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NUMERICAL SIMULATION OF THE QUATERNARY AQUIFER GROUNDWATER FLOW OF THE NORTHERN VISTULA DELTA PLAIN

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Abstract: Results of Quaternary aquifer flow calculations are presented for the Vistula Delta Plain and the southern Kashubian Lakeland edge zone. The Quaternary level is one of the most important water supply resources for the city of Gdansk. The numerical simulations of groundwater flow were performed using the Modflow and Modpath codes and the Groundwater Modeling System (GMS 3.1) package. Calculations representing the state prior to the launch of the Lipce intake were performed under steady state conditions. The model was calibrated, which enabled simulation of groundwater flow under transient conditions. Calculation for the years 1969–1985 have shown the evolution of a Quaternary aquifer depression cone. The inflow from river Dead Vistula to the Quaternary aquifer is recognized through particle path solution for a selected water particle. The numerical solution has confirmed the observed increase of Cl^- ions in the Grodza Kamienna intake after 1969.

Keywords: groundwater flow, numerical calculations, Modflow code, groundwater resources

1. Introduction

Nowadays, ground water is predominant in fresh water supply. The last surface water intake in the Gdansk agglomeration (in Straszyn) will be closed in a few years and the city's fresh water supply will soon depend entirely on groundwater intake. Groundwater in the Gdansk region is absorbed from Cretaceous, Tertiary and Quaternary aquifers. The disposable groundwater resources in the area from Wejherowo to Tczew have been estimated at $2900\,\mathrm{m}^3/\mathrm{h}$ in the Quaternary level, $720\,\mathrm{m}^3/\mathrm{h}$ in the Tertiary level and $2350\,\mathrm{m}^3/\mathrm{h}$ in the Cretaceous level [1]. Most of the groundwater intakes of the Gdansk agglomeration are situated in the lowest areas of Gdansk, Sopot and Gdynia, namely, in the Kashubian ice-marginal valley (to the north of the agglomeration), along the sea shore (to the east of the agglomeration), and in the western part of Vistula Delta Plain (to the south of the agglomeration).

There are two municipal intakes localized in the Vistula Delta Plain region: Grodza Kamienna and Lipce.

The Grodza Kamienna intake is a groundwater intake situated in the lowest part of Gdansk. The aquifer's exploitation was started there the early 20th century. The maximum discharge from the Quaternary aquifer at Grodza Kamienna occurred in the 15 years following the opening of the Lipce intake. The total Quaternary aquifer outflow from water intakes reached 2200 m^3/h in 1975–1983, which equal the estimated value of disposable groundwater resources.

The Lipce intake was launched in 1969. It is situated 5 kilometers south of the Grodza Kamienna intake and exploits Cretaceous and Quaternary aquifers. Nowadays, the Lipce intake is the only one localized in the Vistula Delta Plain which exploits Quaternary aquifer.

2. Characterics of the investigated area

The area of our numerical calculations consists of the western part of the Vistula Delta Plain and the southern part of the Kashubian Lakeland edge zone, also known as the Orunia region (see Figure 1). The two regions differ in their physiographic structure. The Kashubian Lakeland is consists of moraine hills and postglacial eroded valleys elevated up to 200 meters above the sea level. The altitude of the Vistula Delta Plain varies close the level of the Baltic sea. The prevailing groundwater flow conditions are presented in Figure 2.

Figure 1. Numerical model boundaries: cartographic source [2]

There are two principal groundwater aquifers in the Vistula Delta Plain region: the Cretaceous and the Quaternary strata. The Cretaceous level consists of a large aquifer covered with waterproof rocks roofed at an average of 100 meters below the sea level. The tertiary strata had been accumulated only in the eroded valley during Quaternary glaciation. The Quaternary aquifer is built of clay levels of the last glaciation and earlier porous layers of fine-grained sands accumulated by proglacial waters. Sand strata are dominant near the groundwater intakes. The

