MINE WATERS OF KOSVA FIELD OF KIZEL COAL BASIN DURING AND AFTER ITS OPERATION, FORCAST OF HYDROCHEMICAL REGIME OF MINE WATERS THAT ARE DISCHARGED ON THE SURFACE

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ABSTRACT

The article considers the issue of mine waters' formation during and after the usage of Kosva deposit in Kizel coal basin. Rationalization for the possibility of using logarithmic regression equation is given for the prediction of changes of pollutant concentration in the mine waters of the man-made horizon.

Keywords: the Kizel coal basin, Kosva coal deposit, mine waters, man-made horizon, hydrogeological forecast.

INTRODUCTION

Kizel Coalfield brings together a number of coal deposits in the Western Urals that are situated in the eastern part of the Perm Krai in Russian Federation. Elongated in a narrow line with the width of 5-20 km it extends for 150 km along the western slope of the Urals. The basin area is about 1500 km^2 (Fig. 1). Coal production in small volumes was launched here in 1797 in the 'Zaprudnaya' shaft on the right bank of Kizel River [1]. The most intensive works were carried out in the reserves of the basin during 1940-1980. The production maximum - 12 million tons - was reached in 1959-1961. The distinctive feature of the coal is high content of sulfur, mainly pyrite, amounting on average of 6.5% in different sources. Mines of the basin had complex geological conditions of the works, high injury risks, poor performance and were unprofitable. In this regard, they were all closed during 1993-2000 according to the coal industry restructuring program in Russia.

Kosva coal deposit is one of the major coal basins in the Kizel Coalfield. It is confined to the eponymous syncline slope that stretches from north to south, as well as the other geological structures of the pool located within the boundaries of the Western Ural fold zone. Most coal-bearing deposits are found to the north of Kosva River that crosses the syncline in the latitudinal direction. The total length of the field amounts 36 km, while its northern part reaches 15 km. Deposits of the western wing in the syncline's north part and north circuit of the river were worked out for more than 100 years by 'Rudnicheskaya', 'Central', 'Uritsky', 'Kalinin' mines (see Figure 1). The enterprises excavated 11 and 13 coal seams with the extracting seam capacity amounting 1-1.5 and 1.5-2 m respectively. The depth of works on the deepest mine 'Uritsky' exceeded 1 km, the 'Central' mine was closed in 1996.

Geological section of Kosva syncline is one of the most solid in the coal basin. It is consists of sediments from the Lower Devonian to Lower Permian. Coal bearing capacity is associated with lower coal department of the carboniferous system that is presented by Tournaisian, Visean and Serpukhov tiers. Tournaisian tier consists of carbonate-terrigenous deposits with thickness about 300 m, that are not touched by mine works. Lower and middle parts of the Visean tier have an average capacity of 150m that are represented by terrigenous productive (coal-bearing) strata $(hC_1v_1 +_2)$ with coal seams. The coal-bearing strata overlaps Visean carbonate rocks and Serpukhov tiers $(C_1v_3 + s)$ and has capacity reaching up to 380m. In the upper part carbonate sediments overlie the Middle and Upper Carboniferous and Lower Permian. Middle Carboniferous includes Bashkirian and Moscow stages, the last one includes clay-carbonate bench, which serves as aquitard on the territory of the Kizel basin. The total capacity of carbonate sediments in the top of coal-bearing strata exceeds 700 m above the lower horizon in 'Uritsky' mine and 1000 m in the deepest part of untouched Kosva deposits within the reserves of the 'Kosva Deep' mine field.

