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Recharge of Gdańsk municipal groundwater intakes on the Vistula Delta Plain (Northern Poland)

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Results of the Vistula Delta Plain Quaternary recharge analysis are presented in this paper. This region is situated south of Gdańsk city near the Bay of Gdańsk. There are two municipal intakes situated on the Vistula Delta Plain: Lipce and Grodza Kamienna. Different exploitation of the municipal intakes is considered. The numerical calculations are made for the pre- 1969 period before the Lipce intake started discharging the Quaternary aquifer in the steady-state conditions and for the 15 years period after the opening of the Lipce intake, in the transient conditions. The results of calculations of the natural state of the Vistula Delta Plain Quaternary aquifer are also presented. The numerical calculations were carried out using the Modflow and Modpath code in Groundwater Modelling System (GMS 2.1) package. Presented results of numerical calculations show that the Quaternary aquifer exploited by groundwater intakes Lipce and Grodza Kamienna is connected with inflow from the Martwa Wisła River into the Vistula Delta Plain Quaternary aquifer and confirm the Quaternary aquifer groundwater flow evaluation based on Cl^- ions concentration in the observation wells.

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INTRODUCTION

Till 1985 fresh water supply in Gdańsk area was based entirely on groundwater intakes. In 1985 the surface water intake "Straszyn" was opened, but groundwater still dominated the fresh water supply. Most of the groundwater intakes in Gdańsk agglomeration is situated in the topographically lowest parts of Gdańsk, Sopot and Gdynia cities (Kaszuby ice-marginal valley in the north, along sea shore in the east, the Vistula Delta Plain–Żuławy Gdańskie in the south). In these intakes water is absorbed mainly from the Cretaceous and Quaternary aquifers because the Tertiary aquifer in many places was eroded. The disposable groundwater resources of the Gdańsk agglomeration were estimated by the Polish Geological Institute at 2900 m^3/h in the Quaternary level, 720 m^3/h in the Tertiary level and 2350 m^3/h in Cretaceous level for the area from Wejherowo to Tczew.

Estimation of the groundwater flow in aquifers of the Vistula Delta Plain region in 1980's was based on analytical methods. The increasing calculation capabilities owing to application of high speed computers in 1990's resulted in applying numerical methods for modelling of groundwater filtration. The presented results of numerical simulation are based on the author's model of two different hydrological units: marginal zone of Kaszuby Lake District and Vistula Delta Plain (Fig. 1). It is a new approach to this problem (Szpakowski, 2001*a*). Calculations in steady-state conditions were used for estimation of aquifers' hydrogeological parameters. Numerical simulations for non steady-state conditions of water flow in 1969–1983 years, were done for the first time for this region. They allow to estimate the Martwa Wisła River water participation in the Quaternary aquifer flow.

PRINCIPAL SOURCES OF GROUNDWATER FLOW AND CHARACTERISATION OF THE WESTERN PART OF VISTULA DELTA PLAIN AQUIFERS

lThe Vistula Delta Plain groundwater comprises the Cretaceous and Quaternary aquifers. The Cretaceous level consists of thick aquifer strata covered by impermeable rocks at the average depth of 100 metres below the sea level. Tertiary sediments were eroded during the Quaternary glaciation. Quaternary aquifer consists of clay horizons of the last glaciation and of porous lay-