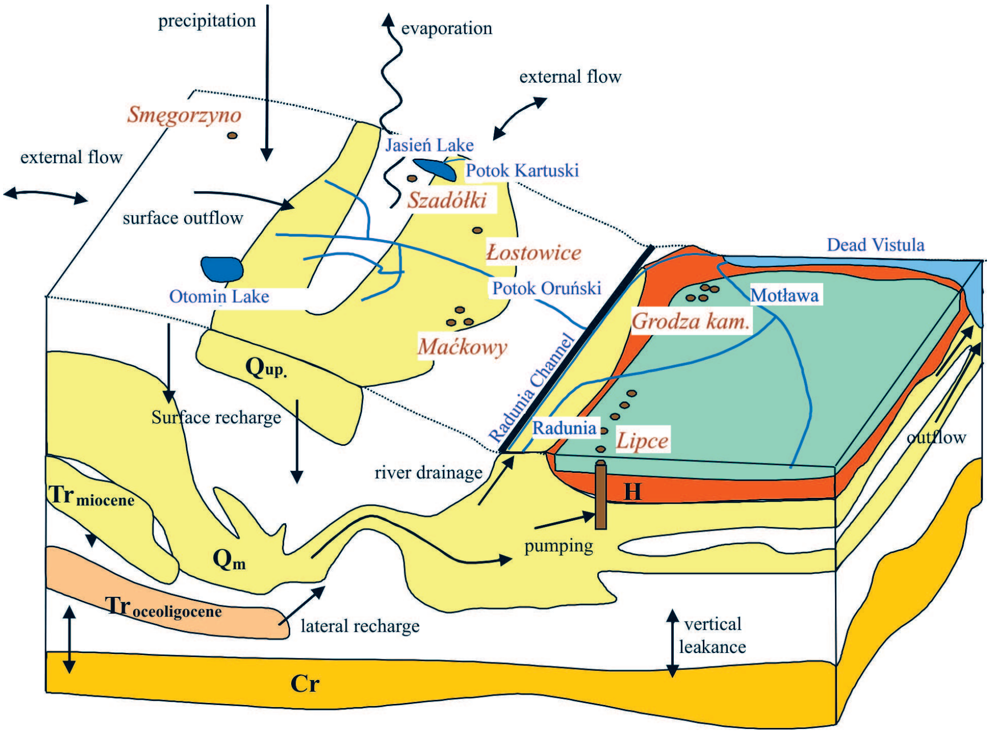

Figure 2. Investigated area: H – Holocene stratum, $Q_{up.}$ – upper Quaternary level, Q_m – main Quaternary level, $Tr_{oligocen}$, Tr_{miocen} – Tertiary levels, Cr – Cretaceous level, color green: the Vistula Delta Plain drainage system

hydraulic conductivity of the fluvioglacial sand varies from 1 to 7m/h. The roof of the Quaternary series remains in Holocene deposits nearly throughout the Vistula Delta Plain (muds and silts). The Vistula Delta Plain Quaternary aquifer has its main recharge zone in the Kashubian Lakeland. Other water inflows include infiltration from the Klodawa and the Radunia River valley, ascent from the Cretaceous aquifer and surface recharge west of the Lipce groundwater intake, where the Quaternary aquifer reaches the terrain surface. In contrast to the Quaternary aquifer, which remains in hydraulic connection with the Bay of Gdansk, the Cretaceous aquifer is isolated from its surface waters with an aquiclude.

In the Kashubian Lakeland edge zone, there exist aquifers in Cretaceous, Tertiary and Quaternary levels. The groundwater structure is very complex because of the effects of glaciation. As can be seen in the hydrogeological cross-section, the Cretaceous aquifer is isolated from younger aquifers (see Figure 3). There are two Tertiary aquifers, the upper part of which remains in hydraulic contact with the main Quaternary aquifer. This most important flow stratum thickness varies from 10 to 30 meters and is completely isolated from the terrain surface with over 30 meters of clays. There also exists an upper Quaternary aquifer, of local range and importance.

The groundwater resources of the Quaternary stratum are exploited by municipal intakes in Grodza Kamienna and Lipce. Up to 480m^3/h with a drawdown of 0.7 meter were discharge from the Quaternary aquifer in Grodza Kamienna till 1955. In the years 1956–1967, the wells' discharge was increased to 600m^3/h. After

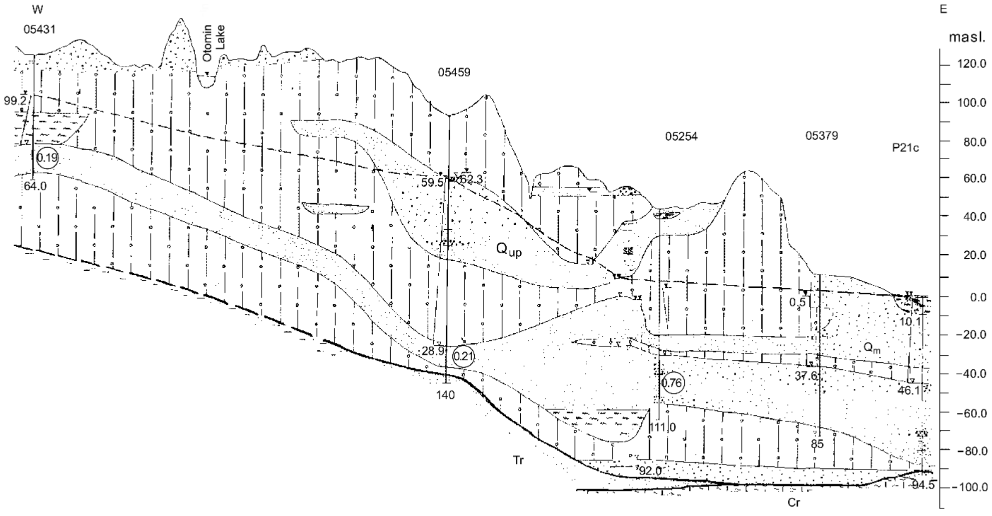

Figure 3. West-east hydrogeological cross-section of the Kashubian Lakeland edge zone [1]. Strata marked as per Figure 2

1967, their discharge exceeded $750\,\mathrm{m}^3/\mathrm{h}$ and reached $1100\,\mathrm{m}^3/\mathrm{h}$ in the 1981–1983 period, with a drawdown up to 4 meters. Exploitation of the Quaternary aquifer at the Grodza Kamienna intake was terminated in 1993 due to the aquifer's salinization.

The Lipce groundwater intake started operation in 1969 with an average rate of $500\,\mathrm{m}^3/\mathrm{h}$. After four years, more wells started discharging and after 1979 the total Quaternary exploitation exceeded $1400\,\mathrm{m}^3/\mathrm{h}$. After 1985 the wells' discharge was reduced to reach about $600\,\mathrm{m}^3/\mathrm{h}$ in the 1998–2000 period. In 1967 and 1969 the disposal resources were estimated for Quaternary aquifer at a flow rate of $1730\,\mathrm{m}^3/\mathrm{h}$. In 2001 the resources shrank to $1210\,\mathrm{m}^3/\mathrm{h}$.

3. The groundwater flow model

The Groundwater Modeling System (GMS) was used to perform the numerical computations. This package is based on the Modflow code, which solves the flow equations for groundwater systems using the volume finite method.

