Application of Hydrochemistry for Predicting Water Irruptions in Zasavje Collieries

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ABSTRACT

Statistical analysis of hydrochemical properties of mine waters in the Hrastnik colliery contributed to a better understanding of inrushes of water and mud into mine workings. Analysis of variance sampling design enabled to estimate representatively temporal and spatial variability of hydrochemical composition of waters, as well as the reliability of sampling and analysis. By R mode factor analysis the source of mine waters could be explained. Discriminant analysis permitted reliable attribution of unknown water samples to one of the two major hydrological subsystems in the colliery on the ground of concentrations of HCO_3^-, SO_4^{2-}, Mg^{2+}, and Na^+ + K^+ in them. Discriminant values of water sampled in workings in areas of known structural geology and hydrogeology as established by mapping, enabled to assess the degree of danger of inrushes of water and mud, and to predict their occurrence.

INTRODUCTION

In the last decades one of the most serious problems in mining activities in collieries of the Zasavje basin is posed by inrushes of water and mud from supposed accumulations above mine workings under exploitation. Coal production is handicapped, at times even stopped by them, and human lives are endangered. For successful conducting of the technological process of coal mining in complex hydrogeological conditions of the Zasavje collieries the knowledge of source areas and of mechanisms of water irruptions are of prime importance. The sources of waters in them have been known to hydrogeologists to a certain degree for quite a while[2,4,5], but the mechanisms of their irruptions have been unsufficiently understood, and the question of their prediction still remained open.

For predicting of inrushes geochemical information carried into mine workings by water was used in the described investigations. The working hypothesis was set up that hydrochemical variables which reflect the geochemical processes at the ground water-rock interface can be used as indicators of mechanisms of irruptions of water and mud into mine workings.

To test this hypothesis, statistical methods were applied. In the Hrastnik colliery a sampling design based on the balanced nested analysis of variance procedure enabled to estimate the quality of sampling and analysis of mine waters, and to assess representatively several kinds of natural variability of their chemical composition in the mine(Uhan & Pirc[11]). Results of the R mode factor analysis led to an understanding of geochemistry of waters which come from various rocks (Mali & Pirc[6]). Stepwise discriminant analysis of data permitted actual prediction of imminent water irruptions on the basis of a single synthetic variable(Uhan & Pirc[12]).

In this paper a short account of these studies is presented, and the description of a test of prediction of water inrushes. In this test a simplified version of the elaborated methodology was used in a panel in the Central sector of the Hrastnik colliery, whose structural and hydrogeologic model is consistent with that in which the discriminant function was developed.

GEOLOGY

Lithostratigraphy and Structure

The Hrastnik coal deposit is situated in the central part of the Tertiary Zasavje basin (Figure 1) which is filled with Oligocene and Miocene beds (Figure 2 a). On Triassic clastic and carbonate rocks unconformingly clastic, mostly clayey Oligocene beds, 20 - 60 m thick, were deposited. They pass gradually into the coal seam. The single coal seam is up to 40 m thick, but only the upper 25 m are mined. The brilliant hard brown coal contains on the average 20% humidity, 21,5% ash and 2;5% sulphur, and its heat content is on the average 15,000 MJ/kg. The 50 - 70 m of calcareous-marly beds of the roof are conformingly overlain by up to 150 m of marine mariy-clayey deposits (called in Slovenian 'sivica', grey clay) which terminate the Oligocene sequence. Above the Oligocene-Miocene unconformity the Lithothamnian sandy limestone (50 to 100 m thick) was deposited which passes upward into the Laško marl (50 to 100 m). The Miocene deposition was closed, after the Tortonian-Sarmatian hiatus, with the deposition of Sarmatian clastic beds[2,3].

