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V.5

Regional prediction of the transport of contaminants from the flotation tailings dam: a case study

Robert Duda

V.5.1. Introduction

General misunderstanding of the groundwater nature and of the impact on its quality, which leachate from bulk industrial waste may cause, has subjected the vast groundwater resource to contamination by many past actions involving the disposal of these wastes on and in the land. The unlined dumping sites/landfills of bulk industrial wastes were predominantly located without any concern about groundwater quality, frequently on sites that are vulnerable to groundwater contamination problems. Over the last decades of the 20th century, reports of groundwater contamination from surface impoundments and landfills had been growing. This has been drawn to the attention of public and environmental agencies of all levels to these sources as areas where the effective control measures are needed. Currently, parallel with efforts to minimize future adverse impacts of industrial waste landfills on groundwater resources, we have to assess and manage environmental consequences associated with past wrong decisions and activities that have long-lasting negative implications.

In the presented case study, these problems are exemplified in the Zelazny Most dam, the biggest industrial landfill (dump) under operation in Europe that for 25 years serves for disposal of copper ore flotation tailings. The area of the dam is 14 km^2, volume, 315×10^6 m^3, and final volume up to 1000×10^6 m^3. A 2D hydrological model for the vicinity of the tailings dam was used as a basic tool for environmental impact assessment, prediction of groundwater pollution and evaluation of methods developed for restricting movements of pollutants and groundwater protection.

V.5.2. Hydrogeological characteristic of the dam area

Tailings from the flotation of copper ores in the Lubin-Glogow Copper District are being collected in the Zelazny Most dam, the biggest industrial waste 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. V.5.1). The hills are a frontal moraine and the

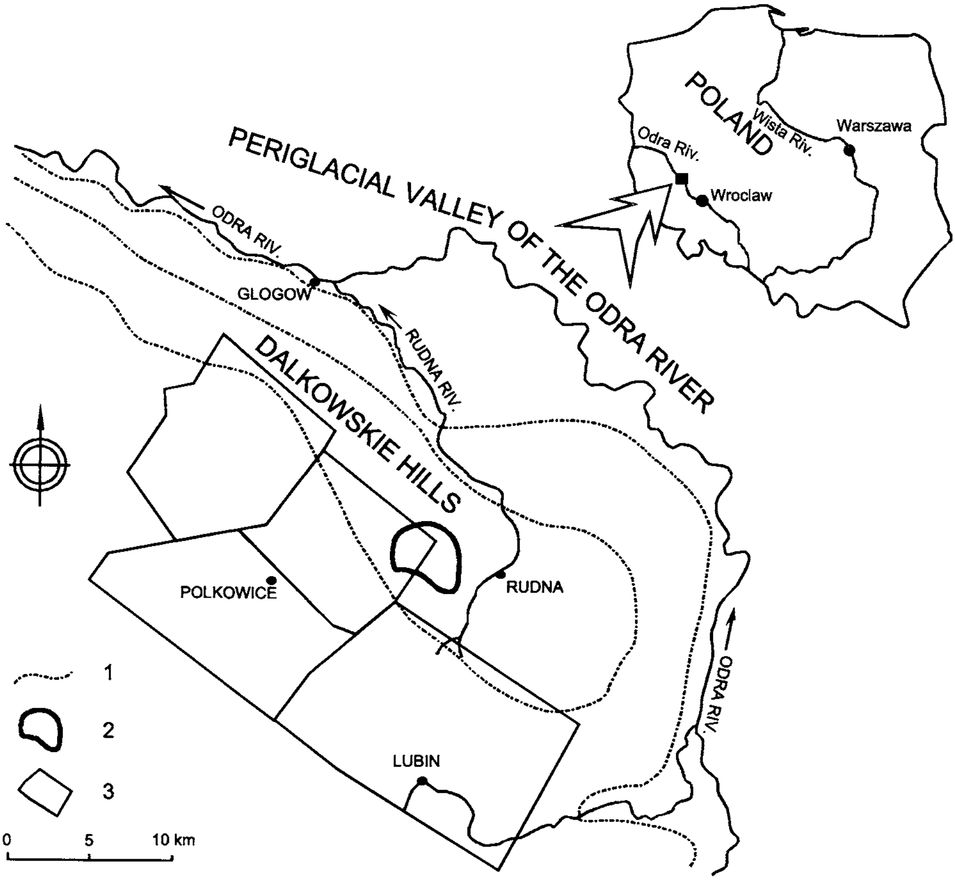

Figure V.5.1. Localization of the Zelazny Most flotation tailings dam. 1 – extent of geographical units, 2 – tailings dam, 3 – extent of mining fields.

depression, which is a melt structure, 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. V.5.2), 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. V.5.3), a left-bank tributary of the Odra River.

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

- An upland area, situated within the zone of glacitectonic disturbances, confining quaternary and tertiary strata, which form an immediate bedrock of the dam.
- A periglacial valley area, which is probably a glacitectonic depression, later filled by melt and river waters.

