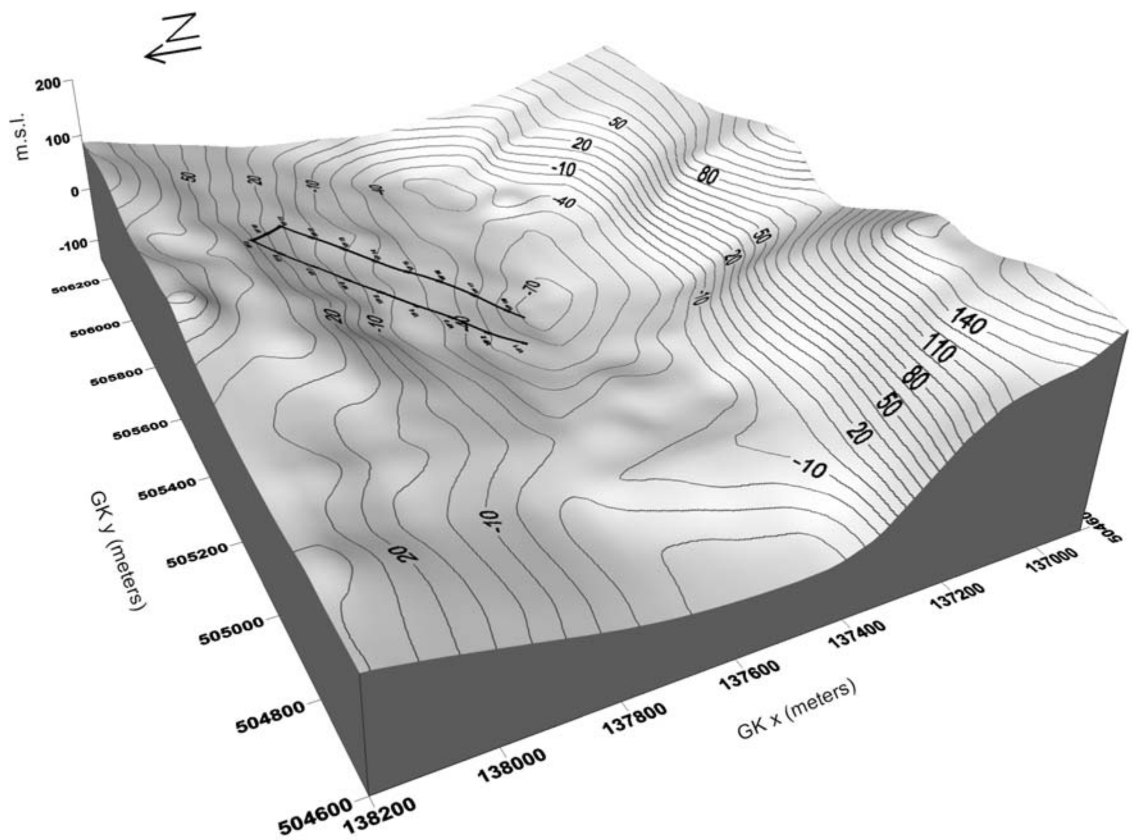


Figure 3. 3D bottom-wall elevation map for the Pliocene water-bearing sands P11 in the years before 2007 [14].

Table 1. The working scheme for "drive-in" filters is mainly dependent on the mining operations along the longwall.

Name of "drive-in" filter	Prescribed water head [m.s.l.]	Start to work [day]	Stop to work [day]
VF-1	-54.70	0	510
VF-18	-64.00	14	477
VF-2	-57.60	28	477
VF-17	-61.40	42	442
VF-3	-50.30	56	442
VF-16	-50.10	70	409
VF-4	-41.90	84	409
VF-15	-43.90	98	372
VF-5	-31.20	112	372
VF-14	-35.00	126	337
VF-6	-20.80	140	337
VF-13	-23.60	154	302
VF-7	-8.60	168	302
VF-12	-13.40	182	267
VF-8	2.50	196	267
VF-11	-4.00	210	230
VF-9	16.30	224	230
VF-10	4.10	230	230

