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Modeling of the transport of contaminants from the Żelazny Most flotation tailings dam

Key words

Groundwater, modeling, mass transport, prediction, flotation tailings

Abstract

The Żelazny Most dam, the biggest industrial dump in Europe, which serves as a recipient of copper ores flotation tailings, has been operating for 25 years. The area of the dam is 14 km^2, volume 315×10^6 m^3, and final volume up to 700×10^6 m^3. The water from the dam seeps into an underlying phreatic porous aquifer. The aquifer is quite heterogeneous, of variable thickness from 1 up to 20 m, including layers of high transmissivity up to 300 m^2/d. Several plumes flow into the aquifer mainly containing chlorides and sulfates. The largest plume extends 900 m downstream of the dam. A two-dimensional regional model for the vicinity of the tailings dam serves as a basic tool for environmental impact assessment, prediction of groundwater pollution and methods of groundwater protection. The model is permanently fitted and calibrated every 4—5 years according to hydrogeological, hydrological and geophysical monitoring. Technologies for groundwater pollution control were developed. The idea is to limit hydraulic outflow from the dam. Series of wells were designed around the dam to modify hydraulic patterns. New water divides are going to develop and restrict movements of pollutants.

1. Hydrogeological characteristic of the dam area

Tailings from the flotation of copper ores in the Lubin-Głogów Copper District (Monografia... 1996) are being collected in the Żelazny Most dam, the biggest industrial dump in Europe. It was constructed in 1977 as a field, open and unsealed dam, located in a natural depression within the Dalkowskie Hills (Fig. 1). The hills are a frontal moraine and the

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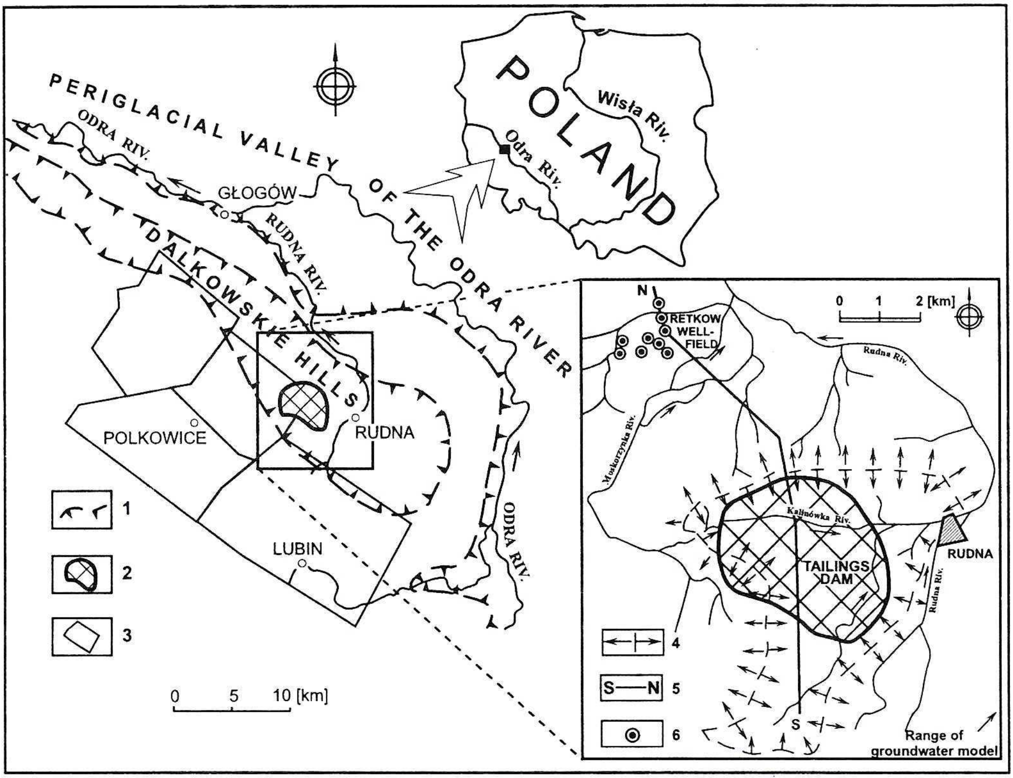

Fig. 1. Localization of the Żelazny Most tailings dam and range of the groundwater model
1 — extent of geomorphological units, 2 — tailings dam, 3 — extent of mining fields, 4 — position of a local watershed prior to the construction of the dam, 5 — the line of a simplified geological cross-section S-N from Fig. 2, 6 — wells of the Retków well-field

Rys. 1. Lokalizacja składowiska odpadów Żelazny Most i zasięg modelu numerycznego wód podziemnych
1 — zasięg jednostek geomorfologicznych, 2 — składowisko, 3 — zasięg obszarów górniczych, 4 — przebieg lokalnego wododziału przed budową składowiska, 5 — linia uproszczonego przekroju geologicznego S-N z rysunku 2, 6 — studnie ujęcia Retków

depression, which is a melt structure, was formed during the glacier recession. Immediately south of the dam area, there is a hill range that is a piled frontal moraine. North of the depression the dam is bordered by glacitectonically piled hill ranges (Fig. 2), separating it from a periglacial valley of the Odra River, further north. The flotation tailings dam is located on land that was used for agriculture and forestry. The area of a hydrogeological model close to the dam belongs wholly to the left-bank catchment of the Rudna River (Fig. 1), a left-bank tributary of the Odra River.

The surroundings of the tailings dam are two areas with different types of geological structure:

— an upland area, situated within the zone of glacitectonic disturbances, confining quarternary and Tertiary strata which form an immediate bedrock of the flotation tailings dam;

— a periglacial valley area, which is probably a glacitectonic depression, later filled by melt and river waters.