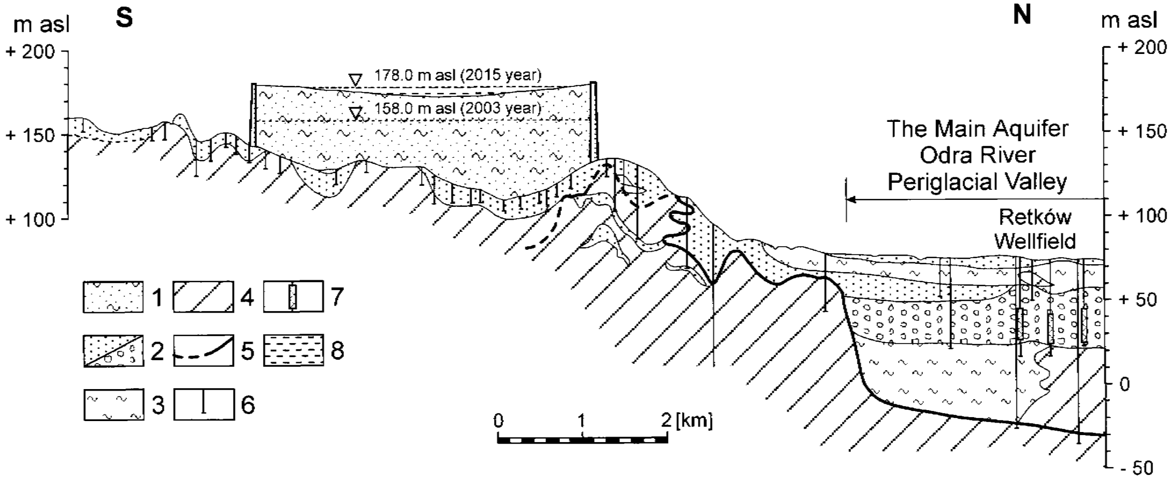

Figure V.5.2. Simplified geological cross-section S-N (the line of cross-section marked in Fig. V.5.3.). 1 – flotation tailings (silts, sandy silts), 2 – permeable rocks (sands, sands and gravels), 3 – semi-permeable rocks (silty and loamy sands, sandy silts), 4 – low-permeable rocks (loamy silts, sandy loams, boulder clays, clays), 5 – inferred boundary of the top of tertiary clays, 6 – piezometers and observation boreholes, 7 – wells of the Retkow well-field, 8 – pond

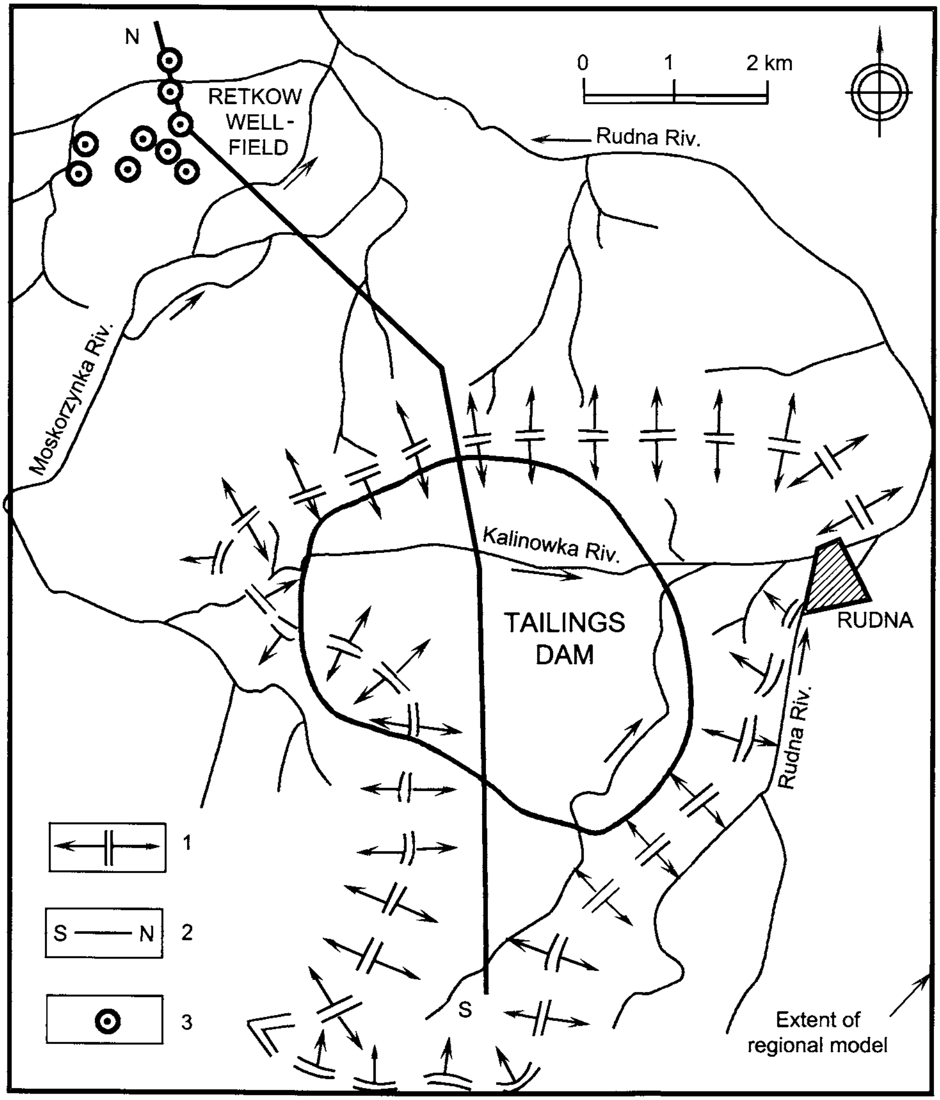

Figure V.5.3. Range of the regional model of groundwater flow in the dam area against hydrographic sketch. 1 – position of a local watershed prior to the construction of the dam, 2 – the line of a simplified geological cross-section S-N from Figure V.5.2., 3 – wells of the Retkow well-field.

Glacitectonic forms are very different, from regular folds to scales and caps, composed both of quaternary and tertiary strata (Fig. V.5.4). 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 lithology. They may be from a few to almost 100 m thick (the latter thickness in local potholes), on an average