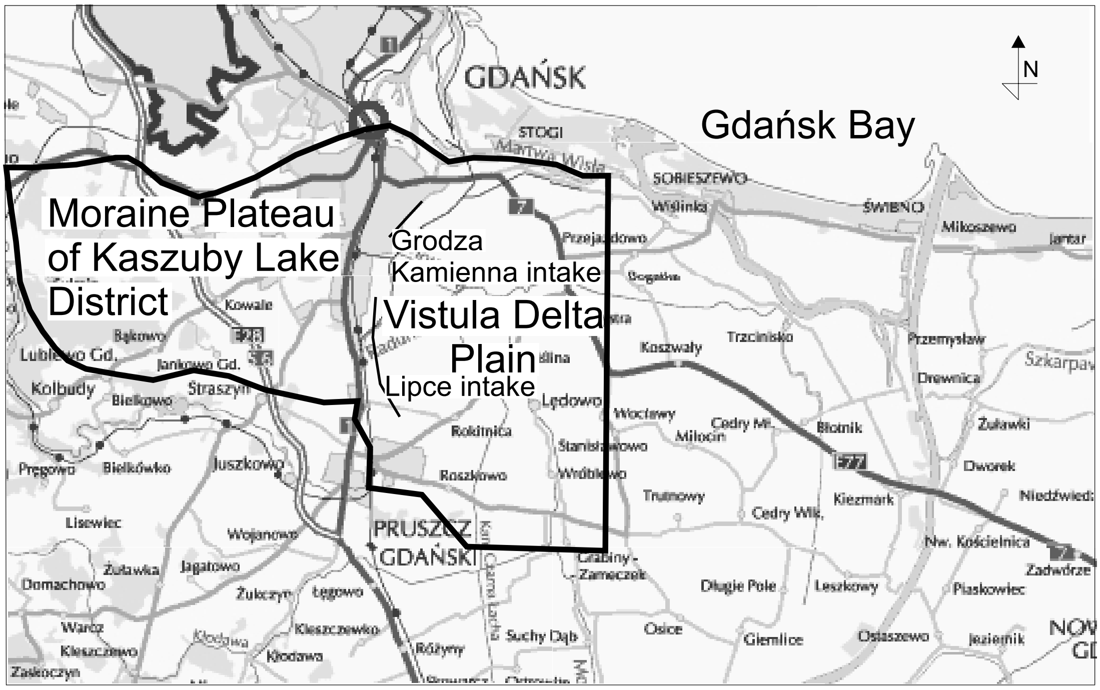


Fig. 1. Boundaries of modelled area

ers of fine-grained sands accumulated by proglacial waters. Near the groundwater intakes sand strata dominate (Fig. 2). Hydraulic conductivity of the fluvioglacial sand varies between 1 and 7 m/h. The top of the Quaternary series in almost the entire area of the Vistula Delta Plain comprises Holocene muds and sills. Groundwater has been here exploited since 19th century, by one of the first groundwater intakes — Grodza Kamienna. In 1969 Lipce groundwater intake was opened. Initially only the Quaternary aquifer was exploited, but since the 1970's the Cretaceous aquifer has been used as well. Figure 2 presents the location of municipal groundwater intakes in the western part of the Vistula Delta Plain.

Till 1955 up to 480 m^3/h of fresh water was discharged annually in the Grodza Kamienna intake from the Quaternary aquifer with a drawdown of 0.7 m. Till 1967 wels' discharge increased to 600 m^3/h. During 1969–1985 the discharge was higher than 750 m^3/h reaching 1100 m^3/h with a drawdown of 4 metres between 1981 and 1983. Because of huge concentration of Cl^+ ions, exploitation of the Quaternary aquifer in the Grodza Kamienna intake was terminated in 1993.

Exploitation of the Lipce groundwater intake commenced in 1969 producing an average of 500 m^3/h. After 1973 more wells came on line and the total Quaternary exploitation after 1979 exceeded 1400 m^3/h. After 1985 the wells' discharge gradually decreased to about 600 m^3/h in 1998–2000. The disposal resources in 1967 were estimated at 1730 m^3/h. Such level was maintained till 1969, but in 2001 it decreased to 1210 m^3/h.

The main recharge source of the Quaternary aquifer on the Vistula Delta Plain is the lateral inflow from the aquifer situated at the edge of the Kaszuby Lake District Plateau. This aquifer is hosted by Quaternary and Tertiary (Miocene) sediments. The Vistula Delta Plain Quaternary aquifer is recharged also from the Kłodawa and Radunia River valley, an ascent from the Cretaceous aquifer and river infiltration. In addition, there is also a surface recharge from the west side of the Lipce groundwater intake, where the Quaternary aquifer reaches the surface. The exploitation of groundwater intakes resulted in the introduction of a new recharge source — an inflow from the Martwa Wisła River into Quaternary aquifer. Figure 2 shows main recharge directions into the Vistula Delta Plain Quaternary aquifer.

Contrary to the Quaternary aquifer which has a hydraulic connection with the Bay of Gdańsk water, the Cretaceous aquifer is isolated from it. Intensive exploitation of the Quaternary aquifer during the 1960's and 1970's caused change of the groundwater flow directions and incursion of saline water in wells situated closest to the Martwa Wisła River (Kozerski *et al.*, 1992). These degradational changes appeared also in the northern part of the Grodza Kamienna intake and Quaternary wells here were closed in 1993.

DESCRIPTION OF GROUNDWATER FLOW MODEL

The 3D movement of groundwater of constant density is based on the general groundwater flow partial-difference equation [1] (Mc Donald and Harbaugh, 1988; Pazdro and Kozerski, 1990; Burzyński and Sadurski, 1990).