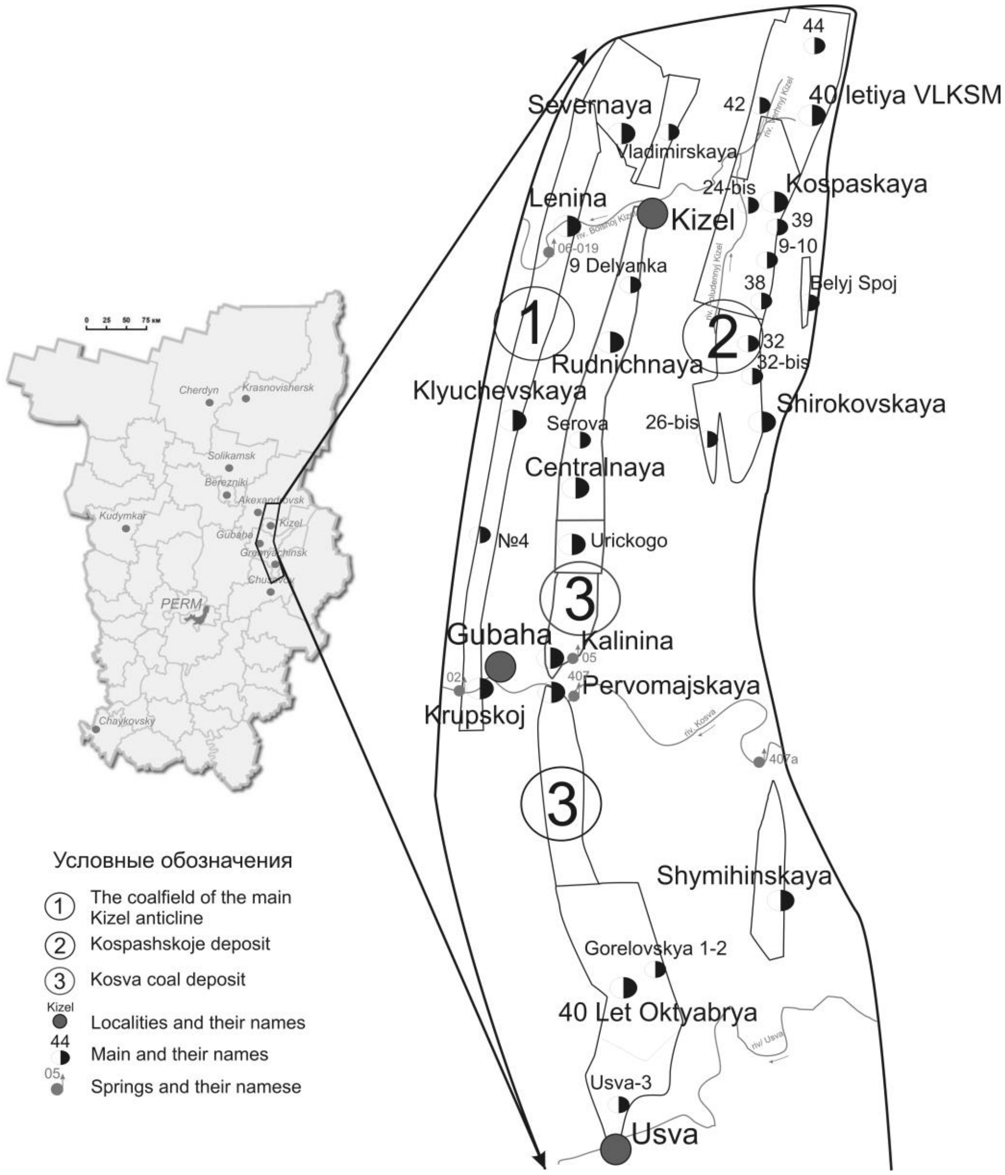

Figure 1. Kosva deposit scheme in Kizel coalfield

The following aquifers are determined on the Kosva Coalfield territory:

• Visean-Artinskian carbonate – C_1v_3+s-P_1a;

• West-Ural regional aquitard sporadically watered – hC_1v_{1+2} (coal-bearing strata);

• Frasnian-Tournaisian carbonate – D_3fr-C_1t;

• Devonian clastic – D

In addition, after the flooding of the abandoned mine fields technogenic horizon of mine waters have formed in the coal-bearing strata. From the mentioned water aquifers Visean - Artinskian and Frasnian - Tournaisian aquifers of fractured karst waters have the highest water abundance. Fractured karst waters of coal-bearing strata and Visean - Artinskian waters have participated in inundation of all mines of the Kizel basin. With few exceptions, the remaining aquifers did not participate in mine water inflow. Visean-Artinskian aquifer system of fractured karst waters on the territory of Kizel basin consists of two aquifers: the Moscow- Artinskian and Visean – Bashkirian that are separated by regional aquitard of Middle Carboniferous. Because of the current confining layer the impact of mine works on the hydrodynamic regime of ground waters of Visean-Artinskian aquifer is limited with primarily Visean-Bashkirian horizon.