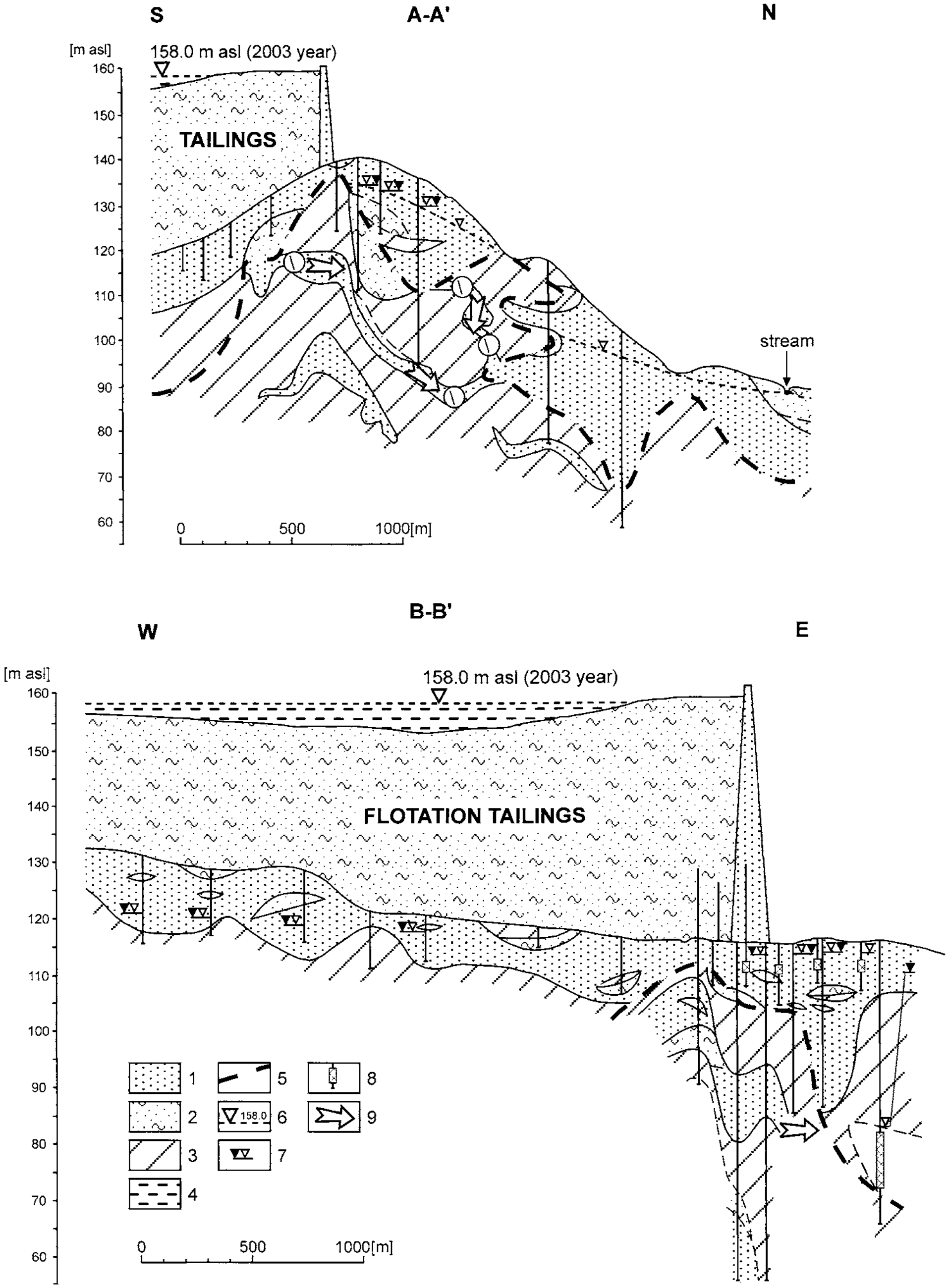

Figure V.5.4. Hydrogeological cross-sections A – A' and B – B' (the lines of cross-sections marked in Fig. V.5.6.). 1 – permeable rocks (sands, sands and gravels), 2 – semi-permeable rocks (silty and loamy sands, sandy silts), 3 – low-permeable rocks (loamy silts, sandy loams, boulder clays, clays), 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.

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 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 rests 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 in 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 groundwater basins (MGWB) in Poland, i.e. the MGWB No. 314—the Odra River Periglacial Valley, which should be under special protection (Kleczkowski, 1990). It is composed of an aquifer, 30–40 m thick, underlain by 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 on the south.

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 well field (Retkow) is localized within the Odra periglacial valley and has exploitation reserves of 370 m^3/h.

The range of chemical contaminants, penetrating from the Zelazny Most flotation tailings dam to groundwater may be determined if natural, i.e. original, and current, i.e. anthropogenically modified, hydrogeochemical baseline of this groundwater are established. Prior to the construction of the dam, the chemical composition of the quaternary aquifer water was typical for 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 actual velocity of the groundwater flow. Characteristic levels of the current hydrogeochemical baseline for the chloride concentrations in groundwater have been distinguished; they depend on the land use, and range from

20 mg Cl/l for a forest area to 50 mg Cl/l for an agricultural land, and to 85 mg Cl/l for a residential area.

V.5.3. Characteristics of the flotation tailings dam as a source of groundwater contamination

Earth embankments of a local gravel-sandy material were raised in the first phase of the flotation tailings dam construction. They are currently overbuilt with properly selected, coarser sandy fractions of the flotation tailings. 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 Zelazny Most flotation tailings dam is planned to cease with the cessation of copper mining in the Lubin-Glogow Copper District. The flotation tailings dam will then have a volume of 1 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 V.5.1 to visualize the rate of its continued 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. V.5.5), with a beach, composed of the coarsest fractions; some part of the discharged water may infiltrate 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.

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

The overflow water represents saline waters of $Cl-SO_4-Na-Ca$ type, with total dissolved solids content from 15,000 up to 22,000 mg/l. Chlorides, sulfates and sodium are the major components leached from the flotation tailings dam to the water environment. In 2000, the mean concentration of chlorides in leachate was 8800 mg/l, of sulfates 2900 mg/l, and of sodium 5500 mg/l. Such high concentrations of major ions in water

Table V.5.1. Technical characteristics of the Zelazny Most flotation tailings dam.

