ARCHIVES OF ENVIRONMENTAL PROTECTION

vol. 40 no. 4 pp. 87 - 99 2014

DE GRUYTER

PL ISSN 2083-4772
DOI: 10.2478/aep-2014-0041

THE INFLUENCE OF DRAINAGE WELLS BARRIER ON REDUCING THE AMOUNT OF MAJOR CONTAMINANTS MIGRATING FROM A VERY LARGE MINE TAILINGS DISPOSAL SITE

ROBERT DUDA

AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection
al. A. Mickiewicza 30, 30-059 Krakow, Poland
Corresponding author's email: duda@agh.edu.pl

Keywords: mining waste, tailings, disposal site, wells, barrier, vertical drainage, contamination, effectiveness, Żelazny Most.

Abstract: The subject of the research is one of the largest World's mine tailings disposal sites, i.e. Żelazny Most in the Legnica-Głogów Copper Mining District (south-western Poland), where flotation tailings are poured out after copper ore treatment. The protective hydraulic barrier made of 46 vertical drainage wells was characterized and evaluated in view of reduction of major contaminants (Cl, Na, SO_4, Ca) migrating from the facility to its foreground. The efficiency of groundwater protection was determined on the basis of a new approach. In applied method the loads of characteristic and commonly recognizable compounds, i.e. salt (NaCl) and gypsum ($CaSO_4$) were calculated, instead their chemical components. The temporal and spatial variability of captured main contaminants loads as well as its causes are discussed. The paper ends with the results of efficiency analyses of the barrier and with respect to the predicted increase in contaminant concentrations in the pulp poured out to the tailings site.

INTRODUCTION

The tailings disposal sites, especially the ones with non-insulated bottom, create a hazard for soil and water environment in their vicinity [10, 11, 13, 19]. The risk related to the mining waste disposal sites, mainly the flotation tailing sites, is additionally connected with the applied wet technology of deposition, composition of waste and its volume [8, 11, 13].

Vertical hydraulic barriers in the form of cut-off walls [2, 10] and abstraction wells are used for groundwater protection or remediation. The application of a leachate-proof barrier of wells along the border of the source of contamination has been described by [3, 10, 18].

Prior to undertaken activities aimed at groundwater protection the efficiency of the applicable methods was modelled as this method allows for various scenarios to be evaluated based on a temporal and spatial analysis. The following efficiency criteria of the barrier operation are most frequently assumed in the modelling (i) time after which the aquifer will be remediated, and (ii) area of plum contamination migrating in the aquifer [1, 5, 7, 14, 17, 22]. For the reason of comparing the efficiency of various ways of groundwater protection with the wells barrier, other quantitative criteria can be used, e.g. relative evaluation making use of a productivity parameter, which is the ratio of cumulative mass of contaminant captured from an aquifer in a specified time to total volume of groundwater abstracted to remove the mass [14]. Another criterion is the absolute mass of contaminant in the leachate, removed from an aquifer in a specified time.

The aim of this work is twofold: firstly, to suggest a new quantitative criterion for evaluating the effect of drainage wells barrier on reducing the amount of contaminants transported in groundwater from the facility towards the nearby streams, and secondly, to use that criterion for assessing the influence of the wells barrier on groundwater protection in the vicinity of Żelazny Most disposal site during its twenty-years activity (1991−2010).

The main pollutants frequently threatening the quality of water environment in the vicinity of most of the mine tailings disposal sites are chlorides (Cl^-), sulphates (SO_4^{2-}) and sodium (Na^+), as they occur in highly concentrated leachates seeping through tailings to the aquifer in the facilities bedrock. Their loads in leachates captured by the wells are usually applied as an effectiveness parameter of the hydraulic barrier. However, to increase the clarity of observation and interpretation of ecological effectiveness of the protective barriers, the author proposed a novel approach. In this method it was the loads of characteristic and commonly recognizable compounds, which were quantitatively evaluated, instead of the loads of the constituent chemical components. In this case it was the salt (NaCl) and gypsum ($CaSO_4$). This type of alternative parameter of water protection effectiveness evaluation is very important when disseminating knowledge about the anthropogenic impact on groundwater quality and feasible protective measures [12, 15], as well as the undertaken effectiveness activities, especially when contaminations are emitted by very large sources over long periods of time.

MATERIALS AND METHOD

Characteristics of the research scope

Żelazny Most, the subject of the research, is world's second largest copper tailings disposal site where copper floatation tailing pulp is deposited in wet technology. The facility is located in the Legnica-Głogów Copper Mining District (LGOM) in the south-eastern Poland. It covers an area of 13.94 km^2, and the dams surrounding the site extend to 14.3 km [4, 11]. In 2010 waste discharged there amounted to about 480 million m^3. The waste disposal facility characteristic, especially the geotechnical aspects of the design and construction are described by [8]. The groundwater protection problems in the vicinity of this waste disposal site and results the groundwater monitoring obtained by geophysics methods are presented in [9]. The environmental impact on vegetation and soil was analyzed by [6].