Visean-Bashkirian aquifer is the most water abundant. It is linked in the pool by series of groundwater sources with an output of more than 100 l/s. Particularly, the unloading of horizon's fractured karst waters from the northern Kosva syncline after closing of local mines forms a large source 05 with an average daily flow of 267 l/s. Larger source 407 on the left bank of Kosva River discharges Visean-Bashkirian horizon waters from the southern Kosva syncline. Average flow rate of the source is 407 l/s (see Figure 1). Given the good quality and large deposits the waters of horizon are widely used for water supply of settlements on the territory of the coal basin. Fractured karst waters meet the requirements of drinking water to the depth of at least 1 km, so they were used at most mines in fire suppression and dedusting systems. For these purposes the drill of hydrogeological wells on the Visean-Bashkirian horizon was performed directly from the mine workings.

Aquifer system of coal-bearing deposits experienced direct and most powerful draining impact of mining operations that were carried out in the productive strata. Groundwater flow of the system occurred in preparatory workings as well as in longwall goaf. Coal-bearing deposits were drained through man-caused cracks over empty coal beds. Groundwater levels in this part of the coal-bearing strata were dropping almost to the lower limit of mining. Water abundance of the complex in general is low, the component aquifers are confined to the sandstone layers and are separated by a mudstone and siltstone, and by coal seams and streaks. Mine water inflow in the upper levels of mines that were formed only by ground waters of coal-bearing strata usually did not exceed 150-200 m^3/hr.

Visean-Bashkirian horizon irrigated the most mines of the basin, and formed for many of them, including 'Central', 'Uritsky' and 'Kalinin' mines, the main source of mine waters. Fractured karst waters inflow in the mine workings of all three mines occurred through man-caused cracks in the top rocks of coal seams as a result of their displacement to the goaf. A prerequisite for the drainage of fractured karst waters was the spread of man-caused water deriving fractures to Visean-Bashkirian aquifer. In addition to relatively dispersed and areal flow of fractured karst waters through man-made fractures, on the ‘Central’ mine from 1965 until its closure there was observed a concentrated inflow of water into the main crosscut of VII horizon from opened karsted limestones of Visean stage. During the last hydrogeological surveyings of ‘Central’ minings during 1986-1988, the inflow of fractured karst waters in crosscut was 310-370 m^3 hr. or 36-38% from the total inflow of mine waters (Table 1).

Table 1. Water inflow in ‘Central’ mine during 1986-1988

Underground hydrogeological survey, year	The total inflow of mine waters at the ‘Central’ mine, m^3/hr	Ground waters inflow in the main crosscut of VIII horizon	
		m^3/hr	% from total flow
1986	1002	370	37
1987	873	330	38
1988	855	310	36

Active participation of fractured karst waters of Visean-Bashkirian horizon in the formation of mine waters for long time led to a significant amount of mine water inflow. By ‘Uritsky’ mine average mine water inflows in 1954 reached 603 m^3/hr., at ‘Central’ mine in 1966 - 853 m^3/hr. Due to the closure in the 1960s ‘Rudnichnaya’, ‘Uritsky’ and ‘Kalinin’ mines the water discharge was redirected to the ‘Central’ mine, resulting in the concentration of mine water inflow from all over the Kosva field in this mine from 1970. The average number of annual inflow of mine waters in 1970 reached 1295 m^3/hr, later it declined and was fairly stable in the past five years prior to the flooding phase of ‘Central’ mine in 1989, averaging 891 m^3/hr . In the five-year period from 1984 to 1989 the inflow of mine waters pumped from ‘Central’ mine reached 7% of the total mine waters inflow of running in this period coal enterprises of Kizel basin.

Due to the draining effects of mine workings on the Visean-Bashkirian aquifer the level of fractured karst water of the horizon experienced significant downward on mine fields. The greatest decrease in the water levels the took place in the area of the main crosscut of VII horizon, which has the absolute mark (-) 244 m, here the groundwater level dropped almost to the level of crosscut or more than 470m from its natural position. The main natural drains of groundwater of Kosva syncline is Kosva River, in which the water level, at the river intersection of worked of deposits, is 156 m. Based on the data, we can say that during the operation of the northern part of the Kosva field the discharging area of Visean-Bashkirian horizon waters from its territory was not the river network, but mine workings.