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	≈6.5	≈6.5
Volume of pond water (10^6 m^3)	13.5	10.7	7.5	≈10.5	≈10.5
Datum of the pond lifting (m asl)	140.5	148.2	154.6	158.0	178.0

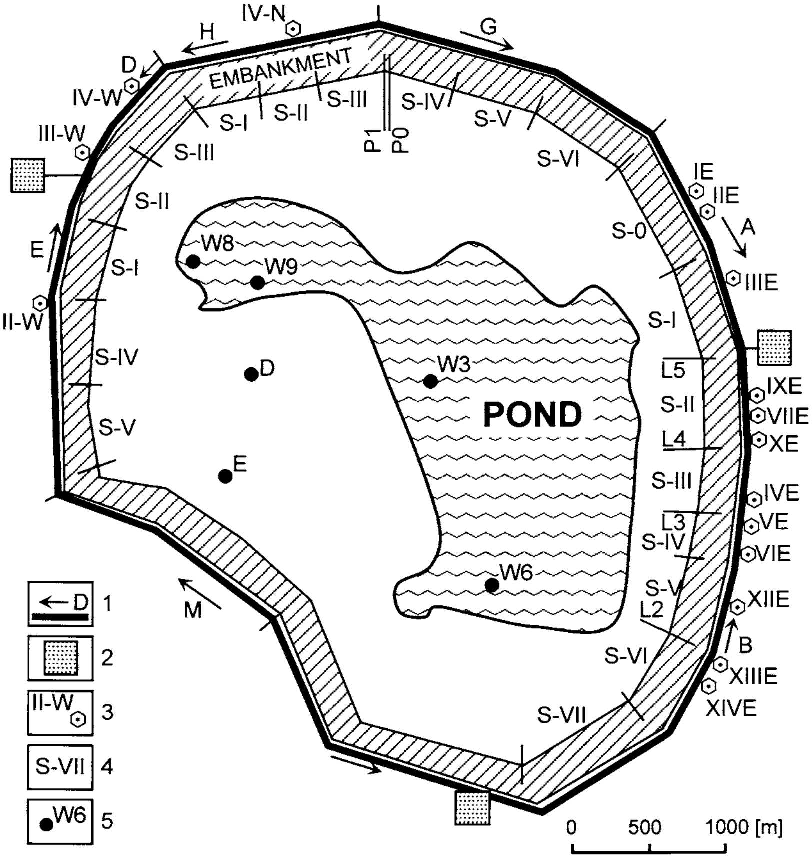

Figure V.5.5. Sketch of the dewatering installation of the dam. 1 – dewatering ditch (arrows indicate water flow direction), 2 – pump stations with water reservoirs, 3 – wells of the vertical drainage, 4 – pipe sections discharging flotation tailings, 5 – overflow spill-towers.

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 xanthenes.

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 migration of the water toward the dam foreground. The infiltrating saline water degrades the quality of fresh groundwater and also subsequently, surfacewater. The contaminated streams will become a secondary source of groundwater contamination, particularly around the Retkow well field (Duda and Witczak, 1994; Duda et al., 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 chloride concentration (Fig. V.5.6) results from mixing of the leachate infiltrating from the dam, with the fresh groundwater flowing through the bedrock from hills south of the dam. The

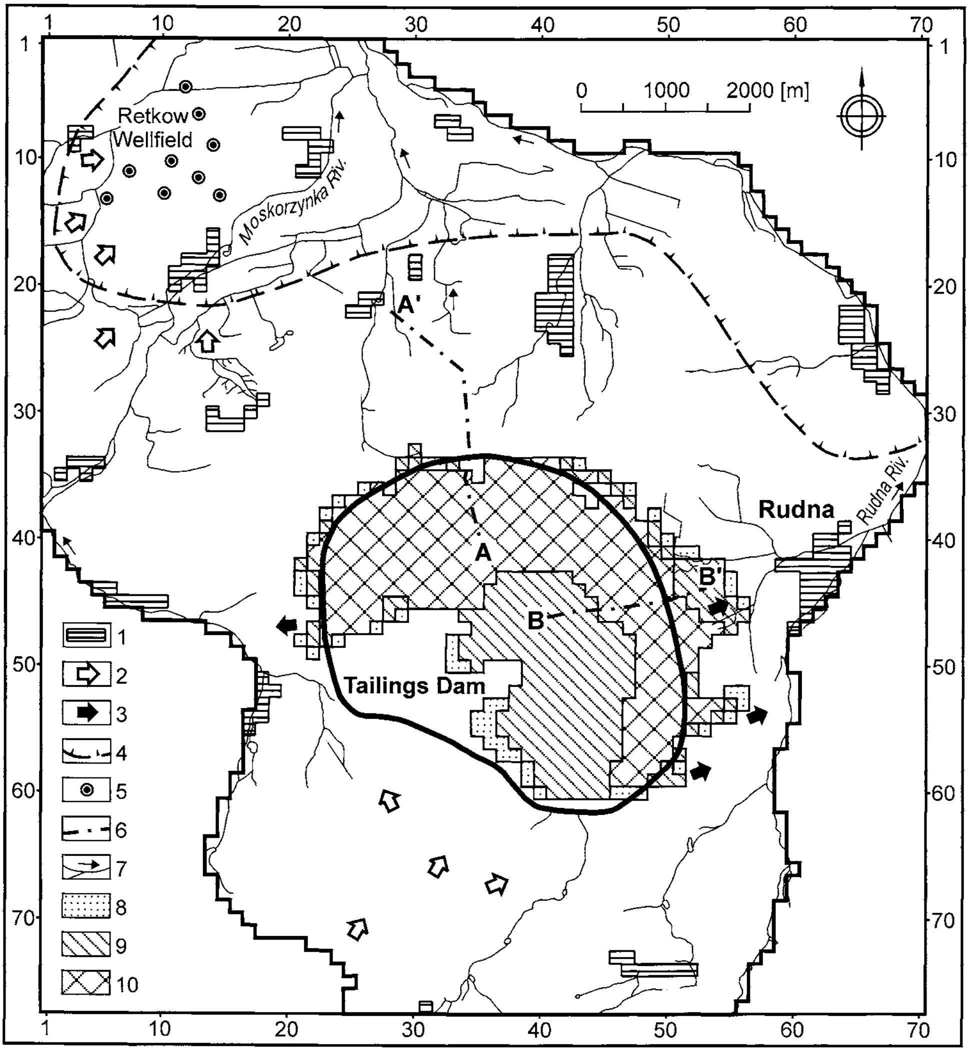

Figure V.5.6. Spatial distribution of the chloride concentration in groundwater assumed in the current prediction for the calibrated (1988) regional model of the dam area. 1 – residential area, 2 – directions of fresh groundwater flow, 3 – directions of contaminants migration from the dam, 4 – the range of the MGWB No. 314 - the Odra River Periglacial Valley, 5 – wells of the Retkow well-field, 6 – lines of hydrogeological cross-sections from Fig. V.5.4., 7 – streams and rivers, 8–10 – spatial distribution of chlorides in groundwater: 100–300 mg/l (8), 300–3,000 mg/l (9), >3,000 mg/l (10).