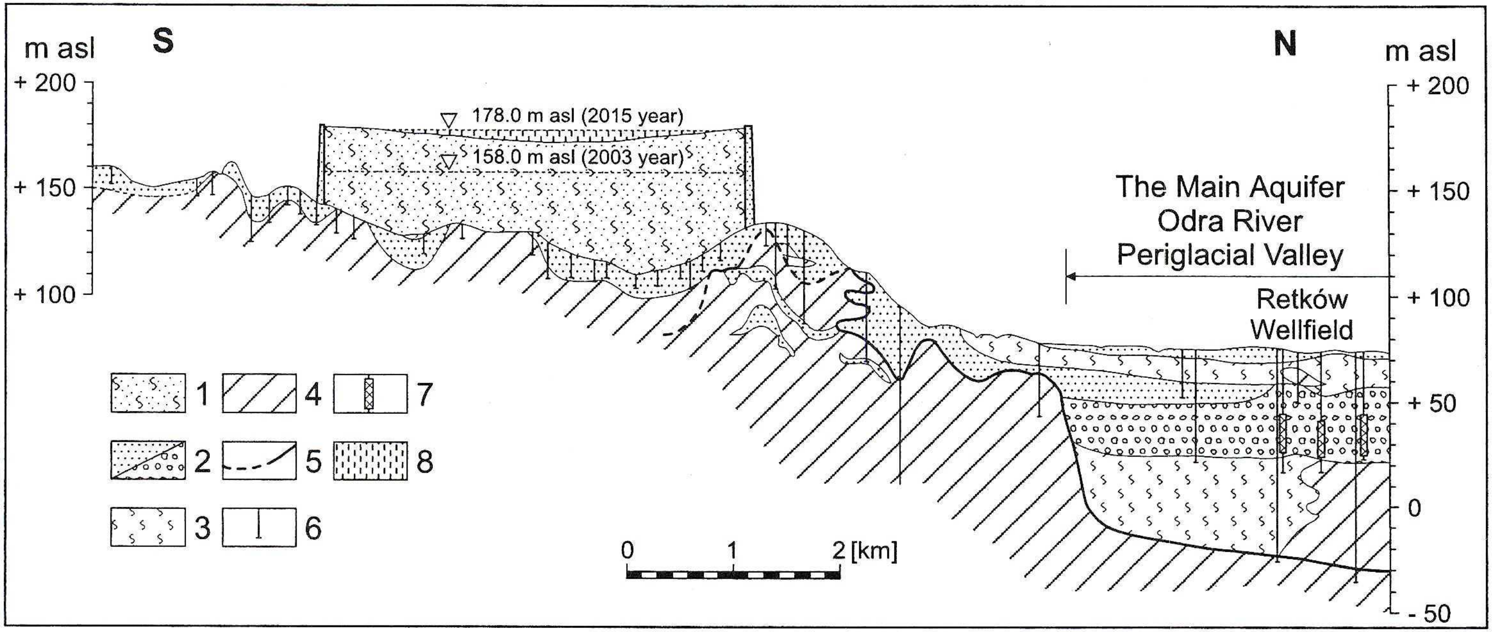

Fig. 2. Simplified geological cross-section S-N (the line of cross-section marked in Fig. 1)
1 — flotation tailings (silts, sandy silts), 2 — permeable strata (sands, sands and gravels), 3 — semi permeable strata (silty and loamy sands, sandy silts), 4 — low permeable strata (loamy silts, sandy loams, boulder clays, clays), 5 — inferred boundary of the top of Tertiary clays, 6 — piezometers and observation boreholes, 7 — wells of the Retków well-field, 8 — pond

Rys. 2. Uproszczony przekrój geologiczny S-N (linia przekroju zaznaczona na rys. 1)
1 — odpady poflotacyjne (pyły, pyły piaszczyste), 2 — utwory przepuszczalne (piaski, piaski ze żwirami), 3 — utwory półprzepuszczalne (piaski pylaste i gliniaste, pyły piaszczyste), 4 — utwory słaboprzepuszczalne (pyły zaglinione, gliny piaszczyste, gliny zwałowe, iły), 5 — przypuszczalna granica stropu iłów trzeciorzędowych, 6 — piezometry i otwory badawcze, 7 — studnie ujęcia Retków, 8 — akwen wód nadosadowych

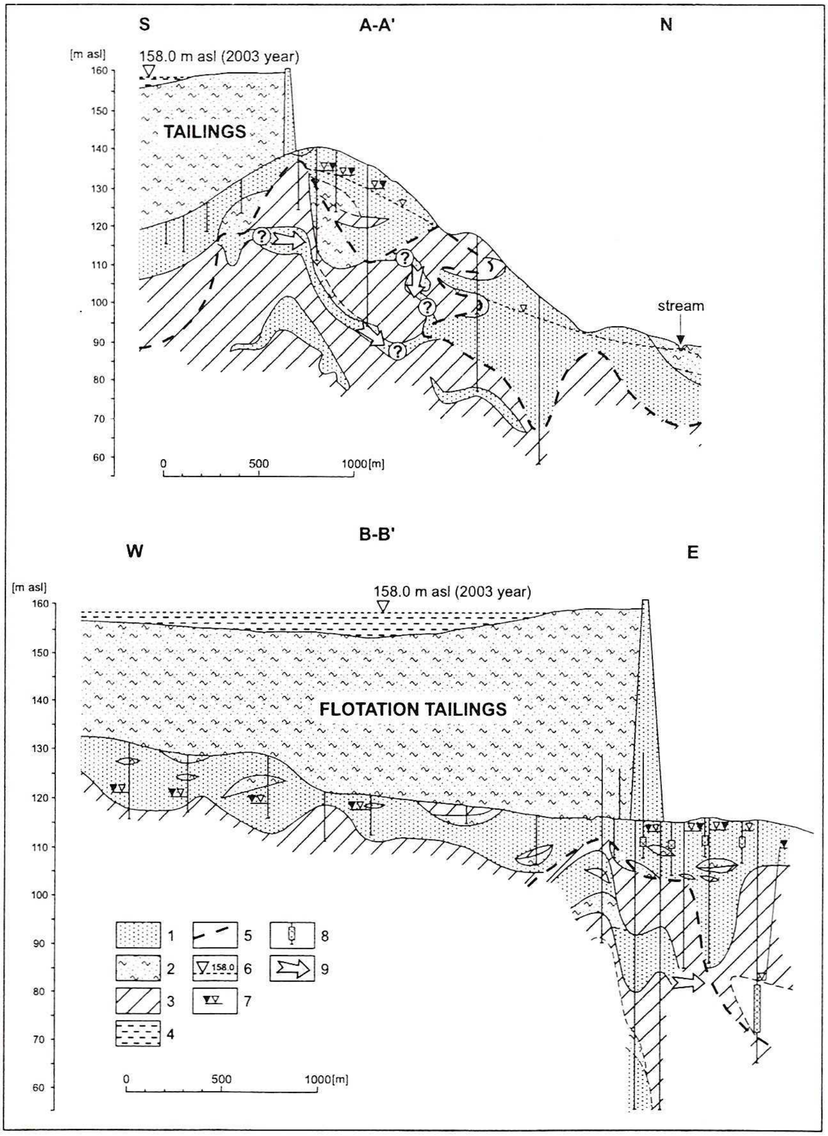

Fig. 3. Hydrogeological cross-sections A-A' and B-B' (the lines of cross-sections marked in Fig. 6)
1 — permeable strata (sands, sands and gravels), 2 — semi permeable strata (silty and loamy sands, sandy silts), 3 — low permeable strata (loamy silts, sandy loams, boulder clays, clays), 4 — pond, 5 — inferred boundary of the top of Tertiary clays, 6 — datum of the pond lifting, 7 — static and dynamic piezometer head, 8 — piezometers, 9 — supposed paths of groundwater flow

Rys. 3. Przekroje hydrogeologiczne A-A' i B-B' (linie przekrojów zaznaczone na rys. 6)
1 — utwory przepuszczalne (piaski, piaski ze żwirami), 2 — utwory półprzepuszczalne (piaski pylaste i gliniaste, pyły piaszczyste), 3 — utwory słaboprzepuszczalne (pyły zaglinione, gliny piaszczyste, gliny zwałowe, iły), 4 — akwen wód nadosadowych, 5 — przypuszczalna granica stropu iłów trzeciorzędowych, 6 — rzędna piętrzenia wód nadosadowych, 7 — statyczne i dynamiczne ciśnienie wody, 8 — piezometry, 9 — przypuszczalne kierunki przepływu wód podziemnych

Glacitectonic forms are very different, from regular folds to scales and caps, composed both of Quaternary and Tertiary strata (Fig. 3). Due to the glacier position, their general strikes follow the E-W trend.

The Quaternary strata are represented by Pleistocene fluvioglacial deposits and Holocene river and valley sediments. Within the upland area, the Pleistocene deposits are considerably differentiated in their thickness and lithologies. They may be from a few to almost 100 meters thick (the latter thickness in local potholes), an average 20—30 m. Boulder clays and fluvioglacial sands and gravels are dominant, while in the periglacial valley the major rocks are sands and gravels 30—40 m thick. The thickness of the Tertiary strata is variable, from 160 m to 400 m, and consists of muds, clays, sands and gravels, with big lenses and layers of brown coal. The Pliocene strata with a thickness up to 150 m rest on top and generally are developed as clays. In the tailings dam area they are strongly disturbed by glacitectonic movements and can be seen out cropping on the surface or close to it.

In the flotation tailings dam area there are two aquifers: the Quaternary, and the Tertiary. The aquifers in question are separated by Quaternary low permeable strata, developed as boulder clays, or by Pliocene clays. The continuity of the clays may be glacitectonically interrupted and then an immediate hydraulic contact of the two aquifers is possible. In turn, extrusions of the clays, as well as older boulder clays, on the surface disturb the continuity of the permeable Quaternary strata. These phenomena result in a relatively strong differentiation of hydrogeological conditions is most important, with respect to the flotation tailings dam, Quaternary aquifer.