Waters of coal-bearing strata and Visean-Bashkirian horizon in vivo are bicarbonate-calcic, neutral or slightly alkaline, have salinity usually not exceeding 0.5 g/dm^3. In the mining conditions they are transformed into acid mine waters under the influence of sulfuric acid produced by the oxidation of pyrite contained in large quantities in coal of Kizel basin. Mine waters in ‘Central’ mine in Kizel coalfield are characterized by highest content of pollutants. In recent years, before the mine flooding, mine waters that were pumped on the surface were characterized by the magnitude of pH 2.5 and had a dry residue 6.4 g/dm^3. The main components of the mineral composition of these waters were iron and aluminum, virtually absent in the original natural waters (Table 2). The iron content exceeded the maximum permissible concentration for drinking water adopted in Russia in more than 4.5 thousand times, for fishery water bodies – in more than 13.500 times.

Table 2. The chemical composition of mine waters in northern Kosva syncline

Observation points	Observation years	pH	Concentration of pollutants, mg/dm^3							
			Dry residue	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^++ K^+	Fe^{2+}+ Fe^{3+}	Al^{3+}
Total discharge of mine waters fom 'Central' mine on the surface	Average value									
	1986-1988	2.5	6365	4505	251	108	110	12	1367	195
Shaft of 'Kalinin' mine	2000	2.9	17636	11668	12	243	467	64	4139	333
	2002	3.0	19759	11357	16	371	399	65	4160	251
	2004	3.0	16706	9455	18	343	335	105	4131	223
	2011	3.05	8807	4482	18	334	167	58	1971	47

Drainage of 'Central' mine in 1989 proved to be insufficiently prepared for the spring flood, during which there is an increase of inflow and acid of mine waters. Flooding occurred in lower - IX and X horizons that were not drained due to the small amount of remaining coal reserves, later other horizons were gradually flooded. For water receiving from neighboring mine fields the 'Central' mine was connected with them by mine workings, so its flooding occurred simultaneously with the rest of the mines of the northern part of the Kosva field area.

In 1972, the level of mine flooding rose to the Kalinin mine's shaft and mine waters began to flow through the shaft collar to the surface. In worked out mine fields the man-made horizon of mine waters was formed and it reached up to 20 m. It became the main aquifer in the complex of coal-bearing strata at the worked out mine fields, the discharge of the horizon is executed on the surface through the mentioned above output. Systematic observations of the mine waters regime that flows out of the shaft, started in the year of 2000, with a frequency of once per quarter the flow of mine water was determined and hydrochemical sampling was conducted to explore macro and micro component composition. Mine water consumption during the observation period from 2000 to 2011 ranged from 127 to 1440 m^3/hr depending on the year of observation, and the particular season: the maximum point was usually reached with the spring floods period, the minimum occured in winter and spring low water flow. Average consumption of mine waters for the entire observation period was 409 m^3/hr, while in the first six years it was equal to 422 m^3/hr, for the remaining six years - 396 m^3/hr . Thus, we can say that a significant reduction in the flow of mine waters during their spout on the surface did not happen.

The supply of man-caused mine waters horizon as well as coal-bearing strata aquifer generally occurs by infiltration process of precipitation on the area of coal-bearing deposits outputs under coverslips bodies. In addition, this horizon gets flowing waters through the man-made fractures from Visean-Bashkirian horizon. In 'Central' mine conditions the waters of Visean-Bashkirian horizon, which come into the main crosscut of VII horizon, are likely to play a significant role in the replenishment of man-made horizon. A certain amount of mine waters is formed by surface waters entering the mine fields by dips that are formed at the outputs of coal seams on the surface area. The precipitation in Kizel coal basin is almost twice the amount of evaporation of water from the surface areas; this factor determines the appropriate conditions of all aquifers supply, including mine water horizon. Represented data indicates highly favorable supply conditions of the man-made horizon in mine fields of northern Kosva deposits. This fact explains the relatively small decline of mine waters after the cessation of coal production, which amounted 54% relatively to the volume of mine waters before flooding of considered mines. On average in Kizel basin corresponding level of mine waters declining is significantly higher and reaches 83%. Based on the data, the significant decrease of mine waters flowing from 'Kalinin' mine in the next decade is not expected.

Flooding of mines in Kizel basin did not lead to cessation of acidic mine waters formation process, moreover the concentration level of pollutants in mine waters on the initial period of the spout was much higher than the one observed at coal mining enterprises. Marked by a large increase in mine water salinity is explained by the fact that during the process of flooding the mine waters dissolved all products of pyrite oxidation in the worked out space of mines, more filling itself with sulfuric acid and sulfates, iron, aluminum and some other substances. Later, after the release of mine waters on the surface a gradual reduction of solids and concentrations of the components occurred or continues to happen in the mineral composition of mine waters. Onset and duration of this process depends on the size of mine field, depth of mining operations, quantity and capacity of coal seams workings and some other factors. At a small 'Belyj Spoj' mine the process began during the first months after the release of mine waters on the surface, for a group of interconnected mines in the northern part of the Kosva field it started only in 6 years after the mine waters began to flow from the 'Kalinin' mine shaft.