Three-dimensional motion of ground water with constant mater density is based on the following general partial-differential equation:

$$\frac{\partial}{\partial x}\left(K_X\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_Y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_Z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}+q, \tag{1}$$

where K_X, K_Y, K_Z are principal values of the hydraulic conductivity tensor [m/h], $h(x,y,z)$ represents potentiometric head [m], q is potentiometric flux per unit volume, which represents sources and sinks of water [$\mathrm{m}^3/(\mathrm{h\ m}^3)$], and S_s is the specific storage coefficient [1/m]. The solution of Equation (1) is based on the finite volume method applied to the discretized aquifer system with a mesh of blocks called cells. A single cell, defined as an i,j,k element, has dimension $\Delta x,\Delta y,\Delta z$ (see Figure 4).

Derivative $\frac{\partial h}{\partial t}$ is approximated by backward finite difference. The general external flow term for cell (i,j,k) is defined as follows [3]:

$$q_{i,j,k}=-(P_{i,j,k}\cdot h_{i,j,k}+Q_{i,j,k}), \tag{2}$$

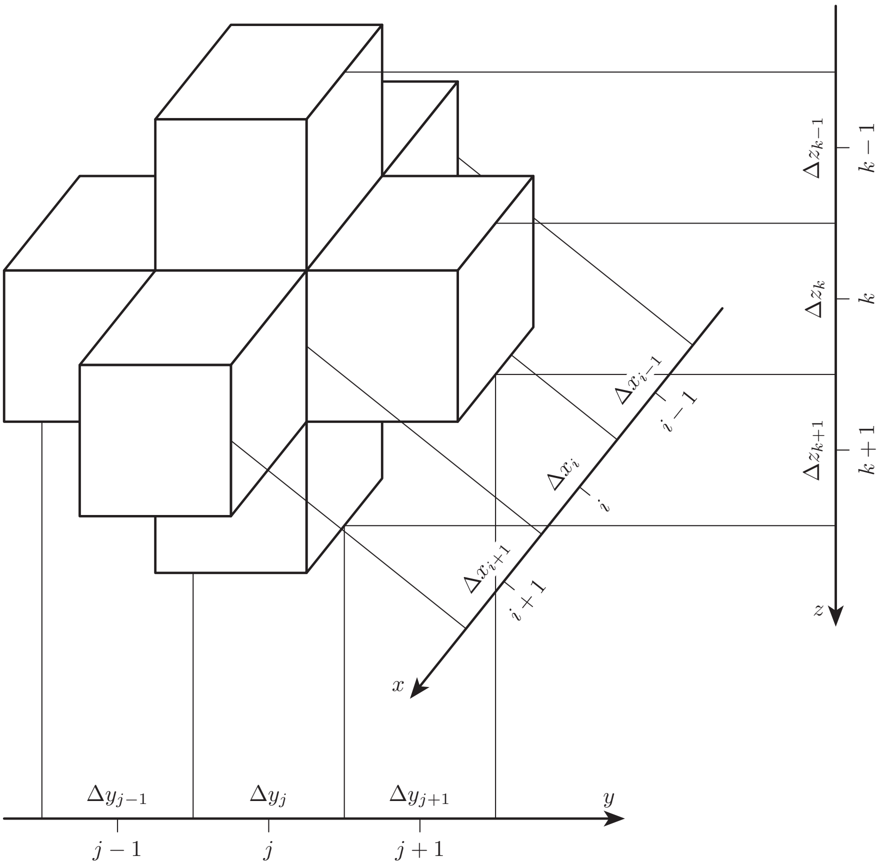

Figure 4. Cell i,j,k and six adjacent cells

where $P_{i,j,k}$ are external sources in cell (i,j,k) dependent on potentiometric head $h_{i,j,k}$. $Q_{i,j,k}$ represents external sources in cell (i,j,k) independent of head $h_{i,j,k}$. Indices (i,j,k) symbolize the row, column and layer numbers. The resulting equation for cell (i,j,k) in time step m is as follows:

$$\begin{aligned}
&Cy^m_{i,j-1/2,k}\cdot\left(h^m_{i,j-1,k}-h^m_{i,j,k}\right)+Cy^m_{i,j+1/2,k}\cdot\left(h^m_{i,j+1,k}-h^m_{i,j,k}\right)+\\
&Cx^m_{i-1/2,j,k}\cdot\left(h^m_{i-1,j,k}-h^m_{i,j,k}\right)+Cx^m_{i+1/2,j,k}\cdot\left(h^m_{i+1,j,k}-h^m_{i,j,k}\right)+\\
&Cz^m_{i,j,k-1/2}\cdot\left(h^m_{i,j,k-1}-h^m_{i,j,k}\right)+Cz^m_{i,j,k+1/2}\cdot\left(h^m_{i,j,k+1}-h^m_{i,j,k}\right)+\\
&P_{i,j,k}\cdot h^m_{i,j,k}+Q_{i,j,k}=Ss_{i,j,k}\cdot\Delta x_i\Delta y_j\Delta z_k\cdot\frac{h^m_{i,j,k}-h^{m-1}_{i,j,k}}{t^m-t^{m-1}}.
\end{aligned}\tag{3}$$