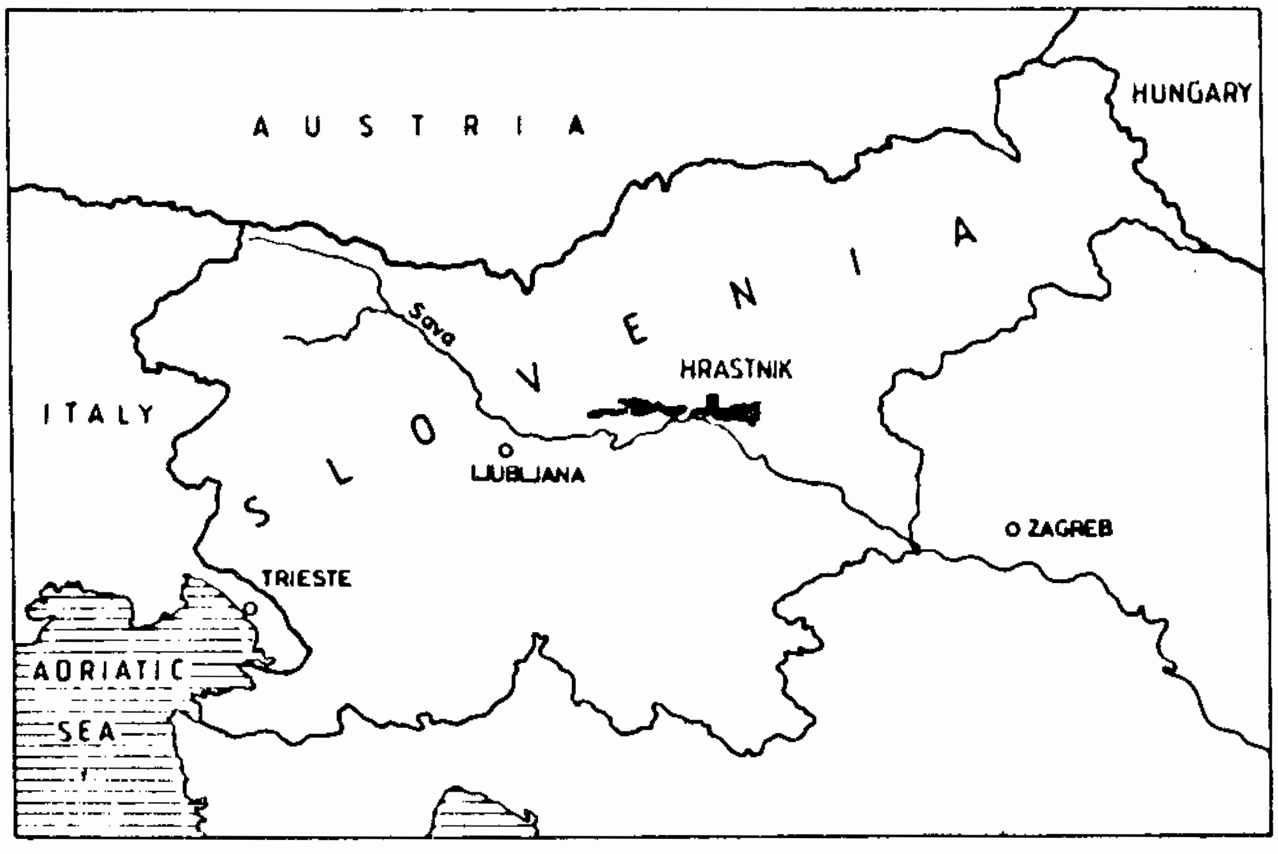

Figure 1: Locality map of the Zasavje brown coal basin and the Hrastnik colliery.

All Tertiary beds with their basement were tectonically deformed. The most pronounced are Post-Sarmatian overthrusts and deformations parallel to them which in the central part separated the steeper coal seam in the north from the remaining domed part of the coal deposit (Figure 2a). This tectonic separation is a peculiarity of the structure of the Hrastnik deposit[8], and represents the essential element of the structural model constructed for hydrogeochemical discrimination of unknown water inflows to mine workings in the dome areas of the deposit. To this structural type belong also the workings of the Central sector of Hrastnik colliery. They are situated in a structural unit between two W trending reverse faults which are considered accompanying faults of the major Hrastnik overthrust[2,8]. All these structural features are cut by gentle dipping NW trending faults which brought about depressions of the roof plane of the coal seam, and presumingly also of the Oligo-Miocene unconformity (Figure 2a).

Hydrogeology

The beds occurring in the structure of the Hrastnik region can be subdivided on the ground of their primary and secondary aquifer properties into several categories[2,10](Figure 2a,b). To primary aquifer belong next to Triassic beds also certain more permeable parts of the Lithothamnian horizon. Permeability and accumulation capabilities of these limestones are increased by karstification and by subsidence fracturing induced by underground mining. A more characteristic rock for these secondary aquifers is the roof marl. Its permeability is greatly increased by shattering and subsidence above the mine workings. Hydrogeologically most important are two screening clayey beds. The predominantly clayey floor beds of the seam form an about 50 m thick hydrological barrier between Pre-Tertiary aquifers and the underground mine workings. The second hydrological screening layer, the grey clay, separates the permeable Lithothamnian limestone from the secondarily permeable roof marl. This layer, up to 150 m thick, of Oligocene marine clay is characterized by high swelling properties. In cases when the swelling of grey clay does not follow deformation processes above mine excavations, communication of the Lithothamnian aquifer with mine workings can be established[5,9].

