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A HYDROGEOLOGICAL ASSESSMENT OF THE ŁĘŻKOWICE BRINE PUMPING STATION NEAR BOCHNIA (THE CARPATHIAN FOOTHILLS)

Abstract: In 1991 the Łężkowice brine pumping station closed after 23 years activity, leaving soil and alluvial groundwater heavily contaminated with salt. Piezometry and observations on site suggest that this saline groundwater is discharging directly into the nearby river Raba, an important source of drinking water.

By studying trends in chloride concentration and water levels, two possible salt sources were identified on the site. The first is residual salt dissolved from the soil surface and unsaturated zone and carried to the groundwater during recharge events. The second is most active at low groundwater levels and is interpreted as a connection to a source of brine beneath the alluvial cover. Groundwater flow and chloride transport modelling were used to provide a quantitative estimate of saline discharge.

Because of the limited availability of model data, many of the parameters used were estimated. In order to validate the model's results, all available data sets were used for calibration. Daily chloride flux measurements made in the Raba river were analysed using a method similar to the baseflow separation of hydrographs in order to give an estimate of groundwater discharge. Short term transient modelling during flood periods was also found to provide a useful calibration and highlighted possible inaccuracies in the initial hydraulic conductivities used.

Short term modelling demonstrates that, although the salt supplied to the river by groundwater discharge from the site is only a small percentage of the total load, timing of this discharge is critical. Most of the groundwater discharge occurs at low flow when the river is most vulnerable. When river flows are high and able to accept large quantities of salt, groundwater discharge halts completely.

The study concluded that saline groundwater discharge from the site is not a problem at present but may increase in future as the site degrades and underground caverns developed during mining begin to collapse. A ground conductivity survey is suggested as a good method of identifying salt sources should a more detailed study be required.

1. Introduction

Solution mining in Łężkowice began in 1968 with a series of boreholes into the underlying Miocene placed 35m apart in an equilateral triangular array covering the site. A 300 m wide borehole free safety zone was placed next to the Raba river and all solution mining was designed to occur below 120 m depth. Cavern development was monitored during exploitation by echo sounding. The site was engineered to operate for a period of between 8 and 10 years (Garlicki, 1993).

Between 1968 and 1984, water was pumped into the ground at between 16 and 20 atmospheres pressure. During this period, increasing volumes of saline water escaped from the Miocene deposits into the Raba river via the overlying alluvium, as seepage and springs. Calculations by the mine suggested that in 1982 when the problem was at its worst, over 60 tonnes of salt a day were being discharged into the Raba. After 1984, mining methods were changed to reduce the environmental impact of the operation and discharge gradually decreased. The operation of the site eventually ceased completely in 1991, 23 years after starting and 13 years after the proposed closing date.

Five years after the closure of mining operations, salt concentrations in the alluvium of Łężkowice are still elevated, suggesting the existence of an ongoing source of salt. A white salt crust covers the ground in many areas and several seepage faces can be seen discharging highly saline water directly into the Raba river. Echo soundings of the site demonstrated that massive cavern development has occurred. Despite attempts to stabilise these caverns by injecting fill materials, subsidence of up to 5 m has occurred in parts of the site.

1.1. Hydrogeology

Bedrock in the area is the low hydraulic conductivity, Miocene flysch containing the salt deposits previously exploited by the mine. The main aquifer is a layer of alluvial sands and gravels between 3 and 10 m thick overlain by alluvial silts and clays. In cross-section, the aquifer forms a wedge shape with its greatest thickness on the east side of the valley. The thinnest part of the aquifer occurs close to the river on the west side of the valley and in certain areas bedrock can be seen on the riverbed.

Piezometric data suggest that the river is in hydraulic continuity with the aquifer and is effluent. Two small streams cross the site, neither are hydraulically connected to the aquifer although the northernmost one fills a pond which does appears to leak to groundwater (Fig. 1).

2. Previous work

The Saltmine Bochnia has been taking monthly measurements of water levels and chloride concentrations from sampling points on and around the site for several years. The main purpose for the collection of this data was to assess the flux of salt to the Raba river. This was done by averaging the piezometric head measured on the site, and using the distance from the centre of the site to the river to estimate a gradient. Darcy's law was then used to calculate the flow of water. By then multiplying this figure with an average salt concentration for the site, a figure for the total flow of salt into the river from groundwater was achieved. This was then added to the flux of salt via surface water to give a total salt flux.