extent of water contamination in the dam foreground has been determined from chloride concentrations in groundwater. The boundary isopleth has been established at 100 mg Cl/l, i.e. the chloride content in 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 predictions, and was confirmed during monitoring aimed at checking earlier predictions (Duda and Witczak, 1994). 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.

Within the northern dam foregrounds the propagation of contaminants in groundwater appeared to be smaller than the earlier predictions. But one cannot exclude waters infiltrating from the dam that may appear somewhere further, if remote 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. V.5.4, A′–A′ section).

V.5.4. A model of groundwater flow in the area of the flotation tailings dam

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 special attention:

- formation of water seepage through the tailings and into the dam bedrock from the pond and from the beaches;
- 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 and Moreno (1996) and ASTM (1999). As a tool in preparation and calibration of a hydraulic field model, a MODFLOW program has been selected. This modular, 3D, finite-difference groundwater flow model developed by US Geological Survey has become the most popular hydrogeological model in the world and since 1988 underwent several revisions, MODFLOW-96 (McDonald and Harbaugh, 1996; Harbaugh and McDonald, 1999), and consecutively MODFLOW-2000 (Harbaugh et al., 2000; Hill et al, 2000; Clement, 2001; Mehl and Hill, 2001; Zheng et al., 2001) being the latest versions by 2002.

For this model, a number of groundwater modeling software packages and graphical user interfaces have been elaborated (e.g. Chiang and Kinzelbach, 1998). To use this model, complementary papers about the methodology were also published (Prudic, 1989; Goode and Appel, 1992; Hsieh and Freckleton, 1993). The most recent release based on the MODFLOW model is an integrated Visual MODFLOW Pro 3.0 package that integrates several tools extending calibration techniques, and visualization and animation capabilities of the model (Waterloo Hydrogeologic, 2003). It has been continuously developed and upgraded, though the basic features of this core, 3D groundwater flow and contaminant transport model remain unchanged.

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 and Appel, 1992). 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 2D, 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.

Creation of a conceptual model required certain schematization of the geological structure and hydrogeologic 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 originated from earlier predictions. The thickness of the aquifer has been generally determined as effective, as it is the thickness interpreted without insets of low permeable strata that is partly corrected for non-homogeneity of hydraulic conductivity along the vertical profile of the aquifer. The thickness in question ranges from 1 to ≈ 30 m.

The hydraulic conductivity of sands and gravels of the quaternary aquifer varies from 0.3 m/d to over 20 m/d. These values have been arrived at by a calibration of the transmissivity of the aquifer on the model, the distribution of computed hydroisopleths (groundwater contours) on the model corresponded well with the distribution observed in the field. 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 assumed as a product of a mean hydraulic conductivity and an effective thickness of water-bearing strata in each of the cells of the model. A probable 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.

The data in the case of an unconfined/confined aquifer have been assumed as:

- data for 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 for the bottom of an impermeable horizon, overlaying an aquifer, in the areas of confined conditions.

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 means 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 assumed that within the upland area composed of rocks with low permeability, about 10% of annual rainfall infiltrates, while this value is about 25% within the flat area composed of permeable rocks and covered with woodlands and meadows. Also some transition regions, with infiltration values between the two mentioned above, have been distinguished.

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 dewatering wells. Also a comparison of amounts of water penetrating into a dam foreground, calculated from the model, with field hydrogeological observations coupled with measurements of a flow velocity rate of saline water infiltrating from a dam outside is an important element of model validation.

The balance of outflow from the embankment drainage and girdling ditches has indicated that approximately 90% of water infiltrating through tailings collects in the ditches (horizontal drainage of the tailings dam). Hydrogeological data have 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 catchment area being modeled. The estimated amounts of overflow water infiltrating into the dam bedrock have been compared and balanced against the amount of flow in the drainages and the increased outflow from partial catchments, draining the dam foreground (Table V.5.2, Fig. V.5.7). The total flow in streams in 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. The correctness of the whole regional model of a hydrodynamic field is reflected in the balance of groundwater computed for the calibrated model (Table V.5.3).

V.5.5. Model of Contaminant 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 next 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 in groundwater (Zheng and Bennett, 1997. The calculations were carried out using MT3DMS – a modular 3D multispecies transport model designed by

Table V.5.2. Model-computed balance of the amounts of overflow saline water and loads of chlorides migrating into the dam foreground.