On the basis of primary lithological characteristics, tectonical deformations of beds and secondary deformations owing to mine excavations in the structure of the Hrastnik coal deposit the Miocene and the Oligocene hydrogeological roof subsystems can be distinguished. The hydrological subsystem in Miocene beds (A) is represented by the primary sandy-limestone Lithothamnian aquifer which is replenished by surface infiltration of rainfall. The infiltration surface of the Lithothamnian aquifer is moderately karstified and in part fractured owing to subsidence caused by mining, which increases the permeability of the limestone.

The hydrological subsystem in Oligocene (B) is composed prevailingly of roof marl. Owing to subsidence in underground exploitation areas these beds lost their primary screening properties[4]. When fractured, these beds are considered as the second roof subsystem with infiltration of rainfall water.

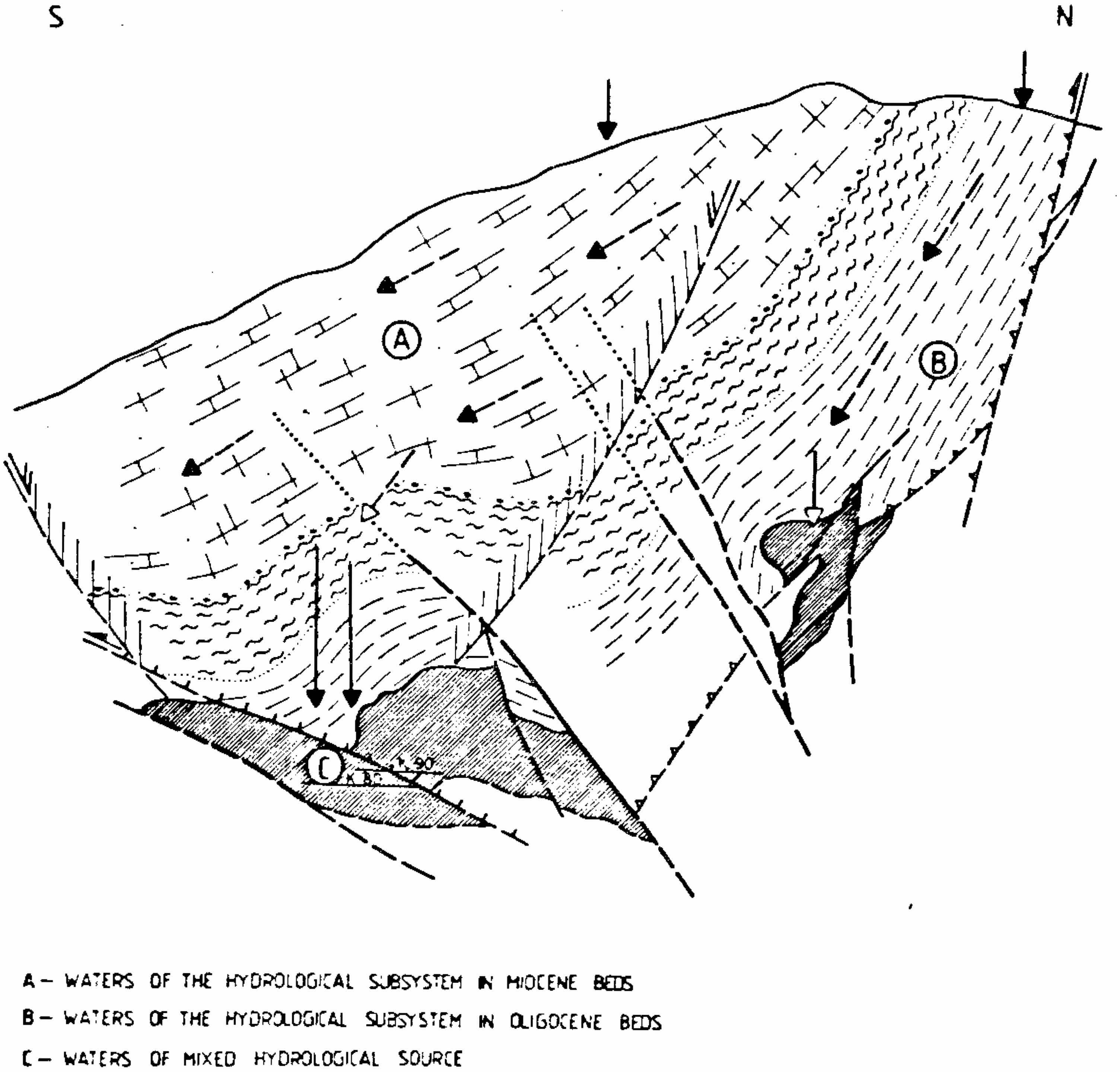

Figure 2a: Schematic geological section across the Central sector of the Hrastnik colliery.

