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FORECAST OF INFLUENCE OF PLANNED SAND OUTPUT FROM UNDER WATER FROM "OBORA" SANDPIT ON LEVEL AND QUALITY OF UNDERGROUND WATER

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ABSTRACT

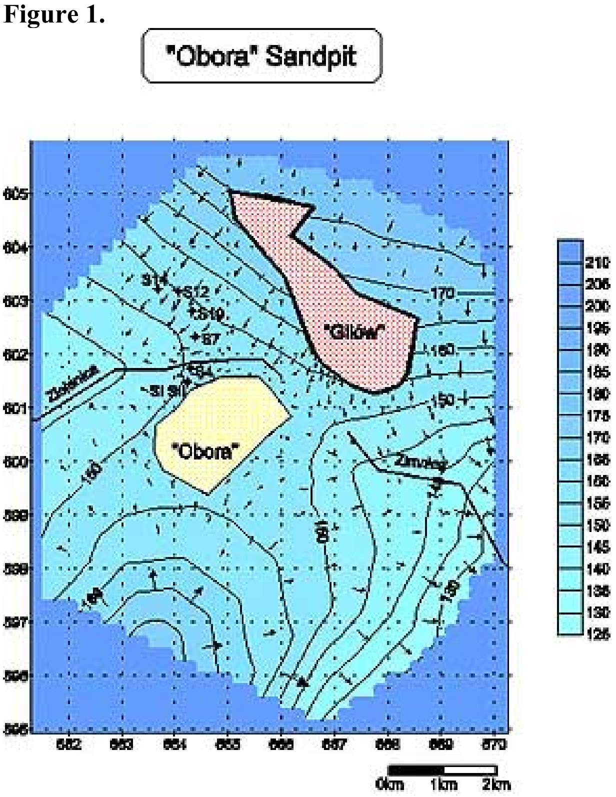
The analysis of the influence of planned increase of sand output from under water in "Obora" sandpit on water relations of neighboring areas is conducted in this paper. The bases for the performed simulations were mathematical models based on Boussinesq equations and hydrodynamic dispersion equations. The model includes all most important factors occurring in a given area influencing the hydroisohipses system and lines of chemical pollutant concentrations. Apart from typical hydrogeological elements such as water-courses, wells, and supplying from the aeration zone, the terrain's depression caused by copper ore exploitation was also considered. As results from the carried out multi-variant simulation computations, the planned sand output will not cause the formation of depression hopper and will not significantly deteriorate the quality of underground water in the area surrounding the sandpit.

Key words: Boussinesq equation, hydrodynamic dispersion equation, mathematical model, filtration, contaminant migration

INTRODUCTION

A considerable increase of sand output from under water in "Obora" sandpit is planned for the next 10 years, accompanied by successive enlargement of the open reservoir area from present 5 to planned 35ha. Unfortunately, it may have a significant impact on the arrangement of piezometric pressure around the sandpit. The fact that the water intake of Owczary – SI and SII wells is located in the close neighborhood of the sandpit (Figure 1) calls for particular attention. Besides, the potential formation of enlarged depression hopper might result in increased inflow of contaminated water from "Gilow" reservoir of post-flotation waste located 3km away. A precise answer to these basic questions requires the application of advanced simulation technologies taking into account all the most important factors influencing the level variation of ground water, and contaminant migration.

Figure 1.



Hydroisohipses map - year 1967

MATHEMATICAL MODEL

Mathematical models of water and contaminant flow in the saturation zone are based on Boussinesq equation for water movement and the hydrodynamic dispersion equation for contaminant migration. In both cases, two-dimensional models of horizontal nature were applied including space variables x, y,

- Boussinesq equation

$$\mu h_t = (T_x h_x)_x + (T_y h_y)_y + w$$

where x, y – space variables,
t – time
μ - effective porosity,
$T_x = k_x(h - a)$, $T_y = k_y(h - a)$
k_x, k_y – coefficients of water-permeability along OX and OY axis
h – ordinate of piezometric pressure,
a – impermeable layer ordinate of aquiferous layer
w – source function.

- equation of hydrodynamic dispersion

$$(1+\beta)c_t = \mathrm{div}(D \bullet \mathrm{grad}(c)) - \vec{v} \bullet \mathrm{grad}(c) + Q$$

where t – time,
x, y – space variables,
β- delay coefficient,
c(x, y, t) – contaminant concentration in point (x, y) at moment t
D - dispersion tensor
$\vec{v}$ - velocity vector of ground water flow
Q - source function.

The application of dynamic models, i.e. taking into account time, allows not only for obtaining the stationary state picture, but also for evaluating the dynamics of phenomena occurring in the saturation zone. The accepted equations permit to take into account the variation in time of interior boundary conditions, the intensity of water input in wells, and also the variation in time of the level of contaminant sources. Both equations are solved simultaneously by means of the finite elements' method based on triangular elements with linear base functions. The computations were carried out by the use of FIZ author's program [1].