Conditions of water migration within the Quaternary strata are strongly differentiated on a regional scale. In the periglacial valley there occurs a big and regular basin of groundwater, recognized as one of the major aquifers in Poland, i.e. the aquifer No. 314 Odra River Periglacial Valley, which should be under special protection (Kleczkowski 1990). It is composed of an aquifer from 30 m to 40 m thick, underlain by an almost impermeable strata. The aquifer is built of sands and gravels with high permeability. The mean hydraulic conductivity is 26.4 m/d. The water-bearing layer is directly recharged by infiltrating rainwater plus surface and underground run-offs from the upland area to the north.

In the area of the moraine upland, lithological variations are complicated by glacitectonic disturbances. As a result, irregular water basins with a variable thickness and shapes of glacial troughs, oval ponds and big lenses have been formed. Part of the water flows in a cascade-like manner through successive basins down to the Odra periglacial valley. A continuous aquifer with a thickness up to 35 m, one of a few in the dam area, may be distinguished in the valley, in which the Kalinowka river flowed, prior to the construction of the dam.

The water of the Quaternary aquifer, in the dam area is utilized locally as a source of potable and industrial waters. The most important wellfield (Retków) is localized within the Odra periglacial valley and has exploitation reserves of 370 m^3/h.

The range of chemical contaminants, penetrating from the Żelazny Most flotation tailings dam to groundwater may be determined if natural, and current, i.e. anthropogenically modified, hydrogeochemical baseline of this groundwater are assessed. Prior to the construction of the dam, the chemical composition of the Quaternary aquifer water was typical of zones with an active water exchange. The characteristic range for the natural baseline of chlorides was 2—10 mg Cl/l, and the total dissolved solids amounted to 200—600 mg/l. Chlorides have been selected as a contamination tracer because of their conservative character; they are neither sorbed nor enter into chemical reactions with the surrounding environment of an aquifer, and thus migrate with the real velocity of the groundwater flow. Characteristic levels of the current hydrogeochemical baseline for the chlorides in groundwater have been distinguished; they depend on the land-use, and ranges from, 20 mg/l for a forest area, to 50 mg/l for an agricultural land, and 85 mg/l for a housing area.

2. The flotation tailings dam as a source of contamination of groundwater

Earth embankments of a local gravel-sandy material were raised in the first phase, of the construction of the flotation tailings dam. They are currently overbuilt with properly selected, coarser sandy fractions of the flotation tailings (Lewiński, Wolski 1996). In addition to the flotation tailings, copper smelter slag has been used in construction of parts of the dam since 1990. The highest part of the embankment, some 45 m above the local surface level, is situated in the center of the eastern dam section. The exploitation of the Żelazny Most flotation tailings dam is planned to cease with the cessation of copper mining in the Lubin-Głogów Copper District. The flotation tailings dam will then have a volume of a one billion m^3, i.e. 1 km^3 of disposed tailings. The essential technical characteristics of the dam, in selected time spans, are presented in Table 1 to visualize the rate of its continuing filling and the scale of the object.

The dam is filled with silt- and sand-size fractions of flotation tailings, disposed, in the form of a pulp, with a density of 180—200 g/l. The pulp is discharged from pipes, situated along the dam embankment. Each of the sections forms a discharge zone some 500 m long (Fig. 4), with a beach, composed of the coarsest fractions, some of the discharged water may filtrate through the beach. Such a technique creates a pond in the central part of the dam, over finer, semi--permeable and low permeable flotation tailings (Fig. 5).

Along the base of the embankment, from its outer side, a drainage system was installed, controlling outflow of excess water, seeping through the embankment and the dam bedrock. The system is composed of dewatering ditches (horizontal drainage), supported (from 1996) by a barrier of dewatering wells (vertical drainage). Overflow water is reversed in a hydrotransport cycle, and its part is periodically discharged to the Odra River (Czaban i in. 1995).

The overflow water represents salt waters of Cl-SO$_4$-Na-Ca, with total dissolved solids content from 15000 up to 20000 mg/l. Chlorides, sulfates and sodium are the major components of the flotation tailings dam on the water environment. In 2000, the concentration of chlorides was 8800 mg/l, of sulfates 2,900 mg/l, and of sodium 5,500 mg/l. Such high concentrations of major ions in water migrating toward the foreground of the dam significantly threaten the quality of the Quaternary aquifer whose total dissolved solids content is 200—600 mg/l. The presence of heavy metals in the overflow water is an additional hazard, somewhat retarded due to sorption. The water also contains microelements and contaminants associated with processing of copper ores, and their amounts exceed permitted levels. These substances include detergents, phenols, cyanides and xanthates, which are use in ore separation in the mining industry.

The flotation tailings dam also threatens the water environment through infiltration of overflow water with the dissolved chemical substances to the dam bedrock, and further

TABLE 1

Technical characteristic of the Żelazny Most flotation tailings dam

TABELA 1

Techniczna charakterystyka składowiska odpadów poflotacyjnych Żelazny Most

Parameter	1988	1994	2000	2003	2015
Volume of tailings disposed [10^6 m^3]	144.2	241.3	315.0	350.0	600.0
Dam area [km^2]	11.9	14.0	14.0	14.0	14.0
Overflow pond area [km^2]	6.0	6.1	7.3	ca 6.5	ca 6.5
Volume of pond water [10^6 m^3]	13.5	10.7	7.5	ca 10.5	ca 10.5
Datum of the pond lifting [m asl]	140.5	148.2	154.6	158.0	178.0

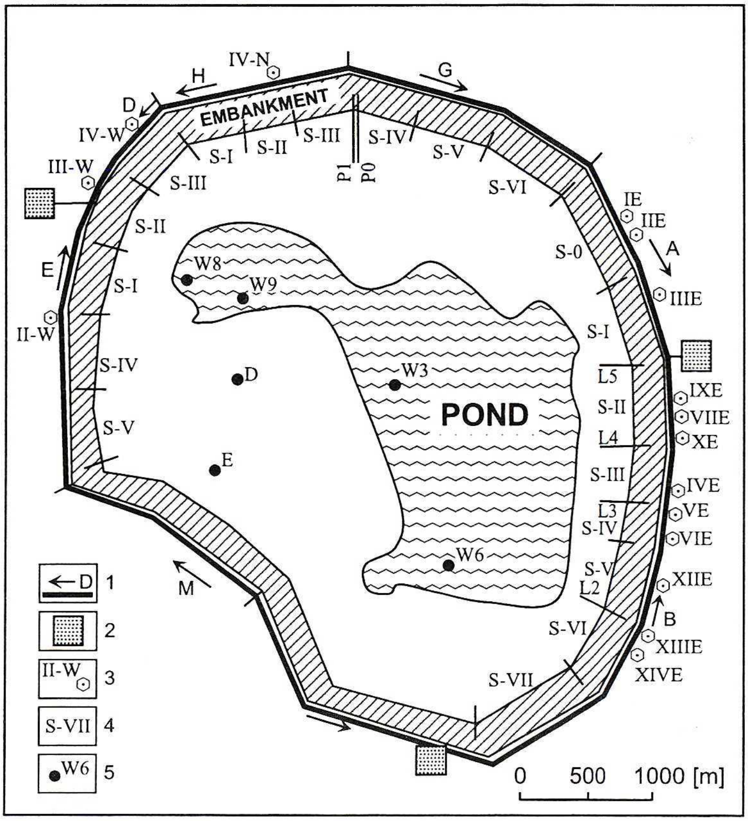

Fig. 4. Sketch of the dewatering installation of the dam
1 — dewatering ditch, arrows indicate water flow direction, 2 — pump stations with water reservoirs, 3 — wells of the vertical drainage, 4 — pipe sections discharging flotation tailings, 5 — overflow spill-towers

Rys. 4. Schemat instalacji odwadniającej składowiska
1 — rów odwadniający, strzałki wskazują kierunek spływu wód, 2 — pompownie i zbiorniki wodne, 3 — studnie drenażu pionowego, 4 — sekcje namywu odpadów, 5 — wieże przelewowe dla nadmiaru wód nadosadowych