The facility does not have any ground insulation, which results in tailing leachates polluting the Quaternary aquifer [7, 11]. The natural hydrodynamic conditions of the site area cause that contaminants are transported in groundwater from the disposal site mainly towards the eastern and western foregrounds (Fig. 1), as well as northern, yet in the latter case with a slightly lower intensity which results from the geological structure of the analyzed site. The degree to which groundwater and surface water in the vicinity of the facility are contaminated is related to the use of highly saline water from mine drainage used for hydro-transport of tailings. Sludge supernatant water gathering in a central part on the deposition site is indicative of high concentration of chlorides amounting to 12,400 mg/dm^3 and sulphates (on the average 2,950 mg/dm^3) [16]. The supernatant pond water also contains heavy metals and microelements associated with copper ores processing, i.e. detergents, phenols, cyanides and xanthene's [4]. The presence of heavy metals and toxic substances in the pond water creates an additional hazard. This impact is retarded by the sorption processes accompanying the effluent leakage through tailings [11].

Numerical predictions of chlorides transport in groundwater near the facility have shown that technical protection is necessary to limit the groundwater pollution zone within the facility's infrastructure [7, 20]. In order to capture and reduce the outflow of leachates from the disposal site, different types of horizontal drainage and a vertical drainage wells barrier were used (Figs 1 and 2). The wells decrease a groundwater head near the dams; in some areas the original groundwater flow directions are restored (i.e. preceding the construction of the facility in 1977). The concept of a vertical drainage wells barrier system was presented by S. Witczak in 1986 in his unpublished work, and then supplemented in [20].

Systematically expanded since 1991 (Table 1), the wells barrier near the facility has become an integrated part of a comprehensive drainage system capturing saline water seeping through tailings. At the end of 2010, the barrier consisted of 46 active wells: 20 wells along the eastern dam, 10 wells along the northern dam and 16 wells along the western dam and its foreground [16].

Method

The loads of major contaminants captured by the wells barrier, NaCl and $CaSO_4$ loads were evaluated on the basis of annual calculations performed in the years 1991–2010. The source information was acquired from the SYZEM database (SYstem ZElazny Most), which contains monitoring data of the facility and groundwater in its vicinity [16].

The first stage involved calculation of average daily concentrations of Cl, Na, SO_4 and Ca in particular wells and average daily wells discharges. Although concentrations of Na, Cl, Ca, SO_4 in discharged water varied in time, they were measured only a few times a year. For the sake of simplicity, it was assumed that the concentrations of particular ions in groundwater were constant between measurements; they were additionally taken to be the mean values of two consecutive measurements.

Discharges of individual wells also varying in time. In order to obtain an annual average of wells discharges, the values of pumped out water indicated by water meters was subtracted from the values measured at the end of year, then divided by 365, as a result of which a daily discharge of wells was obtained.

The methodology used for calculating NaCl and $CaSO_4$ loads was given on the example of NaCl. An analogical approach was used for calculating $CaSO_4$ load. The Na and Cl concentrations in leachates captured by wells, expressed in mg/dm^3 were converted