FILTRATION AREA

The computations were conducted for the area of the shape close to a polygon determined by geodetic points 351, 354, 369, 371, 353, 360, 356 357, 355 according to the Hydrogeological Map of Poland [2]. The description of geodetic points mentioned above is included in Table 1.

The coordinates of points in kilometers in the system of topographic coordinates are provided in column 2 and 3 of this table. Column 4 contains ordinates of piezometric pressure for the initial condition accepted on the basis of the Hydrogeological Map [2] of year 1967, measured in meters from the sea level. These points were selected in such a way that the distance from the area edge to the centrally located "Obora" sandpit was not shorter than 4-5 km. With this distance, the impact of boundary conditions on potentially enlarged depression hopper is hardly significant, considering the coefficients of water-permeability and effective porosity present in this area. Further calculations confirmed the legitimacy of this initial assumption. Also, the defined area comprises all significant elements influencing the form of piezometric pressure in the past, at present and in future, i.e.:

- Obora sandpit,
- water intake of Szklary-Jedrzychowice,
- Owczary water intake,
- Zielenica and Zimnica rivers,
- post-flotation waste reservoir Gilow.

Table 1.

Geodetic point	***Coordinates X [km]***	***Coordinates Y [km]***	***Initial condition [m.]***
351	661.290	597.510	151.1
354	661.400	602.800	144.7
369	664.580	605.970	180.4
371	669.980	604.210	179.6
353	670.260	600.360	138.1
360	670.060	598.130	126.8
356	669.490	597.330	124.6
357	669.090	596.480	127.7
355	666.820	594.940	132.2

The assigned area was divided into 276 triangles by means of 151 nods, the division being congested in the region of Obora sandpit, in the area of the planned open reservoir as well as in the forearea of Gilow reservoir. The division was less congested in the borders of the region. Important hydrological points of the area were selected as network nod points.

HYDROGEOLOGICAL DATA

The level of the impermeable layer deposition of quaternary layer and the terrain's surface was accepted on the basis of data procured from [5]. Piezometric ordinates from the map elaborated by Downarowicz for the year 1967 [4] were accepted as the initial condition of the simulation (figure 1). In the paper, the ordinates of impermeable layer, terrain and piezometric pressure were considered in relation to the sea level in all figures. The coefficient of effective porosity was accepted as [5] equal to $\mu=0.14$. The coefficient of water permeability for a selected region is provided in available research papers in the range from 2m/d [7], through 18m/d [5], up to 20m/d [6]. As these measurements demonstrated a non-univocal character in

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further computations, originally a uniform and estimated coefficient of water-permeability was accepted for the whole area, equal to k=15 m/d. In the phase of the model taring, this coefficient was modified in selected regions of the area.

EXTERNAL BOUNDARY CONDITIONS

Along nearly the whole border of the region, boundary conditions of Dirichlet type were assumed, providing the ordinates of piezometric pressure in boundary nods complying with the hydroisohipses arrangement in the year 1967. It was accepted that these ordinates did not change in time and were valid throughout the simulation period. Only in the north-western section of the border, between the geodetic points of 354 and 369, the Neuman condition equaling zero was accepted, since the region's border in this area overlaps with the border of Zielenica river basin.

INTERNAL BOUNDARY CONDITIONS AND STRUCTURES CAUSING CHANGES IN WATER LEVEL

There are two rivers in the discussed area: Zielenica and Zimnica. In water nods, through which the two rivers flow, Dirichlet type conditions were assigned complying with mean water levels in water courses [5,8]. The water intakes of Owczary-Jedrzychowice were marked with appropriate symbols SI, SII and S4, S7, S10, S12 and S14 in all figures according to source maps. In the network nods locating the water intakes mentioned above, the source function was assigned with the input rate complying with the output table in the years 1967-1996, and with the output forecast up to the year 2005 in m^3/year [9] – table 2.

Table 2.

Year	***S I [m^3]***	***S II [m^3]***	***S4 [m^3]***	***S7 [m^3]***	***S10 [m^3]***	***S12 [m^3]***	***S14 [m^3]***
1967	0	230049	207360	0	0	0	0
1968	33408	329400	90720	0	0	0	0
1969	0	0	254040	0	0	135780	0
1970	219600	0	315360	0	0	175200	0
1971	197280	0	77760	164241	0	175020	0
1972	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0
1976	31248	0	0	0	3906	79200	92232
1977	306432	248880	0	131760	0	245952	172800
1978	276192	43920	0	324120	0	98496	222528
1979	154080	183600	0	278160	0	83904	184032
1980	219000	280320	0	175680	0	0	0
1981	394200	92448	0	350400	0	0	65880