[1]

$$\frac{\Delta}{\Delta x}\left(K_X \frac{\Delta h}{\Delta x}\right)+\frac{\Delta}{\Delta y}\left(K_Y \frac{\Delta h}{\Delta y}\right)+\frac{\Delta}{\Delta z}\left(K_Z \frac{\Delta h}{\Delta z}\right)=S_S \frac{\Delta h}{\Delta t}+q$$

where: K_X, K_Y, K_Z — principal values of the hydraulic conductivity tensor (m/h); $h(x,y,z)$ — potentiometric head (m); q — potentiometric flux per unit volume and represents sources and sink of water (m^3/h m^3); S_s — specific storage coefficient (1/h).

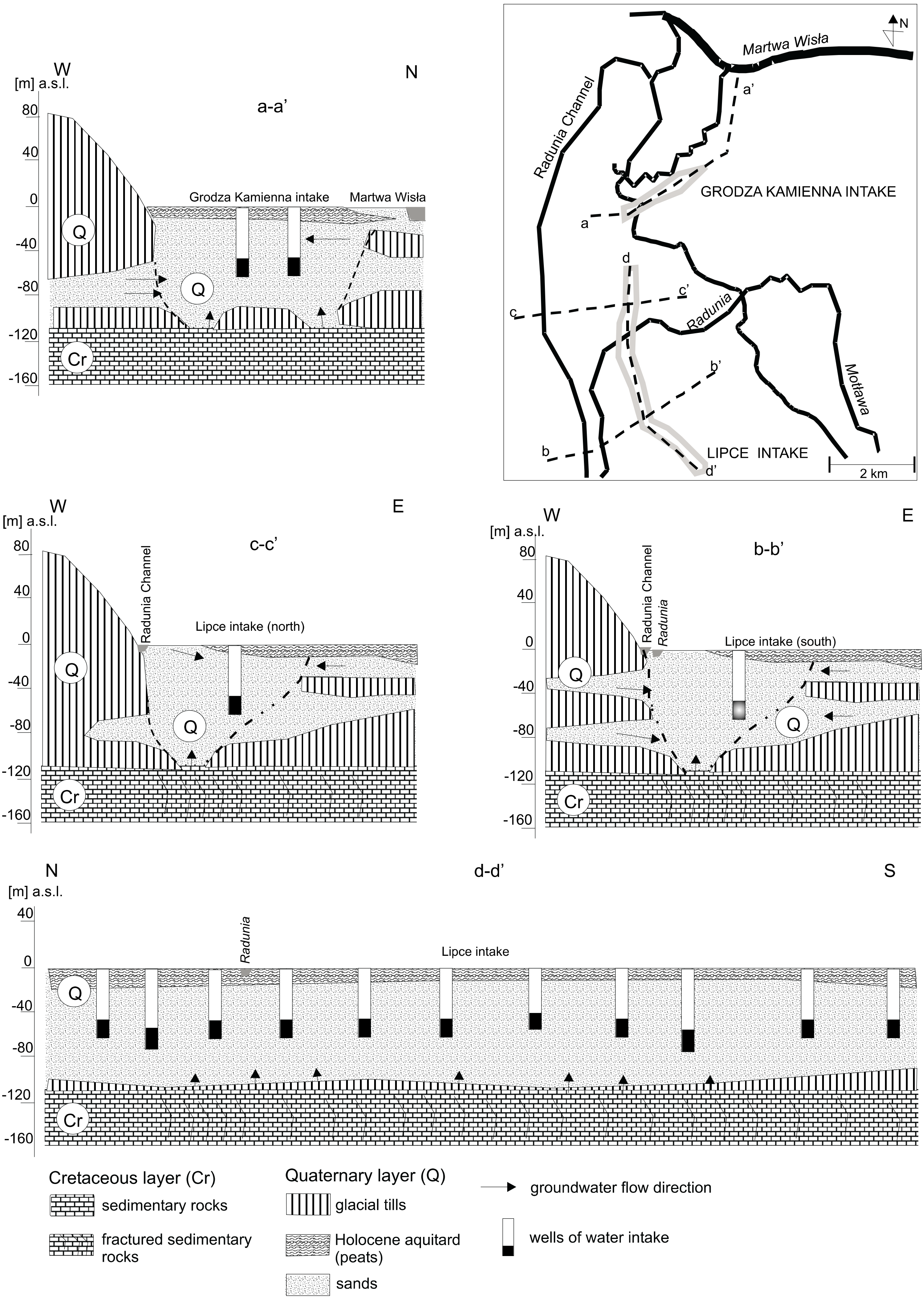


Fig. 2. Schematic cross-sections with the principal flow directions

Table 1

Mean annual values of flow in Quaternary aquifer before the Lipce intake started and in 1969–1983

