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Qualitative and quantitative variations of the groundwaters from the vicinity of Tarnobrzeg resulting from sulphur mining

The groundwaters of the Quaternary horizon have become quantitatively and qualitatively degraded over an area of about 150 km^2 of underground sulphur melting in Jeziórko and in the open pit Machów. Within the mining fields of Jeziórko and nearby areas the groundwaters display an increase in the content of sulphates and chlorides resulting from the pumping of salt waters into the Tertiary beds. The degradation of groundwater resources is an effect of the dewatering of the open pit Machów. In Jeziórko sulphate migration into consumption waters of the Quaternary is observed. The aquifers under the external dump have also been degraded. The sulphates and chlorides which penetrate the groundwaters within the Quaternary sediments, are quickly diluted and their extent is limited. After complete exploitation of the Jeziórko mine the groundwaters of Quaternary deposits may retrieve their primary quality.

INTRODUCTION

The sulphur mines near Tarnobrzeg are mining investments, which relatively quickly had a negative impact on the natural environment. This results from the properties of sulphur. Sulphur is intensely oxidised and it forms various compounds, mainly sulphates. The latter are harmless but in a high concentration-detrimental both for a human health and elements of the natural environs, including groundwaters. In the Tarnobrzeg region two sulphur mines exist, with different exploitation systems: the open pit at Machów and the Jeziórko mine with underground sulphur melting (*Materiały archiwalne...*,1951–1991).

Both mines have directly influenced on the groundwaters over an area of about 150 km^2, where the water has been qualitatively and quantitatively degraded. The qualitative degradation developed relatively quickly due to the fact that the Quaternary deposits there form an open groundwater basin with no overlying impermeable horizon. The pollutions could

infiltrate into groundwaters on a whole area. The polluting effect of these waters was variable due to a favourable regional hydrodynamic pattern, directing the groundwater flow northward, to the Vistula and San rivers.

The main groundwater basin nearby Tarnobrzeg is located within Quaternary deposits, from 5 to 35 m thick, characterized by good hydrogeological properties (S. Pawłowski *et al.*,1953–1976). The average value of a coefficient of permeability is 27 m/d, and of the filtering coefficient is 0.188 but the water transimissivity is about 1000 m^2/d. The groundwater level occurs from 184 m a.s.l. southward from the above mentioned mines, to 141 m a.s.l. at the Vistula and San rivers. The difference between these levels (43 m over a distance of about 30 km) documents a high hydraulic gradient — 1.43 m/km. The sulphur mine area and surrounding zones are intensively drained by such rivers and streams as San, Łęg, Trześniówka, Mokrzyszówka, Babulówka and Vistula. This high gradient and deep drainage have a significant influence on the rapid dilution of any pollutions quite close to their sources. This hydrodynamic pattern is deformed in the area of the Jeziórko mine due to mine dewatering and the generation of sink holes up to 7 m deep. These sink holes drain part of the groundwaters and some hydroisohypses such as 145, 146, 147 and 148 m a.s.l. are closed systems and as a result "local" microhydrodynamic patterns are formed. Only the hydroisohypse 149 m a.s.l. has a regular course and is probably a boundary of marginal conditions between the Machów and Jeziórko mines.

QUALITATIVE VARIATIONS OF GROUNDWATERS

The common opinion about a good quality of groundwaters from the Tarnobrzeg region was based on limited data before the beginning of sulphur exploitation. The systematic periodical studies, carried out by SIARKOPOL, indicated a gradual increase in sulphates content that caused a decline in the water quality and involved the oposition of local inhabitants and claims for damages. This situation pressed SIARKOPOL in 1988 to charge the Polish Geological Institute with the task of the description of actual water quality over an area of 1000 km^2, surrounding both sulphur mines. One of the purposes was to establish a control system able to detect quite early water quality changes and to initiate protection action (J. Malinowski *et al.*, 1991).

The realization of this task lasted 3 years and about 3000 chemical analyses of waters and 600 verification analyses were done. The results of these studies are as follows.

The mineralization distribution in the "triangle", bounded by the Vistula and San rivers and the line Padew Narodowa – Nowa Dęba, indicates that the groundwaters with mineralization lower than 800 mg/dm^3 and which are utilizable (53.3% of analyses) predominate there. The waters with mineralization higher than 800 mg/dm^3 are unutilizable without water treatment and they occur over an area of 30–40 km^2 in the Jeziórko mine (46.7% of analyses). The increased mineralization is mostly noticed locally, in areas from several hectares to several square kilometres. The largest ones are located nearby the exploitation faces and in completely exploited sites (Fig. 1). The general level of mineralization greatly varies. The lowest value is 156 mg/dm^3, the highest is 4500 mg/dm^3 at one point. The high values are between 1800 and 2200 mg/dm^3.

