INJECTION OF THE SALINE MINE WATERS INTO GROUND

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ABSTRACT

In this paper, the problem of river water contamination by the Upper Silesian Coal Basin saline mine waters is described and the start-up and work of the Krupinski coal mine saline water borehole injection system are presented and resulting environmental consequences discussed.

INTRODUCTION

In the Upper Silesian Coal Basin area there are 65 active or partly abandoned hard coal mines that pump out waters with an average value of NaCl content of 12.7 kg/m^3 at a rate of 796 000 m^3/day. The distribution of that quantity according to the water mineralization classification used in Polish coal mining industry is shown in Table 1.

Mineralization group	Water quality	Content of Cl+SO$_4$ g/l	Rate of water inflow m^3/day	Quantity of salt in water t/day
I	drinking water	< 0.6	262 000	131
II	industrial water	0.6 : 1.8	252 000	428
III	brackish water	1.8 : 42.0	226 000	4 181
IV	saline water	> 42.0	56 000	5 426
Total			796 000	10 166

Table 1. Distribution of water inflow to Polish coal mines according to the water mineralization classification.

As a result of the efforts undertaken by coal mines to manage the low mineralization waters and to reduce the saline water inflows the amount of mine water pumped into rivers is smaller in size than the amount of water pumped out from the mines. However, the yield of chlorides and sulphates dissolved in mine waters flowing into rivers still is very large and amounts to 4600 t/day. Various attempts have been made to solve the problem of river water contamination by saline mine waters. The application of the hydrotechnical method, which involves the disposal of saline waters into rivers via the appropriate storage reservoirs, has turned out to be inadequate as the amount of inflowed salt considerably exceeds the rivers' sorption capacity that can be defined as the permissible river water's salinity.

The methods for mine waters desalination are highly energy-consuming and require constructing complex and very costly desalination plants. The hydrogeological methods involve injection of the saline mine waters into ground causing them to be irreversibly dumped in isolated aquifers and also involve the recirculation process that relies on pumping water into the underground layers drained by the mine workings located outside the mine area. These methods appear to be full of promise.

THE UP TO DATE ATTEMPTS TO INJECT THE SALINE MINE WATERS INTO GROUND

The water recirculation method was patented in the Central Mining Institute in 1988 and a feasibility research program on the application of this method to reduce the rivers salinity has been developed. It follows from the analysis of the lithological composition of the Carboniferous Coal Measures formations, conducted with the aim of optimally locating the injection boreholes, that the best filtration and storage properties has the Cracow sandstone series, KSP, of the Westphalien B and C age. This series comprises a complex of thick and very extensive sandstone layers reaching its maximum thickness of 800 m in the central part of the Main Trough. The KSP series is overlain by a thick argillaceous formation of the Miocene age that protects the shallow aquifers against the saline waters that are being injected deep into the Carboniferous system layers.

The Piast and Czeczott coal mines discharge large amounts of saline waters into the Vistula river and have, therefore, been chosen as test sites for conducting pilot studies. In the Czeczott coal mine area, two test water injection / recirculation boreholes about 450 m deep and three piezometric boreholes about 300 m deep were drilled in 1991. All the boreholes were adequately cased, filtered and hydrogeologically tested. Installing the borehole water injection facilities was hampered by the difficulties in reaching an agreement with the local authorities.

Thus, only short duration pumping of water into one borehole was successfully performed in 1995. The pumping which was preceded by treatment lasted 3 days. The river water deprived of the suspended matter by means of bag filters has been used for the pumping. The filtration coefficient values calculated from the results of the test pumping varied in the range of 2.5 to 5.0 x 10^{-7} m/s.

The KSP sandstone occurrence zone, located north of the Krupinski coal mine area, where four planned injection boreholes were situated, has been chosen according to the feasibility study on the application of the recirculation method to the Rybnik Coalfield conducted in 1989. The total sorption capacity of those boreholes was estimated at 3.78 m^3/min with the assumption that the sorbing series is approximately 108 m thick and that the filtration coefficient k is equal to 5.9 x 10^{-7} m/s and taken as an average value for the KSP series of the Piast and Czeczott coal mines region.