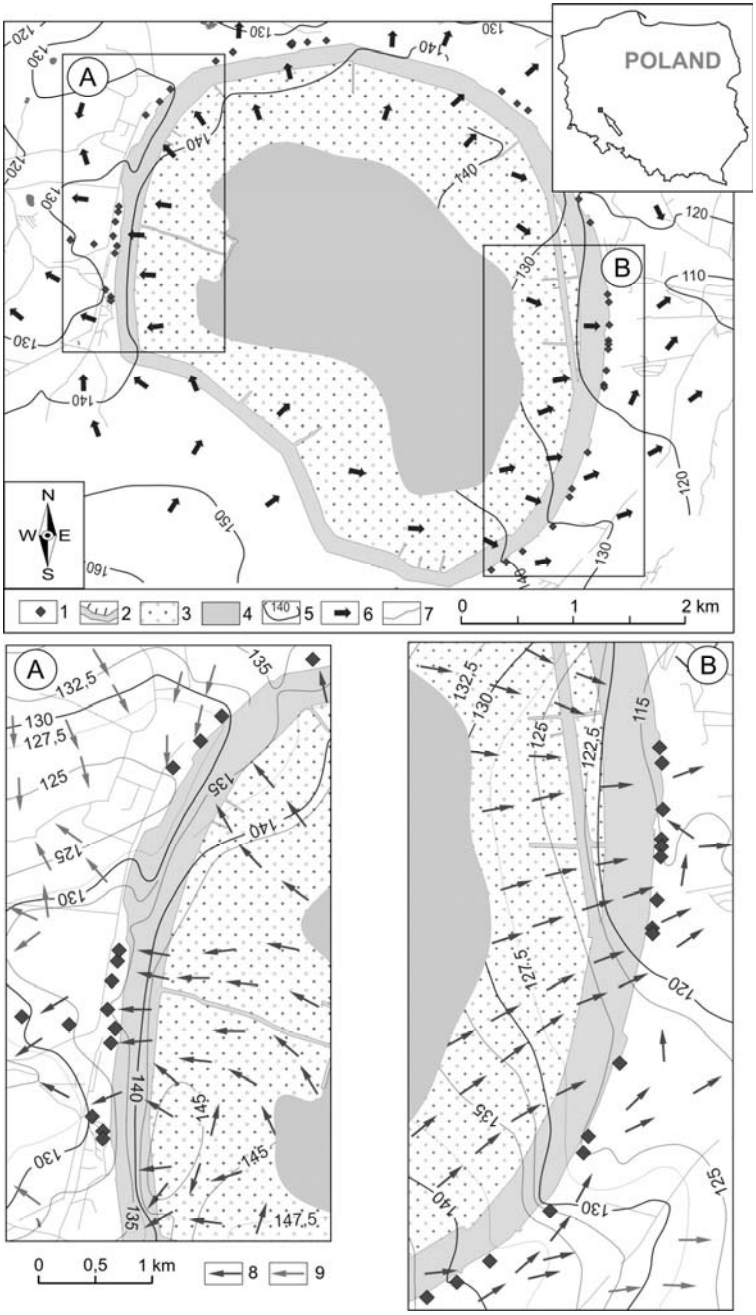

Fig. 1. Żelazny Most tailings disposal site and a wells barrier: 1 – drainage well, 2 – dam, 3 – tailings, 4 – sludge supernatant pond, 5 – contour line of groundwater head, 6 – main directions of groundwater flow in the Quaternary porous aquifer, 7 – water courses, 8 – flow directions of contaminated groundwater in aquifer, 9 – flow directions of fresh groundwater, A, B – fragments of western (A) and eastern (B) part of the disposal site and its foreground

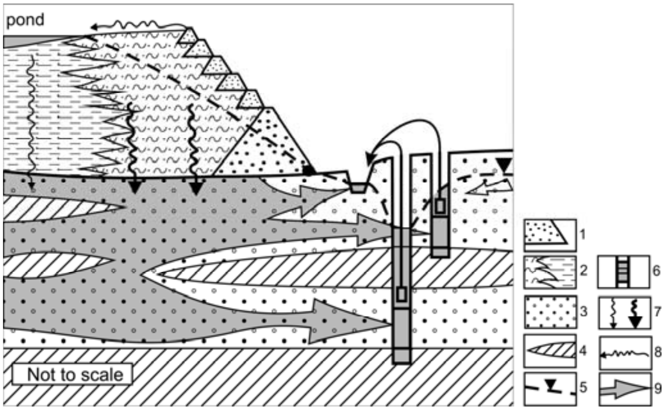

Fig. 2. Model of capturing contaminated groundwater by a drainage wells barrier (after [21], modified): 1 – dam, 2 – tailings, 3 – sandy deposits, 4 – low permeable deposits, 5 – groundwater head, 6 – drainage well, 7 – saline water seepage through tailings, 8 – tailings silting up, 9 – directions of contaminated groundwater flow in aquifer

Table 1. Expansion of vertical drainage wells barrier near the Żelazny Most mining waste facility before 2010 (after [16])

Dam	Number of used wells						
	1991	1993 1994	1998 1999	2000 2001	2002 2003	2007	2010
eastern	3	2	3	6	5		1
western	2		3	2	2	3	4
northern	1		5	3			1

into Mg/m^3, and then divided by their molar masses. For each value obtained in this way, a smaller value determined for Na and Cl was substituted in formula (1).

$$C_{NaCl} = (c / m) \cdot M_{NaCl} \tag{1}$$

where C_{NaCl} – NaCl concentration, c – Na or Cl concentration, m – molar mass of Na or Cl, M_{NaCl} – molar mass of NaCl.

The average daily NaCl load captured by an individual well was calculated by multiplying NaCl concentration value by an average daily well yield. Then, the load was multiplied by 365 and the annual NaCl load captured by a well was obtained. Apart from this, wells discharge values and major contaminant loads per single well were calculated for individual years as the arithmetic mean of yields and NaCl and $CaSO_4$ loads specified for all active wells in a given year.

RESULTS AND DISCUSSION

Major contaminants load captured by the barrier

Figure 3 shows Na and Cl loads expressed as NaCl, as well as SO_4 and Ca loads expressed as $CaSO_4$ compounds captured within a year by drainage wells barrier near the facility in the years 1991–2010 versus saline water volume abstracted annually. Within 20 years the wells barriers captured as much as 53,069,915 m^3 of saline leachates from the disposal site. The accumulated NaCl and $CaSO_4$ loads amounted to 363,523 Mg and 119,097 Mg, respectively. In terms of volume, this would correspond to 165,091 m^3 and 49,194 m^3, respectively. These immense quantities of contaminations were captured by the barrier, and thus the negative impact on water environment in a function of time (Fig. 3) and in a function of space (Fig. 5, Table 2) could be notably reduced.