Sulphate is the most common component of groundwaters. Four concentration groups of this anion were defined: 0–200 (permissible value), 200–400, 400–600, and over 600 mg/dm^3. The first group predominates (Fig. 1), the others concentrate in relatively small areas within the exploitation zone. The highest ion concentrations are observed in the completely exploited sites.

The local, punctated increased concentrations of sulphates are located at great distance from the mining areas and are not related to a mine. Their sources are wastes from fertilizer production in Machów mine. During a dozen or so years they have been used by local farmers for the hardening of road surfaces and due to the oxidation and disintegration processes they have supplied sulphates to groundwaters.

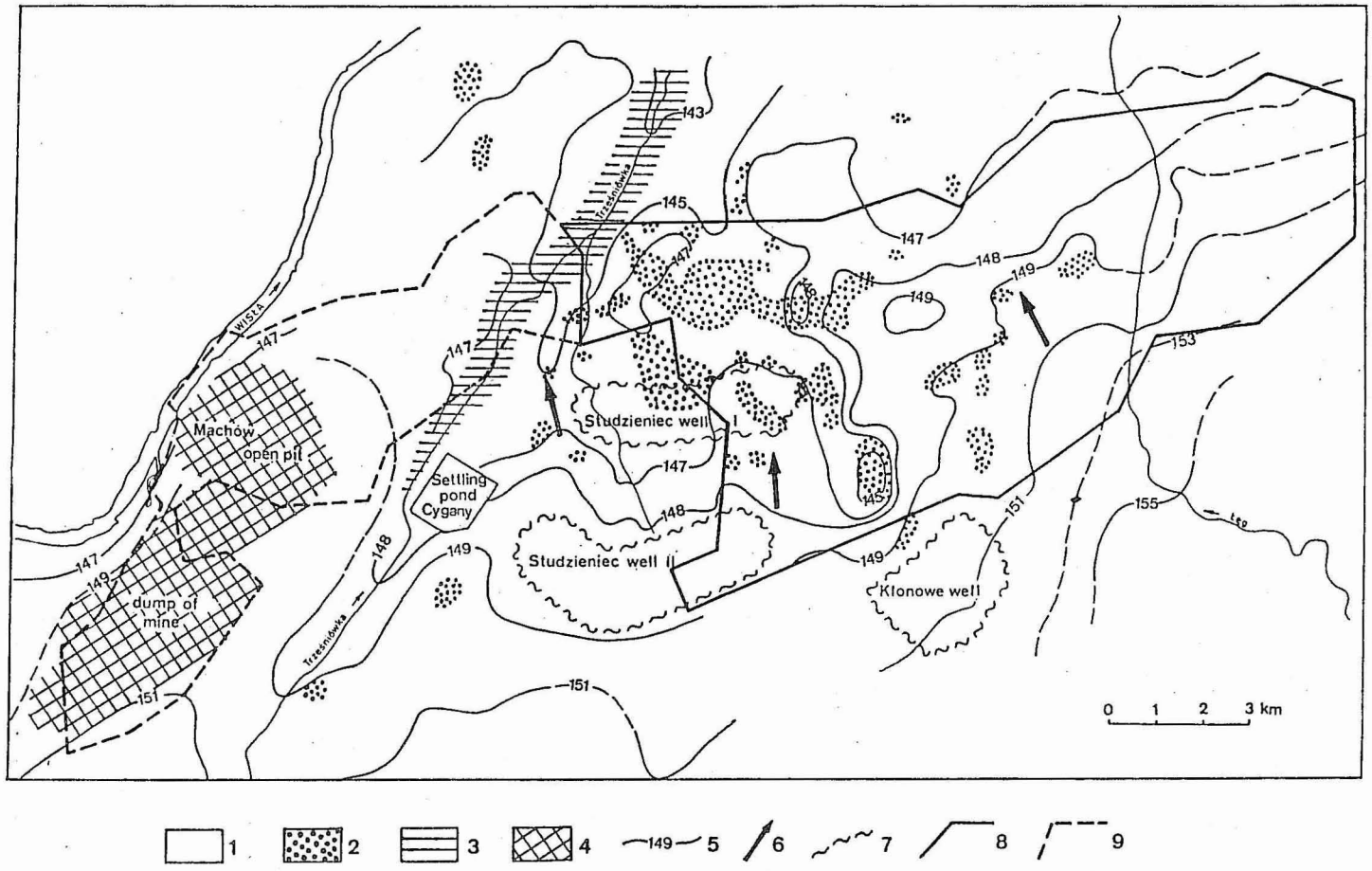
Hydrogen sulphide occurs most often in the vicinity of exploitation fields, rarely outside mining areas. It emanates periodically, during water eruptions in the Jeziórko mine. Sometimes its content exceeds the permissible values. It could be supposed that this compound, after oxidation, becomes the next source of sulphuric acid generation on field surface.