The Krupinski coal mine has been preparing an installation for injection of the saline mine waters into the KSP sandstone series located to the north-east of the mining area since 1992. From among three injection and two piezometric boreholes planned in that area only two T-2 and T-3 injection and one piezometric boreholes were drilled in 1992. These boreholes were hydrogeologically tested and it has been found that their sorption capacity is low with the T-3 borehole showing the higher value.

In the years that followed, steps were undertaken to enhance the sorption capacity of the T-3 borehole and the Krupinski mine water injection system was designed and built.

GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERIZATION OF THE T-3 BOREHOLE SITE

The geological section of the T-3 borehole site consists of the Quaternary, Tertiary and Carboniferous deposits.

The Quaternary complex is composed of the sandy sediments with silty intercalations 10 - 50 m thick. The thickness of the Quaternary sediments exposed by the T-3 borehole is 20 m.

The Tertiary sediments constitute a marly-argillaceous complex with sandy-argillaceous intercalations 100 - 300 m thick. The Tertiary sequence exposed by the T-3 borehole is 148.4 m thick.

The Carboniferous is represented by the KSP series 300 - 350 m thick and the underlying Orzeskie layers.

The KSP series, being a sorbing system in the T-3 borehole, is composed of sandstones of various grains, mostly medium-sized, with thin claystone and mudstone intercalations. The thickness of the KSP series exposed by the T-3 borehole is 332 m including the sandstone beds of a total thickness of 194 m.

The Quaternary aquifer is composed of sands and gravels and shows discontinuity as it is in some places divided by the lenses of silt and/or clay. The thickness of the whole complex varies from several to 50 m. The Quaternary free ground water level lies at a depth of 10 m and is in contact with the precipitation and surface waters. The Quaternary waters are isolated from the deeper lying strata and do not show any filtration into the Carboniferous system.

The Tertiary sediments, in general, form an impermeable argillaceous complex in which thin water saturated ashy sands are intercalated.

The KSP layers aquifer is of the stratified and porous nature and its water table has been stabilized in the T-3 borehole at a depth of 45 m. The aquifers consist of sandstone beds with claystone and mudstone intercalations that often accompany coal seams.

DRILLING OF THE T-3 BOREHOLE AND CONDUCTING OF TESTS

The T-3 borehole of 500 m depth was drilled during the period 18.05 - 22.08.1992. The simplified geological section across the borehole is as follows:

- 000.0 - 020.0 m Quaternary silts and sands,
- 020.0 - 168.4 m Tertiary clays intercalated with sandy sediments,
- 168.4 - 500.0 m The Carboniferous KSP series composed of sandstones with thin claystone, mudstone and coal intercalations.

The borehole has been cased with ϕ24" pipes down to a depth of 23.2 m and ϕ16" down to a depth of 200 m. Both casing pipelines has been cemented in the rock mass. The injection ϕ95/8" pipeline was sunk to a depth of 500 m. Its segment from 200 to 500 m was perforated at depth intervals corresponding to sandstone layers earlier encountered by the geophysical surveys. The slots in the percolating filter were 4.5 mm wide and 300 mm long (66 slots per 1 running meter). The space between the slot filter and the rock body was backfilled by the gravels with grain sizes in the range of 5 - 10 mm.

Drilling was performed using the glycocell processed saline fluid. During the drilling operation a loss of fluid amounting to 8 m^3/48 h has been observed. In the borehole, at a depth of 172 m, a confined water horizon in the roof of the KSP layers has been encountered. Inflows were observed during drilling through the next sandstone beds. The stable water table was found at a depth of 45.0 m.

As a result of the test pumpings, the value of the filtration coefficient was determined under conditions of steady and transient state flows. The average value of the filtration coefficient was estimated at 9.3*10^{-8} m/s.

The theoretical sorption capacity of the borehole, taking into account the afore-mentioned value of the filtration coefficient, was estimated at 0.28 m^3/min. and the permissible wellhead injection pressure yet inducing no rock fracturing was estimated to be in the range of 3.0 - 3.5 MPa.