Year	Mean annual values of flow				Participation of the Martwa Wisła River recharge in Quaternary groundwater flow against the background of intakes exploitation	
	Quaternary aquifer wells discharge		Martwa Wisła River recharge [m³/h]	Martwa Wisła River discharge [m³/h]	Grodza Kamienna [%]	The Vistula Delta Plain [%]
	Grodza Kamienna intake [m³/h]	Lipce intake [m³/h]				
Natural state	–	–	0	290	0.0	0.0
Before Lipce intake	750	–	51	35	6.9	6.9
1969	791	455	197	29	24.9	15.8
1970	804	491	113	30	14.1	8.7
1971	774	492	125	30	16.1	9.9
1972	927	469	188	26	20.3	13.5
1973	1009	850	354	20	35.1	19.0
1974	924	928	243	21	26.3	13.1
1975	967	1020	538	15	55.6	27.1
1976	1164	886	389	14	33.4	19.0
1977	1012	894	309	17	30.5	16.2
1978	1017	993	293	18	28.8	14.6
1979	921	1275	343	16	37.2	15.6
1980	1003	1206	318	16	31.7	14.4
1981	923	1150	289	18	31.3	13.9
1982	901	1357	648	11	71.9	28.7
1983	878	1317	348	15	39.6	15.9

Groundwater flow in single layer can be treated as 2D movement because the horizontal dimensions are much larger than the vertical one. Assuming isotropic layer material, equation [1] for the unconfined aquifer is:

$$\frac{\Delta}{\Delta x}\left[K(h-\sigma)\frac{\Delta h}{\Delta x}\right]+\frac{\Delta}{\Delta y}\left[K(h-\sigma)\frac{\Delta h}{\Delta y}\right]=\mu\frac{\Delta h}{\Delta t}+q_p \quad [2]$$

where: K — hydraulic conductivity (m/h); σ — bed level of aquifer; μ — dimensionless storage coefficient (or effective porosity coefficient); q_p — represents sources (m/s).

For the confined groundwater surface the water storativity coefficient S is taken instead of the storage coefficient μ. The dimensionless water storativity coefficient is a product of specific storage and aquifer thickness:

$$\frac{\Delta}{\Delta x}\left[T\frac{\Delta h}{\Delta x}\right]+\frac{\Delta}{\Delta y}\left[T\frac{\Delta h}{\Delta y}\right]=S\frac{\Delta h}{\Delta t}+q_p \quad [3]$$

where: T — transmissivity coefficient (1/h).

Solution of equation [1] is based on finite difference method on the discretised aquifer system with a mesh of blocks called cells. The single cell has dimension $\Delta x, \Delta y, \Delta z$. Expression $\frac{\Delta h}{\Delta t}$ is approximated by backward finite — difference.

Numerical solution of groundwater flow in the Quaternary aquifer describes the area of over 200 km² comprising southern part of the marginal zone of the Kaszuby Lake District and western part of the Vistula Delta Plain. The modelling area of the Vistula Delta Plain region is over 110 km². Two layers are defined: Holocene aquitard, and Quaternary plus Tertiary (Miocene) aquifer collectively called a Principal Quaternary Aquifer because of a hydraulic connection between these two layers in the marginal zone of Kaszuby Lake District region. The study area is divided into 20 631 blocks in each layer. Each block represents surface area of 10 000 m² and variable thickness dependent on average layer thickness. Holocene aquitard consists of blocks situated only in the Vistula Delta Plain region. Values of filtration parameters are constant in every cell.

Model boundary in the marginal zone area coincides with impermeable boundaries in the aquifer — no flow conditions are declared. Model boundary in the Vistula Delta Plain region is defined outside the depression cone in the maximal intake discharge condition. The north boundary situated at the Martwa Wisła River is defined by constant head condition, the head corresponding to the average level of the Baltic Sea. The southwestern boundary corresponds to the Radunia River. Other boundaries are declared with no-flow condition. Additional boundary conditions, called internal conditions are inside the area. They are taken into account in source term. Vertical flow between Cretaceous and Quaternary aquifers is based on evaluation of the existing data from the previous projects (Kwaterkiewicz *et al*., 1980; Zalewski *et al*., 1980; Sadurski, 1989; Kozerski *et al*., 1992). The mean inflow rate for the Vistula Delta Plain decreased from 2.05 x 10^{-6} (m/h) in 1969 to 8.26 x 10^{-7} (m/h) in 1983. The values of the precipitation water participating in the groundwater movement are counted using hydrological balance (Szpakowski, 2001*b*). Pumping rates for the intakes' wells are quantified using compilation of existing data (Kwaterkiewicz *et al*., 1980; Zalewski *et al*., 1980; Alenowicz *et al*., 1983; Sadurski, 1989) and presented in Table 1. The Vistula Delta Plain melioration system and a surface water network which is in direct contact with modelling layers was also taken into account as internal source (Janik *et al*., 1996).