Mine waters of anthropogenic horizon that was formed in the worked out mine fields of northern Kosva field, at the exit of the shaft in 2000-2003 were characterized by large dry residue and high concentrations of sulphate and iron, which are determined mainly by mineralization of mine waters. Magnitude indicators of dry residue and sulphate and iron concentration before 2004 were relatively stable and exceeded those indicators before flooding almost in three times. Since 2004 a decrease of dry residue and sulphate and iron concentration began in these waters (see Table 2). It must be noticed that others from the listed in the table macrocomponents in mine waters, exceeding many times those that are adopted in Russia of the maximum permissible concentration for drinking water and fishery, there is a number of microcomponents: beryllium, manganese, nickel, cobalt, zinc, lithium.

For the conditions of Kizel basin the process of reducing the mineralization of mine waters that are poured on the surface of the flooded mine workings, as well as reducing the concentration in these waters of sulfates, iron and aluminum is quite verifiably described by the following equation [2]:

$$Y = c\ln(x) + b,$$

where y – the dependent variable, which shows the concentration of the chemicals in a certain period of time, *x* – independent variable that takes the value of the sequence of natural numbers (1 , 2, 3 , ...) and expresses the length of the spout of mine waters on the surface, the coefficients *b*, c are constants.

To assess the quality of the model the coefficient of determination R^2 is used, i.e. the accuracy of approximation or reliability level. Coefficient of determination quantifies the measure of analyzed relation. Trendline is most closely approximates to the one given in the graphs for the values R^2 equal or close to 1. The closer R^2 is to 1, the more the regression equation explains the accuracy of the concentration decrease of chemicals in a given time.

Based on the results of chemical analyzes of mine waters the graphs are given for variation of dry residue and sulphate and iron concentrations in the mine waters that are poured on the surface through the ‘ Kalinin’ shaft, depending on the time of pollutants level reduction. Each graph is provided with corresponding logarithmic regression equation and the coefficient of determination R^2 (Fig. 2). For the graphes coefficient R^2 ranges from 0.87 to 0.98, i.e. approaches 1. Large values of the coefficient allow the usage of a logarithmic type of regression to predict changes in the chemical composition of mine waters that flow out the ‘Kalinin’ shaft.

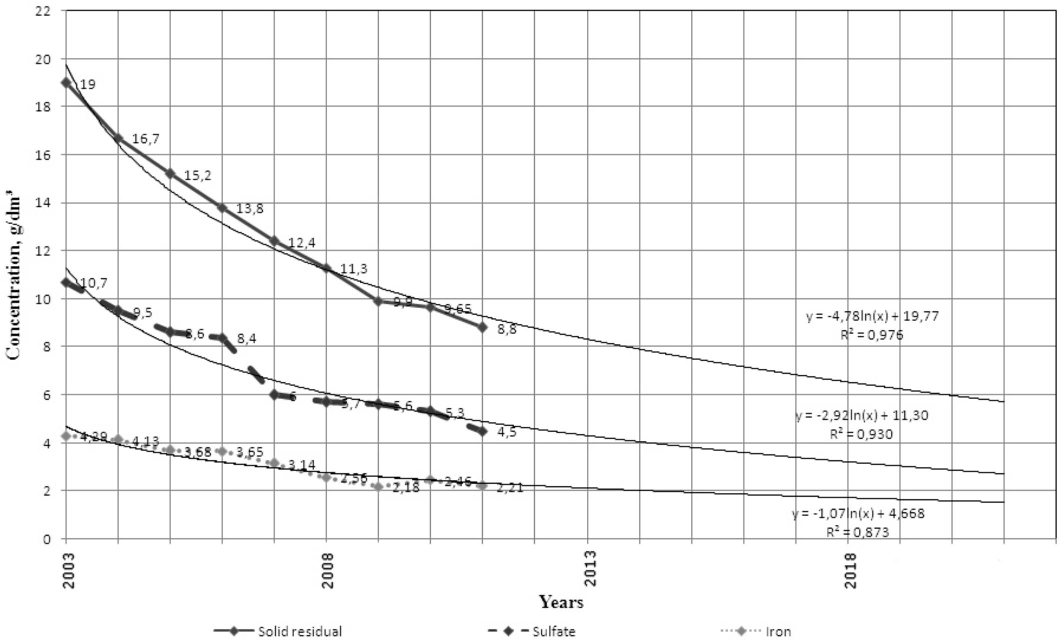

Figure 2. Graph of the reduction from 2003 of pollutant concentration in mine waters, flowing from the ‘Kalinin’ shaft