In Equation (3), Cx, Cy, Cz are hydraulic conductances in directions x,y,z defined as follows for a horizontal isotropic layer:

$$Cy_{i,j-1/2,k}=2\frac{T_{i,j-1,k}\cdot T_{i,j,k}}{T_{i,j-1,k}+T_{i,j,k}},\tag{4}$$

$$Cy_{i,j+1/2,k}=2\frac{T_{i,j,k}\cdot T_{i,j+1,k}}{T_{i,j,k}+T_{i,j+1,k}},\tag{5}$$

$$Cx_{i-1/2,j,k}=2\frac{T_{i-1,j,k}\cdot T_{i,j,k}}{T_{i-1,j,k}+T_{i,j,k}},\tag{6}$$

$$Cx_{i+1/2,j,k} = 2\frac{T_{i,j,k} \cdot T_{i+1,j,k}}{T_{i,j,k} + T_{i+1,j,k}}, \tag{7}$$

$$Cz_{i,j,k-1/2} = K_{i,j,k-1/2} \cdot \frac{\Delta x_i \cdot \Delta y_j}{\Delta z_{k-1/2}}, \tag{8}$$

$$Cz_{i,j,k+1/2} = K_{i,j,k+1/2} \cdot \frac{\Delta x_i \cdot \Delta y_j}{\Delta z_{k+1/2}}, \tag{9}$$

where T represents the transmissivity coefficient [1/h] and K is hydraulic conductivity [m/h]. The hydraulic conductivity coefficient is independent of the flow direction, as the layer material is assumed to be isotropic. The governing equation for an unconfined aquifer is as follows:

$$\frac{\partial}{\partial x}\left[K(h-\sigma)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(h-\sigma)\frac{\partial h}{\partial y}\right] = \mu\frac{\partial h}{\partial t} + q_p, \tag{10}$$

where σ is the aquifer's bed level, μ is a dimensionless storage coefficient (or the effective porosity coefficient) and q_p represents sources [m/s]. For a confined groundwater surface, the dimensionless water storativity coefficient, S, is used instead of the storage coefficient, μ:

$$\frac{\partial}{\partial x}\left[T\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T\frac{\partial h}{\partial y}\right] = S\frac{\partial h}{\partial t} + q_p. \tag{11}$$

The numerical solution of groundwater flow in the Quaternary aquifer describes a real surface of over $200\,\mathrm{km}^2$, the Vistula Delta Plain constituting more than a half thereof ($110\,\mathrm{km}^2$). Two layers are defined: index $k=1$ corresponds to the Holocene aquitard, whereas index $k=2$ corresponds to the Quaternary and Tertiary Miocene aquifer called the Principal Quaternary aquifer. Each block represents a surface area of $10\,000\,\mathrm{m}^2$ and variable thickness dependent on the average layer thickness. Values of the filtration parameters have been assumed to be constant in every cell. The model boundary in the edge zone area coincides with waterproof boundaries in the aquifer, where no flow conditions are declared. The model boundary in the Vistula Delta Plain region has been defined outside the depression cone, under maximal well intake conditions. At the northern boundary, situated at the Dead Vistula, a constant head has been imposed corresponding to the average level of the Baltic Sea. The south-western boundary corresponds to river Radunia. The other boundaries have been declared with no flow conditions.

The vertical flow between the Cretaceous and Quaternary aquifers, which is represented as a source term, has been evaluated earlier [4–6]. The source term also represents the Vistula Delta Plain melioration system. A part of surface water in the open channel network is in direct contact with the modeled layers and recharging infiltration with values counted using water balance [7]. Pumping rates for the intake wells have been quantified by synthesis of the existing records [4–6, 8].

Model calibration performed for the steady state condition prior to launching the Lipce intake (1969) involved adjustments to the transmissivity field, especially on the principal Quaternary aquifer in the Kashubian Lakeland edge zone. It became evident that additional recharge of the modeled area through this boundary should be introduced; this was achieved by flux rate addition [9]. Good agreement between the measured and simulated potentiometric surfaces was obtained after calibration (see Figure 5). Observations from twelve piezometers installed in the Vistula Delta Plain region and over forty piezometers in the Orunia area were taken into account for statistical evaluation. The parameters, presented in Table 1, were calculated separately for each region.

Table 1. Mean error and dispersion measures for the calculated and observed values of piezometric level in observation wells for the initial state

Statistical parameter	unit	Kashubian Lakeland edge zone	Vistula Delta Plain
Number of piezometers	–	44	12
Minimum level	masl	1.6	0.0
Maximum level	masl	116.7	1.0
Maximal absolute error	m	8.8	0.44
Mean error	m	0.26	−0.20
Mean absolute error	m	3.69	0.20
Standard deviation	m	4.39	0.11
Average deviation	m	3.71	0.09
Correlation coefficient	–	0.996	0.927

The maximal absolute error seems to be unacceptable in some piezometers of the Orunia region, due to accidental observation times and the date of installation. All the piezometers used in the Orunia region were installed during the years 1969–1980.

The flow balance in the initial state is a result of steady state calculations (see Figure 6). In 1969, the principal inflow of water to the Quaternary aquifer was due to precipitation infiltration (over 42%), river infiltration and inflow from Tertiary and Cretaceous strata (35%). The natural outflows were the Vistula Delta Plain drainage system (55%) and the Dead Vistula (6%). The groundwater intake exploitation exceeded 33% of Quaternary aquifer inflow. While analyzing the flow balance in the groundwater system, inflow from the Dead Vistula to the Quaternary strata was detected.

4. Analysis of the Lipce intake's impact on the Quaternary groundwater piezometric surface

Quaternary aquifer exploitation of the Lipce intake induced significant changes in groundwater piezometric surface. The depression cone rapidly engulfed an area including both intakes. The presented numerical model was very useful in evaluating the impact of groundwater resource management. It may also be helpful in evaluating a single intake well's pumping.