Datum of the overflow pond lifting		150.2 m asl (in 1996)		158.0 m asl (predicted for 2003)					
Computing scenario		Calibrated model		Scenario A) without the additional vertical drainage		Scenario B) with the additional vertical drainage		C) Difference B − A	
		m^3/d	kg Cl/d	m^3/d	kg Cl/d	m^3/d	kg Cl/d	m^3/d	kg Cl/d
Q_1	Seepage of overflow water into the dam bedrock	21,788	123,102	23971	135,436	25,588	144,572	1617	9136
Q_3	Water drainage by girdling ditches	15,039	–	10,732	–	10,282	–	−450	–
Q_4	Water drainage by supporting system of vertical wells	4030	–	12,746	–	16,237	–	3491	–
Q_5	Ditches and wells recharging from a dam foreground	2306	–	2502	–	2594	–	92	–
Q_6	Amount of saline water migrating into a foreground	5024	28,386	2995	16,922	1095	6187	−1900	−10,735

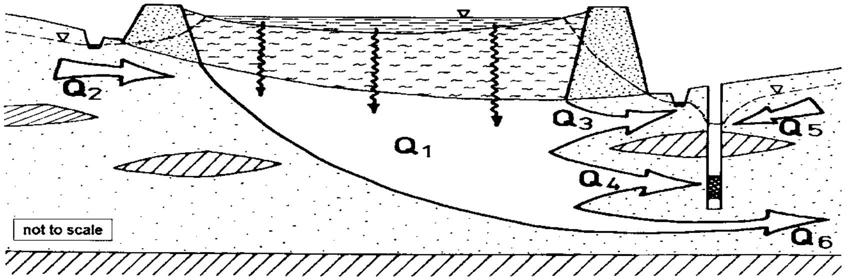

Figure V.5.7. Conceptual model of groundwater flows in the immediate vicinity of the dam. Q_1–Q_6 – water inflows balanced during calibration of the permanent regional model (Table V.5.2.)

Zheng and Wang (1998) and linked with MODFLOW. MT3DMS has been revised; the last upgraded one is MT3D99 (Zheng et al., 2001).

Setting of initial conditions in a mass migration model equals 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 assumed, depending on land use (forest, agricultural or residential 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 for the area of the Zelazny Most flotation tailings dam on a basis of an analytical method at 8 m (Maloszewski 1978). Later, an average flow velocity of

Table V.5.3. Groundwater balance for the regional model (relative error = 0.04%).

Balance components	Inflow into the model (m^3/d)	Outflow from the model (m^3/d)
Infiltration of rainwater	20,010	–
Yield of wells exploited within the area	–	4030
Flow across the borders of the model	3850	17,450
Seepage from the dam and into streams and drainage ditches	24,040	26,400
Total	47,900	47,880

groundwater was estimated at 44 m/year and dispersion at 43 m (Szczepinski, 1993). 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.

A calibrated model of migration of the contaminants tracer in groundwater in the vicinity of the flotation tailings dam can be validated quantitatively in the form of the following mass balance with a relative error of 0.1%:

- injection of a mass into the model – 115,671,769.0 g/d,
- increase of a mass in the model – 16,107,564.0 g/d,
- outflow of a mass from the model – 99,678,312.0 g/d.

V.5.6. Prediction of contaminant migration

Seepage of water into bedrock through the flotation tailings accumulated in the dam is one of the fundamental elements of the model. This process has been modeled considering:

- the durations of tailings discharge and the ranges of a shoreline of the overflow water pond during exploitation of the dam in 1985–1996,
- a 2D profile model of water seepage through the flotation tailings, combined with a water flow through an unsaturated zone as a basis of assumptions, to construct a regional model as the part of the dam itself.

The relationships and processes obtained for the profile model of water infiltration into flotation tailings and for its seepage through the tailings into an aquifer (Fig. V.5.8) indicate an important role of filtration through the most permeable part of a beach being formed. The seepage into bedrock has been simulated accepting head-dependent boundary conditions.

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. 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,

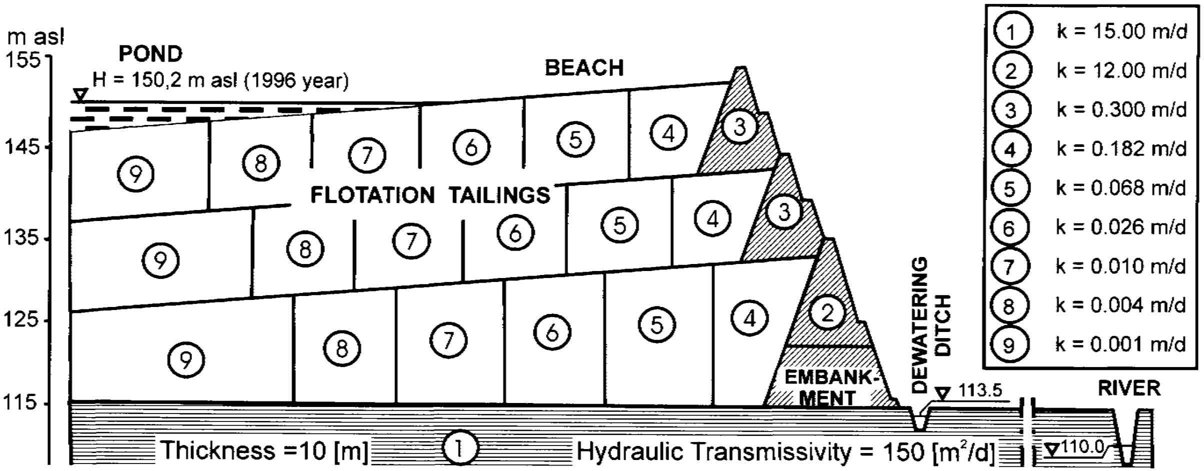

Figure V.5.8. Conceptual model of the hydrodynamic field within a part of the flotation tailings dam and its bedrock created for modelling of overflow infiltration trough the vadose zone in the tailings. 1 – hydraulic conductivity of an aquifer in the dam bedrock, 2–3 – hydraulic conductivities of materials, used in the construction of embankments, 4–9 – hydraulic conductivities of flotation tailings.

which controls the discharge of overflow saline water from the Zelazny 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 seepages into the dam bedrock. The shoreline of the dam is also of random character. This means that technological processes within the dam, despite their controlled regime, may and should be treated as random variables in a prognosis because it is not possible to accept that the shoreline will be maintained in a constant distance from the embankments. The distribution of changes of the shoreline (Fig. V.5.9) indicates that the horizontal range of beaches oscillates from − 270 to + 270 m around a mean value with a probability of 90%.