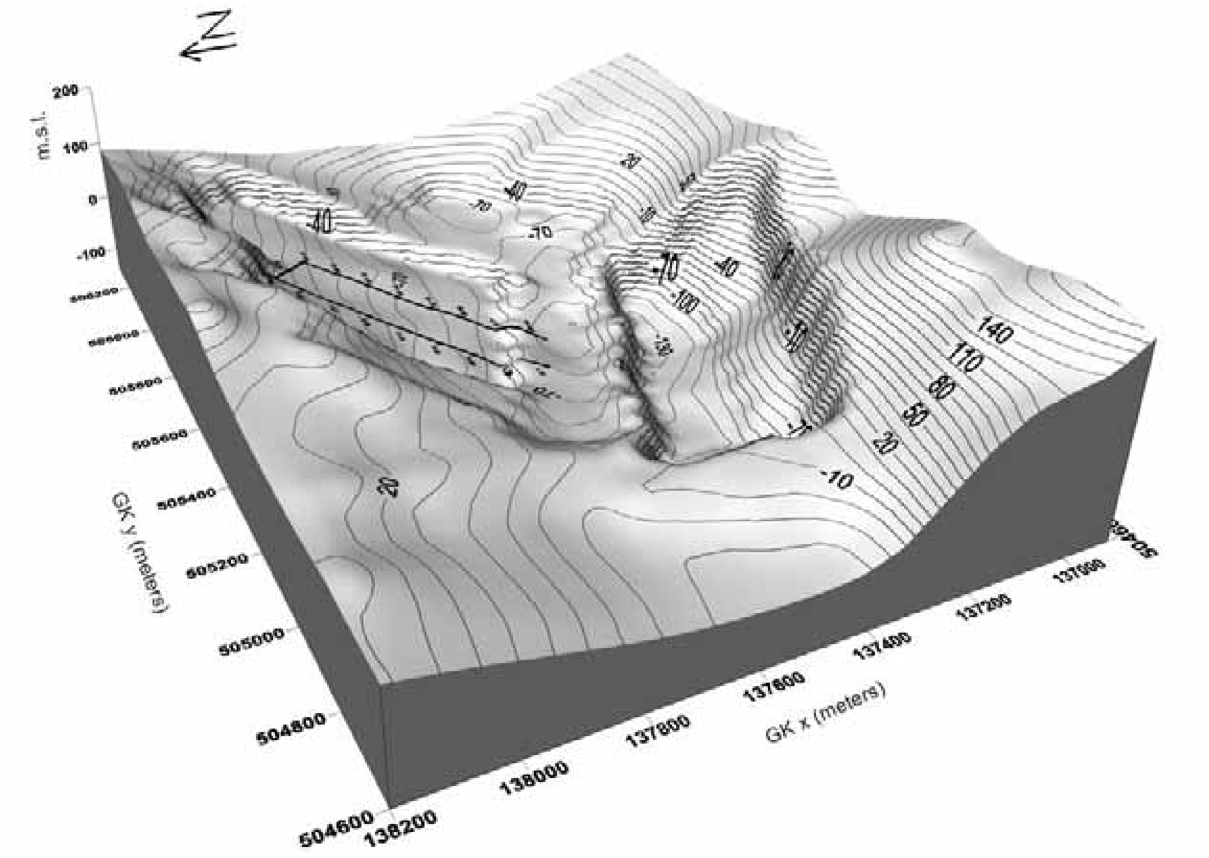


Figure 4. 3D bottom-wall elevation map for the Pliocene water-bearing sands Pl1 in 2012.

As is clear from Graph 1, the central pumping line is now pumping more than 300 l/min. This stable pumping line is to be disused due to mining operations and has to be replaced with another one, drilled from the surface, or with a series of in-mine drilled "drive-in" filters. There are many objections to a stable pumping line, but the most important is that the pumping line will face the same end as the central pumping line with the mining works still going on. So, only the "drive-in" filters can be constructed for dewatering the part where longwall face mining operations are in progress. For this reason the model has to be very accurate in terms of groundwater-pressure predictions. Due to the very well-known problems of the FDM explained before, the FEM was selected.

5 MODELLING AND "DRIVE-IN" FILTER DEWATERING SYSTEM DESIGN

To predict the effects of sand subsidence, of the shutdown of the existing pumping line due to mining operations and of a replacement of the shutdown wells with "drive-in" filters around the longwall face and underground roadways (Fig 5 & Fig. 7), a 3D FEM FeFlow 5.1 modelling program for flow, mass and heat transport was used [1].

For the "drive-in" filter design there are many hydraulic and geo-chemical parameters which have to be taken into consideration [13]. In the case of the Velenje coal mine, the geo-chemical parameters have less impact on the operation of the "drive-in" filters than the hydraulic ones. If we take into consideration that the "drive-in" filters will be in operation for less than 510 days the chemical or geo-chemical factors can be neglected. From this, the decision was taken that only the flow has to be modelled. The main objective was to model the maximum flow rates at the sites of the "drive-in" filters and to analyze the influence of the geometry of the water-bearing Pl1 sands on the flow pattern.

The modelling in such a case has to be as much as possible realistic, so it was important to understand the processes that will take place in 2012 along the longwall. When the problem was analyzed more closely it was