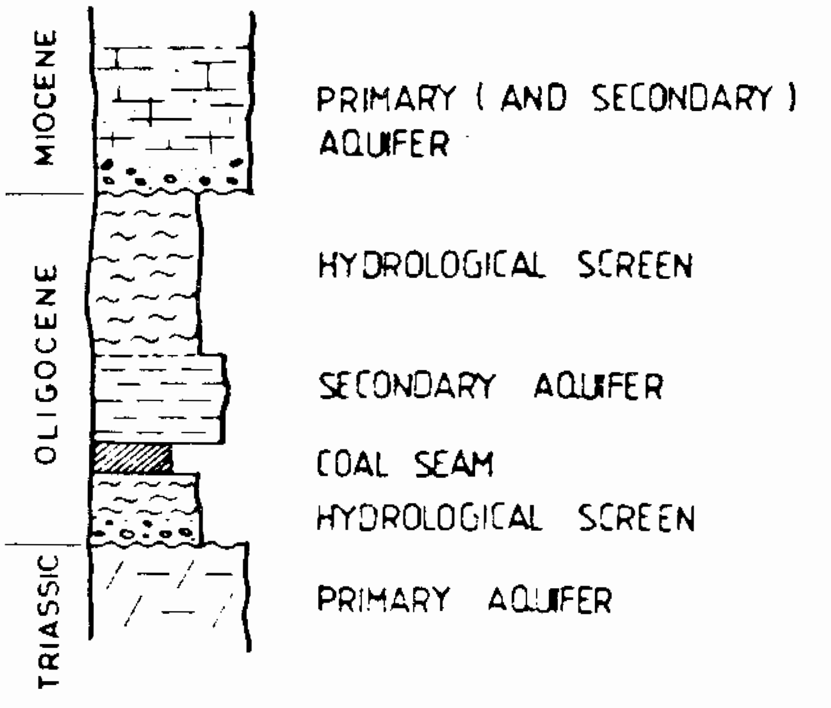

Figure 2b: Schematic geological column of the Hrastnik area.

On the ground of this subdivision waters for statistical analysis for distinguishing the inflows of the Miocene from those of the Oligocene subsystems were selected. Inflows of water to the area C (Figure 2a) represent water communication of the Lithothamnian aquifer (A) with underground workings in areas in which the fracturing processes exceed the swelling properties of the primarily screening grey clay. This communication may take form of slow percolation, increased inflows, and also of heavy inrushes from presumed accumulations in primary or secondary depressions of the contact plane Lithothamnian limestone-grey clay(5). Influence on mining is of varying degree, from smaller disturbances of the mining process and menaces to human safety, to interruptions of exploitation. The estimation of the rate of percolation of water through disturbed Oligocene overburden can assure the basis for implementation of appropriate safety measures.

The chemical properties of water are dependent upon the lithology of the percolated rocks and upon its residence time in accumulations. This thesis represents the hydrogeological starting point for the attempt of chemical discrimination of water inflows into exploitation workings of Zasavje collieries.

PERFORMED INVESTIGATION

Sampling and Analysis

If water analyses were to be used for monitoring the danger of water inrushes, first a representative insight into the variability of hydrogeochemical properties of mine waters was needed. It was provided by sampling waters in two well studied, structurally and hydrogeologically similar mine workings of the nearby Hrastnik and Ojstro collieries (Uhan & Pirc(11)). Sampling was performed at five monthly intervals according to an unbalanced nested analysis of variance sampling design similar to that used by Miesch(7) in regional geochemical studies in Missouri. The design involved sampling in two pits of the collieries, in several panels within the pits, and in several working faces within the panels. Splits of some samples were used for estimating analytical error (Uhan & Pirc(11)).

At sample sites water was collected in 1 litre polyethilene bottles with filtering through FILTRAK 389 medium wide pores filter. Analytical splits were prepared by samplers. Samples of water were not acidified. They were carried in cooling bags to storage room where they were kept refrigerated. Samples were submitted to laboratory in a random sequence.

In the Laboratory of Zasavje Collieries in Trbovlje in waters Na^+ and K^+, Ca^{2+}, Mg^{2+}, NH_4^+, HCO_3^-, SO_4^{2-}, Cl^-, NO_2^-, NO_3^-, Fe_{tot}, $KMnO_4$, pH, specific electroconductivity and dry residue at 105° C were performed according to Yugoslav standards. Potassium and sodium were determined by spectrophotometric method, sulphate by gravimetry, calcium, magnesium, chlorine and bicarbonate by volumetry.

Analysis of Variance

According to the results of analysis of variance excessive analytical error above 40% of total variance precluded the use of ammonia, iron, chloride, nitrogene oxides, potassium permanganate and dry residue determinations in further considerations. Normality tests performed on data show that only the distribution of $Na^{+}+K^{+}$ concentrations is close to normal, others were closer to lognormal. Therefore for them logarithmic values were used in statistical procedures.