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1982	184464	165000	0	262800	0	0	0
1983	306432	175200	0	262800	0	0	0
1984	236520	271560	0	144540	0	0	0
1985	236520	332880	0	183960	0	0	0
1986	254040	254040	0	201480	0	0	0
1987	210240	210240	0	197100	0	0	0
1988	236520	250240	0	183960	0	0	0
1989	183960	183960	0	32400	0	0	0
1990	201480	220752	0	0	0	0	0
1991	210240	208488	0	0	210240	0	0
1992	183960	178704	0	0	199728	0	0
1993	183960	183960	0	0	183960	0	0
1994	192720	188340	0	0	183960	0	0
1995	192720	188340	0	0	0	0	0
1996	192720	188340	0	0	0	0	0
1997	367920	0	0	0	0	0	0
1998	367920	0	0	0	0	0	0
1999	367920	0	0	0	0	0	0
2000	367920	0	0	0	0	0	0
2001	367920	0	0	0	0	0	0
2002	367920	0	0	0	0	0	0
2003	367920	0	0	0	0	0	0
2004	367920	0	0	0	0	0	0
2005	367920	0	0	0	0	0	0

The region of Obora sandpit was treated in an analogous way. The sandpit was marked in the central part of the filtration area in all figures. The planned and enlarged water region will be located in the northern part of the sandpit. The sand output will take place only in the area of the water region. In the network nods located in the area of the planned water region a source function was assumed complying with the table of sand output from under water comprising the period of 1992-1997 [10] – table 3. In the years 1998 – 2007 the output was assumed according to the project of the order of 350000 m^3 per year. Apart from increasing the sand output, the enlargement of open water region of up to 35 ha is planned in the forecasted period. In the model, the water volume filling the water region is assumed to be equal to the volume of put out sand. Thus, it was assumed that the values of the source function describing the output are equal to the values provided in table 3, while the output in particular operation years is spread on larger and larger area according to the planned water region enlargement [3].

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Table 3.

Year	*Output [m^3]*
1992	30000
1993	92000
1994	122265
1995	122485
1996	125240
1997	152970

Gilow reservoir of post-flotation waste was treated as a dry reservoir in the model, having no influence on the arrangement of equipotential lines. It results from the fact that the reservoir's operation ceased in 1980, which led to its nearly complete drying-up after several years. Therefore, its impact was taken into consideration only in the part of the model concerning the quality of underground water.

CONTACT WITH AERATION ZONE

The distributions of index spatial evaporation, current evapotranspiration and precipitation deficiencies in lowland Poland in the period of 1951-1990 are included in papers [11,12,14]. As for the data related to mathematical modeling of retention capacity of small lowland river basins of regions located tens of kilometers northwards from the discussed area, they are presented in paper [13]. The analysis of evaporation, evapotranspiration and precipitation was made for each day of simulation in three variants, for dry, average and wet years. An example of the evapotranspiration value is presented in table 4. The characteristic of precipitation was accepted on the basis of measurements from the precipitation post of Lubin comprising the period of 1961-1995 (table 5). For the subsequent years, after 1995, the characteristics of precipitation was accepted as average values from the whole period of 1961-1995, preserving the division into dry, average and wet years. In the regions of open reservoirs, the values of index evaporation were accepted instead of the values of evapotranspiration. The analysis elaborated in this way was introduced into the model as a source function.

Table 4.

Month/ Year	*1 [mm]*	*2 [mm]*	*3 [mm]*	*4 [mm]*	*5 [mm]*	*6 [mm]*	*7 [mm]*	*8 [mm]*	*9 [mm]*	*10 [mm]*	*11 [mm]*	*12 [mm]*	*Total [mm]*
Dry	10.1	18.7	42.9	43.2	71.8	83.3	77.9	67.5	38.4	34.3	15.9	15.3	519.1
Average	14.4	17.4	33.2	41.0	62.5	75.3	68.1	62.1	28.0	23.3	14.4	13.1	452.8
Wet	9.8	19.2	24.2	45.1	69.8	76.1	82.7	62.6	32.1	40.4	14.0	15.6	491.6

Table 5.

Month	*1 [mm]*	*2 [mm]*	*3 [mm]*	*4 [mm]*	*5 [mm]*	*6 [mm]*	*7 [mm]*	*8 [mm]*	*9 [mm]*	*10 [mm]*	*11 [mm]*	*12 [mm]*	*Total [mm]*
	Year 61-70												
Dry	9	23	16	7	26	20	4	42	12	4	30	12	486
Average	33	39	37	46	81	65	64	81	44	43	50	39	623
Wet	66	73	53	72	135	117	155	192	119	83	105	69	752