Two sorption tests were conducted giving two following sorption capacity values:

- 0.376 m^3/min. at pressures ranging from 2.3 to 2.8 MPa,
- 0.567 m^3/min. at a pressure of 3.4 MPa.

As a whole, 645 m^3 of brine was pumped into the borehole. Earlier, the same amount of brine had been pumped out from the same borehole.

The borehole sorption capacity forecast estimated from the hydrogeological investigation project for the sandstone formation 197 m thick based on the filtration coefficient k = 6.9*10^{-7} m/s assumed to have been an average value of the results of studies performed for the nearest boreholes was around 1.6 m^3/min. The permissible pressure in the roof of the Carboniferous and the injection pressure were then assumed to have been 3.75 MPa and 2.5 - 3.0 MPa, respectively. These values were estimated based on the assumption that the water table in the KSP sandstone series becomes stable at a depth of about 50 m.

The borehole sorption-affected zone extent and pressure variation forecasts estimated by the analytical methods showed that, without activation efforts, it would be possible to enhance the injection capacity. However, if the activation procedures had been carried out the borehole sorption capacity would have been enhanced to around 0.6 m^3/min.

The activation treatment of the borehole sorption zone involving the injection of the $NaHCO_3$ and MR-17 rokamide aided brine boosted by air tamping was performed in May, 1995. During the course of activation treatment the compression tests were carried out five times and the sorption capacity during that period fluctuated from 0.26 m^3/min. at the initial phase to 0.10 m^3/min. at the final phase. It follows from the treatment efficiency analysis that the borehole sorption capacity has only shown slight improvement. Its forecast values obtained for the wellhead pressure of 3 MPa were found to be in the range of 0.5 - 0.6 m^3/min.

WATER CHEMICAL COMPATIBILITY

The sediment-trapped water encountered in the T-3 borehole is highly mineralized with a concentration of soluble constituents of approximately 50 g/dm^3 and with the hardness and pH values of around 115 mval/dm^3 and 6.6 - 6.7, respectively. The main mineral constituent is the sodium chloride, the content of which is 70%. In the water, no sulphate ions have been found. However, some concentrations of barium and strontium ions (196 and 46 mg/dm^3, respectively), as well as a high content of both iron ions and iron precipitates (Fe og = 64.3 mg/dm^3), were found. To properly conduct the water injection process, the chemical compatibility of the sediment-trapped and injection waters should be preserved.

As, in recent years, the Krupinski coal mine has been conducting operations associated with the disposal of the electric power plant wastes and fly-ashes intermixed with mine waters into the mine workings, the arising leachates have changed the physico-chemical characteristic of the waters pumped out to the surface. Unfortunately, the sulphate ions have been introduced into the waters. If these waters containing the sulphate ions had mixed with the rich in barium ions sediment-trapped waters, they might have induced the deposition of the barium sulphate in the near borehole zone.

It should be noted that the inflowing natural waters do not contain sulphate ions. However, they contain barium ions as it is the case in the T-3 injection borehole sediment-trapped waters. To prevent the barium sulphate from deposition, steps were undertaken to introduce the fly-ashes of suitable chemical composition into mine workings so that the arising leachates cannot enhance the content of sulphate ions in the injection predestinated waters.

AN INSTALLATION FOR WATER TREATMENT, TRANSPORT AND INJECTION

The main elements of the installation are as follows:

- mine water treatment station located near coal mine's main establishment;
- pipeline connecting the treatment station with the T-3 borehole site;
- filter plant and pumping station near the T-3 injection borehole site.

In the technical scheme of the operation-ready mine water treatment station located near the mine water settlement ponds of the Krupinski coal mine a technology for the removal of suspensions (particles ϕ > 3 μm) from water has been included.

The mine water was taken from the mine water settlement pond and pumped into the water treatment station by means of the I stage pumps. During the first phase of treatment process, the coagulation of suspension matter done by polyaluminium chloride, PAC, and magnofloc polymer had been used. Next, the water flowed through the DYNASAND filters and then it was directed to the intermediate buffer reservoir. Since the water pH value could be enhanced after the filtration, the diluted hydrochloric acid was added in order to lower the pH value to that of the sediment-trapped water. Next, the water was pumped by the II stage pumps via the pipeline to the treatment station located near the injection borehole.