The probability cited on the axis of ordinates may be treated as a fraction of time during which a given part of the beach is inundated. The distribution obtained for selected cells of the model which simulate the Zelazny Most dam, has allowed determination of the fraction of time when water infiltrates through the cell surface into the bedrock. As it is a random process, a mean annual infiltration resulting from oscillations of the shoreline may be computed in the same way as the rainfall: by multiplying the infiltration rate by a relative time during which a single cell of the model is inundated. The predicted range of the pond has been averaged from the mean water levels, observed every 6 months during 1985–1996.

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

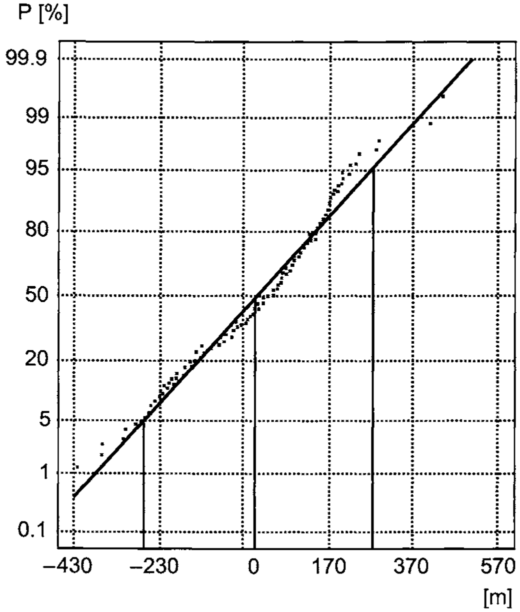

Figure V.5.9. Probability graph of deviation of a shoreline of the pond from the mean value for individual sections.

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.

Seepage 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 Zelazny 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 prognosed time span. Such a situation is caused by the drainage around the dam embankments, which collects approximately 90% of water infiltrating from the dam into its bedrock.

In the prediction, the hydrodynamic field from the year 1996 has been calibrated for a pond lifting datum of 150.2 m asl. According to a current extension variant of the Zelazny Most tailings dam, a predicted pond lifting datum of 158.0 m asl for the year 2003 has been accepted.

The following concentrations of chloride 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 Cl/l;
- within the areas of infiltration of rainwater through the soil and vadose zone – 20 mg Cl/l for forested land, 50 mg Cl/l for an agriculturally used land, and 85 mg Cl/l for a residential area,
- within the areas of water infiltration from streams into an aquifer in the Retkow 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 hydrodynamic field pattern within the dam foreground were small, the process, which in fact is transient, has been split into two periods, each 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 Zelazny 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. V.5.3). 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 and Duda, 1995). This may be accomplished 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 et al., 1992).

The error that results from splitting of a longer time period, during which migration is transient, into two shorter, steady-state periods is reflected by the shape of breakthrough curves for chlorides. The curves, observed in points localized along particularly important migration paths within a model, depart from smoothed lines (Fig. V.5.10). However, the general trend of chloride concentrations growing in time is preserved with accuracy. The predictive simulation gives also visualization of a spatial distribution of a tracer concentration until the year 2003 (Fig. V.5.11).

Predictive simulations for the scenario without an additional vertical drainage have shown that infiltration of overflow saline water into a tailings dam foreground at a datum of 158.0 m asl will be equal to 2995 m^3/d (Table V.5.2, Fig. V.5.7). Most of the water will be collected by the horizontal drainage of the embankments supported by system of vertical wells, thus lowering the hazard of groundwater contamination. Infiltration into a foreground will decrease to 1095 m^3/d for the scenario 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 permeable rocks, making the drainage by girdling ditches ineffective.

Water migrating into the dam foreground, particularly through such zones of ineffective drainage, may be captured substantially by the vertical drainage system, as it has been simulated in the second scenario. 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 saline 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. 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 Retkow well field, threatened by secondary contamination by pollutants carried by rivers.

According to predictive simulation for both scenarios, migration of contaminants from the Zelazny Most tailings dam should not directly pollute the Retkow well field unless its groundwater is extensively exploited. More hazardous for the well field is a secondary contamination from surfacewater, as a substantial amount of the Retkow 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 first scenario at 2630 mg Cl/l, and for the second one at 1030 mg Cl/l. One of the tributaries of the Moskorzynka River flows across an area reached by migrating saline waters from the tailings dam.