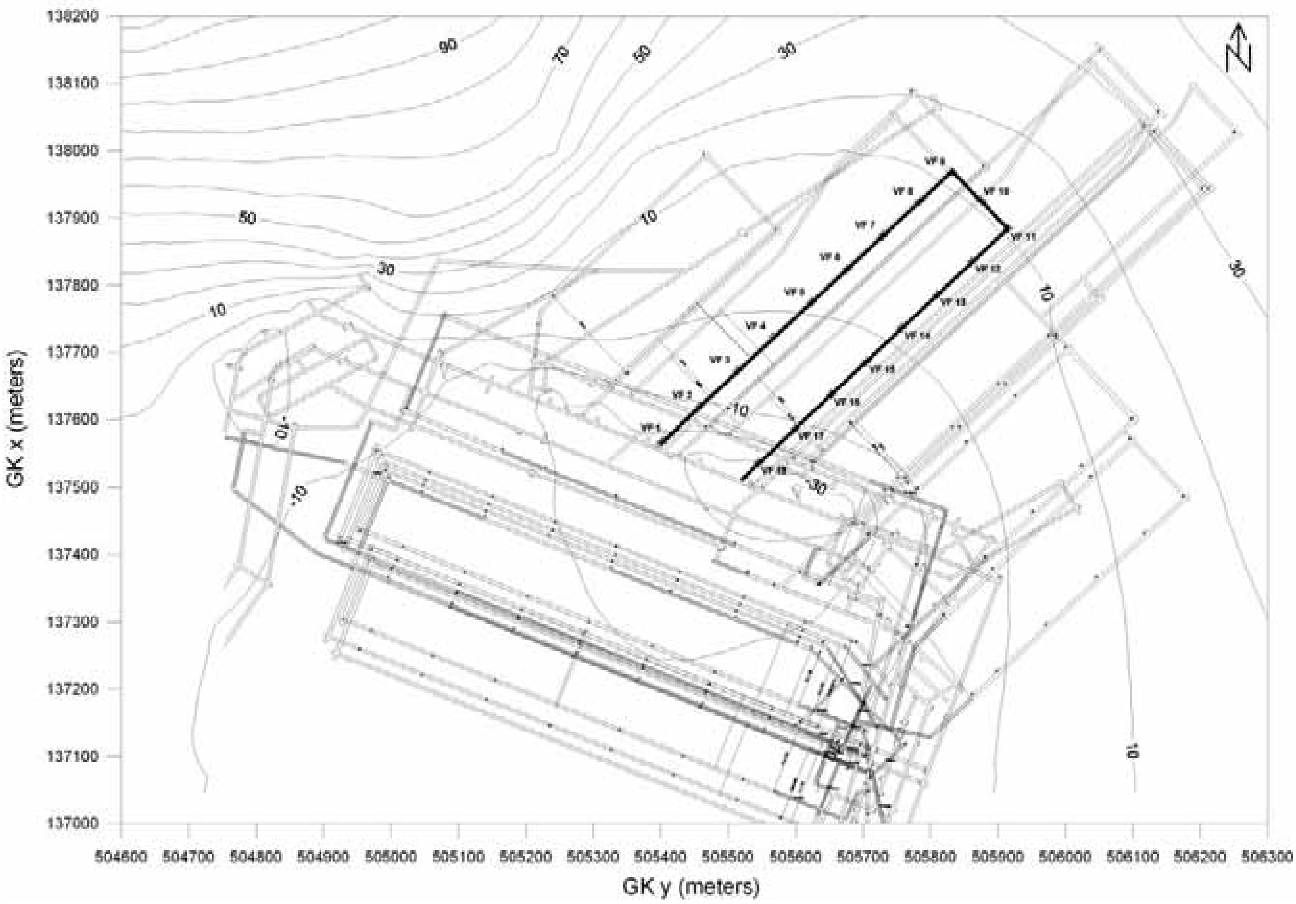
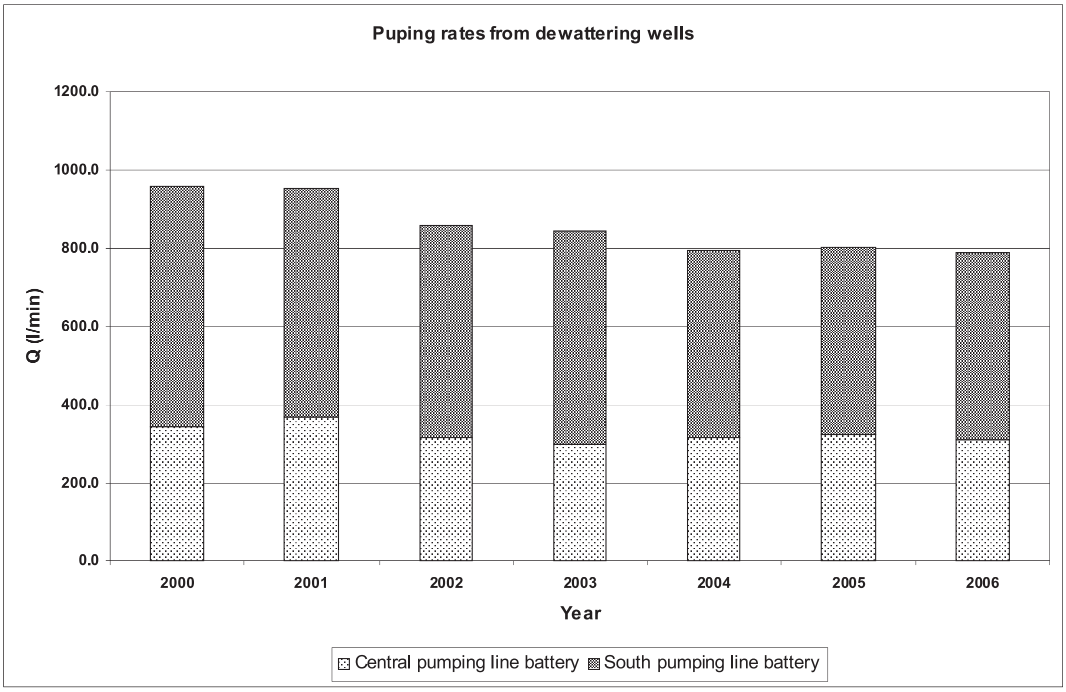


Figure 5. Groundwater-level contour map for the water-bearing sands Pl1 & Pl2 in 2007 (with north to the top). The underground vertical pumping wells are marked with the labels VF (black points).

found that in fact two situations are the most important for the prediction: the first one, which has to show how the hydrological situation will evolve when the "drive-in" filters start to operate; and the second one, which has to show the groundwater-level rebound after the "drive in" filters stop.

The design documents and papers state that the mining operations along the longwall face will take 510 days (Table 1). This includes the preparation works and the excavation works. Here, the time needed to move from one longwall face to another also has to be taken into consideration. From the mining documentation it seems that this time is mostly a function of the mining-operations management rather than a technical problem. However, the time needed to move from one face to another is also very important, especially if it is taken into account that no pumping via the "drive-in" filters will be possible during that period. The situation will be even more critical due to the fact that the central pumping line also has to be switched off because of the excavation works. To make the scenario more realistic it also had to be taken in account that the first sand water-bearing layer (Pl1) geometry will change with time. From a previous, detailed mining surveying [9] it is known that the subsidence caused by the groundwater pumping and excavation works amounts to nearly 80% of the excavating space height. Starting from this experience and feeding the current data to Surfer 8.0, the upper and lower borders of the water-bearing sands (Pl1) were first constructed for the current time situation (Fig. 3). Then, according to the planned future mining operations, defined in the mine design documents, a prediction for the Pl1 sands' geometry was made for 2012. The results of the gridding process are shown in Fig. 4.