The pipeline bringing water to the borehole following the I stage of treatment was 8547 m long and its initial segment consisted of steel-made, factory-insulated pipes 300 mm in diameter and its final segment from 3427 m to 8547 m consisted of polyethylene pipes 250 x 22.7 mm in size. At the highest points of the pipeline the vents in water collecting sumps were installed and at the lowest points the dewaterers were installed.

The water treatment and pumping station located near the T-3 borehole comprised a multifunctional chamber and a final reservoir of treated water along with the network of technological pipelines and the external sewage system. In the multifunctional chamber three filters with the Hoogovens TS type replaceable cartridges of a capacity of 35 m^3/h each were installed The purpose of the filters was to treat water next to the DYNASAND filters and to retain more than 90% of suspensions of more than 3 μm in size.

Two filtration units were working at a flow rate of 50 m^3/h while the third one with clean cartridges was on stand-by. Each filter was equipped with pressure loss meters and on the pipeline supplying the filters with water a manometer was installed. On the delivery pipeline a test tap for sampling water was installed. Having been treated in filters, the water flowed through the pipeline 200 mm in diameter to the final reservoir.

The final buffer reservoir of treated water of a volume of around 45 m^3 was designed and built from a steel pipe ϕ2400 mm, 10 m long. The reservoir was equipped with an air valve, tap and a water table monitoring gauge. The water from the reservoir was pumped under high pressure into the ground.

START-UP OF THE INSTALLATION AND THE INJECTION PROCESS

The injection operation started on 25 August 1998 after 10 000 m^3 of mine water of stabilized chemical composition and of as low sulphate content as possible had been collected in the settlement pond. The operational parameters of the I stage filtration system have been obtained and optimized based on that water. The system can be characterized as follows:

- filtration capacity of around 0.8 m^3/min;
- suspended matter reduction to several dozen mg/dm^3;
- SDI index value less than 6.

The injection operation was preceded by the flushing of the delivery pipeline with mine waters from the I stage filtration in order to turn the pipeline sludge back to the coal mine settlement pond by means of tank cars. The pipeline had turned out to be highly polluted by the sludge and corrosion related products.

During the injection process the water at the delivery pipeline outlet was becoming systematically cleaner until on 14 October 1998 the suspension matter content reached a value of 1.6 mg/dm^3, which was comparable to the water purity after the I stage filtration.

After the water was directed from the delivery pipeline to the II stage filtration unit the buffer reservoir located near the T-3 injection borehole and the injection system with pressure pumps were flushed with the filtrated water. Figure 1 shows the course of pumping water into the borehole and its sorption variations as a function of pumping time. The sorption capacity obtained at the beginning of the experiment met the borehole specification forecast based on pumping test results. In December 1998 the borehole sorption capacity increased probably as a result of the increased foliation and permeability of the sorbing stratigraphic series. The geophysical surveys have found no pumped water breakthrough to the Quaternary sedimentary system.

The theoretical analyses of the aquifer sorption capacity and the water overpressure propagation in sorbing strata and the sorption capacity formation forecast were conducted based on the results of the hydrogeological tests performed in the T-3 borehole and on the observations and measurements made during the experimental water pumping into the borehole.

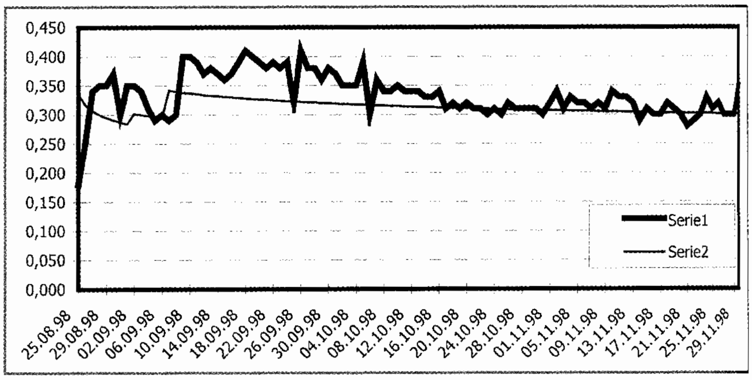

Figure 1. Graphics of the real (serie 1) and theoretical (serie 2) absorption capacity of the wellbore T-3 during the period 25.01.1998 - 29.11.1998.