Numerical calculations under transient conditions required the piezometric surface, which defines the initial condition. This time-dependent condition was a result of the steady state calculation's initial model, while the boundary condition remained the same as in the steady state model. The evolution of piezometric pressure surface

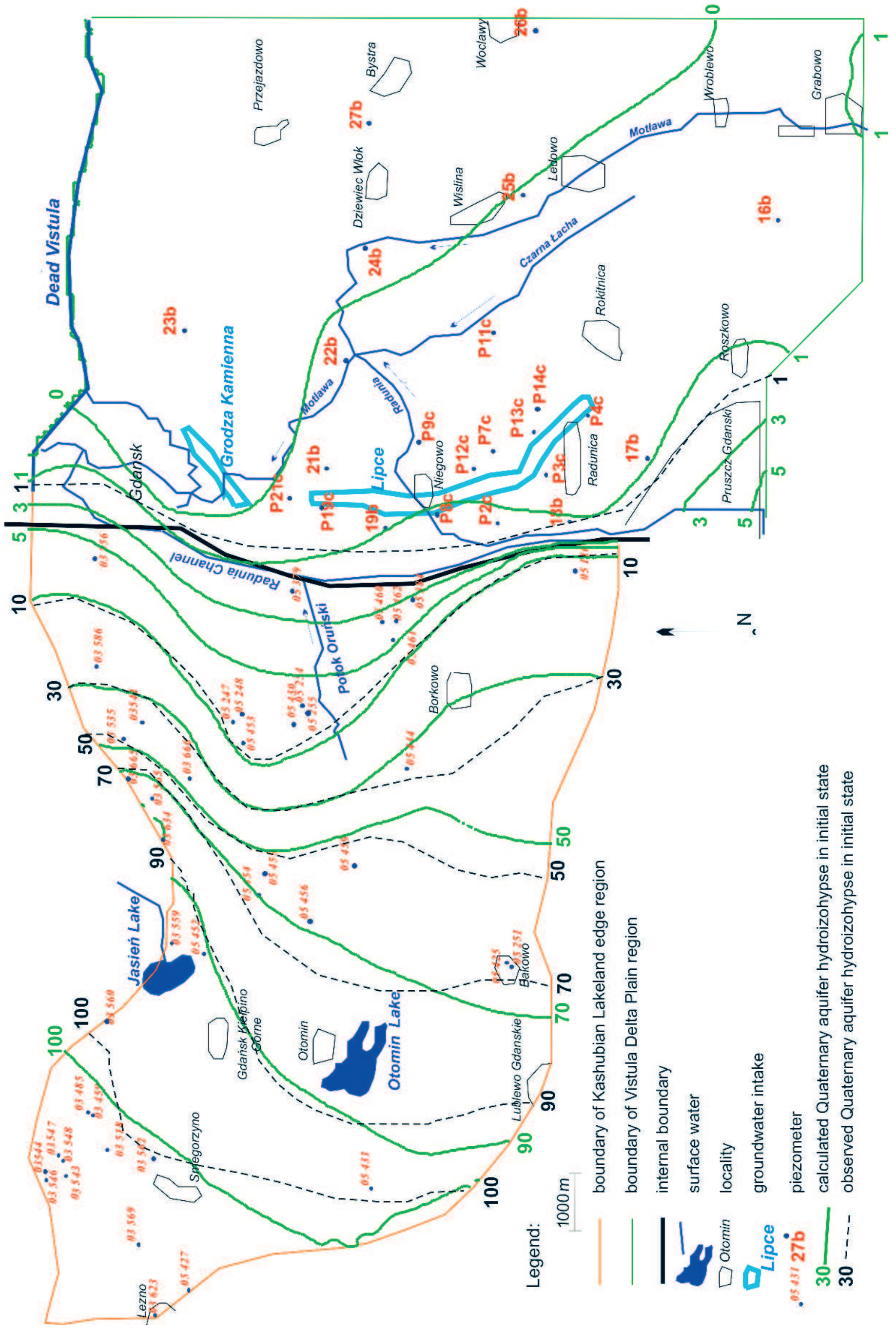

Figure 5. Results of numerical computation for the initial state

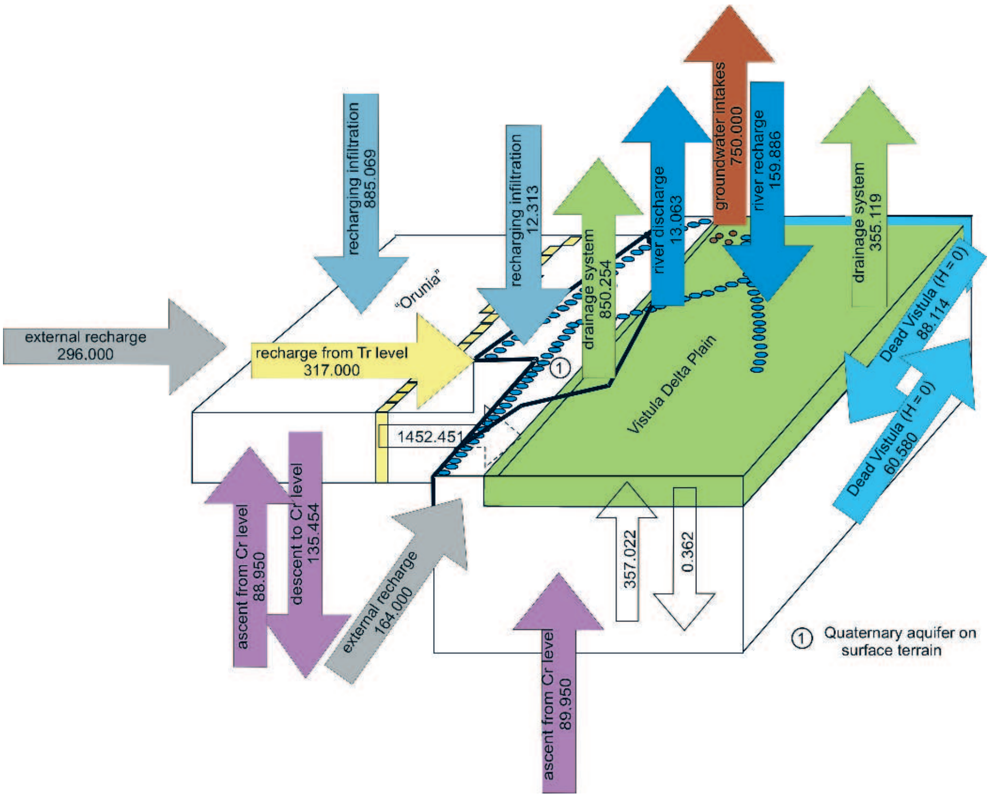

Figure 6. Flow balance for the initial state (all values in m^3/h)