After the geometry data needed for the model were defined, in the next step the water-balance data were analysed. This is particularly important because the hydrological system of the Velenje mine is now in a quasi-steady state[11]. For this a series of measured flow data for the central pumping line battery and south line pumping battery were taken into consideration (Graph 1). The grids already presented in Fig. 3, Fig. 5, Fig. 6 and the data from Graph 1were used to calibrate the model for the current hydrological (Fig. 5) and mining situation (Fig. 3). After the calibration on the current hydrological and mining situation (Fig. 5) the calculated and calibrated heads were used as the initial condition for predicting the groundwater levels in 2012 (Fig. 4). For the flow boundary the Cauchy type was selected on the north, north-west and north-east parts of the model (Fig. 7). The prescribed "in-flow" in the model domain was equal to the amount of groundwater pumped out with the current pumping wells. The secondary constraint was also used in the form of minimum prescribed heads, which are in accordance with the



Graph 1. Pumping rates for the central and south pumping line battery. In 2012 the central pumping line battery will cease to work.

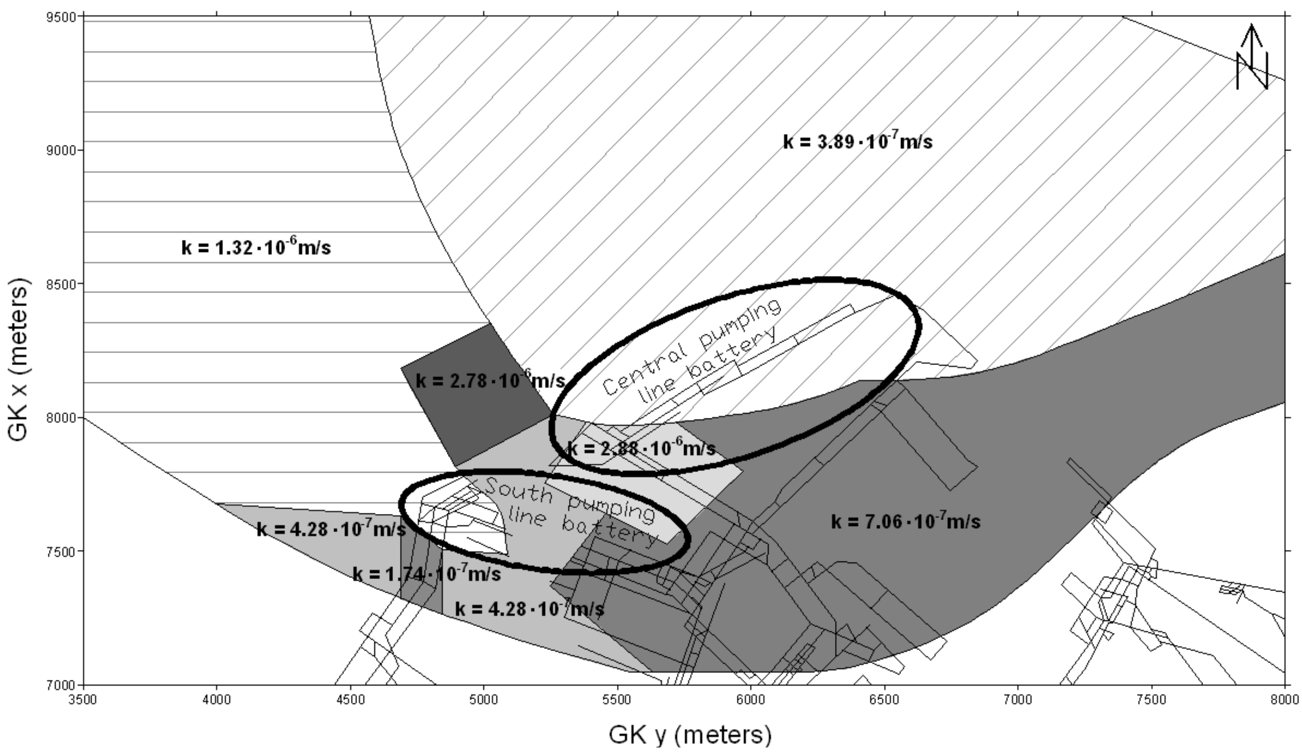


Figure 6. Map of the hydraulic conductivity zones of the modelled Pl1 sands deduced from a series of pumping tests. The zones were defined in one of the previous models in the ModFlow 4.2 FDM (North is orientated vertically).

heads on the head map presented in Fig. 5. The water abstraction from the old remaining wells (aligned in the South pumping line) was selected as a single source/sink boundary (Fig. 7). As can be seen in Graph 1, the values of the pumping rates are more or less stable on both pumping lines batteries. For the pumping rates of each well their average rates from 2000 to 2006 were selected. For the estimation of the "drive-in" filters the pumping rates Dirichlet boundary conditions (BCs) were used. The heads of the Dirichlet BCs were prescribed to the maximum groundwater table drawdown by free-flow dewatering (Table 1), because of the possibility that the water level is dropping below the initial level and that instead of pumping, the recharge will begin at the Dirichlet BCs. The additional flow constraints, as the minimum outflows of greater than, or equal to, 0 m^3/day were used. In the model, the starting time and the end of the operation time for the underground vertical wells were also taken into consideration.