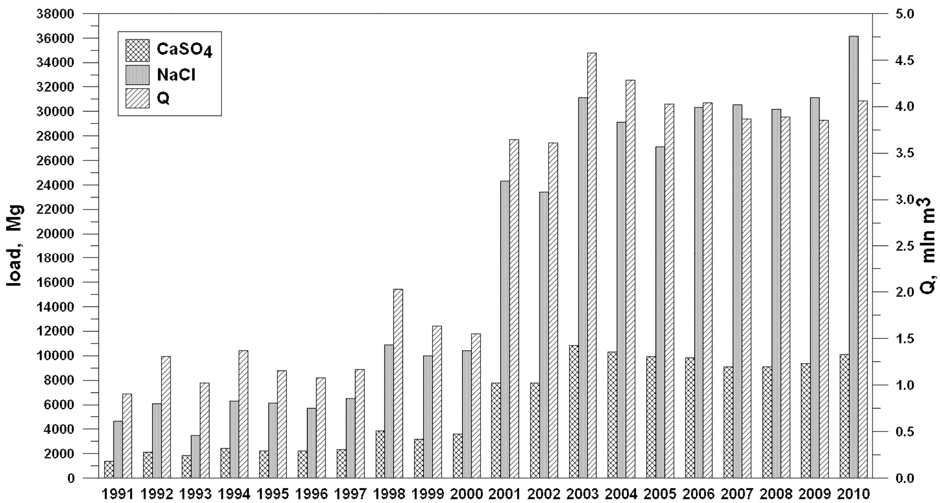

Fig. 3. Time series of chlorides and sodium loads as NaCl and sulphates and calcium as $CaSO_4$ captured yearly by the wells barrier near the facility, and abstracted saline water (Q)

With time the amount of highly polluted leachates pumped out annually systematically rose from 904,840 m^3 in 1991 to over 4,000,000 m^3 in the years 2005–2010. This fourfold increase was mainly caused by a systematic growth of the number of wells in the barrier, particularly in 1998, 2001 and 2003 (Table 1). As a consequence, between the barrier's offset in 1991 and 2010, one could observe an almost eightfold increase the NaCl load captured by the barrier each year. The correlation between the mass of contaminations captured annually and the amount of water abstracted by wells is presented in Fig. 4.

After the year 2005 the abstracted saline water volumes stabilized as the wells reached their maximal possible yields attainable in given hydrogeological conditions of the facility area. However, the load of major contaminants captured by the barrier, especially chlorides, is still significantly growing. The amount of NaCl removed in 2004 (29,140 Mg) increased to 36,130 Mg/year in 2010. The yearly yields of the entire

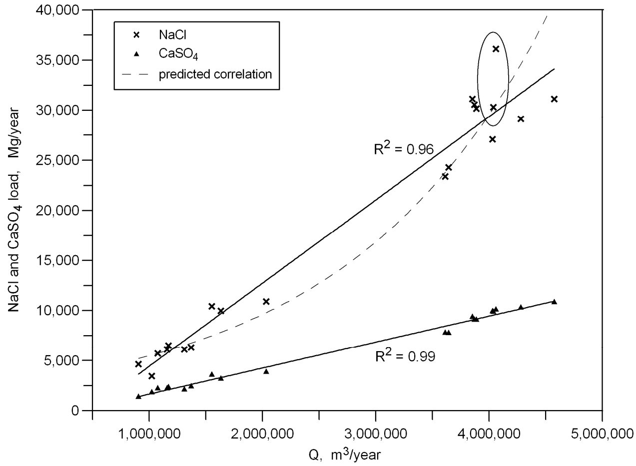

Fig. 4. Chlorides and sodium loads as NaCl and sulphates and calcium as $CaSO_4$ captured by the wells barrier near the facility vs. abstracted saline water (Q)

barrier equalled to 4,281,127 and 4,059,492 m^3 of saline water, respectively, as marked in Fig. 4. This signifies that the drainage system recently captured leachates in which contaminants concentration was increasing. The causes are twofold. At the initial stage of barrier operation, some wells were capturing leachates where chloride and sodium concentrations were lower than in the pulp poured out in the facility. This retarding was due to the time needed for water to seepage through the mass of low permeable tailings, then hydrodynamic dispersion of contaminants transported in groundwater to the wells, especially the deeper screened ones, i.e. at the depth of 30–50 m. This complex process was visualized in a conceptual model showing how the contaminants are migrating and then are captured by the barrier (Fig. 2).

The second cause is related to the recently observed significant increase in chloride concentrations in mine water transported from cooper mines to the facility. The chlorides concentration in sludge supernatant pond doubled from about 6,000 mg/dm^3 in 1994 to about 12,400 mg/dm^3 in 2010 [16]. At that time the yearly chlorides and sodium load (as NaCl load) captured by wells increased from 6,314 Mg to 36,130 Mg, i.e. almost six times, whereas the annual amount of abstracted saline water from 1,369,852 m^3 to 4,059,492 m^3, i.e. only three times. The chlorides concentrations may be expected to be growing in the future due to the intense mining activity in deep-lying copper deposits located in the northern part of the LGOM and, consequently, inflow of more saline groundwater. Therefore, the predicted correlation between the captured load and the amount of water abstracted through the wells, which will remain on a similar level as now, may take a form of an exponential function. This was represented with a dashed line in Fig. 4. However, this dependence should be confirmed by modeling based on assumptions made with respect to the predicted process.