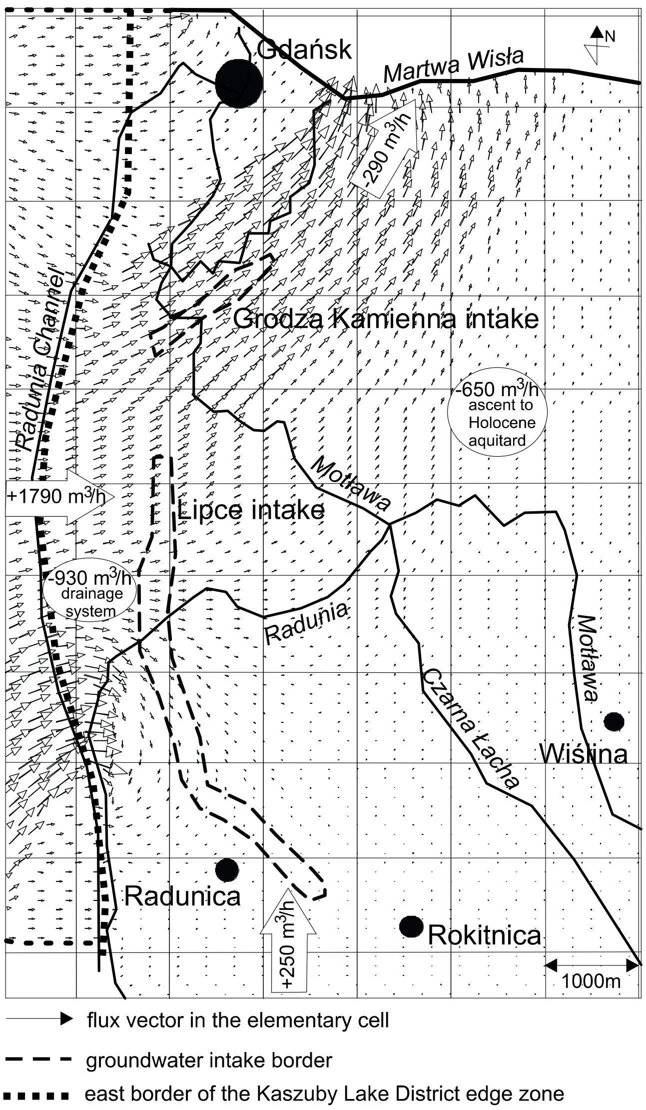


Fig. 3. Groundwater flow in Quaternary aquifer in natural state and principal direction of water flow