For the reason specified before, the development of the "in-flow" rates on the "drive-in" filters are the most important for the filter design. So, the model results were mainly used to predict the rates on spots of the "drive-in" filters. Using the flow budget analyser of the FeFlow the flow rates on the Dirichlet (BCs) were reconstructed, which were representing the "drive-in" filters. The model calculations are presented in Graph 2. The values in this graph are in range from a few decilitres per second up to a few litres per second. The results seem to be in line with the results of the pumping test during the 1980s [12], where in some cases pumping rates up to 15 l/s were measured. From the report of that pumping test [12] it can also be seen that if the pumping rates exceeded 5 l/s the wells were clogged by sand.

The predicted "in-flow" rates are the largest at the beginning (Graph 2). This is typical of the start of the dewatering process. With time the "in-flow" rates start to decrease until the moment when the "drive-in" filters stop functioning one after another. After that, a strong increase in the predicted "in-flow" rates can be seen for the wells that remain operational.

The amount of water inflow to the "drive-in" filters is also dependent on their position and the geometry of the strata. In the case that the geometry of water-bearing sands is very well known an inflow prediction can be made. If, for the sake of strata heterogeneity, the flow at a particular "drive-in" filter is different from that predicted it is usually compensated by another filter in the vicinity.

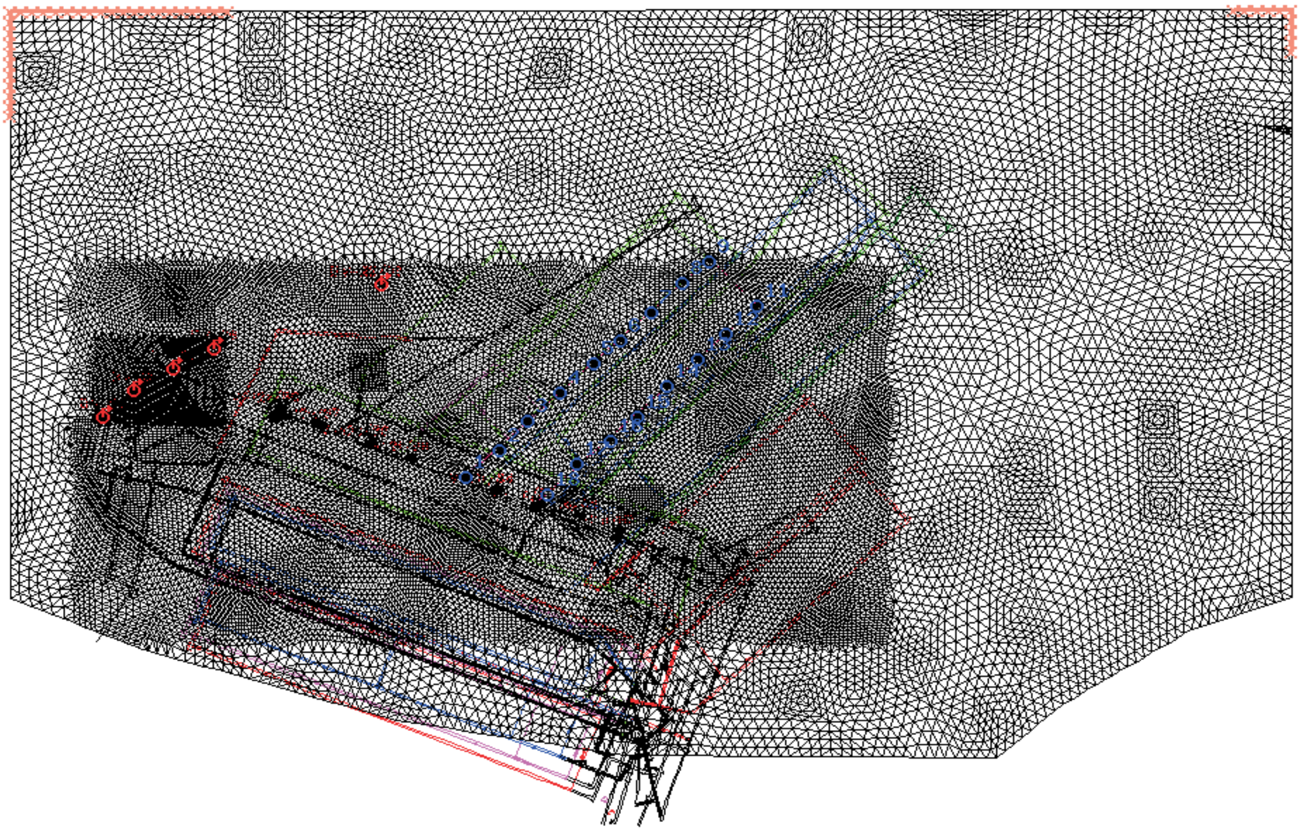
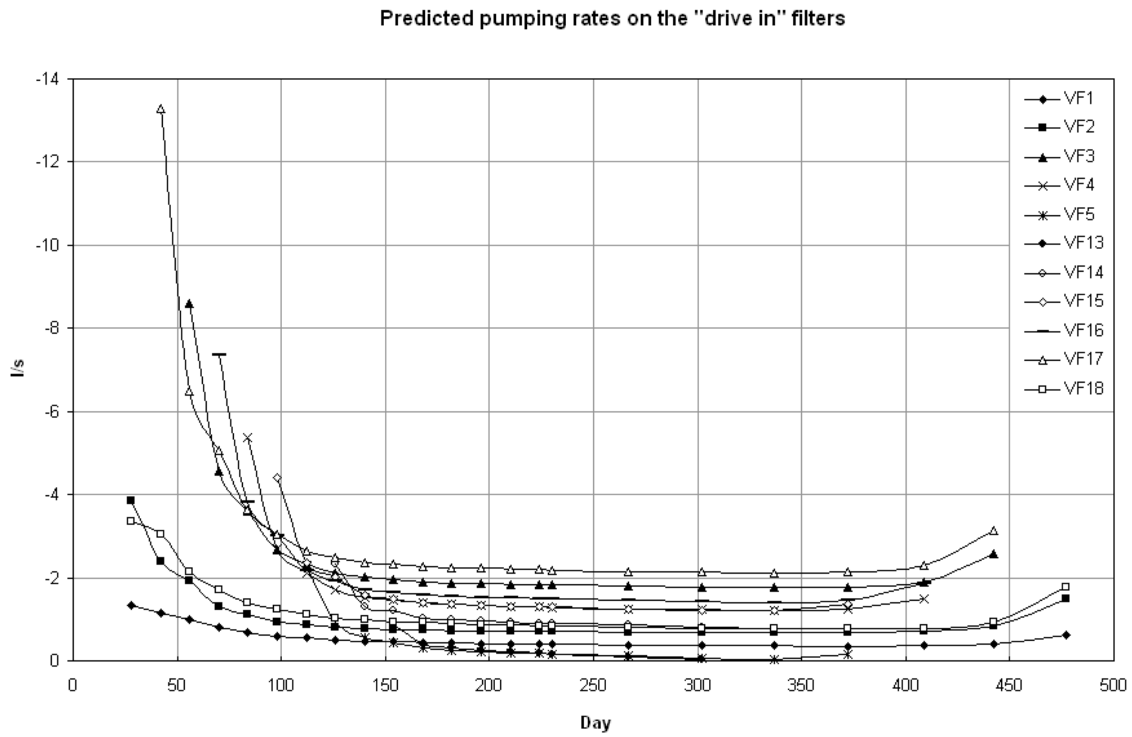