The increased load of leachates has not been observed for $CaSO_4$. The reason for this is a balance between Ca and SO_4 ion concentrations in sludge supernatant pond and the solubility limit of the mineral from which they are derived. As a consequence,

SO_4 and Ca concentrations in the barrier leachates are constant in time, so the amount of the captured load can increase only if the volume of leachates rises (Fig. 4). This is represented by the stabilized $CaSO_4$ load values, which were incremental only in 1998, 2001 and 2003.

Table 2. Chlorides and sodium loads as NaCl and sulphates and calcium as $CaSO_4$ [Mg] captured in the years 1991–2010 by the wells barrier near the facility and along dams

	Abstracted water [m^3]	Load	
		Cl and Na as NaCl	SO_4 and Ca as $CaSO_4$
Northern dam	10,023,268	71,895	22,697
Eastern dam	26,473,811	183,234	63,137
Western dam	16,572,836	108,394	33,262
Total	53,069,915	363,523	119,097

In terms of spatial distribution, the eastern part of barrier turned out to have the highest, i.e. 50% contribution in main contaminants loads capture (Table 2). The analysis of the efficiency of barrier reveals that the eastern barrier wells captured over 2.5 times more NaCl and $CaSO_4$ loads than their northern barrier counterparts. The observed discrepancy stems from the fact that wells located along the eastern dam were put in operation first, then the western and northern sides were activated. In 1998 the northern part of the barrier started to grow in significance (Fig. 5, Table 1). The second cause of the disproportion is the number of wells located along each of the dams (Fig. 1, Table 1). A dependency between the amount of load captured by the barrier and the number of active wells was illustrated by data of 2001. A rapid growth of captured load was observed after putting in operation additional wells on the eastern side of the facility.

The spatial and temporal variability of the entire loads captured by the wells was neither influenced by local groundwater flow directions and flow rates in the aquifer nor by the variability of recharge – a result of the pulp being poured out on the disposal site. Hydrodynamic conditions remained in a steady-state because the tailings started to be deposited in 1977 and the barrier was operational from the 1990s, i.e. tens of years ago. The tailing masses increased by about 1.3 m each year to reach the average thickness of about 50 m in 2010 [4, 8]. The analysis of modeling results of water percolation through tailings reveals hat the seepage process took place slowly [21]. In the periods between consecutive pouring out, the water was drained off the tailings, though this process lasted longer than the intervals between successive pouring out events in a given part of the deposition site, leading to equalization of the yield of water seepages to the aquifer [21]. As a result of this process, the concentrations of chemical components dissolved in seepage water were spatially averaged. Therefore, the concentrations of contaminants migrating from the whole facility to aquifer depend on the salinity of mine water in which tailings were transported to the site.

Unfortunately the Żelazny Most disposal site cannot be compared with other objects of similar magnitude due to the unavailability of the respective environmental

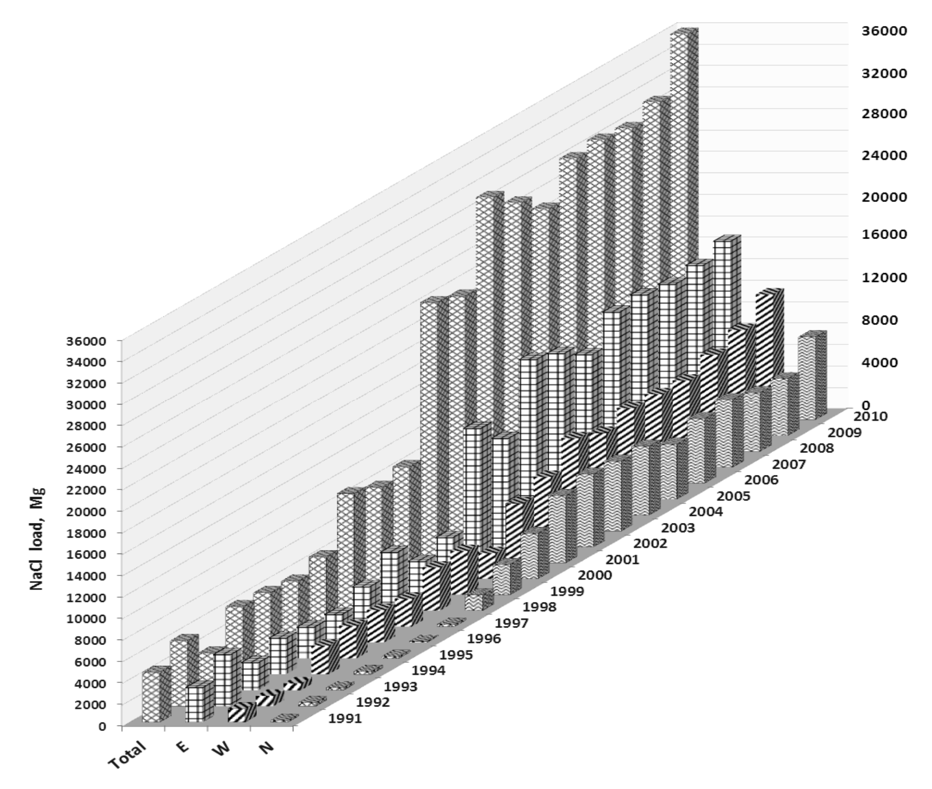

Fig. 5. Time series of NaCl load captured by barrier wells near the facility and along its dams. Total – the whole facility, dams: E – eastern, W – western, N – northern