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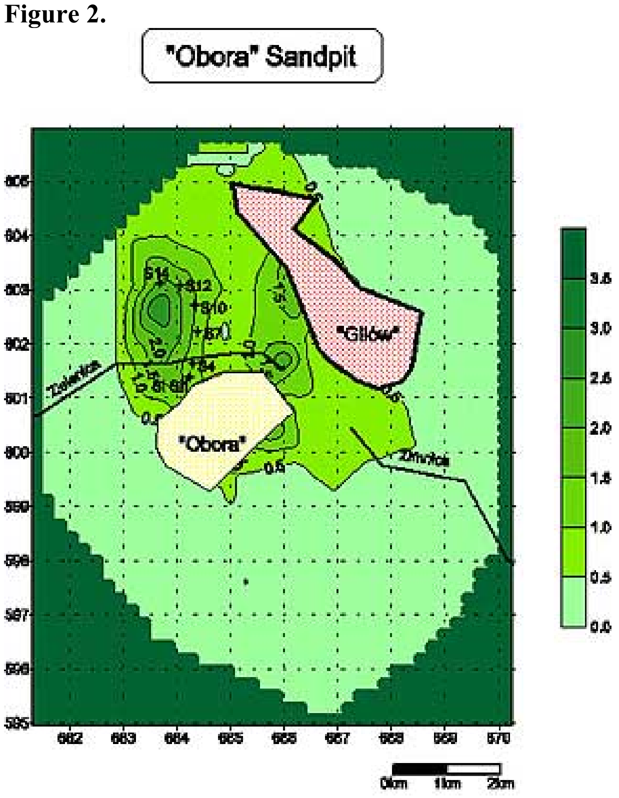
	Year 71-80												
Dry	12	2	3	13	11	25	44	11	14	13	60	7	450
Average	37	24	26	41	56	68	85	62	50	46	39	44	577
Wet	106	45	41	84	108	158	121	151	94	111	61	107	784
	Year 81-90												
Dry	11	8	13	10	21	42	15	29	7	8	12	15	327
Average	32	29	31	38	56	67	72	74	39	29	37	44	548
Wet	55	43	66	61	95	101	205	149	61	76	66	96	715
	Year 91-95												
Dry	16	16	30	15	25	58	32	52	21	7	19	27	462
Average	31	31	53	31	58	69	59	71	52	24	38	43	560
Wet	35	46	53	31	102	73	59	71	61	24	67	43	592

GROUND SETTLEMENT

Non-uniform ground settlement can be observed in the analyzed region for the reason of copper ore output. The value of settlement oscillates between 0.5 and 2.5 meter in various points of the region [17] (Figure 2). A map of forecasted ground settlement of up to the year 2013 is also available in elaboration [15] (Figure 3). On the basis of these data, average-yearly rate of ground subsidence in particular network nods was calculated, separately to the year 1994, and separately in the forecasted period to the year 2007. The ordinates of impermeable layer and terrain were lowered in the simulation period at the beginning of each computation year, in accordance with maps presented in figure 2 and figure 3.

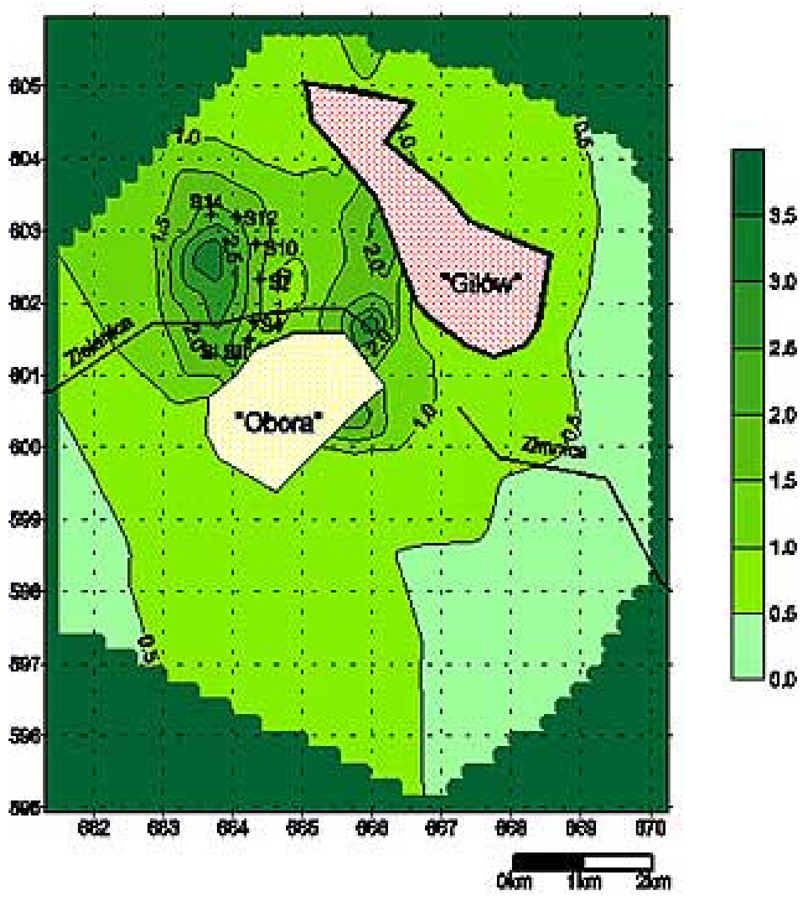
Figure 2.



Ground Lowering - state in year 1994

Figure 3.

