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Groundwaters recharge and drainage in the Żuławy Elbląskie area

Key words

Hydrogeology, groundwaters resources, modelling

Abstract

The Żuławy Elbląskie area is located in the eastern part of the Vistula River delta. The area is a partly depressed flat, alluvial plain. The monotonous relief of the delta is contrasted by elevations of the Iława Lake District and the Elbląg Upland. From the west the area is bordered by Nogat arm which, along with its Cieplicówka arm and with the Elbląg River constitute the principal part of hydrographic system of the Żuławy. The aquatic system is also strongly influenced by the Drużno Lake. The most part of the Żuławy Elbląskie area must be subjected to the land drainage.

Two groundwater horizons are important for water supply: Pleistocene-Holocene (Quaternary sands) and multiage (oldest Pleistocene units, Tertiary sands and Upper Cretaceous carbonates and siliceous sediments). The Żuławy Elbląskie area is recharged laterally from the surrounding uplands. The infiltration of meteoric waters is less important due to impermeable cover and intensive drainage through the system of collector trenches, canals and pump stations.

Utilization of groundwaters is highly limited by their quality, which deteriorates with the distance from the uplands due to increasing concentration of chloride ion (up to 600 mg Cl/dm^3). Another deteriorating factor is the excess of Fe and Mn as well as the increased concentrations of ammonia.

The groundwater balance and the assessment of groundwater resources were based upon the modelling studies. Three model variants were considered: Variant 0 — reconstruction of natural position of groundwater table (unexploited groundwaters), Variant 1 — reconstruction of hydrodynamic conditions for 1999 (model revision) and Variant 2 — hydrodynamic prognosis at the optimum exploitation of groundwater intakes.

Simulations allowed to determine the total amount of groundwaters involved in recharge and drainage of the Żuławy Elbląskie horizons. Total amount of groundwaters in the Pleistocene-Holocene horizon is 21,090 m^3/24 h under natural conditions (Step 0) and 35,040 m^3/24 h at maximum exploitation (Step 2). For the multiage horizon the amount of groundwaters under natural conditions (Step 0) is 8,440 m^3/24 h and increases 5 times at maximum exploitation (up to 43,900 m^3/24 h, Stage 2). The disposable resources obtained from modelling are: 24,000 m^3/24 h for Pleistocene-Holocene horizon and 38,400 m^3/24 h for multiage horizon.

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Introduction

Exploitation of groundwater horizons in the Żuławy Elbląskie area disturbs significantly the natural conditions and may lead to the initiation or preservation of negative hydrodynamic trends. Therefore, the rational water management is crucial for the whole area. Consequently, the protection zones around the water intakes must be respected and already granted water licences must be verified. Decisions on the groundwater withdrawal rates must be based upon the credible calculations which must take into account all factors resulting from geological and hydrogeological conditions as well as water demand in the area.

Hydrogeological recognition of the Żuławy Elbląskie area is based upon the information stored in the Regional Hydrogeological Database (RHD) which in last years led to the construction of 1:50,000 scale hydrogeological maps (Kreczko 1998; Lidzbarski 1998; Prussak 1998; Uścinowicz 1998). The processed data were used for preparation of the schemes of water horizons and their recharge and drainage.

The potable and industrial water supply is provided by two main groundwater horizons: Quaternary and multiage. The disposable reserves are controlled by various factors but crucial role is played by recharge from the surrounding uplands of lake districts. Infiltation of meteoric waters is less important because of the presence of impermeable caprocks and the land drainage of the delta area.

Exploitation of groundwater resources of the Żuławy Elbląskie area is limited by environmental constrains (particularly in the vicinity of Drużno Lake) and by water quality. Excessive concentrations of chloride, iron and manganese ions eliminate the wide utilization of groundwater horizons.

Hydrodynamic changes in the area of Vistula River delta were prognozed by means of the numeric modelling. Results were applied to evaluation of disposable reserves of the area.

1. Conditions of groundwater resources formation

The Żuławy Elbląskie (Fig. 1) cover about 510 km^2 and reveal specific conditions of groundwater occurrence. Almost flat alluvial plain regionally inclined towards the northeast elevates only a few meters above sea level. Significant part is a depression of elevation –1.8 meters above sea level (a.s.l.) in the vicinity of Drużno Lake. In the central part (vicinity of Jegłownik) a mound composed of glacial sediments rises to 11 meters a.s.l. The flat surface is cut by embankments protecting the Drużno Lake, the Nogat River arm and numerous canals. The monotonous landscape is contrasted by surrounding hills belonging geographically to the Iława Lake District (in the south) and Elbląg Upland (in the east). The latter area is cut by scarps several tens of meters high. The scarps bordering the lake district are 20—30 meters high. Northwest of the Nogat River the alluvial plain grades into the Great Żuławy. From the north the study area is bordered by the Vistula River Lagoon.