documentation of such very large objects. What distinguishes Żelazny Most from other large non-hazardous industrial waste disposal sites are the drainage wells barriers, developed for over 20 years. They were applied independently of standard protective solutions, e.g. drainage ditches or drain pipes. The cost of maintenance of a protecting wells barrier is very high therefore typically this solution is used in the pump-and-treat systems for point- and small-scale remediation of groundwater and soil contaminated with toxic substances [3, 5, 10, 17, 18]. However, bearing in mind the results presented in this paper it should be emphasized that despite the costs involved, this method has a great ecological potential and the scale of the benefits flowing from its application goes beyond local.

Major contaminants load captured by a single well

The effectiveness expressed as a yield of a single well is another criterion which can be used for assessing the role of the wells barrier in reducing the amount of major contaminants transported from the tailings disposal site. The evaluation shows that in the years 1991–2010 an average well captured the accumulated load of NaCl and $CaSO_4$ amounting to 12,830 Mg and 4,276 Mg, abstracting a total of 2,345,754 m^3 of the disposal site leachates (Table 3). The annual discharge from a single well decreased from about 180,000 m^3 in the years 1992–1994 to about 95,000 m^3 in the years 2008–2010. However, the environmental impact of an average well doubled in this period from about 400 Mg/year to about 850–900 Mg/year (Fig. 6). This was connected with the increasing content of major components in the captured leachates as a function of time. This confirms that the efficiency of the barrier was systematically increasing.

Table 3. Chlorides and sodium loads as NaCl and sulphates and calcium as $CaSO_4$ [Mg] captured within a year by a single well near the facility compared to saline water abstracted by a single well

Years	Abstracted water, [m^3]	Load		Years	Abstracted water, [m^3]	Load	
		NaCl	$CaSO_4$			NaCl	$CaSO_4$
1991	104 021	291.9	101.8	2001	119 051	792.5	246.6
1992	183 153	391.0	164.3	2002	113 791	729.0	237.0
1993	148 999	294.5	152.5	2003	121 180	840.9	286.7
1994	182 830	499.2	209.0	2004	123 296	852.6	295.8
1995	135 847	482.5	178.7	2005	112 323	794.2	277.1
1996	106 096	449.4	170.6	2006	114 024	922.5	290.1
1997	138 861	478.2	180.0	2007	96 789	859.8	242.0
1998	102 792	514.9	184.6	2008	96 275	830.4	234.8
1999	92 274	561.9	180.0	2009	94 945	849.9	240.6
2000	66 597	472.0	160.5	2010	92 610	921.7	242.9
				Total	2 345 754	12 829.6	4 276.0

Figure 6 illustrates time series of NaCl load changes captured by an average well around the entire facility and in parts of the barrier along the eastern, western and northern dams. The spatial comparison indicates a constant increase of NaCl load removed by an average well in the northern part of the barrier. This may mean that wells along this dam were located in groundwater privileged filtration zones, spanning from the facility towards its foregrounds, and abstracting highly contaminated leachates. Similarly, a rapid increase of NaCl loads captured by a single well near the western dam in 1994 and eastern dam in 2001 confirms that the successive wells were properly located, i.e. on the main pathways of groundwater outflow from the facility to its foreground and nearby water courses.

A decrease in mean NaCl loads received from 2007 by a single well in the western barrier resulted in launching two wells located at a greater distance from the western dam (Fig. 1). As in 2007, the highly contaminated groundwater did not reach this area yet, these wells captured much lower contaminant loads than the remaining wells. The disproportions in the efficiency of wells distributed in different points around the disposal site became smaller in the time function, thus increasing the overall effectiveness of the entire barrier.