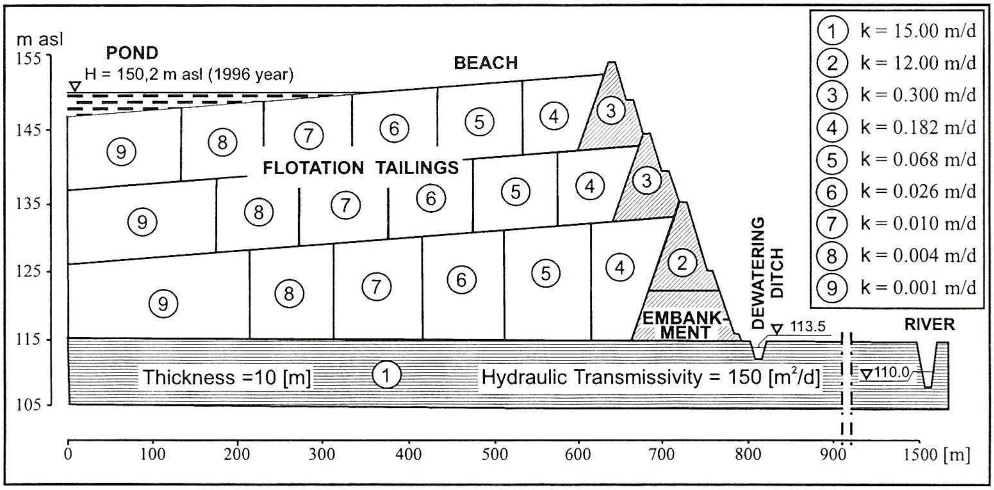

Fig. 5. Conceptual model of the hydrodynamic field within a part of the flotation tailings dam and its bedrock created for modeling of overflow infiltration trough the vadose zone in the tailings
1 — hydraulic conductivity of an aquifer in the dam bedrock, 2—3 — hydraulic conductivity of materials, used in the construction of embankments, 4—9 — hydraulic conductivities of flotation tailings

Rys. 5. Model koncepcyjny pola hydrodynamicznego w obrębie części składowiska i jego podłoża opracowany dla modelowania infiltracji wód nadosadowych przez strefę areacji w odpadach
1 — współczynnik filtracji utworów wodonośnych w podłożu składowiska, 2—3 — współczynnik filtracji utworów, z których zbudowane są zapory, 4—9 — współczynniki filtracji osadów poflotacyjnych

migration of the water toward the dam foreground. The infiltrating saline water degrades the quality of fresh groundwater and next also surface water. The contaminated streams will become a secondary source of contamination of groundwater, particularly around the Retków well field (Duda, Witczak 1993; Duda i in. 1997).

Saline water migrates within the dam foreground first of all through the uppermost aquifer, although recently a migration through lower lying aquifers has also been noted. Migration of saline water is the fastest along preferential flow paths in parts of an aquifer with the highest conductivity. Additionally, the spatial distribution of chlorides concentration (Fig. 6) results from mixing of the leakage water, infiltrating from the dam, with the fresh groundwater, flowing through the bedrock from hills, south of the dam. The extent of contaminated water in the dam foreground has been determined from chlorides concentrations in groundwater. The boundary isoline has been established at 100 mg/l, i.e. the chlorides content of groundwater exceeding the value of the current hydrogeochemical baseline.

The year 1996 has been accepted as a time marker for calibration of a groundwater flow and of a mass transport. At that time the saline water reached a distance from some tens of meters to ca. 900 m from the dam. The extent of the contaminated zone generally agreed with earlier predictions (Duda, Witczak 1993), and was confirmed during monitoring aimed at checking predictions. The model described here is the fourth attempt to determine the hydrodynamic field in the vicinity of the dam. Such a procedure, called a post-audit analysis, is indispensable in evaluation of the quality of permanent hydrogeological models.

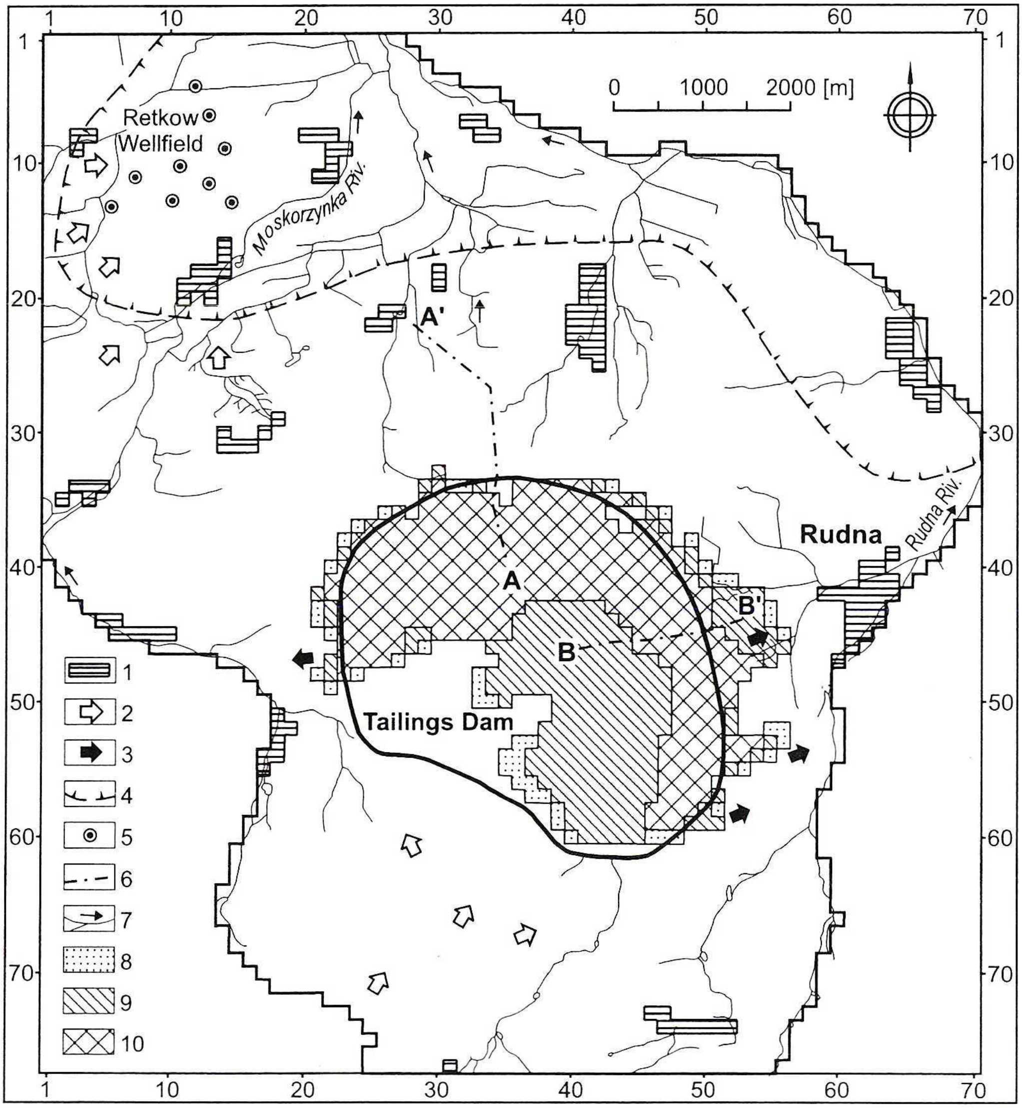

Fig. 6. Spatial distribution of the chlorides in groundwater in 1996 assumed in the calibrated model of the dam area
1 — housing area, 2 — directions of fresh groundwater flow, 3 — directions of contaminants migration from the dam, 4 — the range of the main aquifer the Odra River Periglacial Valley, 5 — wells of the Retków well-field, 6 — lines of hydrogeological cross-sections from Fig. 3, 7 — streams and rivers, 8—10 — spatial distribution of chlorides: 100—300 mg/l (8), 300—3000 mg/l (9), >3000 mg/l (10)