"Obora" Sandpit



Ground Lowering - forecast for year 2013

CONTAMINANT MIGRATION

The main contamination source in the discussed area is Gilow reservoir of post-flotation waste, which operated in the period of 1967-1980 [17]. When simulating the migration process, it was presumed that Gilow reservoir was a superficial contaminant source in this period, realized in the model by Dirichlet condition with the contaminant concentration equal to 100% (Figure 4). After the year 1980, the reservoir was no longer exploited, which caused its drying-up nearly on its entire surface. Only in the southern part of the area there is a tiny water region of contaminated surface water. It was accepted in the model that beginning with the year 1980 the reservoir in Gilow should be described in the non-dried area, by means of Dirichlet condition constant in time with the concentration equal to 100%. As for the dry area, it is not a source of contaminant emission in this period. On the border of the area, the condition of the third type was assumed for the contaminant flow, that is a condition of free outflow/discharge. The constant of the longitudinal dispersion was accepted to be [18] equal 8m. The constant of the crosswise dispersion was defined, in compliance with theoretical recommendations, as several-fold lower; in this case it is 2 m. The process of contaminant adsorption through the ground medium was presumed not to take place in the model.

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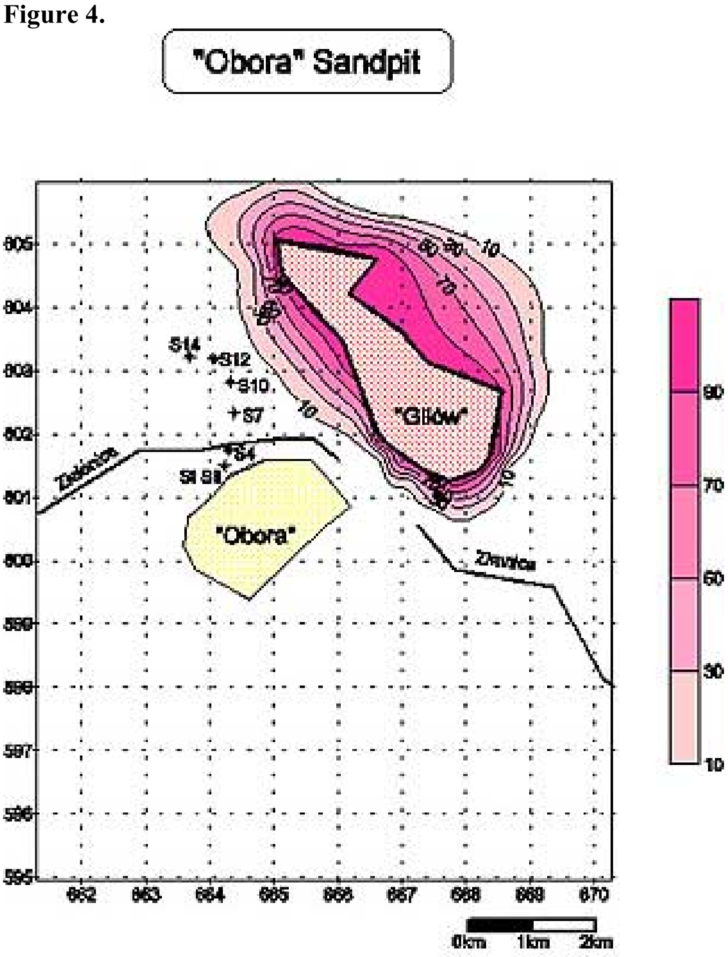
Figure 4.

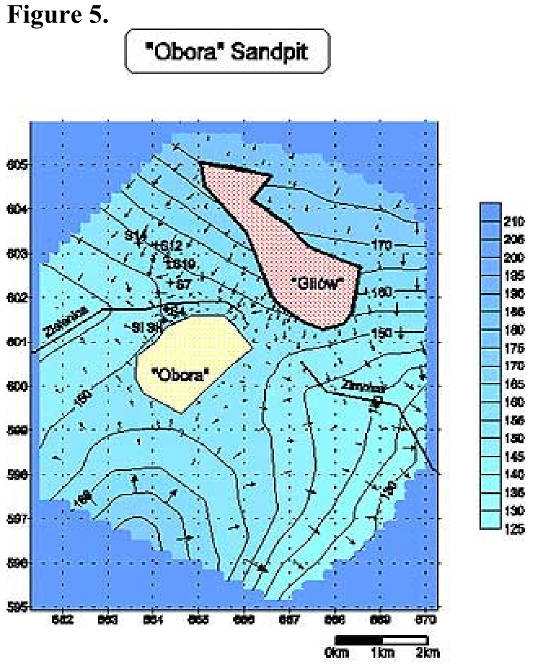


Contaminant concentration - year 1968

MODEL TARING

The empirical material comprising the period of 1967-1997 was used for the model taring. As a result of correction of the water-permeability coefficient accepted in the beginning, it was possible to obtain a realistic piezometric picture (Figure 5). The river basins of Zielenica and Zimnica with the watershed going through the area of the sandpit can be clearly visible in figure 5. The central region is supplied with water from the south, and from the north from the area of Gilow reservoir. The discharges take place eastwards and westwards, in the direction that both rivers flow. Despite intensive sand output from under water in the years of 1992-1997, a significant depression hopper did not appear in Obora sandpit. The ordinates of piezometric pressure stay within the range of 152-153 m in this region. The influence of dry and wet years on the variation of underground water level was also examined in this phase of the model taring. On the basis of simulation computations one can state that one dry year causes the lowering of piezometric pressure of approx. 1m in relation to average years, while a wet year results in the level rising of over a meter.