Figure 7. FEM groundwater model. The red points represent the active pumping wells (south pumping line battery), the blue are the "drive in" filters (Dirichlet BCs) and the pink points represent the Cauchy BCs (North is vertically orientated).



Graph 2. Predicted "in-flow" rates of the planned "drive-in" filters using Dirichlet BCs in the mathematical model.

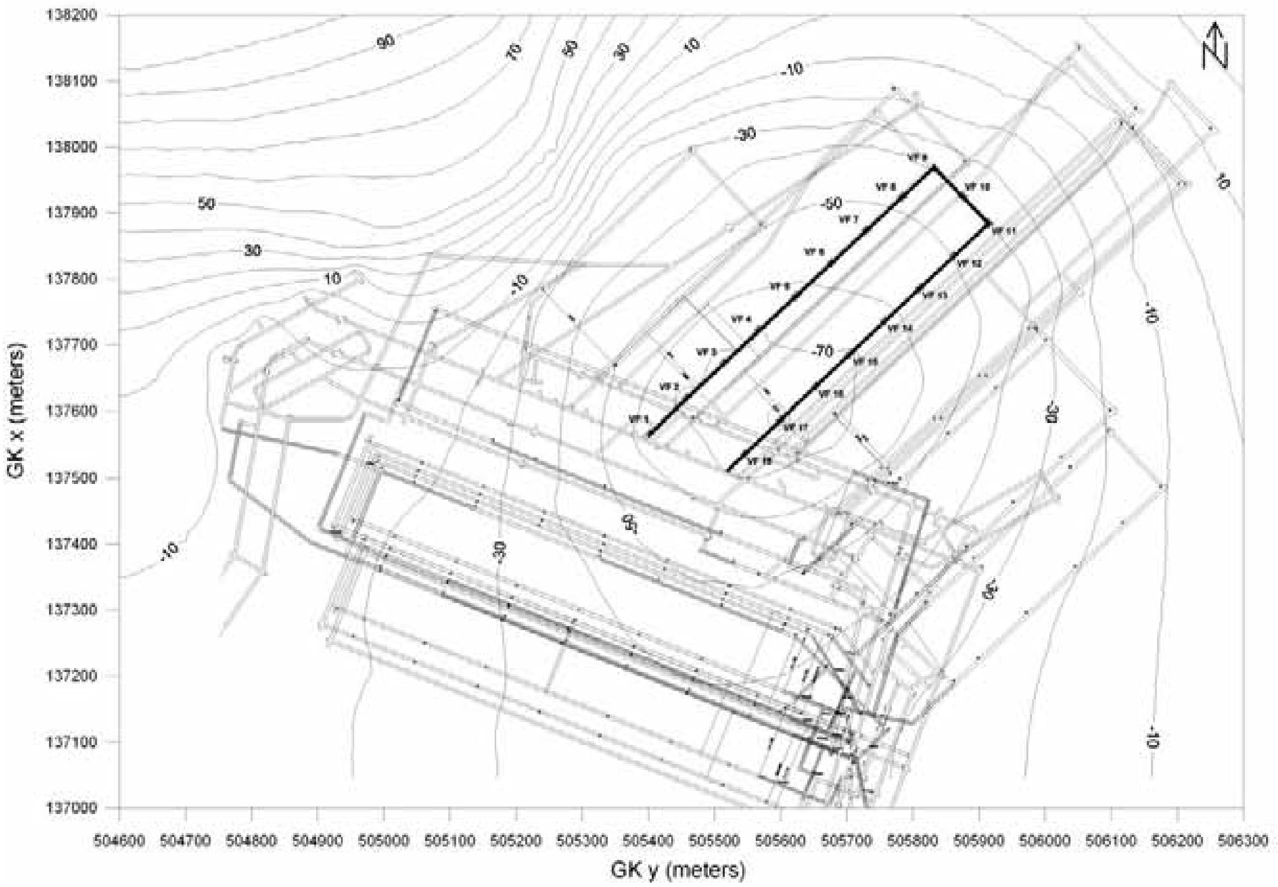


Figure 8. Predicted groundwater-table depression in 2012 after 230 days of mining operations on a longwall face. All the "drive-in" filters are in operation. (North is vertically orientated).