Rys. 6. Rozkład przestrzenny stężenia chlorków w wodach podziemnych w 1996 r. przyjęty na wykalibrowanym modelu rejonu składowiska
1 — obszary zabudowane, 2 — kierunki przepływu czystych wód podziemnych, 3 — kierunki migracji zanieczyszczeń przenikających ze składowiska, 4 — zasięg GZWP nr 314 — Pradolina Odry (Głogów), 5 — studnie ujęcia Retków, 6 — linie przekrojów hydrogeologicznych z rysunku 3, 7 — potoki i rzeki, 8—10 — rozkład przestrzenny stężenia chlorków: 100—300 mg/l (8), 300—3000 mg/l (9), >3000 mg/l (10)

Within the northern dam foreground the propagation of contaminants in groundwater is smaller than the earlier predictions. But one cannot exclude waters infiltrating from the dam that may appear somewhere further, if far zones of preferential conductivity are reached. Such a case is quite probable, because of a complicated geological structure of the area. If the favorable hydraulic link does exist, a fast water flow to the north must be assumed, as hydraulic gradients along this direction are significant (Fig. 3).

3. Model of groundwater flow

A model of groundwater flow has been created for the area that can be affected by the flotation tailings dam. Two separate problems have been given a special attention:

— water seepage through the tailings and into the dam bedrock from the pond and from the beaches being formed,

— a pattern of a regional hydrodynamic field around the dam.

Numerical solution of a differential equation, describing the groundwater flow in a porous medium (Harbaugh 1992), has been found by a finite difference method (FDM). The applied solution has many references, e.g. Spitz, Moreno (1996), ASTM (1999). As a tool in preparation and calibration of a hydraulic field model, a MODFLOW-96 (Harbaugh, McDonald 1996) program has been selected. For this model, a number of groundwater modeling software packages and Graphical User Interfaces has been elaborated (e.g. Chiang, Kinzelbach, 2001). To create a model to use this program, it is necessary to read complementary papers (Prudic 1989; Goode, Appel 1992; Hsieh, Freckleton 1993) as they enable over fully grasp the methodology.

The MODFLOW is particularly useful in modeling water flow between the cells of a grid, discreting the modeled region in the dam area. Its advantage is in averaging of the hydraulic conductivity values in adjacent cells of the grid as harmonic means (Goode, Appel 1992; McDonald, Harbaugh 1996). The use of the harmonic means makes possible the best projection of sudden conductivity changes of an aquifer between adjacent cells of the model and of the presence of low permeable rocks, breaking the continuity of an aquifer within a filtration field.

The two-dimensional, permanent regional model of the dam area with unconfined/confined conditions of the groundwater pressure has been formed for a land tract with a surface of 121 km^2 (10.5 × 11.5 km). This area has been described with a grid of square cells composed of 77 lines and 70 columns; the size of a single cell was 150 × 150 m (Fig. 6).

Creation of a conceptual model required certain schematization of the geological structure and hydrogeological conditions in the vicinity of the dam as well as of technical and technological parameters of its exploitation. A part of the grid cells has been utilized in setting outer and inner boundary conditions. Along the most sections of rivers within the model area, as well as along the girdling ditches, a head-dependent boundary condition has been set, i.e. the condition taking into account the filtration resistance of a stream bottom. The outer boundaries of the area under modeling have been set in some of the cells on distant rivers as a general-head boundary. Along some river sections a constant-head boundary has been set.

The thickness of the Quaternary aquifer has been accepted from a geological survey with some modifications in these regions where further hydrogeological or geophysical surveys or observed behavior of groundwater departed from earlier predictions. The thickness of the aquifer has been generally determined as effective, as it is the thickness interpreted without insets of semi and low permeable strata that is partly corrected for non homogenity of hydraulic conductivity along the vertical profile of the aquifer. The thickness in question ranges from 1 m to ca. 30 m.

The hydraulic conductivity of sands and gravels of the Quaternary aquifer varies from 0.3 m/d to over 20 m/d. Basically, the model has not been calibrated through modification of the hydraulic conductivity of aquifers as the latter parameter affects the velocity of a groundwater flow, and in consequence also the velocity of contaminant migration.

The transmissivity of the aquifer has been accepted as a product of a mean hydraulic conductivity and an effective thickness of water-bearing strata in each of the cells of the model. The data in the case of an unconfined/confined aquifer have been accepted as:

— data of the surface level in the areas of unconfined conditions; it means that the top of permeable rocks is situated above a stabilized groundwater table;

— data of the bottom of an aquitard, overlaying an aquifer, in the areas of confined conditions.

A probable spatial distribution of transmissivity of an aquifer over the whole area of the model has been obtained. The hydraulic transmissivity of the aquifer varies from 1 m^2/d to over 300 m^2/d. These values have been arrived at by a calibration of the transmissivity on the model. The spatial distribution of the computed groundwater level on the model corresponded well with the distribution observed in the field.

Recharging of groundwater by rainwater has been calculated for the model from a long-term, mean annual rainfall, being 592 mm for the catchment area of the Rudna River. It has been assumed that introduction of such a long-term mean is justified as the model will also be used for long-term predictions. In the model, zones with differentiated permeability of bedrock, morphology and land-use have been distinguished. Using a calibration method, it has been accepted that within the upland area, composed of strata with low permeability, ca. 10% of annual rainfall infiltrates, while this value is ca. 25% within the flat area, composed of permeable strata and covered with woodlands and meadows. Also some transition regions, with infiltration values between the two mentioned above, have been distinguished.

Seepage of water into bedrock through the flotation tailings accumulated in the dam is one of the fundamental elements of the model. The whole process of seepage of overflow water through flotation tailings into the dam bedrock can be subdivided into three components:

— infiltration of pond water (i.e. overflow water) through the bottom of the pond,

— infiltration of water discharged together with tailings through the beach being formed,

— infiltration of rainwater through beaches during breaks between successive tailings discharges.

Infiltration is more intensive close to the embankment where the hydraulic conductivity is the highest. The beach is being formed through sedimentation and the coarsest fractions gather near the outlets of the discharging pipes (Fig. 5). However, the process is additionally complicated by a continuous growth of a tailings pile, at about 1,3 m per year, and the resulting consolidation. The permeability of tailings decreases in deeper parts of the dam, and an excess of pore water is being squeezed out of the accumulated tailings.

Besides technological parameters, infiltration of water from the dam surface through tailings depends on the random character of natural conditions. The flow in the Odra River, which controls the discharge of salt overflow water from the Żelazny Most dam, depends randomly on meteorological conditions. Low river water levels make impossible discharging of higher amounts of water from the dam, lifting in consequence the datum of the pond. As a result, the beaches are inundated and more water infiltrates into the dam bedrock.

Seepage of water, during discharges of tailings into the dam is more complex. Water freely flows along the surface of the beach, fully wetting its surface but not exerting any overpressure. Vertical modeling of the dam in a period of such a discharge indicates that infiltration of water into the bedrock is particularly intensive, in beach zones situated close to the embankments, as the hydraulic conductivity of the tailings, is the highest in this area. Predictive computations have been carried out, with a certain simplification, assuming that all the discharging sections were active during the same time, i.e. 8 weeks, in a year.

Infiltration of rainwater into sediments within a beach zone takes place effectively only during a period between successive discharging campaigns. The value of this infiltration is many times smaller from infiltration of water discharged in the form of a tailings pulp. Therefore, the rainfall infiltration has been disregarded in calculations, assuming that it does not exceed the limits of the computing error. Therefore, two superimposing processes have been modeled:

— water seepage through the bottom of the pond, periodically inundating the beaches of the Żelazny Most dam,

— water infiltration through the beach being formed, i.e. during tailings discharges.