Fig. 1. Map of site area.

Ryc. 1. Szkic sytuacyjny obszaru badań.

An example of the calculation performed by the mine for December 1995 is shown below:

Average saturated thickness of alluvium = 4.26 m
Average hydraulic conductivity of alluvium = 21.88 m d^{-1}
Estimated head gradient from site to Raba = 0.003
Width of area across which salt is flowing to the river = 1200 m
Total groundwater flow = 335.55 m^3 d^{-1}
Average concentration of chloride = 11.63 kg m^{-3} NaCl equivalent
Flux of salt to Raba in groundwater = 3902 kg NaCl d^{-1}
Flow in stream = 45 m^3 d^{-1}
Chloride content = 0.3 kg NaCl m^{-3}
Flux of salt to Raba in surface water = 14 kg NaCl m^{-3}

Total flux of salt to Raba = 3916 kg NaCl d^{-1}

A list of calculated values for the years from 1980 to 1994 is shown in Table 1.

3. Interpretation of previous data

Water levels and salt concentrations measured by the Saltmine Bochnia during 1994 and 1995 were made available to this study for re-evaluation. In addition to this data, daily measurements of river stages and chloride concentrations measured at Proszówki, 10 km downstream of the site, were available. Background values of chloride concentrations in the river were measured at Dobczyce reservoir, 24 km upstream of the site.

3.1. River data

By subtracting background chloride flux from the total chloride flux as measured at Proszówki, the maximum possible chloride outflow from the Łężkowice site may be calculated. This chloride flux above background (Fig. 2) is derived from many sources and by removing the effects of sources apart from groundwater discharge, a more accurate maximum chloride flux for the Łężkowice site may be calculated.

This was achieved using a method similar to baseflow separation of hydrographs, the only difference being that in this case troughs as well as peaks had to be filtered out and the data was far more erratic. To overcome these problems, the median rather than the minimum concentration in a period was used, and the periods of measurement were increased. Thus a weekly median chloride concentration was calculated and then the five weekly minima of the medians were plotted. Fluxes calculated from each set of figures are shown below:

Total chloride flux: 41,600 kg $Cl^- d^{-1}$
Flux above background: 13,100 kg $Cl^- d^{-1}$
Weekly median: 12,100 kg $Cl^- d^{-1}$
Five weekly minima: 9,200 kg $Cl^- d^{-1}$.

From these figures the maximum possible contribution of chloride from the site is around 20% of the yearly total. As the yearly average chloride concentration is still low in the Raba, around 35 mg l^{-1}, it may be assumed that the threat to drinking water is insignificant. This is not necessarily the case.

The relationship between flux and flow (Fig. 3) is consistent with the calculation of groundwater discharge at around 20% of the total flow in the Raba. Maximum chloride flux in the river occurs during periods of flood, when most

Tab. 1. List of calculated values of NaCl (kg NaCl d^{-1}) and Cl fluxes (kg Cl d^{-1}) for 1980-1995

Tab. 1. Obliczone wartości dopływu NaCl (kg NaCl d^{-1}) i Cl (kg Cl d^{-1}) w latach 1980-1995.

Year Rok	Flux of NaCl Dopływ NaCl	Flux of Cl Dopływ Cl
1980	10,280	6,238
1981	51,460	31,228
1982	62,720	38,061
1983	60,000	36,410
1984	31,500	19,115
1985	7,974	4,839
1986	8,865	5,380
1987	9,370	5,686
1988	8,023	4,869
1989	9,097	5,520
1990	11,975	7,267
1991	6,161	3,739
1992	3,995	2,424
1993	3,339	2,026
1994	2,962	1,797
1995	3,052	1,852

Fig. 2. Chloride flux.

Ryc. 2. Dopływ chlorków.

of the river water comes from runoff and groundwater discharge is at a minimum. During peak groundwater discharge, when the river level is lowest, the chloride flux falls to a minimum, almost two orders of magnitude lower than its peak. This shows that groundwater discharge is an insignificant source when considering the total chloride load of the Raba river.

Chloride concentrations on the other hand show the opposite relationship, with the highest values occurring when the percentage contribution from groundwater is greatest. For the purposes of public water supplies, it is the peak chloride concentrations that are important. During low flow, concentrations in the river can be as high as 85 mg l^{-1} although the total chloride flux is as low as 7 tonnes per day. At such times, when the river water is most vulnerable, a large proportion of the chloride present in the river may be discharge from the Łężkowice site. Thus peak concentrations of chloride (and therefore the suitability of water for public supply) may be entirely controlled by discharge from the site.