during the first seventeen years of the Lipce intake's operation (1969–1985) is presented in Figure 7. The minimum water level (−2.5 masl) was recorded in the center of the depression cone (piezometers 21B and P21C). The numerical solution was compared with mean water levels recorded in ten observation wells localized in the Vistula Delta Plain region (see Table 2). The results are in accordance with the observations, differences varying from 1 to 67 centimeters. The largest difference at every time step was noted for piezometer 18B, situated in the proximity to the Kashubian Lakeland edge zone.

Dispersion values were calculated in the course of the simulation (Table 3), with mean error below 25 centimeters. The mean absolute error was in the same range for every time step. The numerical simulation was in generally good accordance with the available observations.

5. Sea water intrusion into the Vistula Delta Plain Quaternary aquifer

The problem of salty water in the Vistula Delta Plain Quaternary aquifer appeared when analyzing the initial state of the groundwater system. The Grodza Kamienna intake was first exposed to water degradation due to its proximity to the Dead Vistula. Drawdowns of the potentiometric surface reached three meters during the exploitation of this intake. The Grodza Kamienna groundwater recharge

Table 2. Computed (H_o) and observed (H_p) piezometric water levels of the Quaternary aquifer for the Vistula Delta Plain

Year		Piezometer									
		P3C	P9C	P11C	18B	21B	P21C	22B	23B	25B	27B
1977	H_p	−1.00	−1.70	−1.10	−0.50	−1.80	−1.85	−1.60	−1.00	−0.65	−0.50
	H_o	−1.01	−1.45	−1.03	−0.07	−1.88	−1.93	−1.50	−0.98	−0.58	−0.74
	H_p-H_o	**0.01**	**−0.25**	**−0.07**	**−0.43**	**0.08**	**0.08**	**−0.10**	**−0.02**	**−0.07**	**0.24**
1978	H_p	−1.10	−2.30	−1.30	−0.80	−2.30	−2.30	−1.90	−1.15	−0.65	−0.50
	H_o	−1.20	−1.67	−1.18	−0.14	−2.10	−2.11	−1.64	−1.02	−0.65	−0.77
	H_p-H_o	**0.10**	**−0.63**	**−0.12**	**−0.66**	**−0.20**	**−0.19**	**−0.26**	**−0.13**	**0.00**	**0.27**
1979	H_p	−2.00	−2.80	−1.90	−1.25	−2.80	−2.70	−2.30	−1.30	−0.65	−0.50
	H_o	−1.89	−2.46	−1.91	−0.58	−2.67	−2.54	−2.20	−1.12	−1.00	−0.92
	H_p-H_o	**−0.11**	**−0.34**	**0.01**	**−0.67**	**−0.13**	**−0.16**	**−0.10**	**−0.18**	**0.35**	**0.42**
1980	H_p	−1.30	−2.20	−1.30	−0.75	−2.60	−2.50	−1.95	−1.00	−0.5	−0.40
	H_o	−1.66	−2.35	−1.67	−0.55	−2.73	−2.62	−2.11	−1.18	−0.95	−0.91
	H_p-H_o	**0.36**	**0.15**	**0.37**	**−0.20**	**0.13**	**0.12**	**0.16**	**0.18**	**0.45**	**0.51**
1981	H_p	−1.20	−2.30	−1.40	−0.80	−2.30	−2.20	−1.8	−0.9	−0.55	−0.40
	H_o	−1.54	−2.18	−1.57	−0.48	−2.52	−2.45	−1.97	−1.09	−0.90	−0.89
	H_p-H_o	**0.34**	**−0.12**	**0.17**	**−0.32**	**0.22**	**0.25**	**0.17**	**0.19**	**0.35**	**0.49**
1982	H_p	−1.60	−2.40	−1.60	−1.10	−2.60	−2.45	−2.2	−1.40	−0.60	−0.50
	H_o	−2.04	−2.71	−1.93	−0.80	−2.96	−2.81	−2.29	−1.25	−1.10	−0.97
	H_p-H_o	**0.44**	**0.31**	**0.33**	**−0.30**	**0.36**	**0.36**	**0.09**	**−0.15**	**0.50**	**0.47**
1983	H_p	−1.80	−2.85	−1.60	−1.40	−2.85	−2.70	−2.30	−1.45	−0.65	−0.45
	H_o	−1.99	−2.66	−1.93	−0.78	−2.90	−2.74	−2.25	−1.22	−1.09	−0.93
	H_p-H_o	**0.19**	**−0.19**	**0.33**	**−0.62**	**0.05**	**0.04**	**−0.05**	**−0.23**	**0.44**	**0.48**

Table 3. Mean error and dispersion for the calculated and observed values of piezometric pressure in observation wells (1977–1983)

	unit	1977	1978	1979	1980	1981	1982	1983
Mean error	m	−0.05	−0.18	−0.09	0.22	0.17	0.24	0.04
Mean absolute error	m	0.14	0.26	0.25	0.26	0.26	0.33	0.26
Standard deviation	m	0.18	0.28	0.30	0.20	0.22	0.26	0.32
Average deviation	m	0.13	0.21	0.21	0.16	0.16	0.22	0.25

during ten years' time is presented in Figure 8. The steady state calculation was performed for the 750m^3/h intake pumping rate prior to opening the Lipce intake. An average flow from the Dead Vistula exceeding 50m^3/h was numerically estimated on the basis of the initial state of water balance. The flow time for a water particle from the Dead Vistula to the Grodza Kamienna intake was estimated at over 30 years.