These processes are time-variable, therefore it has been assumed that the cells of the model that are inundated for more than 50% of time are treated in calculations as permanently covered by water, while the cells inundated for less than 50% of time as permanent beaches.

The hydrodynamic field has been predicted in the model for steady-state conditions, associated with the assumed data of pond lifting. It is a simplification, as — in fact — conditions of a pond lifting and collecting of tailings within the dam area are not transient, accepted as permitted with regard to small changes of the hydrodynamic field within the foreground of the dam in the predicted time span. Such a situation is caused by the horizontal and vertical drainage around the dam embankments, which collects almost 80% of water infiltrating from the dam into its bedrock.

One of the main criteria of model fitting, understood as a validation analysis of a numerical model quality in respect to field conditions, is a comparative balance of water amounts: those filtrating through tailings accumulated in the dam to those flowing out through girdling ditches and dam embankment drainage (horizontal drainage) and dewatering wells (vertical drainage). The balance has indicated that almost 80% of water infiltrating through tailings collects in the ditches and wells (Fig. 7, Tab. 2).

Also a comparison of amounts of water penetrating into a dam foreground, calculated from the model, with field hydrological observations coupled with geophysical measurements of a flow velocity rate of salt water infiltrating from a dam outside is an important element of model validation. Hydrological data has been accepted as reliable for the model validation because water infiltrating into the dam bedrock must appear in proximal or more distant rivers within the boundaries of the watershed area being modeled.

The estimated amounts of salt overflow water infiltrating into the dam bedrock have been compared and balanced against the amount of flow in the drainages and the increased outflow

Fig. 7. Conceptual model of groundwater flows in the immediate vicinity of the dam
Q_1—Q_6 — water outflows balanced (Tab. 2) during calibration of the model

Rys. 7. Model koncepcyjny przepływów wód podziemnych w bezpośrednim rejonie składowiska
Q_1—Q_6 — dopływy bilansowane (tab. 2) w trakcie kalibracji modelu

TABLE 2

Model-computed balance of the amounts of salt overflow water and loads of chlorides migrating into the dam foregrounds

TABELA 2

Bilans ilości słonych wód nadosadowych i ładunku chlorków migrujących na przedpola składowiska według obliczeń modelowych

Datum of the overflow pond lifting		150.2 m asl (as for 1996)		158.0 m asl (predicted for 2003)					
Computing scenario		calibrated model		scenario 1 with the deepest vertical drainage		scenario 2 with the additional vertical drainage		difference scenario 1—2	
		m^3/d	kg Cl/d	m^3/d	kg Cl/d	m^3/d	kg Cl/d	m^3/d	kg Cl/d
Q1	Seepage of overflow water into the dam bedrock	21 788	123 102	23 971	135 436	25 588	144 572	1 617	9 136
Q3	Water drainage by girdling ditches	15 039	—	10 732	—	10 282	—	–450	—
Q4	Water drainage by supporting system of vertical wells	4 030	—	12 746	—	16 237	—	3 491	—
Q5	Ditches and wells recharging from a dam foreground	2 305	—	2 502	—	2 594	—	92	—
Q6	Amount of salt water migrating into a foreground	5 024	28 386	2 995	16 922	1 095	6 187	–1 900	–10 735

from partial catchments, draining the dam foregrounds. The total flow in streams on the dam foreground, which is a real measure of the water volume penetrating from a dam into its foreground, has increased at 5024 m^3/d.

4. Model of mass migration

In construction of the model of contaminant mass migration in the vicinity of the dam, the Modified Method of Characteristics MMOC by Zheng (1993) was selected. The FDM was rejected because of a high probability that a phenomenon of numerical dispersion in the model could occur — a Peclet number was 3.5. The reason of selection of the MMOC is its good performance in models where a Peclet number ranges from several to some tens, i.e. for the problems with a significant contribution of hydrodynamic dispersion in a solute transport (Zengh, Bennett 1998). The calculations were carried out using MT3DMS — a modular three-dimensional multispecies transport model designed specifically to handle advectively-dominated transport problems (Zheng, Wang 1998). MT3DMS has been revised; the last upgraded one is MT3D99, which can also handle bioplume-type reactions and daughter products.

Setting of initial conditions in a mass migration model equals to fixing an initial concentration of a tracer in all the cells of a grid at a time for which a model is calibrated. Within the range of observation wells in the dam foreground, the concentration of chlorides has been determined according to field investigations from 1996. In the areas outside the range of the wells, the concentrations of chlorides at the level of the current hydrogeochemical baseline have been accepted, depending on land-use (forest, agricultural or housing areas).

In the model of contaminants migration in the vicinity of the dam, only a boundary condition based on a tracer injection concentration was set in those cells where the water flow into the model was known to be positive. It is the inflow computed for the model of groundwater flow from: infiltration of rainwater, seepage of overflow water through tailings into the dam bedrock, infiltration from rivers into groundwater, and from outer inflows into the model.

The fundamental parameter of migration that characterizes broadening of the front of the contamination plume in a flow of groundwater, i.e. longitudinal dispersivity, was initially determined on a basis of an analytical method at 8 m (Małoszewski 1978). Later, an average flow velocity of groundwater was estimated at 44 m/year and dispersion at 43 m (Szczepiński 1993). The such large value of dispersivity point to a considerable dispersion of the front of contamination plume in groundwater, characteristic of mass migration in a heterogeneous sandy-gravel strata. The second of the cited values, i.e. 43 m, is a result of investigations carried out in a wider and more heterogeneous area. Therefore, this value has been accepted as a representative one for the region analyzed here. Considering an irregular structure of the aquifer in question, the value of transverse hydrodynamic dispersivity has been assumed as 10% of longitudinal dispersivity.

The value of effective porosity of the sandy strata through which mass migration takes place has been assumed as constant for the whole model and equal to 30%. The value of $R = 1$ for the retardation factor of mass transport has been accepted, while parameters characterizing chemical reactions have been neglected because conservative chloride ion only has been used as a tracer in the current prediction.

5. Prediction of contaminants migration

In the prediction, the spatial distribution of the groundwater head level from the year 1996 has been accepted, as a reference time, calibrated for a pond lifting datum of 150,2 m asl. According to a current enlargement variant of the Żelazny Most tailings dam, a predicted pond lifting datum of 158,0 m asl for the year 2003 has been accepted. The following concentrations of chlorides injection have been assumed when predicting mass migration of the contaminant:

— within the area of seepage of overflow water into the dam bedrock — 7000 mg/l,

— within the areas of infiltration of rainwater through the soil and aeration zone — 20 mg/l for forested land, 50 mg/l for an agriculturally used land, and 85 mg/l for a housing area,

— within the areas of water infiltration from streams into an aquifer in the Retków well-field region — the value calculated from a mass balance of contaminants being transported in proximal rivers.

The process of mass migration of contaminants in groundwater has been simulated as a transient one on a basis of a steady-state hydrodynamic field. As the changes of the pattern of the hydrodynamic field within the dam foreground were small, the process, which in fact is transient, has been split into two periods, each of treated as one with a steady-state hydrodynamic field. The prediction has been calculated for two scenarios: with and without a supportive vertical drainage in the form of dewatering wells.

The Żelazny Most flotation tailings dam has got real chances to be a dump with a closed circulation of technological water because of a natural flow pattern toward the dam and along its embankments (Fig. 1). Thus it is necessary to strengthen the drainage close to the embankments in such a way that the natural flow directions of groundwater in the area is reconstructed and maintained (Witczak, Duda 1995). This may be done through keeping a proper level of the groundwater table in the immediate foreground of the dam, i.e. the level that was observed in the area of the dam embankments prior to their construction in 1977. Among some technical means to lower the water table, a supportive vertical drainage with dewatering wells has been recognized as the most suitable. It is an active method of controlling migration of contaminants outside a dam area (Nawalany i in. 1992).