Another groundwater component is chlorine with a permissible content up to 300 mg/dm^3. It is good example of an anthropopressional activity because it is generated during the pumping of saline waters into the Tertiary deposits. These waters partially penetrate the Quaternary waters and contaminate them. The chlorine content is four times higher there than the permissible content. Four intervals of chlorine concentration were distinguished: 0–300, 300–600, 600–900 and over 900 mg/dm^3. The waters with a chlorine content, falling within the first interval, predominate over the most of the area studied. Other waters, with different chlorine concentrations, occur nearby the exploitation faces. Also nitrates, concentrated beyond permissible contents, are found here due to fertilization and bad sanitary conditions.

Hitherto the influence of gas and dust emissions on the quality of groundwaters is unclear in detail. Some scientists (J. Dziewański, 1988, 1991; J. Sękiewicz, 1990; R. Skrzypczak, U. Józefko, 1991) consider that such emissions increase quantitatively the concentration of pollutions. If this is true the increased sulphate content will be noticed outside the mining areas, over the whole studied area. The occurrence of heavy metals is connected with dust emissions but hitherto their content does not exceed permissible contents. Nevertheless, in some cases, the contents of single metals are higher, approaching the permissible value, for instance the content of lead, zinc and cadmium. The studies of water chemistry indicated that during the period 1989–1990 the water quality became constant which suggests that such emissions have little influence on it.

POLLUTION MIGRATION

The main sources of the pollutions of groundwaters are sulphur eruptions from drills, a sulphur, being blown from dumps and the deposition of sulphur dust, emissions of SO_2 and dusts by the factories in Stalowa Wola, Tarnobrzeg, Połaniec, Grzybów and by many boiler-houses in small factories and villages. The most direct and intensive eruptions and events of sulphur dust transportation are within the area of the Jeziórko mine.


Machów
open pit
dump of
mine
Settling
pond
Cygany
Studzieniec well I
Studzieniec well II
Klonowe well
Trzesniówka
WISŁA
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0 1 2 3 km
1
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4
5
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The ground surface nearby the exploitation fields and sulphur dumps is impregnated with sulphur. This sulphur is oxidisied and a sulphuric acid results from the reaction of sulphur dioxide with soil water. It is not sure that sulphuric acid migrates to a saturation zone being totally or partly dissociated but there it is completely diluted. The intensity of this process depends on the hydraulic gradient. The regional flow of groundwaters in the studied area is directed toward the San and Vistula rivers. In some zones the hydraulic gradients are quite large and as a result the sulphate ion content rapidly decreases northwards, to a value of 50 mg/dcm^3, not very far from the exploitation area. It could be stated that on a regional scale the expansion of pollutions is dependent on the hydrodynamic pattern, indicated by the position of the groundwater level. Chlorides and nitrates also migrate together with sulphates and the calculated annual amount of percolated water is about 4 km.

Both the Jeziórko mine and Machów open pit supply their sewage into the Trześniówka river, a tributary of the Vistula river. During high water levels the waters of Trześniówka may percolate through the dykes and groundwaters behind them are enriched in sulphates. This infiltration zone is up to 500–600 m wide on either side of the river, it disappears during longer low water periods. The total width of the pollution zone is up to 1000–1200 m (Fig.2).

The migration of pollutions northward from the mine is also influenced by variations of groundwater level — its rise and fall. During rises high flow gradients are observed and the mixing of pollutions with water is very quick. During falls of the water level the flow gradients decrease and the mixing of both media is slower but locally some stagnation stages are reflected as an increase of mineralization, mainly of sulphates. A relatively high correlation between total mineralization and sulphate content (88%) was noticed in the observation wells (J. Malinowski, M. Perek, 1993). There is no such relation between chlorides and nitrates that indicates an ephemeral and/or an accidental influx of media containing chlorine and nitrates. The fluctuations of groundwater level near Tarnobrzeg are 1–2 m, rarely 3 m. Lack of chemical analyses from periods of distinct water level rises and falls prevents the determination of seasonal water quality changes.