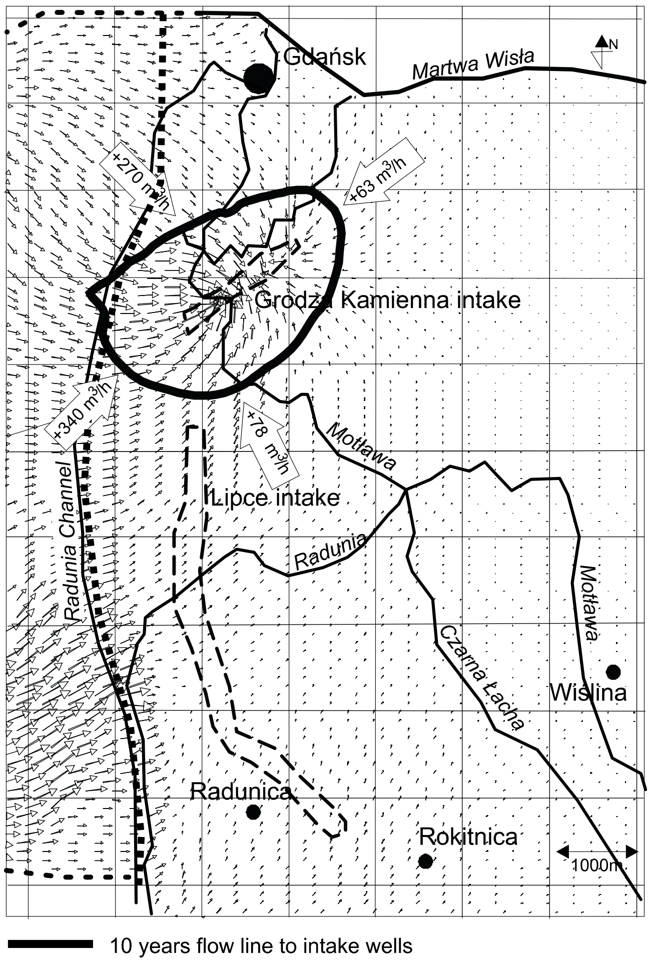


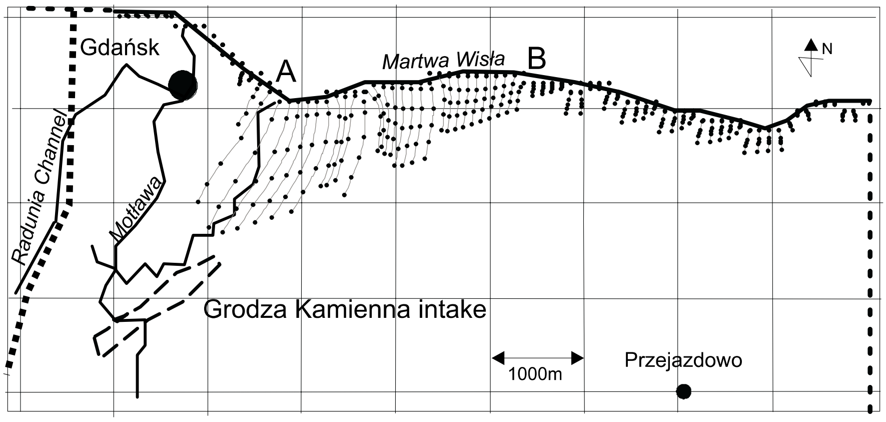
Fig. 4. Groundwater flow in the Vistula Delta Plain Quaternary aquifer before opening the Lipce intake with the principal flow directions

For other explanations see Figure 3

Model calibration applied for the steady state condition, before commencement of pumping at the Lipce intake involved adjustments to the transmissivity field (in particular on the Principal Quaternary Aquifer situated at the marginal zone of the Kaszuby Lake District. It appeared, that the additional recharge of the modelling area through its boundary should be added. It was achieved by the flux rate addition. After the calibration a good visual comparison between the measured and simulated potenciometric surfaces was achieved (Szpakowski, 2001*a*).

RESULTS AND DISCUSSION

Numerical calculations of the natural state were performed in the steady-state conditions. The natural state corresponds to the historical period when there was no groundwater municipal intakes discharge. Groundwater flow directions in the Quaternary aquifer on the Vistula Delta Plain are shown in Figure 3. In



A-B Martwa Wisła River principal infiltration zone

1968 1971 1974 1977 1980 1983 points on the particle path mark particle position in respective years

Fig. 5. Martwa Wisła River particle path in the Quaternary aquifer |in 1968–1983

For other explanations see Figure 3

the natural conditions there are two principal recharge zones: the marginal zone of the Kaszuby Lake District and the Kłodawa-Motlawa valley. All water flowing into the Vistula Delta Plain flows either to the system of drainage and the rivers or directly to Martwa Wisła and Bay of Gdańsk. The vertical leakage to the Holocene sediments flows also to the drainage system.

Drawdowns of the potenciometric surface regressed to three metres during the exploitation the Grodza Kamienna intake. The black curve on the Figure 4 highlights the area of ten years time flow to the Grodza Kamienna wells. The calculation in steady-state conditions was done under the 750 m^3/h Quaternary aquifer discharge, and the average flow from the Martwa Wisła River occurred with an average rate about 50 m^3/h. The value of 750 m^3/h represents the average Grodza Kamienna discharge rate before the Lipce intake became operational. The estimated time for the Martwa Wisła water molecule to reach the Grodza Kamienna intake exceeds 30 years. The Quaternary aquifer drainage system worked with a rate of over 700 m^3/h. A vertical flow from Quaternary aquifer to Holocene aquitard was counted with a rate of about 500 m^3/h. Recharge rates to Quaternary aquifer were the same in natural state.