Predictive simulations for the scenario 1 with deepest vertical drainage have shown that infiltration of saline overflow water into a tailings dam foregrounds at a datum of 158.0 m asl will equal 2995 m^3/d (Table 2). Most of the water will be collected by the horizontal drainage of the embankments supported by system of vertical wells with greater drawdown, thus lowering the hazard of groundwater contamination.

Infiltration into a foregrounds will decrease to 1095 m^3/d for the scenario 2 with an additional vertical drainage. The relatively biggest outflows should be expected in the areas where a bedrock aquifer close to the embankments is contained by low permeability strata, making the drainage by girdling ditches ineffective. The vertical drainage will also eliminate artesian conditions in the bedrock that are unfavorable for the stability of embankments and hinder possible use of the dam foreground because of bottom flooding. However, most of the salt water that reached the foreground before the vertical drainage barrier was active, will not be stopped and will flow away according to a pattern of groundwater movement (Fig. 8).

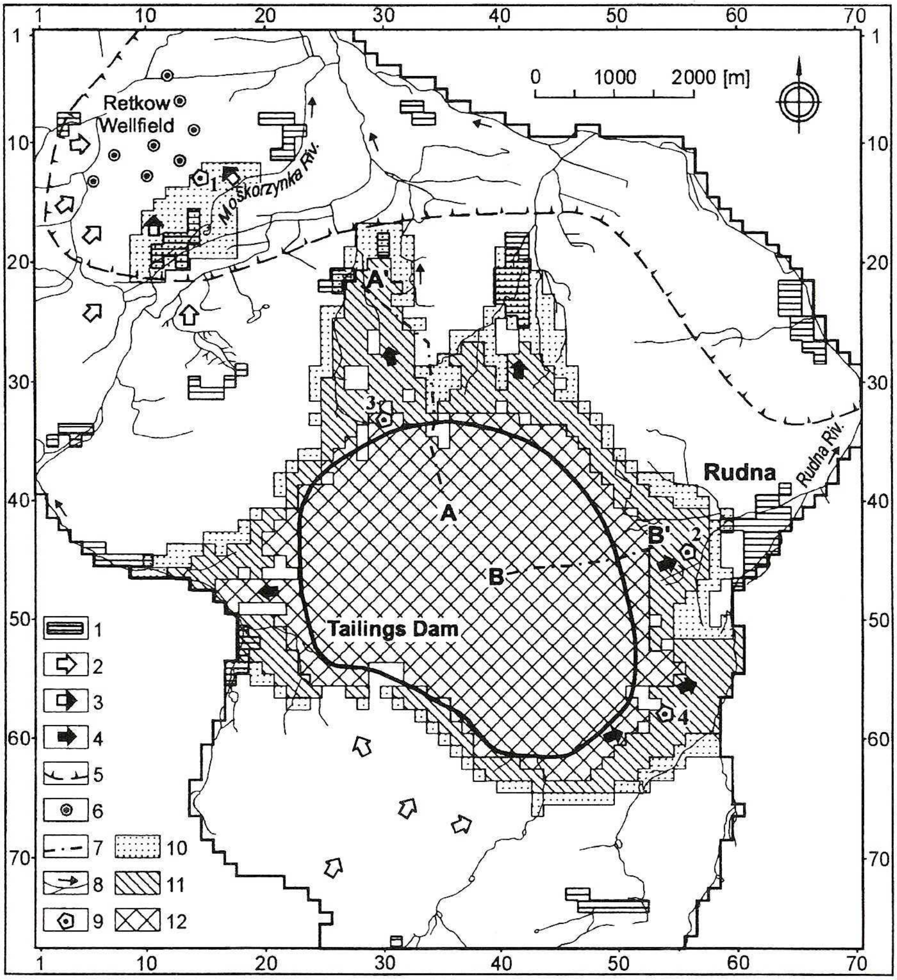

Fig. 8. Prediction of chloride migration in groundwater in the dam area for the year 2003 (datum of the pond 158 m asl); the modeling scenario 2 assuming a additional vertical drainage
1 — housing area, 2 — directions of fresh groundwater flow, 3 — directions of migration from secondary contaminant sources (rivers carrying contaminants originating at the dam), 4 — directions of contaminant migration from the dam, 5 — the range of the main aquifer the Odra River Periglacial Valley, 6 — wells of the Retków wellfield, 7 — lines of hydrogeological cross-sections from Fig. 3, 8 — streams and rivers, 9 — localization of the observation points from Fig. 9, 10—12 — predicted spatial distribution of chlorides: 100—300 mg/l (10), 300—3000 mg/l (11), >3000 mg/l (12)

Rys. 8. Prognoza migracji chlorków w wodach podziemnych rejonu składowiska w 2003 r. (rzędna piętrzenia akwenu 158 m n.p.m.); scenariusz 2 z wspomagającym drenażem pionowym
1 — obszary zabudowane, 2 — kierunki przepływu czystych wód podziemnych, 3 — kierunki migracji z wtórnych ognisk zanieczyszczenia (rzeki odprowadzających zanieczyszczenia przenikające ze składowiska), 4 — kierunki migracji zanieczyszczeń przenikających ze składowiska, 5 — zasięg GZWP 314 Pradolina Odry (Głogów), 6 — studnie ujęcia Retków, 7 — linie przekrojów hydrogeologicznych z rysunku 3, 8 — potoki i rzeki, 9 — lokalizacja punktów obserwacyjnych z rysunku 9, 10—12 — prognozowany rozkład przestrzenny stężenia chlorków: 100—300 mg/l (10), 300—3000 mg/l (11), >3000 mg/l (12)