The study of the 3-dimentional distribution of sulphate content documents that the variations of water quality, caused by sulphur exploitation, are periodic and some wells become slowly desalted. These phenomena reveal the continuous mobility of pollutions.

Fig. 1. Distribution of dissolved substances and sulphates in the Quaternary groundwaters nearby Tarnobrzeg
Content of : 1 — dissolved compounds < 800 mg/dm^3, sulphates < 150 mg/dm^3, 2 — dissolved compounds 800–4900 mg/dm^3, sulphates 200–600 mg/dm^3 (locally > 600 mg/dm^3), 3 — dissolved compounds < 800 mg/dm^3, sulphates 200–400 mg/dm^3; 4 — areas with persistenly degraded resources of groundwater within the Machów open pit and the external dump; 5 — hydroisohypses of groundwater level within the Quaternary deposits (in m a.s.l.); 6 — main directions of groundwaters flow; 7 — protected zones of water catchments; 8 — boundary of the Jeziórko mining area; 9 — boundary of the Machów mining area

Rozkład substancji rozpuszczalnych i siarczanów w wodach podziemnych utworów czwartorzędowych w okolicy Tarnobrzega
Zawartość w wodach podziemnych: 1 — części rozpuszczalnych < 800 mg/dm^3, siarczanów < 150 mg/dm^3, 2 — części rozpuszczalnych 800–4900 mg/dm^3, siarczanów 200–600 mg/dm^3 (lokalnie > 600 mg/dm^3), 3 — części rozpuszczalnych < 800 mg/dm^3, siarczanów 200–400 mg/dm^3; 4 — tereny o zdegradowanych trwale zasobach wód podziemnych w obrębie odkrywki Machów i zwałowiska zewnętrznego; 5 — hydroizohipsy zwierciadła wód podziemnych w m n.p.m. w utworach czwartorzędowych; 6 — główne kierunki spływu wód podziemnych; 7 — strefy ochronne ujęć wód podziemnych; 8 — granica obszaru górniczego kopalni Jeziórko; 9 — granica obszaru górniczego kopalni Machów