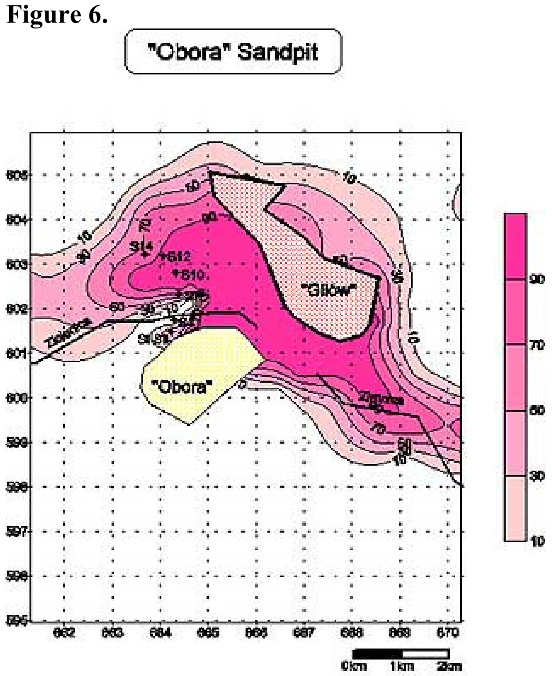
Figure 5.



Hydroisohipses map - year 1997

The basic direction of contaminant migration coming from Gilow is the same as the direction of advective movement determined by the main directions of water flow (Figure 6). The lines of 50% and 10% of contaminant concentration cross the borders of Zielenica-Zimnica rivers and reach the region of the sandpit. After the year 1980, a significant reduction of contaminated water region has been observed, particularly northwards from the reservoir. It is a result of the main direction of pure water discharge from the north and the washing out of contaminated water in the direction of Zielenica and Zimnica rivers.

Figure 6.



Contaminant concentration - year 1997

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PROGNOSTIC COMPUTATIONS UP TO THE YEAR 2007

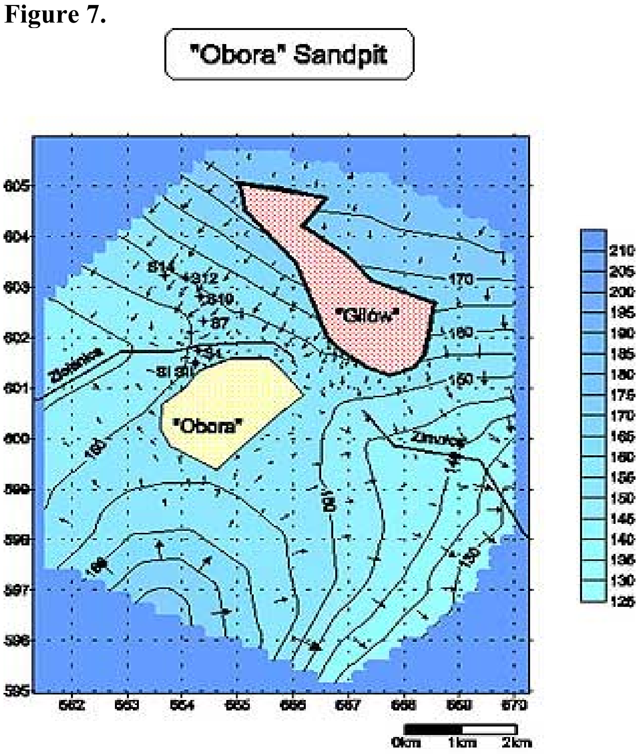
In this phase of the research we attempted to answer three basic questions.

a. Depression hopper – Will the increased operation in Obora sandpit cause the formation of significant depression hopper?
b. Water intake endangerment – Is there a real endangerment for the water of Obora and Owczary intake from the part of contaminated water flowing from the northern side from Gilow reservoir?
c. Ecological disaster – What would be the directions of contaminant migration in case of a potential ecological disaster in the region of Obora sandpit?

Depression hopper

When investigating the problem of potential enlargement of the depression hopper around Obora sandpit, a comparison of computed piezometric pressure was made with the planned output of 350 000 m^3, and then with the output at the level present so far, and with no output in particular years from 1998 to 2007. The comparison was drawn in three computation variants: for dry, average, and wet years. An example of the hydroisohipses map for evapotranspiration and precipitation characteristic of average years, at the end of the year 2006, is demonstrated in figure 7. For the average years, the differences of ordinates of piezometric pressure between extreme computation variants, i.e. between the planned output of the order of 350 $000m^3$, and the results in case of complete resignation from output are not higher than 0.3m (Figure 8). Figure 8 indicates the izolines of differences of piezometric pressure between extreme computation variants. The formed enlarged depression hopper has a diameter smaller than 2km and, in principle, does not go beyond the sandpit limits. In the medium computation variant, with the future output at the level kept so far, the differences of piezometric pressure will be even smaller. The conducted simulation computations show that the two subsequent dry years, with the maximal sand output, cause the lowering of the water level of maximum 2 meters in relation to average years. It gives an estimated rate of lowering of underground water of 1 meter a year. As a result, the piezometric ordinates on the terrain of the sandpit lowered from the average 152 –153m to approx.150m.