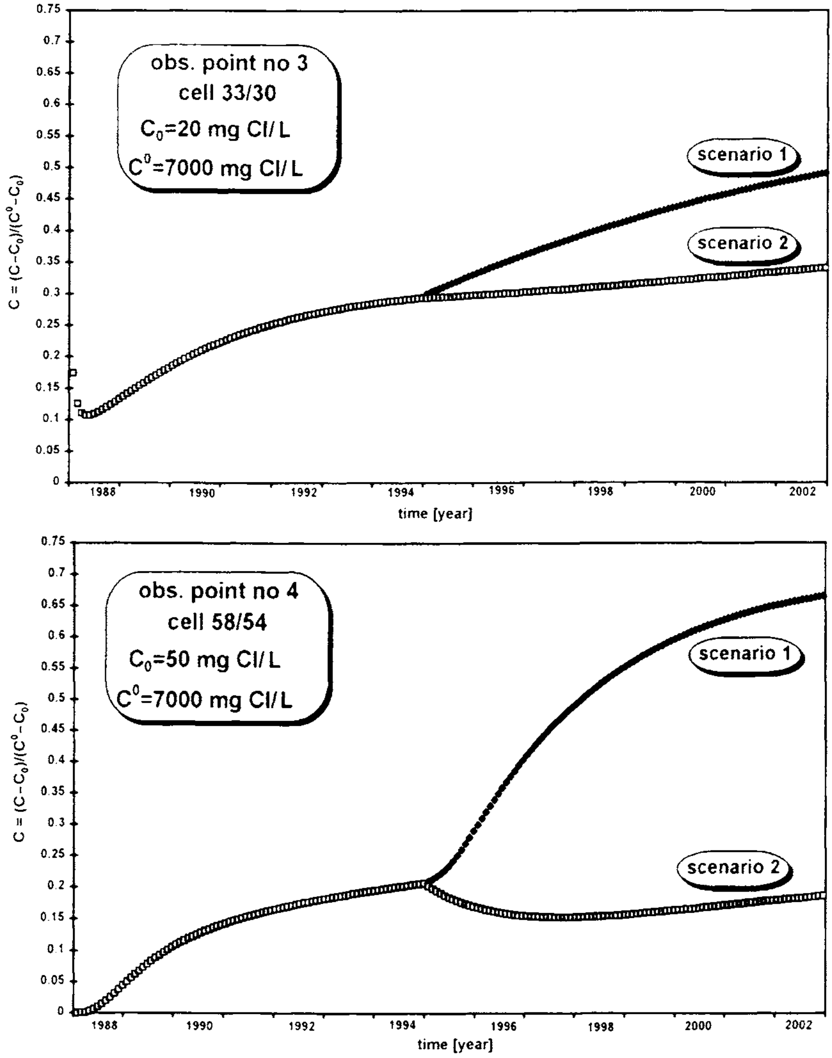

Figure V.5.10. Predicted changes in the concentration of a chlorides in the years 1988–2003 in the selected observation points (localization of the points indicated in Fig. V.5.11.). C_0 – concentration of chlorides for the current hydrogeochemical baseline, C^0 – concentration of a chloride injection.

The likelihood of the hazard predicted for the Retkow 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 within semi-permeable and low-permeable rocks 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

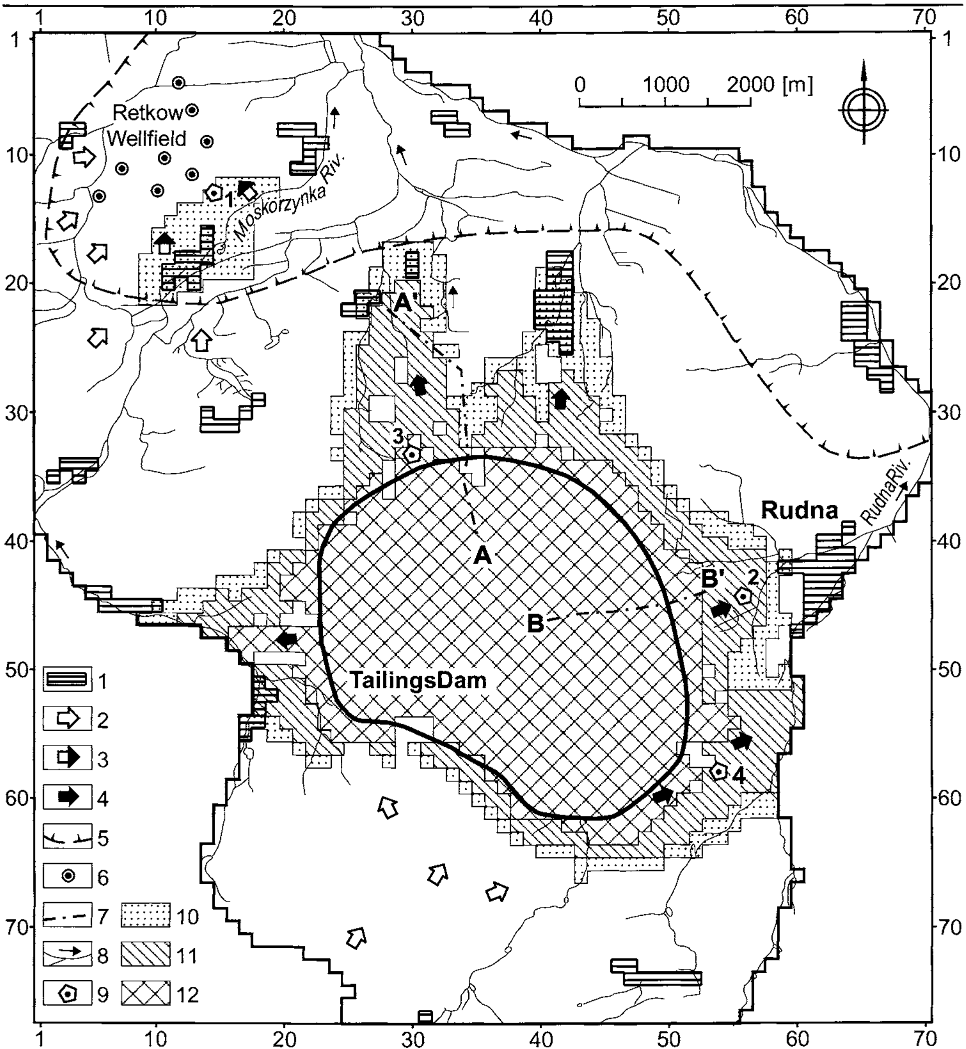

Figure V.5.11. Prediction of chloride migration in groundwater in the dam area for the year 2003 (datum of the pond 158 m asl); the scenario assuming an additional vertical drainage. 1 – residential area, 2 – directions of fresh groundwater flow, 3 – directions of migration from secondary contaminant sources (rivers carrying contaminants originating at the dam), 4 – directions of contaminant migration from the dam, 5 – the range of the MGWB No. 314 – the Odra River Periglacial Valley, 6 – wells of the Retkow well-field, 7 – lines of hydrogeological cross-sections from Figure V.5.4., 8 – streams and rivers, 9 – localization of the observation points from Figure V.5.10., 10-12 – predicted spatial distribution of chlorides in groundwater: 100–300 mg/l (10), 300–3,000 mg/l (11), > 3,000 mg/l (12).

on. The effect has been accepted as resulting from migration of saline water from the dam. Saline Water migrating northward from the flotation tailings dam, may probably contaminate fresh water within a south part of the groundwater basin No. 314 – the Odra River Periglacial Valley.

V.5.7. Conclusion

The presented prediction of contaminants migration in the area of the Zelazny Most flotation tailings dam indicates that only lowering of the groundwater table 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.

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