Such a hypothesis is strengthened by hydrochemical analysis of river water samples collected from the Raba near Łężkowice, soon after a flood. Measured chloride concentration increased from 11 mg l^{-1} Cl^- upstream of the site to 31 mg l^{-1} downstream. It should be noted that 11 mg l^{-1} is close to the background measured at Dobczyce reservoir (24 km upstream) and that 31 mg l^{-1} is close to an average value for Proszówki (10 km downstream). The flow rate measured at Proszówki on the day of sampling was 12.5 $m^3 s^{-1}$ (no chloride concentrations from Proszówki were available) and the salt flux

Fig. 3. Relationship between chloride concentration, chloride flux and flow rate in the River Raba for 1994 and 1995.

Ryc. 3. Współzależność koncentracji chlorków, wielkości ich dopływu oraz przepływu Raby w latach 1994 i 1995.

from the site to the Raba river can be calculated at around 21.6 tonnes per day. The river is large and may not be well mixed at the location where the downstream sample was collected (500 m from the site), so these isolated samples may not be entirely reliable. However they do bring attention to the fact that the figures calculated are yearly averages. In fact whilst the river is in flood, hydraulic gradients may be reversed and discharge from the site may be close to zero. At this time saline water could be held in storage in the aquifer close to the river. As water levels drop, this stored water may be released into the river and salt discharge, as at the time of sampling, would be considerably higher than average.

3.2. Groundwater

3.2.1. Water level versus chloride concentration

Hydrographs and chloride concentrations were plotted for all the sampling locations that were frequently visited between January 1994 and March 1996. The relationship seen between ground water level and chloride concentration for individual boreholes fell into two types, those dominated by brine injections and those dominated by saline recharge.

Brine injection

Figure 4 shows data from a well on the east side of the site and is a good example of the first type. From the beginning of 1995, chloride concentrations have an inverse relationship to groundwater levels. Thus at elevated groundwater levels chloride concentrations are low and during times of low groundwater levels chloride concentrations are high. This type of relationship is common across the site, especially in areas with high salt concentrations in the groundwater. Such relationships are interpreted as being due to isolated high conductivity connections to a deep brine source.

Echo soundings across the site have located many caverns beneath the site left by salt dissolution. The nature of the salt bearing strata means that such caverns are likely to be hydraulically isolated and therefore at a fairly constant pressure. If a low conductivity connection from these brine filled caverns to the aquifer exists, then it is reasonable to assume that the pressure in the caverns would eventually reach the average pressure in the aquifer. When groundwater levels are low, the hydraulic gradient is at a maximum and flow from the deeper source brings saturated brine into the aquifer. At high water levels the gradient is reversed, effectively cutting off the supply of salt.

Possible pathways for the brine include damaged borehole casings left after the termination of pumping activities or subsidence related fractures in the Miocene

Fig. 4. Relationship between chloride concentration, rainfall totals and groundwater level in S8.

Ryc. 4. Zależność koncentracji chlorków od opadów i stanów wody gruntowej na stanowisku S8.

sediments. Both of these proposed sources will become more active with the degradation of the site. This theory is supported by the fact that before February 1995 no such relationship is apparent. It is possible that around this time either subsidence occurred opening up a new fracture in the Miocene, or a rusting borehole casing finally collapsed.

Saline recharge

Figure 5 shows data from a piezometer in the centre of the site and is the most distinct example of the second type of relationship between groundwater level and chloride concentration. Concentrations correlate closely with water levels in the piezometer, often slightly in advance of them. Furthermore these peaks often correlate closely with rainfall events.

This second type is almost certainly due to salt dissolution by recharge, either at the surface or in the unsaturated zone. Alluvial material of low hydraulic conductivity covers the aquifer across much of the site so the response of the groundwater levels to rainfall events is often delayed by at least one month. The first water to reach the groundwater naturally carries the highest salt load as any readily available salt in the soil and unsaturated zone is dissolved. With more rain the salt supply is diminished and concentrations fall, so that by the time the bulk of the recharge occurs (when the

Fig. 5. Relationship between chloride concentration, rainfall totals and groundwater level in P65.