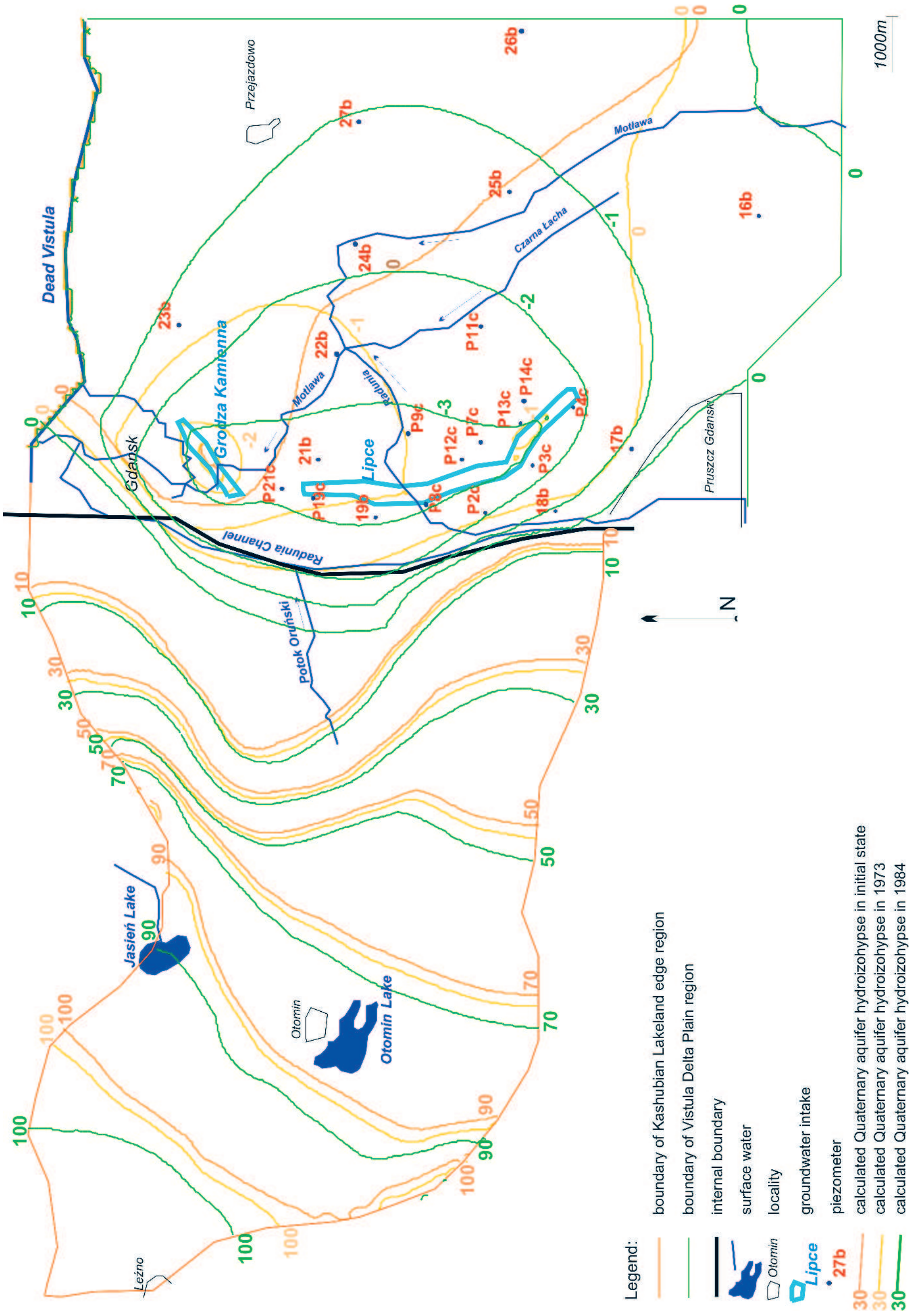

Figure 7. Piezometric pressure surface evolution of the principal Quaternary aquifer 1968–1985