The depression cone has increased after 1969 when the Lipce intake came on line. In 1982 the Martwa Wisła River water recharged the Quaternary aquifer at the rate of up to 648 m^3/h (Table 1). During 1969–1983 the average annual rate calculated in transient state was about 300 m^3/h. Figure 5 shows path lines of water molecules flowing from the Martwa Wisła River to the intakes wells. The most excessive rate of infiltration is observed in the three kilometre section of the Martwa Wisła River situated north-east of the Grodza Kamienna intake (Fig. 5). As discussed above, the Martwa Wisła River molecule reached the Grodza Kamienna intake after only 15 years from starting the Lipce intake. This simulation showed that water originating from the Martwa Wisła River was discharged from the Quaternary aquifer mostly by the northeastern wells of the Grodza Kamienna intake. The calculations confirm the degradation of the Grodza Kamienna intake after 1985.

Average recharge and discharge from the Quaternary aquifer in 1983 is given in Figure 6. Year 1983 corresponds to the maximum rate of over 2200 m^3/h of municipal intakes discharge from the Quaternary aquifer. For the whole range of non steady-state simulation the constant amount of recharge from the Kaszuby Lake District was assumed (1790 m^3/h). It was calculated that in 1983 over 300 m^3/h water flowed from Martwa Wisła River to the Quaternary aquifer. The direction of vertical leakage was also changed. On average over 270 m^3/h flowed from the Holocene aquitard into the Quaternary aquifer. There was almost no flow in the opposite direction. The annual rates of groundwater intakes discharge from the Quaternary aquifer and the Martwa Wisła River participation are presented in Table 1.

It is shown, that some volume of water from the Martwa Wisła River flowed into the Quaternary aquifer before the Lipce intake developed. The directions of flow changed entirely during the exploitation the Lipce intake. During this period of time the groundwater flowed mainly in Quaternary aquifer from the Martwa Wisła River into the Grodza Kamienna intake rather than in opposite direction. After 1972 the participation of the Martwa Wisła water exceeded 13% of Quaternary wells discharge. This conclusion based on numerical calculation is in agreement with Kozerski *et al*. (1992) findings.

SUMMARY

In natural conditions the total amount of water which inflowed into the Quaternary aquifer of the Vistula Delta Plain flowed either to the drainage system or to the Martwa Wisła River. After the first groundwater intake commenced its operation inflow from the Martwa Wisła River comprised only about 7% of total Grodza Kamienna groundwater discharge.

After 1969, when the Lipce intake came on line, the increase of water originating from the Bay of Gdańsk surface system was encountered in the Quaternary wells of Grodza Kamienna in-