Ryc. 5. Zależność koncentracji chlorków od opadów i stanów wody gruntowej na stanowisku P65.

water table actually rises) chloride concentrations are low. This may explain the observed phenomena of the chloride concentrations „predicting" water level rises. Surveys carried out in 1984 measured NaCl in surface soil averaging 2% by weight and up to 10% by weight (Garlicki, 1993). A white salt crust is still visible across many areas of the site during periods of dry weather.

If brine injection dominates site wide chloride concentrations and is controlled by subsidence in the upper layers of the Miocene or by borehole corrosion, then significant salt input to the aquifer and therefore to the Raba may continue well into the future. At best it is highly unpredictable. On the other hand if saline recharge dominates, then it is likely that there will be a fall in the salt output to the river and certainly no increase.

3.2.2. Spatial distibution of chloride

Until December 1995, sampling data only indicated one area of chloride contamination in groundwater. This was towards the west of the site where groundwater chloride concentrations vary between 90,000 and 20,000 mg l^{-1} NaCl. After December 1995, elevated chloride concentrations (30,000 mg l^{-1} NaCl) were also seen in the east. This was interpreted as the development of a second area of brine injection from below.

4. Conceptual model of site area

Contour plots of chloride concentrations for piezometers on site show two plumes. One on the west side and another of bigger concentration on the east side. The relationships discussed in section 3 allow the development of a conceptual model of salt and groundwater transport (Fig. 6).

Salt enters the aquifer from three separate sources:

- as brine flowing up into the alluvial aquifer from infilled salt caverns in the underlying Miocene sediments,
- saline recharge due to leaching of surface salt and,
- as leakage from saline surface water from the pond north of the site.

Salt leaves the aquifer via discharge to the river Raba.

Water enters the aquifer as:

- direct recharge,
- inflow from the adjacent Miocene sediments at the valley sides and,
- leakage from the pond.

Water leaves the aquifer via discharge to the Raba river.

5. Modelling

Groundwater Vistas, MODFLOWwin32 and MT3D were used to model flow of groundwater and chloride in the area around the site. The aims of this modelling were

Fig. 6. Conceptual model of salt and water sources for the alluvium.

Ryc. 6. Model ideowy dopływu solanki do aluwiów.

to test the concepts developed in sections 3 & 4 against real data, and to convert these theories into a quantitative assessment of chloride discharge.

The site was modelled as a two layer system with the confined, low hydraulic conductivity Miocene forming the lower layer, and the higher hydraulic conductivity partially unconfined sandy alluvium forming the upper layer. The overlying low hydraulic conductivity alluvium was not modelled. Northern and southern boundaries approximate to flow lines and were modelled with no flow. The eastern boundary is the Raba river, modelled as a river with a thin, high hydraulic conductivity bed. The western boundary is the effectively infinite Miocene strata. This was modelled using a general head boundary adjacent to an area of recharge, creating a groundwater mound. During calibration, water levels in this area were kept close to ground level as would be expected for a low hydraulic conductivity layer. There was also a large saline pond in the northern half of the site. This was modelled using general head boundaries with concentrations set at the levels determined by sampling. Other sources of chloride included recharge on the site (where salt was present in the soil), and two single general head boundary points designed to model point sources due to deep brine connections.

Piezometric levels, pond discharge and river level for the calibration of the steady state model were all levels measured on June 26, 1996.

5.1. Groundwater flow modelling results

Steady state modelled groundwater levels correlate very closely with groundwater levels measured on site. In most cases the residual is similar to the accuracy of levelling and so further improvements would be of little value (Fig. 7 and Fig. 8).

As flow to the alluvium through the Miocene is a relatively small percentage of the total flow, the model is largely insensitive to variations in hydraulic conductivity and recharge to the lower (Miocene) layer where it is exposed on the valley sides. These can therefore be altered together over a wide range of values whilst still maintaining calibration. The model was rather more sensitive to changes in the amount of water supplied by the pond in the northern half of the site. With no past data on the flow of water in and out of this pond, long term transient modelling of the aquifer was impossible. Little was known about the actual recharge to the site, however this again could be altered together with recharge and hydraulic conductivity of the Miocene, to allow calibration over a range of values.

5.2. Contaminant modelling results

Transient chloride transport was modelled on the steady state groundwater model. Four chloride sources were used, two point sources representing deep brine connections, surface salt dissolution (modelled as saline recharge) and the saline

Fig. 7. Calibration for flow model.