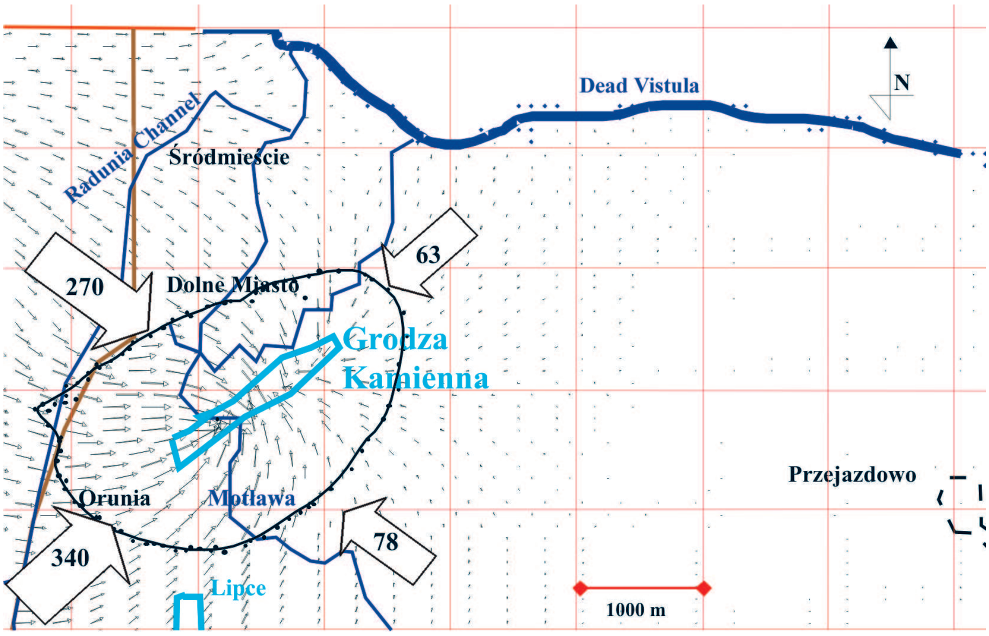

Figure 8. Groundwater flow in the Vistula Delta Plain Quaternary aquifer before opening the Lipce intake with principal flow directions.
Arrows – flux vector in the elementary cell, line with dots – 10 years' flow line to intake wells, cyan line – groundwater intake border, brown line – eastern border of the Kashubian Lakeland edge zone. Flow rate unit: m^3/h

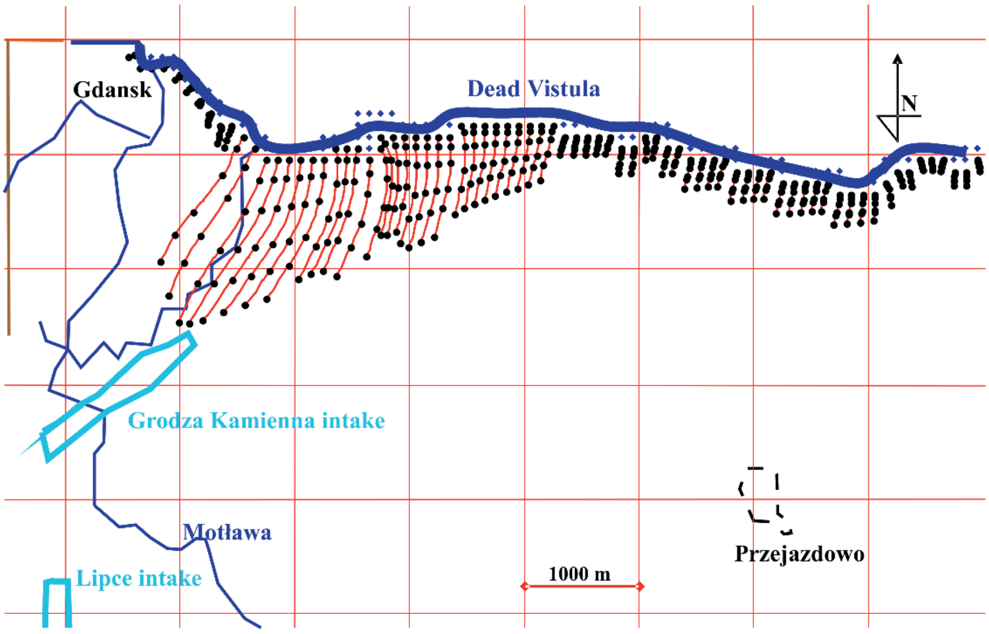

Figure 9. The Dead Vistula particle path in the Quaternary aquifer in 1968–1983.
Cyan line – groundwater intake border. Points on the particle's path mark its position in a given year: 1968, 1971, 1974, 1977, 1980 and 1983

The depression cone increased after 1969, when the Lipce intake was launched. In 1982, the Dead Vistula waters recharged the Quaternary aquifer up to 648 m^3/h. The average annual flow rate calculated in the transient state was about 300 m^3/h during the years 1969–1983. The highest rate of flow from the Dead Vistula was calculated for the three-kilometer section north-east of the Grodza Kamienna intake (see Figure 9); a Dead Vistula water particle reached the Grodza Kamienna intake after 15 years from starting the Lipce intake. This simulation has shown that the water originating from the Dead Vistula was discharged from the Quaternary aquifer mostly by the north-eastern wells of the Grodza Kamienna intake. These calculations confirm the degradation of the Grodza Kamienna intake after 1985.

6. Conclusions

Numerical models solving flow equations under steady state conditions are very useful in groundwater flow systems' analysis and defining the disposable resources. The presented numerical calculations were performed in three stages. Groundwater analysis was performed for the time prior to launching the Lipce intake in 1969. A marginal flow from the Dead Vistula to the Grodza Kamienna intake appeared in the results of flow balance calculations for the Quaternary aquifer. The proximity of sea water to the Grodza Kamienna intake has demonstrated that even relatively small Quaternary aquifer exploitation may cause an inversion of the flow direction (here, from the Dead Vistula to the intake wells).

A calibrated model was basis of numerical calculations under transient conditions. The calculations have confirmed the evolution of a Quaternary aquifer depression cone in the 1969–1985 period. The model is applicable to specific problems. The presented instance is the appearance of salty water in the Grodza Kamienna intake wells. Due to excessive exploitation of the Quaternary aquifer, the main flow directions in the neighborhood of the Grodza Kamienna intake were changed. As can be seen in the calculation results, water containing Cl^- ions from the Bay of Gdansk began to recharge the Vistula Delta Plain Quaternary aquifer, which was the reason why water stopped to be pumped from the Quaternary layer at the Grodza Kamienna intake.

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