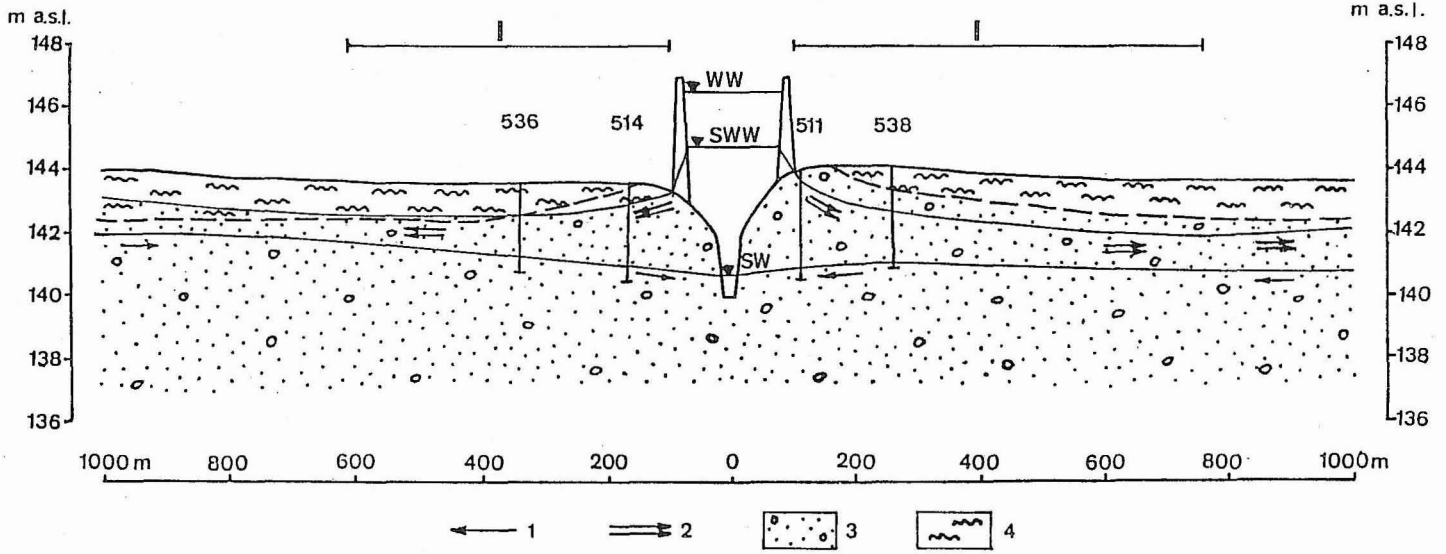

Fig. 2. Scheme of infiltration conditions of waters from the Trześniówka stream

1 — flow directions of drainaged groundwaters, 2 — flow directions of waters infiltrating from the stream, 3 — sands, gravels — Quaternary, 4 — muds, WW — maximum water level in the river in 1945–1985; SWW — average value of maximum annual water levels from the years 1945–1985; SW — average value of mean annual water levels from the years 1945–1985; 536, 514, 511, 538 — numbers of observation wells; I — zones of influences of Trzesniówka stream

Schemat ilustrujący warunki infiltracji wód Trześniówki

1 — kierunki spływu wód gruntowych drenowanych, 2 — kierunki spływu wód infiltrujących z rzeki, 3 — piaski, pospółki, żwiry — czwartorzęd, 4 — namuły, WW — stan maksymalny wód w rzece w latach 1945–1985, SWW — stan średni z maksymalnych rocznych w latach 1945–1985, SW — stan średni ze średnich rocznych w latach 1945–1985, 536, 514, 511, 538 — numery studni badawczych

QUANTITATIVE VARIATIONS OF GROUNDWATERS

The degradation of groundwaters in the Machów open pit results from mine dewatering and from damage of aquifers under the external dump. The whole area of degraded beds is about 30 km^2. The average modulus of groundwater resources near Tarnobrzeg is 268 $m^3/d/km^2$ and the water resources in this area are 8040 m^3/d (2 934 600 m^3/a).

The area of severely degraded aquifers in the Jeziórko mine is about 40 km^2, with water resources of 10 720 m^3/d (3 912 800 m^3/a). In the mining area of this mine (about 60 km^2) groundwaters occur with permissible concentrations of individual components (Fig.1). The total loss of water resources in the mining areas of both mines is 18 760 m^3/d (6 847 400 m^3/a).

The degradation of water resources in the Machów open pit persists because the aquifers under the external dump were disrupted and former hydrogeological pattern will not return even during future open pit liquidation. The liquidation project proposes the filling up of the part of pit and the filling the remaining depression with water to a level just above the sulphur-bearing horizon. But this water could not be usable and actually the loss of water resources is irreversible. The groundwater resources in the Jeziórko mine will be desalted after total exploitation of the deposit.

The total discretionary resources of waters, located in the Tarnobrzeg zone — bounded by the Vistula and San rivers and the line Padew Narodowa – Nowa Dęba — are 97 785 600 m^3/a. The degraded resources constitute about 7% of the total ones, which decreases to a value of 90 938 290 m^3/a. The calculated resource loss is relatively small and it will diminish in the future due to water desalting in the Jeziórko mining area.

The defined variations of groundwater quality in the Tarnobrzeg region are regarded as stabilized ones because no features of worsening quality were observed during 1988–1991 also there are no data about water loss caused by mining. But the activity of other factories in this region, emiting gases and dust (per year about 112 800 t of gases and 260 000 t of dust) such as the power plant in Połaniec, the sulphur mine in Grzybów and the factories in Stalowa Wola and Nowa Dęba, have a strong impact on the natural environment. These emissions could influence on groundwaters for instance — the heavy metals from smoke dusts are noticed in water analyses.

The appraisal of the influence of sulphur exploitation on groundwaters confirms the necessity of advanced systematic hydrogeological studies in the areas of mineral resources. The characteristics of such studies should be as follows:

1. The evaluation of the effect of sulphur exploitation on the quality and volume of groundwaters will be proper if before the exploration the regional hydrogeological conditions and hydrodynamic pattern as well as the water quality and volume are investigated in detail.

2. The fundamental requirement for the proper prediction of further water quality variations is a stationary observation of the groundwater level according to an uniform system of water studies during defined periods, estimated by the impact of sulphur exploitation on groundwaters (such studies should be done once per three months in both sulphur mines).