Ryc. 7. Kalibracja modelu dopływu.

Fig. 8. Modelled water levels in the alluvium on site. Figures indicate the difference between modelled groundwater levels and measured groundwater levels (in m).

Ryc. 8. Model zwierciadła wód podziemnych. Liczby oznaczają różnice między wartościami uzyskanymi z modelu a wartościami rzeczywistymi (w m).

northern pond. The model was run for a period of 10 years with active input from all sources except the second deep brine connection. This was done to simulate steady state conditions, after 28 years of activity at the site. Then the second (western) deep brine source was activated to fit with the present situation. (see section 3.2.2).

Modelled chloride flux to the river was 2.9 tonnes per day. Travel time for the contaminant to reach the river from the centre of the site is around 5 years. The closest match between modelled and observed chloride concentrations was achieved after the simulation had run for 3 years.

Modelled chloride concentrations correlate well with observed data despite the fact that the plume has a relatively complex shape and concentrations vary over a wide range (Fig. 9 and Fig. 10). Poorer correlations occur in certain sample sites in the west of the site where observed concentrations were higher than modelled. This area is upgradient of chloride sources presently identified, so another separate source must be interpreted. One possible explanation of the high measured chloride concentrations may be the proximity of this area to the main brine pipeline to Kraków. Leakage from this pipe has been reported.

Fig. 9. Calibration for chloride concentration model.

Ryc. 9. Kalibracja modelu koncentracji chlorków.

5.3. Modelled river - groundwater interaction

The model was used to test the theory proposed in section 3 that discharge of saline groundwater is confined to periods of low river flow. Initial heads were taken from the steady state model described earlier. Initial concentrations were set at those modelled for the current situation on site. The flow model was then modified to make the river transient with river levels interpreted from records of flow rate and stage at Proszówki. The period chosen was between 3/4/94 and 12/5/94, because this represented a period when the river level was elevated for a relatively long time followed by baseflow recession to a relatively low flow. The results of this modelling are shown in Figure 11.

The model results show that the flux of salt to the river is very sensitive to fluctuations in river level. Around day 30, an increase in river level of only 10 cm caused the chloride flux to halve. Larger changes in level towards the beginning of the modelled period halted discharge completely.

At peak flood, the hydraulic gradient between river and aquifer is clearly reversed. Groundwater flowing from the centre of the site that would normally be discharged to the river, is instead held in storage in the aquifer. As the river level subsequently falls, the hydraulic gradient into the river is restored and the stored water (with chloride) is released. Thus after periods of flood, discharge can increase to up to three times the steady state flux of 2.9 tonnes per day.

Fig. 10. Modelled chloride concentrations for June 1996.

Ryc. 10. Model koncentracji chlorków w czerwcu 1996 r.

Concentrations were calculated using the observed flow rate and the modelled chloride flux (assuming originally clean river water). Obviously they follow a similar relationship to flux but increase dramatically at low river flows. Despite this the highest concentration calculated in the modelled period was only 6.5 mg l^{-1} Cl^{-}. Although the absolute values of modelled chloride concentration in river water are significantly less than those measured at Proszówki, trends in the modelled values correlate well (Fig. 12).

The dashed line in figure 12 is a plot of modified chloride concentrations, made to fit the observed concentrations as closely as possible. After a background chloride concentration was added (13 mg l^{-1}, typical of the values measured at Dobczyce, 24 km upstream), the modelled flux was still found to be 2.5 (lower than the observed figure.

It must be remembered that of the time elements in this model recharge (m d^{-1}), conductance of the pond bed (m^2 d^{-1}), discharge (m^3 d^{-1}) and hydraulic conductivity (m d^{-1}), only hydraulic conductivity has been measured. The model is thus scaled with respect to time, by a single figure whose source is not reliably known (this figure was provided as an average of several measured values). Chloride concentrations in the river (related to chloride flux and therefore groundwater discharge) give another time dependent parameter that can be used for calibration in a transient model. The use of this data as a calibration tool relies on site discharge being a major control on river

Fig. 11. Modelled discharge to river during high flow.

Ryc. 11. Model dopływu chlorków w czasie wysokich przepływów rzecznych.

Fig. 12. Comparison between modelled chloride concentrations and measured chloride concentrations in Raba at Proszówki.