CONTROLLING THE INJECTION OF SALINE MINE WATERS INTO GROUND WITH THE ENVIRONMENT PROTECTION TAKEN INTO ACCOUNT

Three series of geoelectrical measurements using the electrical sounding procedures were made in the vicinity of the T-3 borehole on 3 and 30 September and 17 December 1998. The purpose of the study was to evaluate changes in water mineralization of the Quaternary horizon. The measurements were made along the E -W trending line crossing the T-3 borehole and taken at points positioned 5 m apart. The electrical soundings were made using the Schlumberger configuration with the current electrodes moved symmetrically outward. The maximum current electrodes separation was 250 m / AB/2 = 125 m/.

The T-3 borehole geologic section consists of a sandy clayey sedimentary layer extending from the surface downward to a depth of 6 m, which is underlain by a layer of coarse - and fine-grained sands 8 m thick and a sandy-argillaceous layer 6 m thick in the lower part of the sequence. The roof of the Tertiary sediments has been found at a depth of 20 m. They are composed of partly sandy clays about 148 thick.

The results of the measurements show that in a zone to a distance 15 m from the borehole and down to 20 m depth the electric resistivity of the rock drops to values lower than 5 ohmm. If they were converted into mineralization they would correspond to values around 1500 mg/l.

These data indicate that the Quaternary waters in the aforementioned zone are chemically contaminated. This contamination is a consequence of borehole drilling and activation treatment after which certain amounts of saline waters inflowed from the surface into the Quaternary sandy formations.

It follows from the comparison analysis of the results of the three series of measurements that the saline mine waters pumped into the borehole has not infiltrated to the Quaternary water-bearing horizon either behind the pipeline casing or via the Tertiary impermeable clay series. Some small changes in isoohm values, though contained within the limits of measuring errors, resulted from different atmospheric conditions prevailing during the individual measurement series.

Periodical repetition of geophysical Quaternary strata electric resistivity measurements in the vicinity of the borehole is planned.

The hydrographic mapping involving water flow measurements, surface water course sampling, hydrochemical sampling and the test measurements taken in the wells sunk in the area of a radius of 5 km from the injection borehole was made in the study area in the middle of 1992. The results of those studies were part of a documentation describing the environmental conditions existing in the area prior to the commencement of the water injection tests.

The hydrogeological conditions existing in the vicinity of the T-3 borehole are such that the contamination of the Quaternary horizon by waters pumped into the borehole is impossible.

Date	Piezometer P-1 [m]	Borehole T-2 [m]
October 1992 (after dewatering)	68.00	-
January 1993 (after dewatering)	-	43.80
23 September 1998	72.00	47.75
1 October 1998	70.65	46.60
15 October 1998	68.80	46.40
03 November 1998	67.80	47.10
03 December 1998	64.70	47.40
15 December 1998	62.90	47.25

Table 1. Summary of the results of hydraulic head measurements in piezometer P-1 and borehole T-2.

The thickness of the Tertiary clay series in the Carboniferous system roof elevation area ranges from 40 to 100 m and increases up to about 300 m to the north-east (in the T-3 borehole section = 148 m). It constitutes a layer impermeable enough to prevent the KSP sandstones, which sorb the saline waters, from hydraulically contacting with the Quaternary aquifer.

Within the framework of hydrogeological observations, the local mine teams carry out tasks of monitoring the changes in hydraulic head in the P-1 piezometer and T-2 boreholes (Tabla 1). The results of the study indicate that the hydraulic head in the KSP stratigraphic series, into which waters are pumped, increases.

EVALUATION OF THE EXPERIMENT'S RESULTS

Injection of the Krupinski coal mine saline waters into the T-3 borehole was experimental because, previously, the Upper Silesian Coal Basin area had not experienced such a work. The final results of the experiment have, surely, been affected by its long implementation time.