For the designing of the "drive-in" filters a criterion of maximum flow velocity has to be taken into account [4]. The maximum water velocity through the open spaces of the screen (i.e., the screen opening) should not exceed 0.03 m/s [16]. Based on the model prediction it was possible to estimate the maximum expected flow rate to the "drive-in" filters so the calculation could be made after the equation for designing the necessary screen opening on the screened part of the "drive-in" filters [16]:

$$A_f = \frac{F \cdot Q_f}{v_{dop} \cdot l} \qquad (1)$$

where

A_f	effective open area per metre of screen
F	well-clogging factor
Q_f	flow through the open filters [m^3/s]
l	length of the screens in sands
v_{dop}	maximum admissible screen entrance velocity

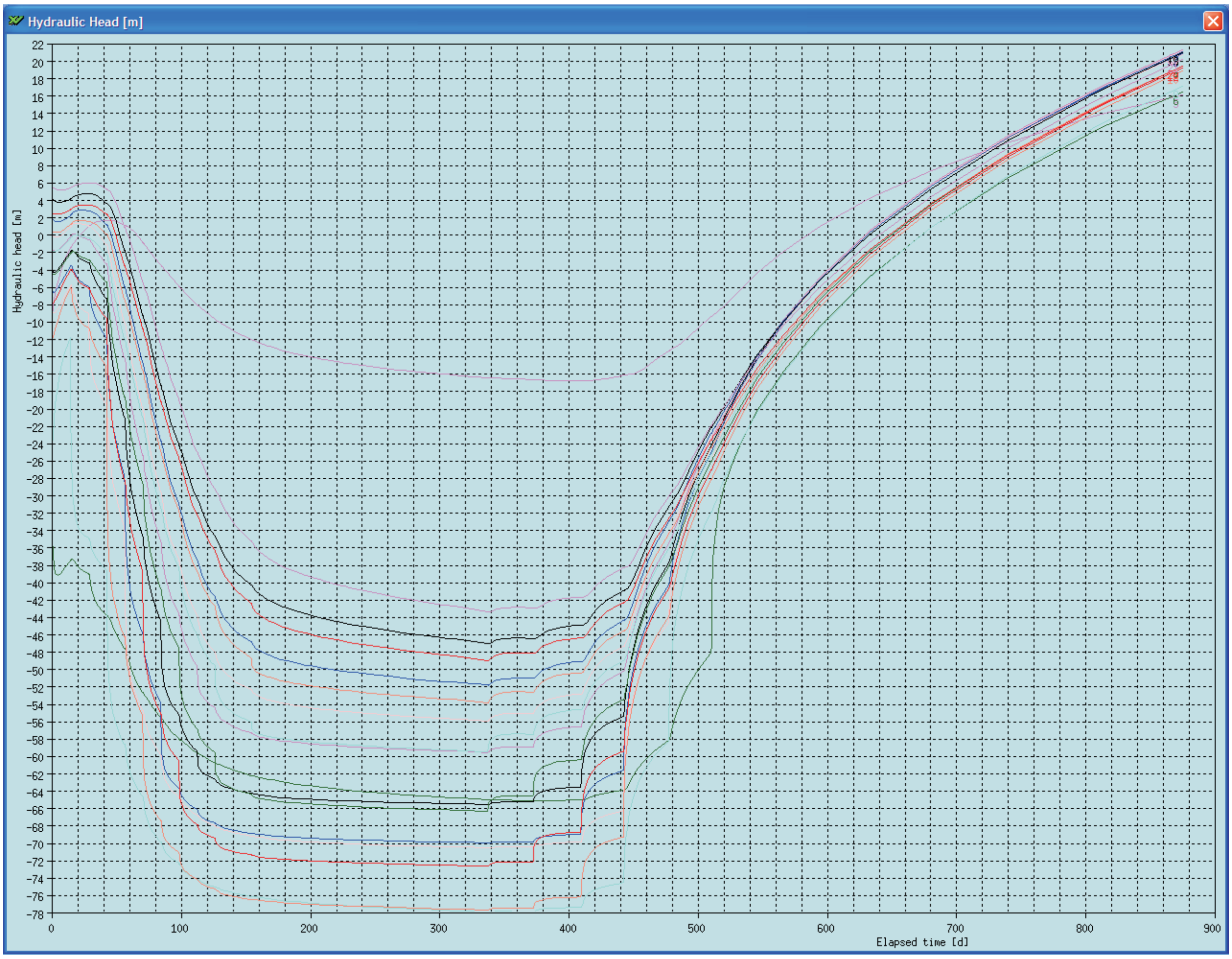
The percentage of screen opening can be calculated [16] from:

$$P = \frac{A_f}{\pi \cdot D_c} \qquad (2)$$

where

P	percentage of screen opening
D_c	diameter of well ("drive-in" filters")

As can be seen, the maximum flow rates, which can go up to 13.5 l/s, are in the initial stages of dewatering around the longwall, but according to the Graph 2 the flow rates at the "drive-in" filters start to decrease with time. So, the "drive-in" filters have to be dimensioned for the period of maximum flow rates. Using equations 1 and 2, this calculation was performed for the clogging factors 1, 2 and 3.