3. It is necessary to study the hydrogeochemical processes, active within a soil bed and the aeration zone nearby sulphur mines. The infiltration of sulphur compounds, independent

of their source and intensity, gives sulphur oxidation and sulphuric acid generation on a soil surface. Further geochemical reactions with this acid produce other toxic compounds, also migrating in the saturation zone. According to some opinions the humus bed forms a sufficient isolation barrier for groundwaters because it absorbs most of the pollutions. Also the influence of acid rains on variations in groundwater quality is unclear.

4. A lot of problems, observed in both sulphur mines, require selective data collection as well as special methodology, accuracy of measurements, sampling and interpretation. The conception of studies should solve such defined problems as a general model of variation dynamics which could be veryfied in the next years.

The studies of groundwater quality in the Tarnobrzeg region were not strictly realized according to the above mentioned requirements. During thirty years of sulphur exploitation a lot of investigations were done but without uniform methodology which could enable the solution of the preventative-protective problems. The reconstruction of variation dynamics of groundwater quality, with participation of various influencing factors, is practically impossible now. Only the current stage of it could be presented, being the basis for further analyses in the future years of sulphur exploitation or after its completion.

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ZMIANY JAKOŚCIOWE I ILOŚCIOWE WÓD PODZIEMNYCH REJONU TARNOBRZEGA POD WPŁYWEM EKSPLOATACJI ZŁÓŻ SIARKI

Streszczenie

Eksploatacja złóż siarki w rejonie Tarnobrzega odbywa się metodą odkrywkową w kopalni Machów (wcześniej także w kopalni Piaseczno) oraz metodą otworową w kopalni Jeziórko.

W obrębie obu obiektów górniczych powstały ilościowe i jakościowe szkody w zasobach wód podziemnych, powodujące ich ubytek. Największe skutki działalności górniczej odnotowano w kopalni Jeziórko. Zostały tu odwodnione warstwy wodonośne czwartorzędu, a erupcje wód złożowych spowodowały ich przenikanie do wód podziemnych, powodując niekiedy wysoką ich mineralizację, co uczyniło te wody niezdatnymi do użytkowania.

Obszar górniczy kopalni Jeziórko obejmuje co prawda ok. 100 km^2, ale zdegradowany chemicznie obszar wód podziemnych ma zaledwie 30–40 km^2, co świadczy o ograniczonym wpływie kopalni, mniejszym niż mniemano początkowo. Stwierdzono, że jakość wód podziemnych odpowiada tu dopuszczalnym stężeniom użytkowania. Zarówno w części obszaru górniczego, jak i terenach leżących na zewnątrz, przeważa mineralizacja ogólna do 800 mg/dm^3, a zawartość jonu siarczanowego jest znacznie niższa od stężenia dopuszczalnego. Mineralizacja ogólna powyżej 800 mg/dm^3 pojawia się natomiast „wyspowo", niekiedy na powierzchniach mniejszych od 1 km^2. Dzieje się tak dzięki korzystnym warunkom hydrodynamicznym, których istota polega na intensywnym spływie regionalnym w kierunku Wisły. Przy dużych spadkach hydraulicznych „strumienie" wody podziemnej „rozbijają" tworzące się zbiorowiska wód podziemnych o podwyższonej zawartości siarczanów na małe powierzchnie, równocześnie je rozcieńczając. Dowodem na to jest koncentracja jonu SO_4^{2-} w wodach podziemnych poza obszarem górniczym, w przewadze do 50 mg/dm^3 i braku przekroczenia stężeń dopuszczalnych.

W obrębie kopalni Machów nastąpiła degradacja warstw wodonośnych czwartorzędu zwałowiskiem zewnętrznym na powierzchni ok. 30 km^2. Moduł zasobności wód w czwartorzędzie ustalono tu na poziomie 268 $m^3/d/km^2$, co daje zasobność 8040 $m^3/d/km^2$. Na obszarze kopalni Jeziórko powierzchnię zdegradowaną szacuje się na 40 km^2, w obrębie której zasoby wód wynoszą 10 720 $m^3/d/km^2$. Łączną degradację zasobów ocenia się więc na 18 760 $m^3/d/km^2$. W stosunku do zasobów zatwierdzonych stanowi to w rejonie Tarnobrzega ok. 7%. Istnieje możliwość, że po rekultywacji kopalni Jeziórko nastąpi wysłodzenie wód i będą one zdatne do użytkowania.