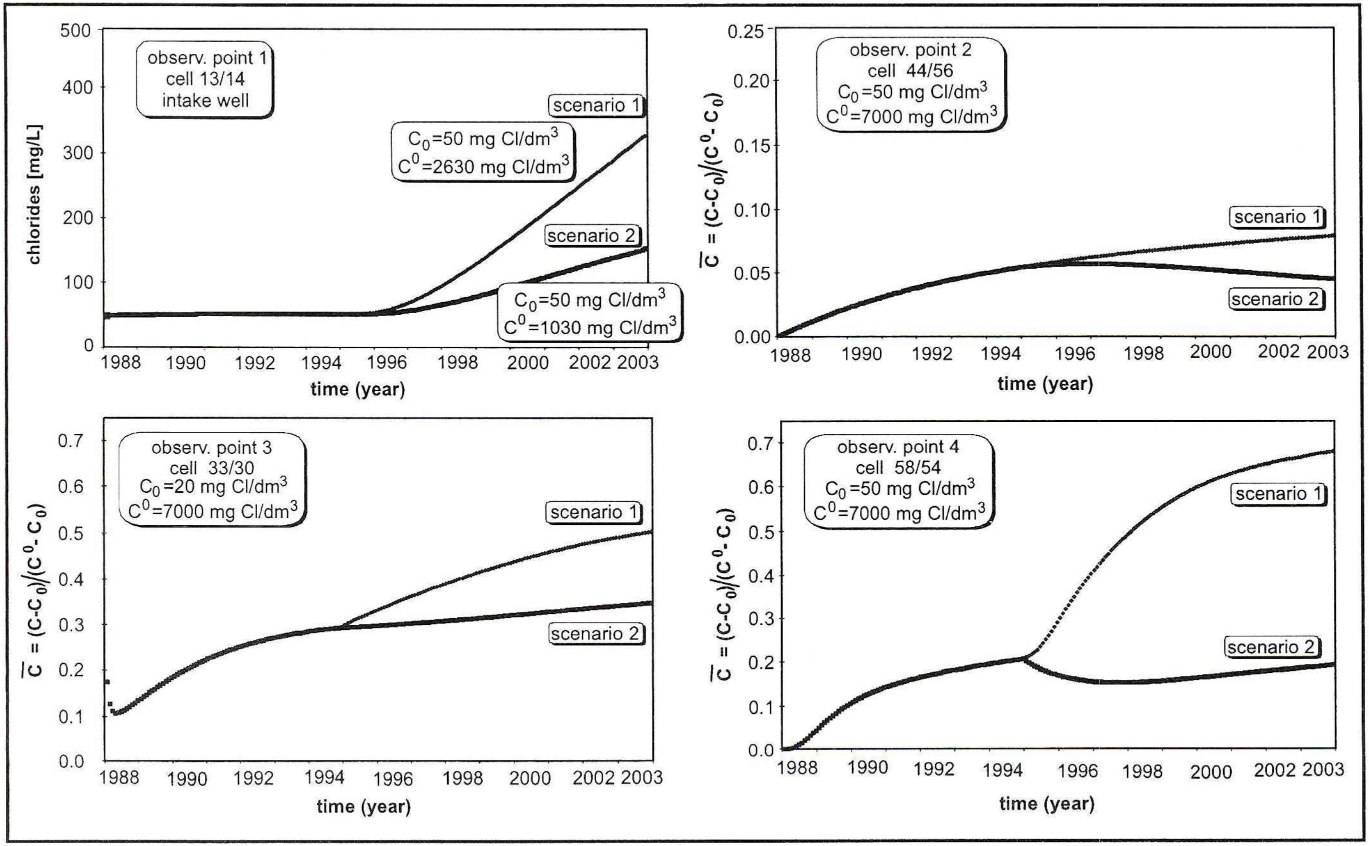

Fig. 9. Predicted changes in the chlorides concentration in the years 1988—2003 in the selected observation points (localization of the points indicated in Fig. 8)
C_0 — concentration of chlorides for the current hydrogeochemical baseline, C^0 — concentration of a chlorides injection

Rys. 9. Prognozowane zmiany stężenia chlorków w latach 1988—2003 w wybranych punktach obserwacyjnych (lokalizacja punktów na rys. 8)
C_0 — stężenie chlorków dla współczesnego tła hydrogeochemicznego, C^0 — stężenie iniekcji chlorków

Another advantage of the dam vertical drainage will result in lowering of the range and concentration of secondary contamination sources. This problem is particularly important for the Retków well-field, threatened by secondary contamination by pollutants carried by rivers. According to predictive simulation for both scenarios, contaminants migration from the Żelazny Most tailings dam should not directly pollute the Retków well-field unless its groundwater is intensively exploited. More hazardous for the well-field is a secondary contamination from stream waters as a substantial amount of the Retków water reserves is formed by infiltration from proximal streams and rivers. The computation has shown that the Moskorzynka River, close to the intake area, will be saline at the mean low streamflow, i.e. the one used in the prediction of contamination: for the scenario 1 at 2630 mg Cl/L, and for the scenario 2 at 1030 mg Cl/L (Fig. 9). One of the tributaries of the Moskorzynka, flows across an area reached by migrating salt waters from the tailings dam.

The likelihood of the hazard predicted for the Retków well-field depends on the proper recognition of water pathways within the western foreground of the flotation tailings dam. The prediction is based on the assumption that under low and semi permeable strata dominating in the area, there are permeable zones facilitating migration of saline waters from the dam. Hydrological measurements have indicated an increased discharge from springs and flow in streams, both observed during calibration of the model and later on. The effect has been accepted as resulting from migration of salt water from the dam.

Saline water migrating northward from the flotation tailings dam, may probably contaminate fresh water within a south part of the Main Aquifer Odra River Periglacial Valley limiting its utilization.

Conclusions

The prediction of migration of contaminants in the area of the Żelazny Most flotation tailings dam indicates that only lowering of the groundwater level close to the dam embankments, resulting from vertical drainage by dewatering wells, may limit propagation of contaminants in groundwater around the dam. This limiting will be based on reconstruction of watersheds existing there prior to the construction of the dam, and on directing the groundwater flow toward the dam or along its embankments, as the two processes will cause that the hydraulic system of circulation of technological water will be closed.

The dam itself is and will remain, however, a permanent source of contamination, hazardous directly for groundwater of the region and indirectly for stream waters. Thus groundwater model should be permanently updated and calibrated every 4—5 years according to data from hydrogeological, hydrological and geophysical monitoring.

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ROBERT DUDA, STANISŁAW WITCZAK

MODELOWANIE MIGRACJI ZANIECZYSZCZEŃ Z SKŁADOWISKA ODPADÓW POFLOTACYJNYCH ŻELZANY MOST

Słowa kluczowe

Wody podziemne, modelowanie, migracja zanieczyszczeń, prognoza, odpady poflotacyjne

Streszczenie

Składowisko Żelazny Most jest największym składowiskiem odpadów przemysłowych w Europie, na którym od 25 lat gromadzone są odpady po flotacji rud miedzi. Powierzchnia składowiska wynosi 14 km^2, objętość odpadów 315 × 10^6 m^3, ostateczna objętość to około 700 × 10^6 m^3. Wody nadosadowe przesiąkają ze składowiska do warstwy wodonośnej o charakterze porowym i swobodnych warunkach ciśnień. Warstwa jest silnie heterogeniczna, o zmiennej miąższości (od 1 do 20 m) i zawierająca strefy o wysokiej przewodności (od 1 do 300 m^2/d). Kilka strumieni zanieczyszczeń z wysokimi stężeniami głównie chlorków i siarczanów migruje ze składowiska na jego przedpola zgodnie z kierunkami przepływu wód podziemnych. Największa strefa zanieczyszczeń sięga na odległość 900 m od składowiska. Dwuwymiarowy regionalny model numeryczny otoczenia składowiska jest narzędziem oceny oddziaływania składowiska na środowisko, prognoz zanieczyszczenia wód podziemnych i metod ich ochrony. Model jest wielokrotnie kalibrowany i dopasowywany co 4—5 lat do wyników monitoringu hydrogeologicznego, hydrologicznego i geofizycznego. Opracowano na nim sposób ograniczenia migracji wód nadosadowych polegający na hydraulicznym zamknięciu wypływu wód ze składowiska. Zaprojektowano barierę studni odwadniających rozmieszczonych wokół składowiska, modyfikujących kierunki przepływu wód podziemnych. Odtworzone w ten sposób działy wód podziemnych ograniczą rozpływ zanieczyszczeń.

ERRATA — brakujący rysunek na stronę 81

Robert DUDA, Stanisław WITCZAK: Modeling of the transport of contaminants from the Żelazny Most flotation tailings dam

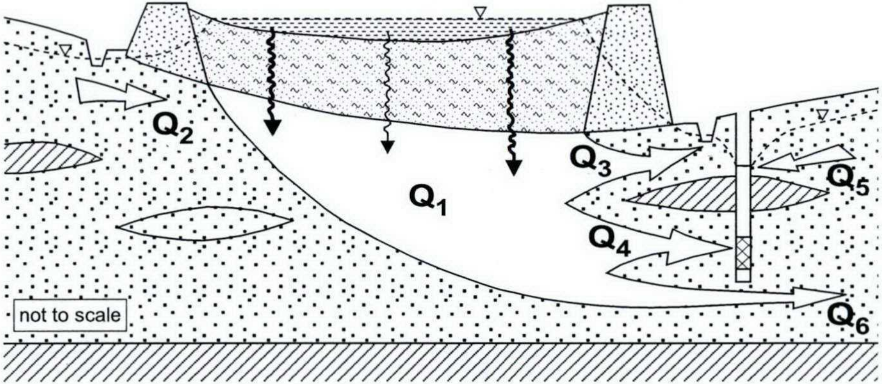

Fig. 7. Conceptual model of groundwater flows in the immediate vicinity of the dam
Q_1—Q_6 — water outflows balanced (Tab. 2) during calibration of the model

Rys. 7. Model koncepcyjny przepływów wód podziemnych w bezpośrednim rejonie składowiska
Q_1—Q_6 — dopływy bilansowane (tab. 2) w trakcie kalibracji modelu