Of other, satisfactorily analyzed consitituents only specific conductivity, which is a measure for total mineralization, shows statistically significant differences at the 5% level with time; differences between the two pits, within time intervals, are significant for calcium, magnesium and pH; differences between panels within pits significant for sodium and potassium, sulphate, specific conductivity and pH, and differences between faces within panels are statistically significant at 5% for sodium and potassium, calcium, magnesium, bicarbonate, sulphate and pH.

The obtained picture of natural variability shows that waters on the average vary a lot locally, within panels, and less between panels, and between the two pits, and very little with time, if looked at monthly intervals. This structure of variability was promising for using water analyses in the study of water inrushes which are localized phenomena.

Factor Analysis

The R mode factor analysis is used for explaining some complex data set of many variables by a smaller number of synthetic variables called factors which may have geological meaning[1]. Mali and Pirc[6] were able to interpret the waters on the basis of three factors having major loadings by calcium, magnesium and sulphate; bicarbonate, conductance and sodium + potassium, and sodium+potassium and sulphate. They explain 65% of total variability in data. Results indicate that mine waters may be quite efficiently distinguished by factor scores of only two factors, the calcium-magnesium-sulphate factor and the sodium-potassium-sulphate factor. These two factors explain almost a half (47%) of total variability within variables. These results were useful in performing the diagnostics of waters by discriminant analysis.

Discriminant Analysis

Discriminant analysis is a multivariate method which efficiently reduces the dimensionality of a multivariate sample set. A simple linear discriminant function transforms an original set of measurements on a sample into a single discriminant score[1]. Uhan and Pirc[12] performed discriminant analysis of hydrogeochemical variables of the above sample set from the Hrastnik and Ojstro collieries. The following linear discriminant function was derived:

$$Yx=14.26(\log HCO_3^{-}-2.77)+3.05(\log SO_4^{2-}-1.97)-4.42(\log Mg^{2+}-1.43)-0.005((Na^{+}+K^{+})-208)$$

Coefficients of the equation are statistically significant at the 0.1% level and 1% level.

Positive values of the discriminant function are characteristical for waters of the hydrological subsystem B in Oligocene beds, and negative values for waters of the subsystem A in Miocene beds. An unknown water sample can be attributed to one of the groups according to its discriminant score.

Uhan and Pirc[12] studied discriminant scores of water analyses in comparison with data on rainfall, water table and data on inrushes of water and mud into mine workings in a well known structure and hydrology of an area in the eastern part of the Hrastnik colliery. They found that the possibility of distinguishing between the Miocene and Oligocene type of waters permits an efficient hydrological control of mine workings. The screening capacity of Oligocene beds becomes reduced owing to their subsidence and fracturing above the advancing mine workings, and the waters from the Miocene aquifer start taking over, with resulting decrease of the discriminant scores of water. They conclude on the basis of several examples that knowing the discriminant scores of mine waters derived from their chemical analysis could help efficiently in estimating the processes and source of filtration into mine workings, and in predicting the danger of inrushes of water and mud.

TEST OF DISCRIMINATION IN THE CENTRAL SECTOR OF THE HRASTNIK COLLIERY

The described interpretation method of hydrochemical discrimination of water inflows into underground workings was tested in 1989 in the exploitation panel at the 80 m level in the Central sector of the Hrastnik colliery. In the sampled waters principal ions were determined and their discriminant scores on the basis of the earlier established discriminant equation calculated. On Figure 3a the 80 m level panel in the Central sector with contours of discriminant values is shown, and limits of the already mined 90 m level above it. On both levels locations of inrush events are indicated; they are evidently connected with the mentioned NW trending primary structural depression.

On the 80 m level coal was mined by advancing towards the west without any water up to the coordinate 4860 E. When the working face approached the depression of the roof contact surface of the coal seam, mining was stopped by a heavy inrush at the southern part of the face. Shortly a weaker inrush at the northern part of the face followed. Sampling could be started owing to safety reasons with a delay of several days. It was continued with the advance of the face to coordinate 4800 E.
Contour lines in Figure 3a and 4 show the distribution of discriminant values which indicate the attribution of waters in the panel to one of the subsystems in the overlying beds, to the subsystem A (in Miocene Lithothamnian limestone), or to subsystem B (Oligocene clayey-marly roof beds).