Graph 3. Predicted drawdown curves for the observation points between the "drive-in" filters positioned along the roadways.

Table 2. Calculated percentage of screen opening.

D_c [mm]	F=1	F=2	F=3
	Percentage of screen opening		
48.3	32.95	65.90	98.85
60.3	26.39	52.79	79.18
76.1	20.91	41.83	62.74
88.9	17.90	35.81	53.71
108	14.74	29.47	44.21

The parameters used for the calculations are as follows:

Q_f 13.5 l/s
l 10 m
v_{dop} 0.03 m/s

A length of 10 m was selected for the screens in the water-bearing sands (Pl1). This value is based on the Velenje mine experience. The reasons are the diameter of the roadways and the time that would be necessary to increase the diameter. This also means that the drilling equipment has to be of limited dimensions and the drilling operations are restricted by difficult working conditions. According to the values in Table 2 a criterion of 0.03 m/s is very difficult to achieve. So, on one hand, we have a result that is showing that the dewatering can be very successful with the "drive-in" filters and, on the other hand, we can see that, physically, almost no small diameter screens are able to meet such requirements. According to Table 2, the required small-diameter screen-opening percentage, as calculated from data of the models, exceeds the technically possible 25 % if any additional screen clogging was taken into account.

However, there is also another condition that we have to take into consideration, and this is related to the maximum velocity of the groundwater flow through the open spaces of the intergranular porous media[5] around the well. This is the well-known Sichardt criterion, which stipulates that the maximum withdrawal from the well also has to take into consideration the flow velocity at which a failure of the aquifer structure due to a displacement of fine fractions could immediately occur. So, the velocity should not exceed the velocity calculated using the Sichardt criterion. The calculation has to be performed with the following equations[5]:

$$V_{Sic} = \sqrt{k} / 15 \qquad (3)$$

and

$$Q_{Sic} = A * V_{Sic} \qquad (4)$$

Where

A	Open area, equal to $A=2\pi r_w l$, with r_w being the screen/well radius in [m^2]
k	Coefficient of hydraulic conductivity
Q_{Sic}	Sichardt criterion flow through the open filters [m^3/s]
V_{Sic}	Sichardt criterion screen entrance velocity

A simple calculation for a 10-m-long "drive-in" filter and a hydraulic conductivity value of 2.88 10^{-6} m/s, combining equations (3) and (4), produces the following result:

$$Q_{Sic} = 0.83 \text{ l/s} = 49.5 \text{ l/min}$$

For these reasons a special guideline has to be made, which addresses the initial and final phase of the dewatering operation along the longwall works. Following the construction of a "drive-in" filter, its activation has to start slowly, enabling a controlled removal of the fine aquifer fractions from its close surroundings, creating an area of enhanced hydraulic conductivity, augmenting its effective radius and open area and establishing the required filter productivity. So, the "drive-in" filters will need to be fitted with a special device that prevents water rushing in from the sands. The valves also have to be used in the final stages of dewatering. Because of the mining works some "drive-in" filters will stop working, resulting in a flow-rate increase for those remaining. This procedure was already successfully applied to some "drive-in" filters [11].

It is also very interesting that, instead of all the planned "drive-in" filters along roadways, a smaller number can produce the same results. By inspecting Graph 2 and Fig. 8 we get the impression that not all the "drive-in" filters are necessary for the required draw down. However, the Sichardt criterion has to be taken into account, so their number, as used for modelling, is already low. This is seen in Table 2 and during the calculation of the Sichardt criterion.

In fact, by modelling with the FEM it was possible to predict the zones in which the "drive-in" filters will produce the maximum dewatering. As an example, in Fig. 8 the maximum depression for the 230th day after the "drive-in" filters start up is shown, as a result of mathematical modelling. As can be seen, the main depression is around the "drive in" filters. According to the development of the water-table depression it can be seen that the dewatering due to the "drive-in" filters is successful (Fig. 8). However, by inspecting the groundwater levels on Fig. 8 and Graph 3 it is clear that after the pumping on the "drive-in" filters is stopped, the water level starts to rise, and in less than 200 days the water pressure in Pl1 would increase dramatically. This is an effect that should not be forgotten when planning to move from one longwall face to another.

CONCLUSIONS

Using the FEM methods a more accurate prediction of groundwater table was made. The drawdown predicted by the FEM is locally much higher than when using the FDM. From our previous experience [11] and from the literature, [8] and [2], it can be seen that the calculated drawdown using the FDM is more a function of the cell size than of the true flow situation. This can be avoided with a large decrease of cell size, but it would result in a FDM numerical instability and slow numerical computing. So, the FEM proved to be a better tool on the local scale.

With the FEM the prediction of the flow rates on the "drive-in" filters is much better. The modelling shows that there is only one problem when using the "drive-in" filters. The velocity of the flow has to be carefully controlled, not to exceed those two criteria used for the calculation. Accomplishing this goal is difficult, because the space for the drilling machines is limited and the working conditions for the drilling-team members are bad. So, instead of drilling long "drive-in" filters a careful activation technique, with a special device for water-rates control has to be used. Based on our working experience from the Velenje coal mine, from a few tests of the "drive-in" filter installations [11] [12], it can be said that the model's results are in accordance with reality. So, it can be concluded that the planned dewatering program has sense only if a special measure of activation will be used, and if the time to switch from one longwall face to another is short enough.

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