Figure 7.



Hydroisohipses map - year 2006

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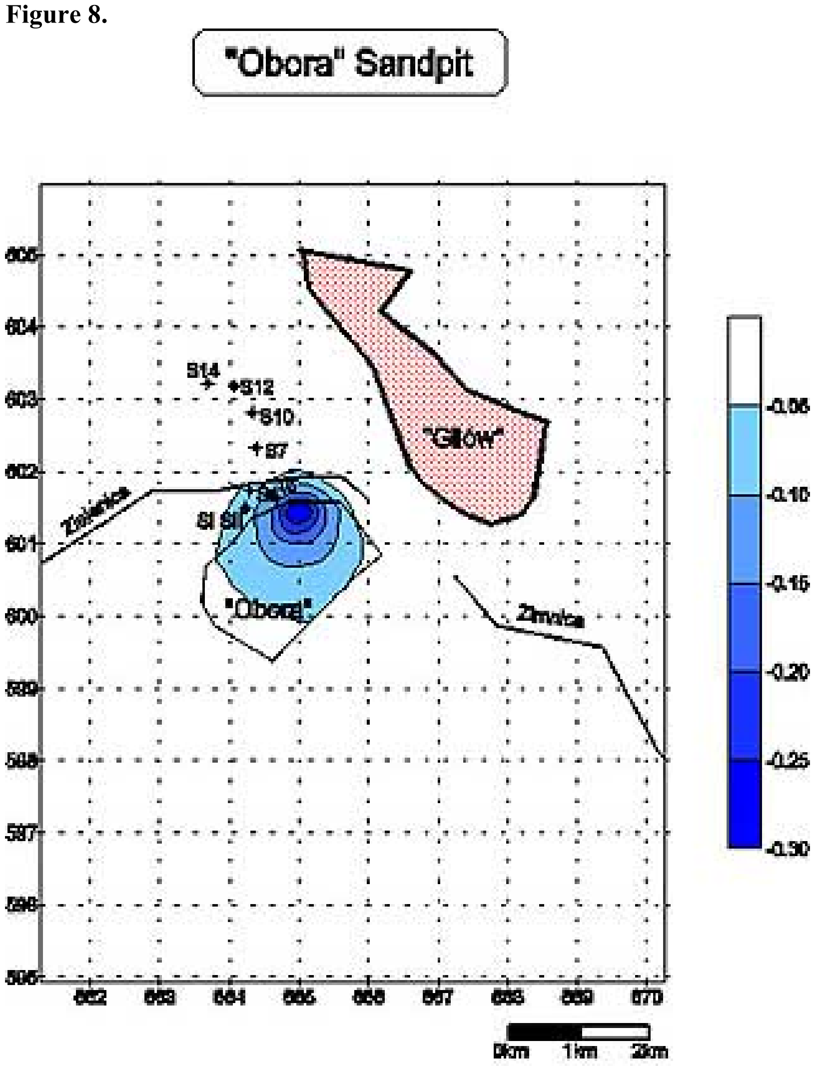
Figure 8.



Enlargement of depression hopper

The lowering does not cause any considerable changes in the izoline arrangement of contaminant concentration in relation to average years. The maximal concentration difference was not more than several per cent. A similar analysis was performed for two subsequent wet years. In this case, an increase of piezometric pressure was observed, maximally of 2.5m in relation to average years. One can infer that the annual rate of rising approx. amounts to 1.2m. Similarly as for dry years, a wet year does not cause any significant changes in the izoline arrangement of contaminant concentration (figure 9). Summarizing this part of the analysis one can state that supplying from the aeration zone has a more vital importance for the hydroisohipses system in the region of the sandpit than the quantity of output from the sandpit.