Proposed method for predicting changes in the concentration of components of the mine waters’ chemical composition is applicable only for a period of declining of these components in the content. After a while there comes a relative stabilization of the concentration of the main components in the mineral composition of mine waters and the method loses its importance. The period of achieving the stabilization for ‘Belyj Spoj’ conditions equals 15 years (Fig. 3) [3]. For regarded mine waters in Kosva field, taking into account the trends that are presented in Figure 2, expected period of pollutant concentration reduction will last generally 25 years and 10 years relatively to 2014. In other words, the proposed method for the mine waters, flowing on the surface through the 'Kalinin' shaft, can be used up to 2025, particularly in the development of environmental measures to prevent or reduce the significant negative impact of mine waters on the environment, especially on the surface waters. Large volume of mine waters and high content of pollutants determine the high cost of environmental activities, that is why a reliable prediction of the chemical composition of the waters and its urgent modification have great importance for enhancing mentioned measures.

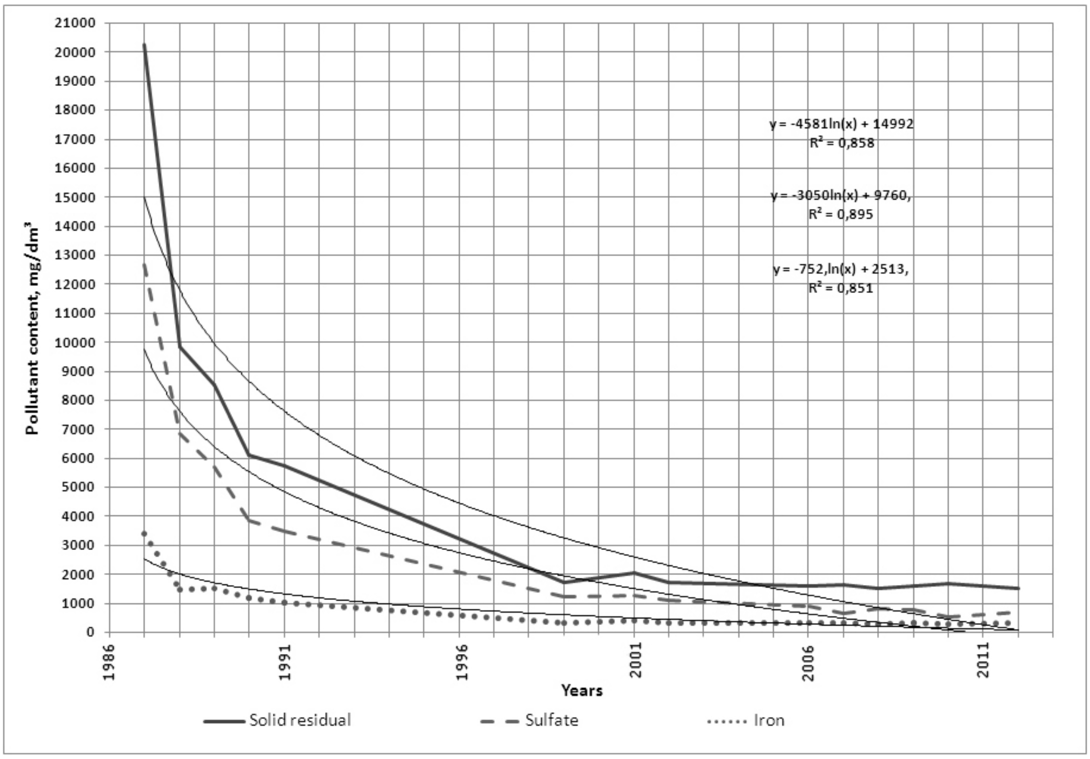

Figure 3. Graph of variation of dry residue content and sulphate and iron concentration in mine waters, flowing from the pit hole 63 of 'Belyj Spoj' mine

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