Ryc. 12. Porównanie między modelowanymi a rzeczywistymi koncentracjami chlorków w Rabie w profilu Proszówki.

water chloride concentrations (above background). Close correlations between modelled and measured concentrations suggest that this is the case. It is therefore possible that a scale increase in time is required in the model.

This „corrected" concentration fits well with concentrations observed at Proszówki. During the initial flood, measured concentrations are higher than modelled. This seems reasonable as the increased suspended load of the river, derived from erosion, may constitute an extra source of chloride. Occasional one off peaks also occur in the observed data that are not present in the model (Fig. 12, day 7 and day 24), possibly due to isolated discharges to the river from other sources. Finally during the last 10 days concentrations are consistently modelled 10 mg l^{-1} below the observed values. Reasons for this are unclear as this is the time when groundwater discharge is expected to be the main source of salt. River bottom elevations, river bed thickness and hydraulic conductivity, aquifer thickness beneath the river and aquifer storage may all be important, but in the absence of any data all these parameters were estimated. It is likely that correlations could be improved with the adjustment of one or more of the estimated parameters.

Although chloride discharge from the site does seem to control peak chloride concentrations in the Raba, it should be noted that flow from the site still represents less than 15% of the Raba's total chloride load. This agrees well with the estimations of a maximum of 20% made in section 3.

5.4. Prediction

The steady state groundwater model was run with transient transport until chloride concentrations across the site were in a steady state. This time was around 4 years after the modelled concentrations matched observed concentrations and 7 years after the activation of the eastern salt source.

Modelled chloride discharge to the Raba river for the year 2000 (when steady state was reached) was 5.9 tonnes per day (without adjustment), double the modelled discharge for the present day. Modelling also indicated that the positioning of current piezometers monitored on site means that this increase is unlikely to be detected.

Future discharges are likely to be strongly influenced by the development of new deep connections to brine sources beneath the site. It is expected that these will occur with continued subsidence and the deterioration of the site, however their location and size can not be predicted so they have obviously been left out of the model. Because of this the predicted discharge stated above is an optimistic estimate.

5.5. Analysis of modelling results

Short term transient modelling of chloride discharge from groundwater related to river level was able to simulate the observed trends in river chloride concentration. In view of the accuracy of this correlation, it would seem that most of the salt in the river in excess of background, does come from the Łężkowice site. If this is the case, then the model underestimates groundwater flow and therefore chloride flux by a factor of 2.5. This interpretation is supported by the analysis of daily chloride flux measurements in the Raba. These figures suggest that 9.1 tonnes of the 41.6 tonnes of chloride carried by the Raba each day are attributable to groundwater discharge, most of which is probably from Łężkowice.

Groundwater flow on the site itself is controlled by hydraulic gradient, saturated thickness and hydraulic conductivity. As the first two are mostly dependent on groundwater levels and these are well calibrated on site, they are unlikely to be in error. The third term, hydraulic conductivity, was taken directly from averages of pumping test analysis performed by the mine. No information on the method of testing, the test results or the form of analysis is available and it would seem that this data is not necessarily reliable. One source of error may be the assumption of confined aquifer conditions, leading to an underestimate of hydraulic conductivity.

By introducing a factor of 2.5 into the time elements of the model, (increasing hydraulic conductivity, conductivity and flow rates) it should be easy to recalibrate the model to fit the observed chloride flux in the river. This would also result in the shortening of travel times on the site by the same factor.

The average discharge of chloride to the river Raba was estimated by the model at 2.9 tonnes per day. Travel times from the centre of the site to the river Raba were estimated as 5 years. If the hydraulic conductivity of the site is 2.5 times greater then these figures would change to 7.25 tonnes of chloride per day and 2 years respectively. Predicted flux in the year 2000 would be around 14.7 tonnes of chloride per day.

It should be remembered that the accuracy of the model depends on the data input. In order to estimate the flux of salt to the Raba more accurately, accurate values of hydraulic conductivity and its variation in both the alluvium and the Miocene would be required. In addition, better estimates of recharge to both layers would allow determination of the proportions of flow from each source of water. A fully transient model would be far more sensitive to the various parameters and may even yield a unique solution. To develop such a model more historical information about flow to and from the northern pond would be required.

In this study, the model has achieved its purpose. An estimation of chloride discharge from the site has been made, and the site has been identified as the major control on low flow salt concentrations in the Raba. If salt concentrations were to reach problematic levels then further investigation of the site would be required.

6. Conclusions

Three main salt sources are present on site.