The design work of the project was performed during the period from 1993 to 1998. The T-3 injection borehole was drilled in 1992, the pumping tests were performed in the same year and the sorption tests were performed in 1993. The borehole sorbing zone activation treatment was done in 1995 and the pumping of waters into the borehole commenced on 25 August 1998. The 6 years long break in borehole work, surely, caused some undesirable physico-chemical changes in the near borehole zone and the resulting sorption decline.

Another unfavorable event was the chemical incompatibility between the mine waters and the groundwaters in the injection zone. In recent years, the Krupinski coal mine has been disposing of electric power plant fly-ashes and wastes mixed with mine waters into the abandoned workings and that is why the resulting leachates have altered the physico-chemical characteristics of the waters pumped out to the surface. The industrial waste materials are utilized at the Krupinski coal mine for removing barium and radium isotopes from mine waters. At the same time, however, they enhance the sulphate content of these waters. The groundwaters near the T-3 injection borehole contain barium with a very low sulphate content. For this reason, a need arose to control the hydraulic process and quality of the power industry waste disposal in mine workings so that the sulphate content of the injection destined mine waters could be lowered and the barium sulphate deposition in a borehole avoided.

It should be noted that the Krupinski coal mine water injection test installation has been designed by assuming three boreholes to be used for the water injection with a predetermined sorption capacity of 4.5 m^3/min. The boreholes sorption capacity forecast included in the hydrogeological project has been determined based on the filtration coefficient k= 6.9 x 10^{-7} m/s that was the mean value of the tests results of the nearest neighboring boreholes. Those boreholes were situated far away from the T-3 injection borehole site location and drilled under more favorable conditions in the sorbing KSP sandstone series. After the T-3 borehole had been drilled in 1992 and the hydrogeological studies on finding the sorbing sedimentary series have been carried out, the filtration coefficient k mean value equal to 9.3×10^{-8} m/s and the borehole sorption capacity value 0.28 m^3/min were stated. Thus the injection installation foredesign was not appropriately verified. Therefore, the sorption capacity of the installation was much higher than the actual sorption capacity of the T-3 borehole. It resulted in the work interruptions of the borehole water injection pumps, necessitated the application of the by-pass and brought about considerable energy losses.

The steel made segment of the delivery pipeline was a vulnerable spot of the water injection installation. Having been unused for 2 years since its laying, it became a secondary source of water pollution by the corrosion related products, and so during the starting of the installation it brought about an excessive load for the II stage filtration system.

Putting aside the oversize problem of the injection installation as far as the actual sorption capacity of one borehole is taken into account, the performed experiment should, from the scientific point of view, be admitted to be successful. An installation for two stage treatment of mine waters and their injection into the borehole located about 8.5 km away from the coal mine has been built and made operational. The actual borehole sorption capacity was consistent with that calculated from the hydrogeological investigations of the sorbing stratigraphic series of the injection borehole site. Approximately 47 000 m^3 of mine waters with the sorption capacity of from 0.30 to 0.41 m^3/min were injected into ground during the period from 25 August to 30 November 1998.

The injection of saline mine waters into ground via the T-3 borehole is being continued despite the borehole's low sorption capacity. The injection wellhead pressure should not exceed 3.0 MPa due to the environmental requirements to protect the Quaternary waters and soils from salinity. To prevent the near borehole zone from the barium sulphate scale formation, the sulphate content of the injected waters should be lower than 10 mg/dm^3. These waters should not be oxidized in order to prevent the iron hydroxide and/or other chemicals from deposition in the borehole or porous matrix of the rock, which may contribute to the scale formation in the near borehole zone.

The water injection economic effect is around 1500 zlotys/day. It might have been much higher if the borehole sorption capacity had been higher. However, even such a value is not trifling.

Irrespective of the economic effect, injection of the mine waters into ground, due to the experimental character of the project, will be continued based on the research test principles with a high pro-ecological significance. The monitoring results of the course of injection process in time, hydrostatic pressure propagation in a sorbing layer and the work of individual installation elements constitute a very important cognitive material that allows us to better understand the feasibility of injection of the saline mine waters into ground.