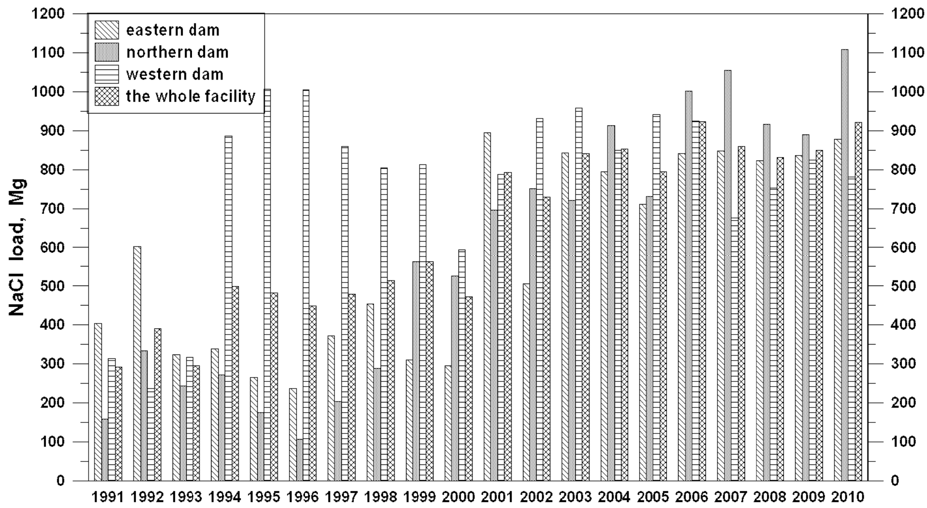

Fig. 6. Time series of NaCl load captured within a year by single well of barrier around the whole facility and in particular barrier parts along the dams

CONCLUSIONS

The results show that the applied novel quantitative criterion of efficiency evaluation of reducing the amount of major contaminants captured by a hydraulic barrier is a good and legible indicator that the assumed ecological objective has been met. A wells barrier fulfils its function by reducing loads of major contaminants migrating in groundwater from Żelazny Most mine tailings disposal facility. It should be emphasized that a significant ecological effect has been produced. However, for small mine tailings disposal sites this way of groundwater and surface water conservation may not be economical due to investment-related costs and maintenance of the barrier infrastructure.

In the future the effect of drainage wells barrier on the reduction the amount of major contaminants loads may grow proportionally to the increase of loads transported to the disposal site. The future operation of the barrier is therefore necessary in the case of such a large source of groundwater contamination.

Further research should focus on evaluation of the expected effectiveness of the hydraulic barriers of the mining tailings disposal sites. It should account for various scenarios of chlorides concentrations in the pulp poured out in the facilities and the number of active wells. To make the results more universal, classifications or some efficiency standards for this type of barriers should be worked out based on the proportion of the major contaminants loads captured by wells to their loads in leachates seepages through the tailings to the aquifer.

ACKNOWLEDGEMENTS

The author thanks the reviewers for insightful remarks and suggestions that improved the quality of this paper. The research work was partly supported under the AGH University of Science and Technology Research Program no 11.11.140.026.

Special words of gratitude go to the management of Hydrotechnical Facility, branch of KGHM Polska Miedź S.A., who gave access to the archival source materials indispensable for this paper and granted consent to publish the results. A. Kiecak and E. Kret are kindly acknowledged for their help during the research works related to the publication of this paper.

REFERENCES

[1] An, D., Jiang, Y., Xi, B., Ma, Z., Yang, Y., Yang, Q., Li, M., Zhang, J., Bai, S. & Jiang, L. (2013). Analysis for remedial alternatives of unregulated municipal solid waste landfills leachate-contaminated groundwater, *Frontiers of Earth Science*, 7, 3, 310–319.

[2] Anderson, E.I. & Mesa, E. (2006). The effects of vertical barrier walls on the hydraulic control of contaminated groundwater, *Advances in Water Resources*, 29, 1, 89–98.

[3] Arlotti, D., Bozzini, R., Petitta, M., Mancini, M., Pianu, M., Alberto Blanco, G., Sbarbati, C. & Colombo, R. (2012). Control and dynamic management of a sixty-seven wells hydraulic barrier, *Chemical Engineering Transactions*, 28, 247–252.

[4] Badura, J., Czmiel, J., Górski, R., Janicki, K. & Król, P., et al. (2007). The Żelazny Most tailings disposal site. in: *The Monograph of KGHM Polska Miedź S.A.*, Piestrzyński, A. (Ed.), Wyd. II, KGHM CUPRUM Sp. z o.o. CBR Wrocław, Lubin, pp. 579–625 (in Polish).

[5] Bayer, P. & Finkel, M. (2006). Conventional and combined pump-and-treat systems under nonuniform background flow, *Ground Water*, 44, 2, 234–243.

[6] Dobrzański, Z., Kołacz, R., Lewiński, J. & Mizera, A. (1992). The impact of copper ore flotation tailings pond to the content of heavy metals in some plant feed. *Archives of Environmental Protection*, 18 (3–4), pp. 135–142 (in Polish).

[7] Duda, R. & Witczak, S. (2003). Modeling of the transport of contaminants from the Żelazny Most flotation tailings dam, *Gospodarka Surowcami Mineralnymi – Mineral Resources Management*, 19, 4, 69–88.

[8] Jamiolkowski, M., Carrier, W., Chandler, R., Hoeg, K., Swierczynski, W. & Wolski, W. (2010). The geotechnical problems of the second world largest copper tailings pond at Zelazny Most, Poland, *Geotechnical Engineering Journal, SEAGS & AGSSEA*, 41, 1, 1–15.

[9] Lasocki, S., Antoniuk, J. & Moscicki, J. (2003). Environmental protection problems in the vicinity of the Żelazny Most flotation wastes depository in Poland, *Journal of Environmental Science and Health, Part A – Toxic/Hazardous Substances and Environmental Engineering*, 38, 8, 1435–1443.