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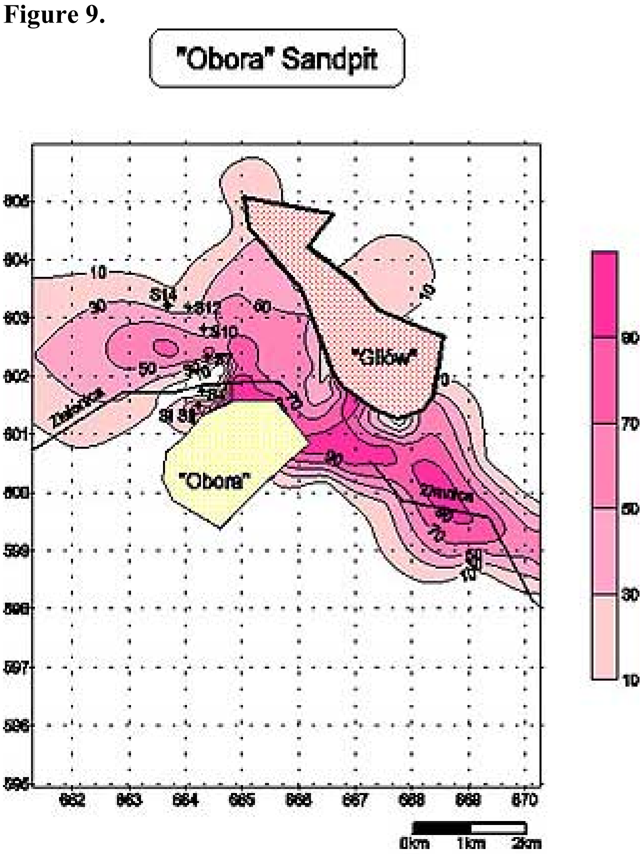
Figure 9.



Contaminant concentration - year 2006

Water intake endangerment

The computations of contaminant concentration were carried out for all three calculation variants, i.e. for the planned output, for the one applied so far and for the case of giving up the operation of Obora sandpit. The comparison of calculated concentrations prove that neither the quantity of output in the sandpit nor supplying from the aeration zone have a considerable influence on the range of the contaminated water front. The process of reducing the area of contaminated underground water was not inhibited in any computation variant. It is worth highlighting that the simulation computations of up to 2007 were conducted with the assumption that the region of contaminated surface water in the southern part of Gilow would be present. However, a potential sooner drying-up of the region may have a significant impact on reducing the area of contaminated water in the pre-area of Gilow.

Ecological disaster

It was assumed in this variant that the entire region of open water in Obora sandpit is the momentary contamination source. The contamination concentration equal to 100 % was assumed in all the network nods forming the sandpit in the model. In order to isolate the influence of Gilow reservoir on the arrangement of concentration lines being formed around the sandpit, the computations in this variant were realized with the assumption that the contaminants from Gilow reservoir did not migrate. Using such an assumption, the main direction of contamination migration would be a westward direction towards SI and SII wells. After one year, the contaminant concentration in the nod corresponding to the location of the wells mentioned above amounted to 0.2%, and after two years of simulation – over 1%

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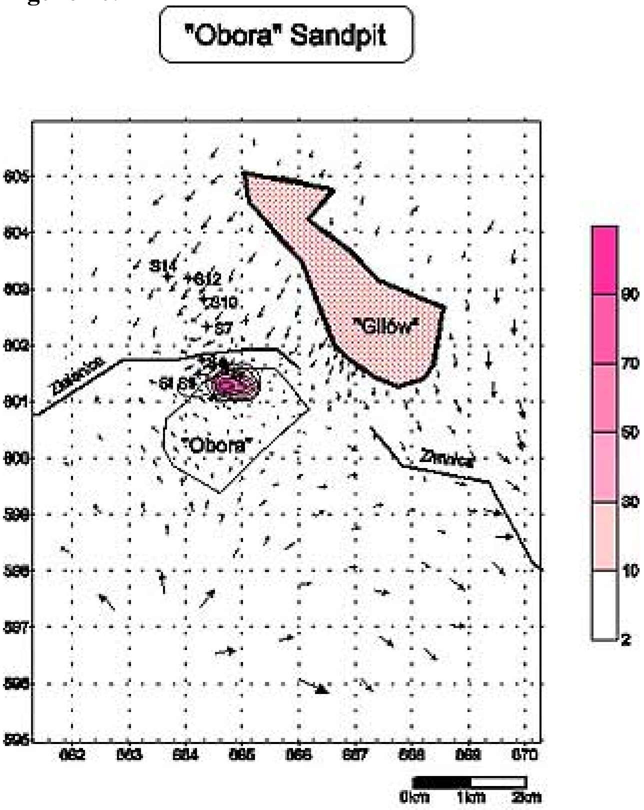
(Figure 10). The slow course of the migration process results mainly from small gradients of underground water flow in the area of the sandpit. A potential ecological disaster in the area of the sandpit is believed to have a minimal importance for the quality of underground water, in comparison to the effect of operation of Gilow reservoir.

Figure 10.



Contaminant concentration after 2 years of momentary injection

CONCLUSIONS

The multi-variant simulation computations conducted in the region surrounding Obora sandpit allow stating that there is no risk of considerable enlarging or deepening of the depression hopper, with the assumed, for the nearest 10 years, increased sand output from under water of up to 350 000 m^3 per year, and successive enlarging of the open water region of up to 35ha. The output should not reduce the discharges of surrounding water intakes in Owczary, either. Besides, there is no danger of inhibiting the positive tendency of regression of the contaminant front migrating from Gilow reservoir. As a result, the water quality in the planned open reservoir and Owczary intake will not deteriorate. Also, a potential momentary ecological disaster in the area of the sandpit will not cause the water endangerment in Owczary intake, though the contaminant concentration in the wells will increase in the course of time.

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