3a

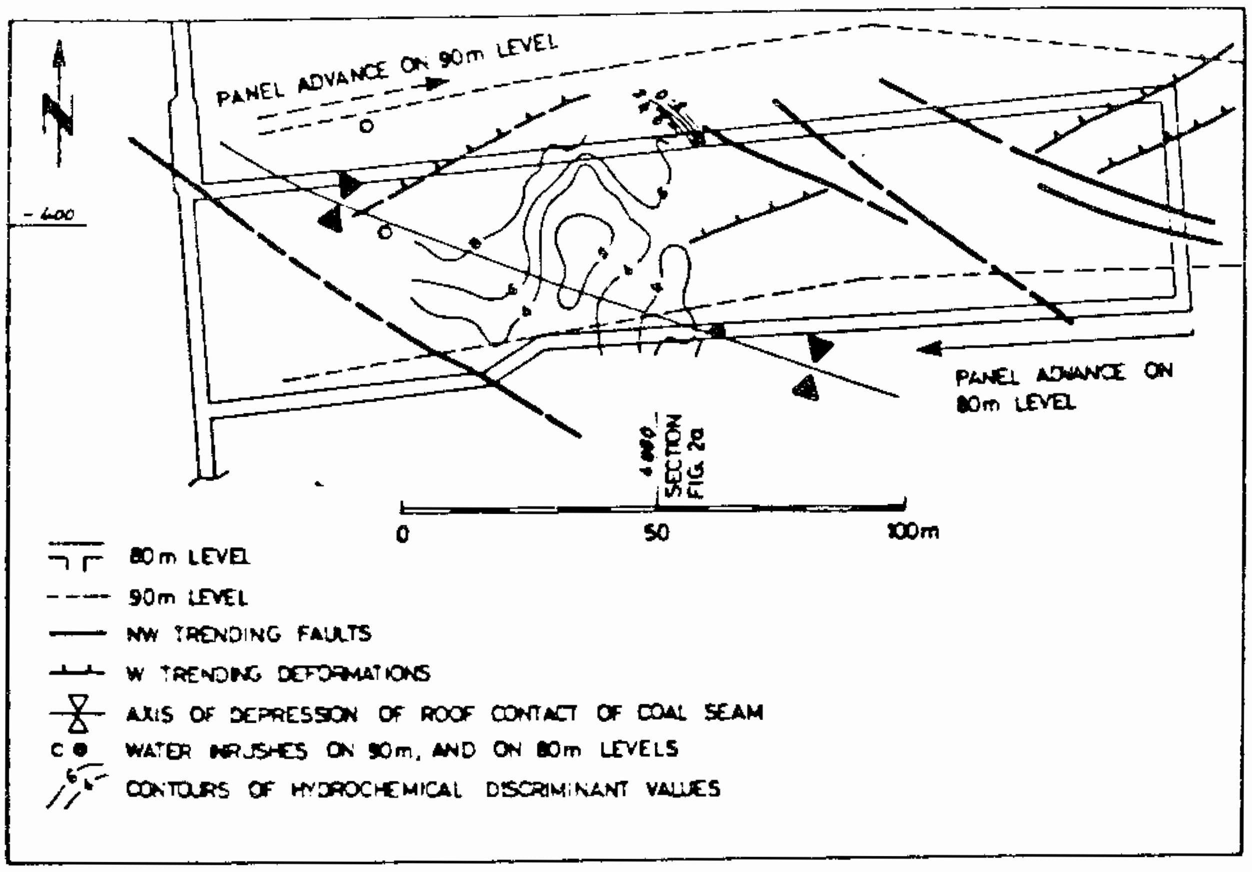

Figure 3a: Sketch map of 80 m level in Central sector of Hrastnik colliery with contours of discriminant values.