The first is a large pond to the north of the main road which is in hydraulic continuity with the alluvial aquifer. This pond receives saline water from a stream draining a pumping station on the main brine pipeline to Kraków just west of the site.

The second is salt present in the soil and unsaturated zone which is washed down to the alluvium by rainwater during recharge events. This source is probably present across most of the central area of the site.

The third source forms two well defined plumes on the site believed to be emanating from two point sources, flowing in a northeast direction, towards the Raba river (see Fig. 10). Concentration distributions and modelling point to the presence of two point sources, one in the west around grid reference 581025 394275 and another around grid reference 581625 394175. Past observations suggest that the eastern plume has only recently become active and is of a far higher concentration. If the sources of these plumes are broken borehole casings and subsidence-induced fractures then they are directly related to the degradation of the site. With time, the site will degrade further and more sources may develop. Model prediction based on the development of the eastern source suggests that discharge will double in the next few years, but this estimate is considered conservative as it takes no account of additional, as yet undiscovered brine connections.

The average discharge to the river Raba is estimated at around 8 tonnes of chloride per day. During the period modelled, this discharge from the Łężkowice site only accounts for 15% of the total salt load of the Raba river, however the timing of the discharge is highly dependent upon the river level. Modelling of river - groundwater interactions indicate that saline water flowing from the site may be stored in the aquifer until the river is most vulnerable, i.e. at low river flows. Peak discharges can be as high as 3 times the average. This relationship means that discharge from Łężkowice may still control peak chloride concentrations in the river.

Previous calculations significantly underestimate salt discharged to the Raba via groundwater, but the flow of salt from the Łężkowice site does not present a serious threat to public abstraction from the river at the present time. However the nature of the sources of salt on site are such that the problem is likely to become worse rather than better in the foreseeable future.

7. Recommendations

Travel times for contaminated groundwater from the centre of the site to the Raba river are approximately 2 years, so advanced warning of problems should be possible by monitoring groundwater conductivity.

A geophysical conductivity survey on and around the site, could identify developing salt plumes which are not presently intersected by piezometers. Results of this survey would give some indication of the number and locations of new sources and hence give advanced warning of future problems. With highly saline water occurring within a sandy aquifer at a depth of between 5 and 12 m, the site is ideal for such a survey. The only possible hindrance to a conductivity survey may be the presence of iron pipework on site.

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References

Garlicki A. (1993): *Solution mining of Miocene salts in Poland and it's environmental impacts*, Seventh Symposium on Salt, Vol. I, pp 419-424, Elsiever Sci. Publ.B.V., Amsterdam.

Ney R. et al. (1974): *Outline of Paleogeography and evolution of lithology and facies of Miocene layers on the Carpathian foredeep*, Prace Geol., 82.

Poborski, J. (1952): *Złoże solne Bochni na tle geologicznym okolicy*, Biul. Państw. Inst. Geol., 78.

Hydrogeologiczna ocena skutków eksploatacji solanki w Łężkowicach koło Bochni (Pogórze Karpackie)

Streszczenie

W 1991 r., 23 lata po rozpoczęciu, zaprzestano eksploatacji solanki w Łężkowicach koło Bochni. Skutkiem tej eksploatacji jest zasolenie płytkich wód gruntowych oraz gleby. Ukształtowanie zwierciadła płytkich wód podziemnych wskazuje na bezpośredni dopływ solanki do pobliskiej rzeki Raby, stanowiącej ważne źródło zaopatrzenia w wodę.

Badania koncentracji chlorków w wodach gruntowych wraz z pomiarami położenia zwierciadła pozwoliły na stwierdzenie dwóch ognisk zasolenia. Pierwszym - jest sól pozostała na powierzchni terenu i w glebie, która po opadach jest rozpuszczana i wymywana do wód podziemnych. Drugim - jest dopływ solanki z większych głębokości. W celu oceny wielkości tego dopływu zastosowano metodę podobną do metody ścięcia fali wezbraniowej przy wydzielaniu odpływu podziemnego.

Badania modelowe wykazały, że znaczny dopływ solanki do Raby następuje przede wszystkim w czasie niskich stanów wody w rzece, a więc wtedy, gdy Raba jest najbardziej podatna na zanieczyszczenie. W czasie trwania stanów wysokich dopływ solanki jest niewielki lub całkowicie ustaje. W miarę osiadania terenu dopływ solanki może się zwiększyć.