[10] Millano, E.F., Jones, H.V. & Ball, R.O. (1993). Hazardous waste: storage, disposal, remediation, and closure, *Water Environment Research*, 65, 4, 442–452.

[11] Nierzewska, M., Mizera, A. & Lewiński, J. (2007). Environmental impact of the Żelazny Most flotation tailings pond. in: *The Monograph of KGHM Polska Miedź S.A.*, Piestrzyński, A. (Ed.), Wyd. II, KGHM CUPRUM Sp. z o.o. CBR Wrocław, Lubin, pp. 881–921 (in Polish).

[12] Quevauviller, Ph. (2010). General introduction on communication and education needs, [In] Ph. Quevauviller (ed.), Water Systems Science and Policy Interfacing, pp. 305–309, RSC Publishing, Cambridge.

[13] Rosik-Dulewska, Cz., Karwaczyńska, U., Cichy, K. & Wróbel, R. (1998). Assessment of natural environment hazard due to zinc and lead flotation tailings dumped in Piekary Śląskie and wastes after repeated flotation. *Archives of Environmental Protection*, 24 (2), pp. 119–130 (in Polish).

[14] Sawyer, C.S. & Lieuallen-Dulam, K.K. (1998). Productivity comparison of horizontal and vertical ground water remediation well scenarios, *Ground Water*, 36, 1, 98–103.

[15] Stalnacke, P., Nagothu, U.S. & Quevauviller, Ph. (2012). Developing the science-policy interface to integrate water research and management, [In] C. Sessa (ed.), Sustainable Water Ecosystems Management in Europe, from Bridging the Knowledge of Citizens, Scientists and Policy-makers, pp. 7–14, IWA Publishing, London.

[16] SYZEM (2010). SYZEM – the numerical system of information on the Żelazny Most tailings disposal site; the database as of 31 December 2010. KGHM Polska Miedź S.A. o. Zakład Hydrotechniczny, Rudna (in Polish).

[17] Tsanis, I.K. (2006). Modeling leachate contamination and remediation of groundwater at a landfill site, *Water Resources Management*, 20, 1, 109–132.

[18] Vo, D., Ramamurthy, A.S., Qu, J. & Zhao, X.P. (2008). Containment wells to form hydraulic barriers along site boundaries, *Journal of Hazardous Materials*, 160, 1, 240–243.
[19] Wiencław, E. & Garbulewski, K. (1993). Assessment of contamination of water and soils in the Łuków landfill substratum. *Archives of Environmental Protection*, 19 (3-4), pp. 203–220 (in Polish).
[20] Witczak, S. (1995). Drainage of saline water flowing to foreground of Żelazny Most tailings pond – a base of groundwater and surface water protection. in: Proc. of VII Sozological Conference „Environmental problems around the Żelazny Most flotation tailings disposal site. Polkowice, CPPGSMiE PAN Publishing, Kraków, pp. 41–47 (in Polish).
[21] Witczak, S. & Duda, R. (2009a). Groundwater hazard and protection in the Żelazny Most tailings dam area – conceptual model of groundwater flow in tailings dam and its bedrock. *Geologia – Kwartalnik AGH*, Kraków, 35 (2/1), pp. 289–295 (in Polish).
[22] Witczak, S. & Duda, R. (2009b). Groundwater hazard and protection in the Żelazny Most tailings dam area – water environment impact assessment. *Geologia – Kwartalnik AGH*, Kraków, 35 (2/1), pp. 297–304 (in Polish).

WPŁYW BARIERY STUDNI DRENAŻOWYCH NA OGRANICZENIE ILOŚCI GŁÓWNYCH ZANIECZYSZCZEŃ MIGRUJĄCYCH Z BARDZO DUŻEGO SKŁADOWISKA ODPADÓW WYDOBYWCZYCH

Przedmiotem badań jest jedno z największych na świecie składowisk odpadów górniczych Żelazny Most w Legnicko-Głogowskim Okręgu Miedziowym (południowo-zachodnia Polska), na które wylewane są odpady po przeróbce rudy. Scharakteryzowano zabezpieczającą środowisko wodne barierę hydrauliczną składającą się z 46 studni drenażu pionowego i oceniono jej wpływ na ograniczenie ilości głównych zanieczyszczeń (Cl, Na, SO_4, Ca) migrujących z obiektu na przedpola. Efektywność ochrony wód podziemnych określono na podstawie nowego podejścia polegającego na obliczeniu ładunków charakterystycznych i powszechnie rozpoznawalnych związków chemicznych, zamiast ich poszczególnych składników. W tym przypadku były to sól (NaCl) i gips ($CaSO_4$). Scharakteryzowano czasową i przestrzenną zmienność ilości ładunków przejętych studniami i omówiono jej przyczyny. Artykuł zakończono wnioskami dotyczącymi oceny skuteczności bariery na podstawie przeprowadzonych badań i w odniesieniu do przewidywanego wzrostu stężeń głównych zanieczyszczeń w pulpie wylewanej na składowisko.