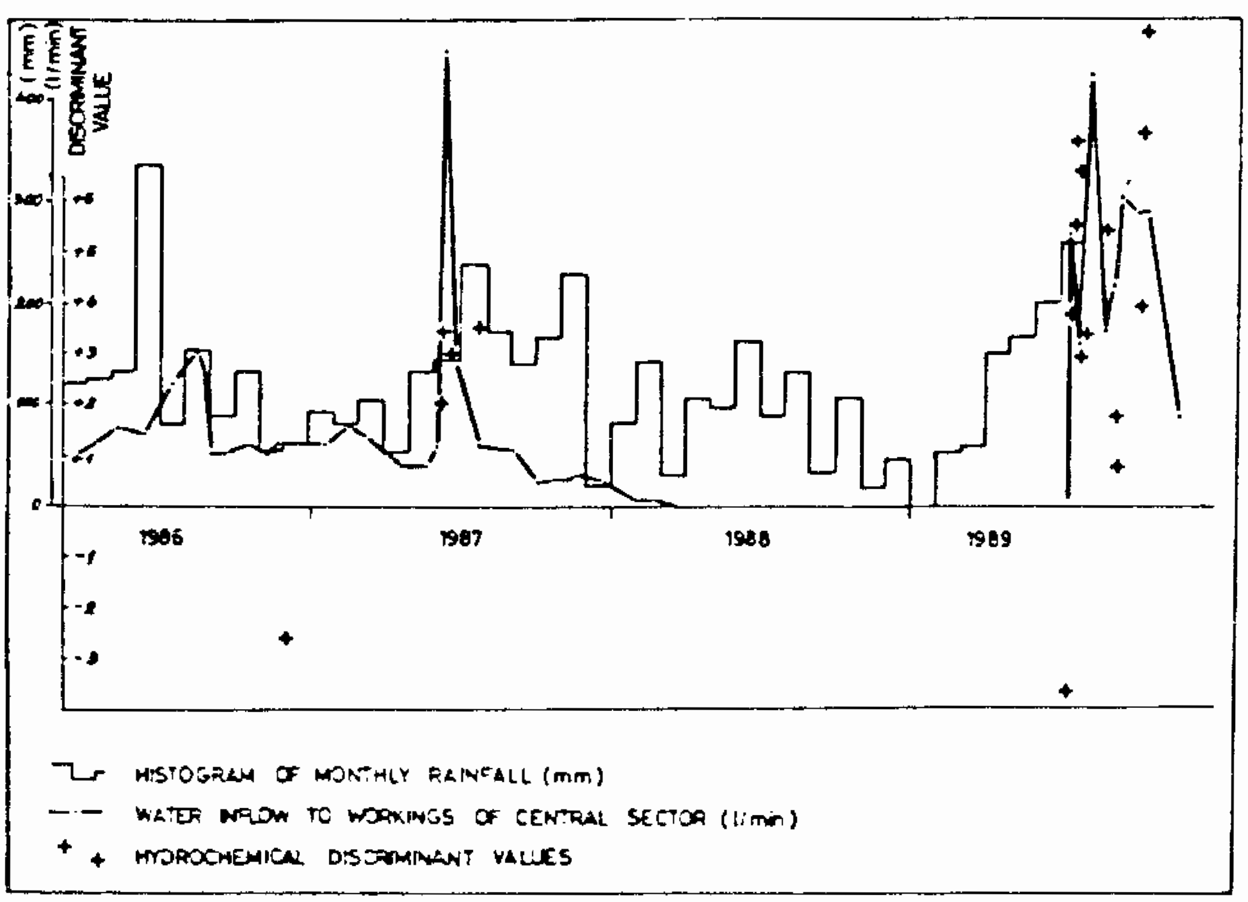

Figure 3b: Plot of rainfall, water inflow and hydrochemical discriminant values in Central sector with time.