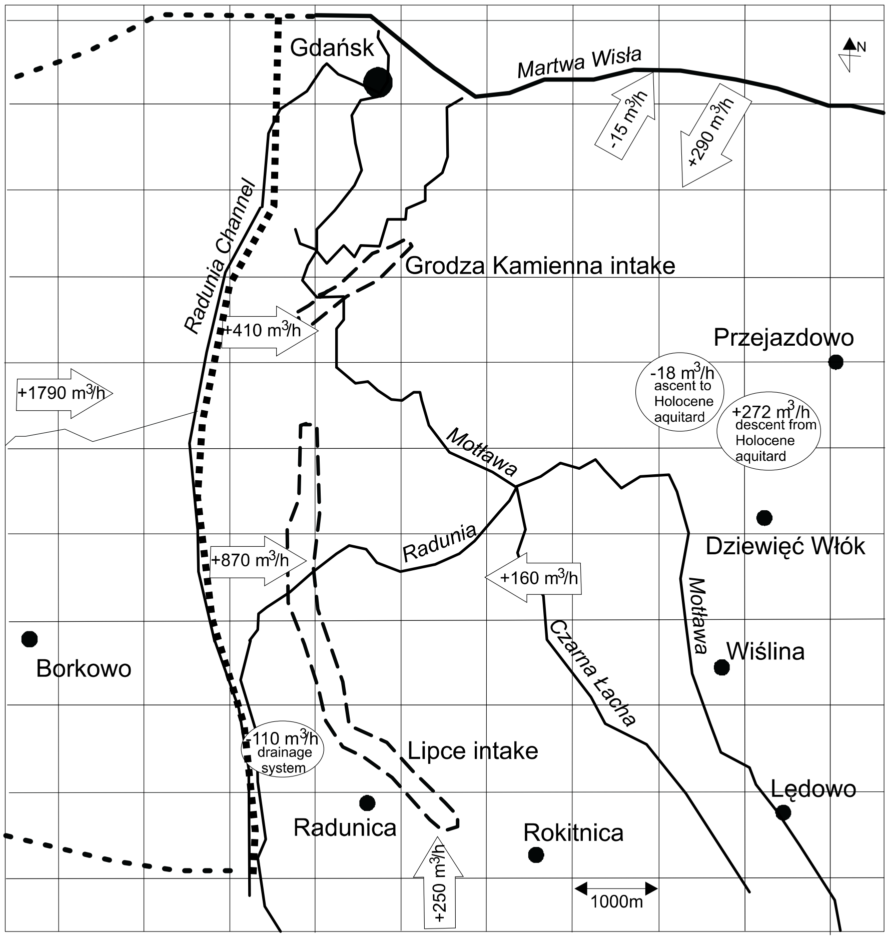


Fig. 6. Principal flow directions in 1983 in the Vistula Delta Plain Quaternary aquifer

For other explanations see Figure 3

take. Till 1972 an average of 170 m^3/h flow reached the Quaternary aquifer from the Martwa Wisła River. More extensive infiltration from the Martwa Wisła River appeared during the dry years of 1969 and 1971–1973 when annual precipitation values were less than 60% of average annual fall.

After 1973 due to doubled discharge in the Lipce intakes the average flow from Martwa Wisła River into the Quaternary aquifer reached about 310 m^3/h. During the very dry year of 1982 this value was doubled. After 1979 the mean annual Lipce intake discharge was tripled in comparison with the initial discharge values. After 1973 nearly the whole length of Martwa Wisła River recharged the Quaternary aquifer. The drainage part of this river was noticed in the estuarial part.

Most of the numerical calculations presented in this paper confirm the previous findings by Kozerski *et al.* (1992), who observed the increase of Cl^- content in the Grodza Kamienna intake after 1969. Cl^- ions content higher than in natural state have been noted mainly in the northern part of Grodza Kamienna intake. In 1993 due to the degradation of Quaternary water nearby the Grodza Kamienna intake the wells discharging this aquifer were closed. The presented results for the first time show the Martwa Wisła River particle path in the Quaternary aquifer.

REFERENCES

ALENOWICZ M., OLAŃCZUK-NEYMAN K., OLESZKIEWICZ-GOTDZIELEWSKA A., KWATERKIEWICZ A., SUKOWSKI T. and KOZERSKI B. (1983) — Groundwater analysis and evolution evaluation in the Tricities region. Politechnika Gdańska, Wydział Hydrotechniki, Gdańsk.

BURZYŃSKI K. and SADURSKI A. (1990) — The groundwater exchange rate of the southern Baltic coastal lowland. J. Hydrol., **119** (1–4): 293–306.

JANIK B., MŁYŃCZAK A., ORŁOWSKI R., ROEDING E. and ŚWIERSZCZ W. (1996) — Geological works project in view of preparing hydrogeological documentation of Żuławy and the Vistula peninsula. Przed. Hydrogeol. Gdańsk.

KOZERSKI B., KWATERKIEWICZ A. and SADURSKI A. (1992) — Zagrożenie wód podziemnych strefy brzegowej morza w rejonie Gdańska. In: W służbie polskiej geologii. Wyd. AGH.

KWATERKIEWICZ A., SADURSKI A., SUKOWSKI T. and KOZERSKI B. (1980) — Complex groundwater intake Lipce analysis. Final report from the hydrogeological investigations. Politechnika Gdańska, Instytut Hydrotechniki, Gdańsk.

McDONALD M. G. and HARBAUGH A. W. (1988) — A modular three-dimensional finite-difference ground-water flow model. Sc. Software Gr., Washington, D.C.

PAZDRO Z. and KOZERSKI B. (1990) — Hydrogeologia ogólna. Wyd. Geol.

SADURSKI A. (1989) — Upper Cretaceous system of the East-Pomerania groundwater (in Polish with English summary). Zesz. Nauk. AGH, **1324** (46).

SZPAKOWSKI W. (2001*a*) — The use of modflow code in the Lipce area analysis. Inżyn. Mor. Geotech., **3**.

SZPAKOWSKI W. (2001*b*) — Hydrological balance for the south part of edge zone of Kashubian Lake district (in Polish with English summary). Materiały XXI Ogólnopolskiej Szkoły Hydrauliki, Sasino, 17–21.09.2001.

ZALEWSKI A., STRÓŻYK M. and TOMASZEWSKI A. (1980) — Hydrogeological documentation of Quaternary aquifer research in the Lipce region in Gdańsk. Kombinat Geologiczny "Północ" — Zakład Projektów i Dokumentacji Geologicznych w Warszawie, Oddział Gdańsk.