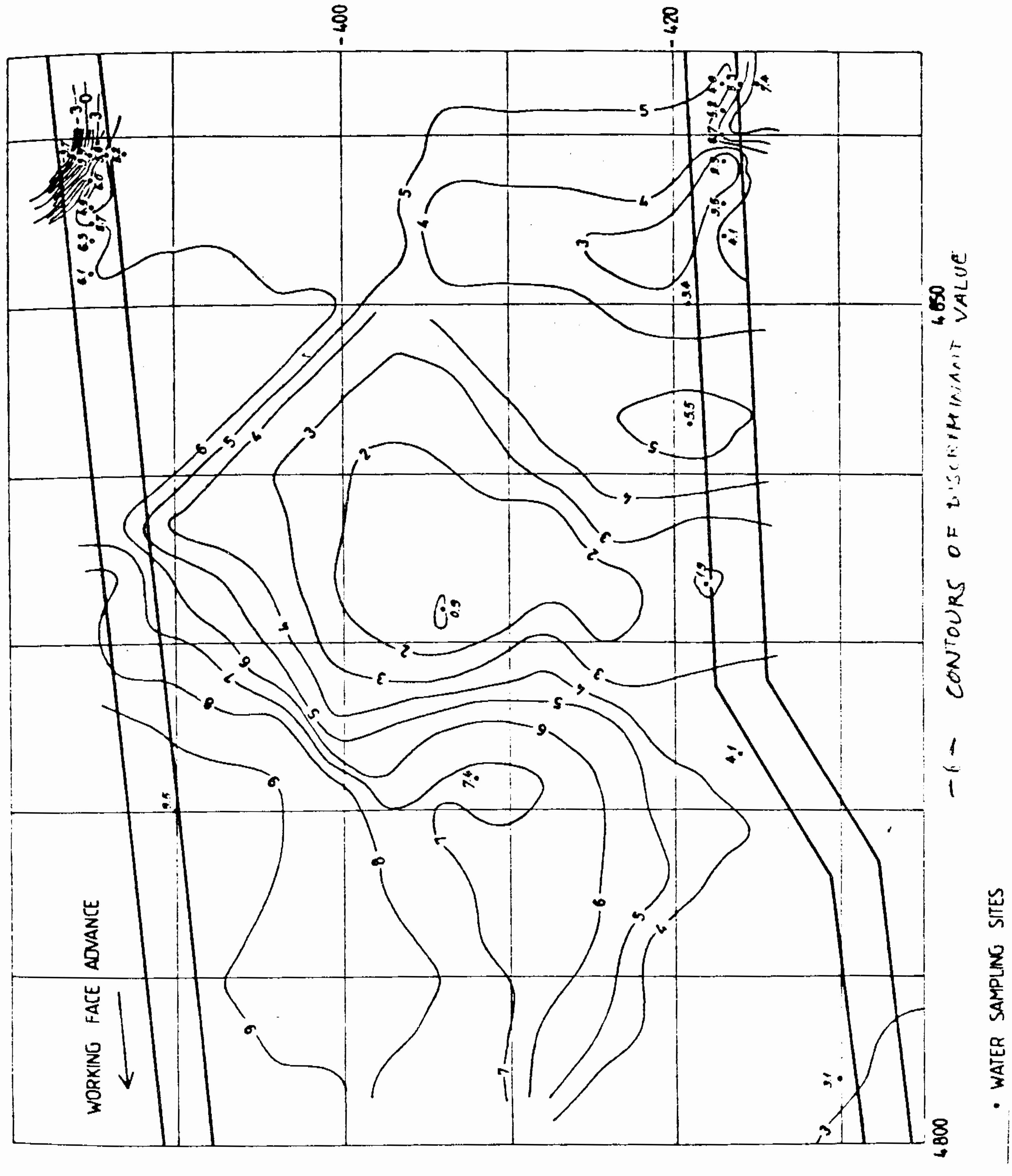

Figure 4: Level map of exploitation panel 80 m in Central sector of Hrastnik colliery with contours of discriminant value.

Positive values of the discriminant function indicate waters from subsystem B, slowly draining from the Lithothamnian limestone through secondarily disturbed roof clayey-marly beds of low primary permeability. Widening of fractures in the subsidence zone in the screening beds of grey clay results into increasingly better connection of the water accumulation in the Lithothamnian aquifer with the mine workings, as expressed by a drop of the hydrochemical discriminant value. Its negative gradient can be used in such a case for relative assessment of the degree of danger of water inrush from the Lithothamnian aquifer. The mentioned water inrush at the southern side of the working face of panel on the 80 m level was accompanied by a negative anomaly of the discriminant function. This suggests that the source of water was the water accumulation in Lithothamnian limestone fractured owing to subsidence. This hypothesis is confirmed by the expressively positive gradient of discriminant values after the inrush. Its positive character may be explained by earlier fast emptying of the Lithothamnian accumulation and by partial subsequent consolidation of primarily screening clayey beds in the shattered zone.

At coordinate 4835 appeared in the middle and southern part of the panel in waters of abundant inflow (425 l/min) a new hydrochemical anomaly (discriminant values 0.9 and 1.9). Subsidence fracturing probably also in this case attained the screening layer and the Liothothamnian aquifer. It is believed that in this case owing to carefully applied mining measures in the coal winning process the inrush was sucessfully prevented.

Next to the described hydrochemical anomalies the 80 m level in this panel (Figure 3b and 4) is characterized by moderate inflow of waters with positive discriminant values which is typical for the subsystem B in the Oligocene. They suggest slow draining of waters of the Lithothamnian limestone through Oligocene beds. Also the inrush on the 90 m level is connected to the same structural depression, which was, however, attained by the working face owing to a different direction of advancing about 70 m to the west from that on the 80 m level (Figure 3a). Also this inrush event was preceded by a negative anomaly of the hydrochemical discriminant value end of 1986 (Figure 3b).

Both cases of inrushes of water indicated by their preceding negative anomalies of the discriminant value a very early establishment of communication with the Miocene aquifer. With sudden subsidence processes in the Oligocene screening layer the conditions for triggering an inrush of water became favourable. Water on its way activated larger or smaller amounts of muddy and silty Oligocene material from the fractuired zone.

CONCLUSIONS

The presented results of investigations form a good basis for predicting inrushes of water and mud into mine working in collieries. A prerequisite for implementation of prediction on basis of the discriminant function is a good understanding of the structural geology and hydrology of the areas of the deposit where coal is being mined. For every structural and hydrological situation discriminant analysis of chemical properties of waters has to be performed first. The derived discriminant function can be then routinely used for analyzed waters in mine workings, and on gound of its values the danger of water inrushes can be assessed and predicted on short term.

ACKNOWLDEGMENTS

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