The groundwater horizons of commercial values are hosted in Quaternary and Tertiary sediments (Fig. 2 and 3). In older formations groundwaters are saline. The main groundwater horizons occur in:

— Pleistocene-Holocene alluvial sediments underlain by Eemian Interval deposits,

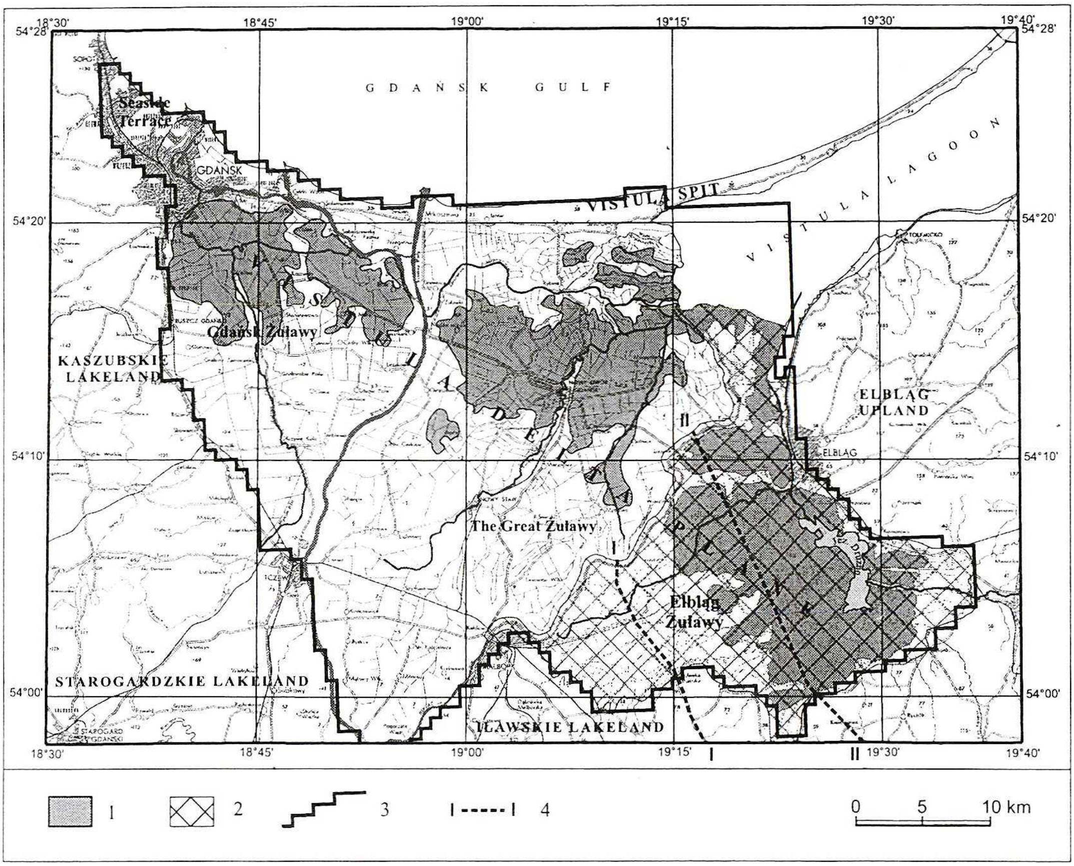

Fig. 1. Location of Żuławy Elbląskie area
1 — depression (<0 m. a.s.l.), 2 — Żuławy Elbląskie area, 3 — model domain boundary,
4 — line of hydrogeological cross-section

Rys. 1. Położenie Żuław Elbląskich
1 — depresja (<0 m n.p.m.), 2 — obszar Żuław Elbląskich, 3 — granice obszaru badań modelowych,
4 — linia przekroju hydrogeologicznego

— multiage sediments comprising Upper Cretaceous carbonates and siliceous rocks as well as Upper Cretaceous, Tertiary and Lowest Quaternary sands.

1.1. Pleistocene-Holocene groundwater horizon (Q)

The Pleistocene-Holocene groundwater aquifer covers practically the whole Żuławy Wiślane area. Lithology, thickness and origin of water-bearing rocks are highly diversified (Kozerski, Kwaterkiewicz 1990). Favourable conditions for its occurrence were found along the right bank of the Nogat River, northeast of Malbork town. On the contrary, the Quaternary horizon is absent from some sites in southern and eastern parts of the Żuławy Elbląskie. Largest gap was observed in the vicinity of Drużno Lake.

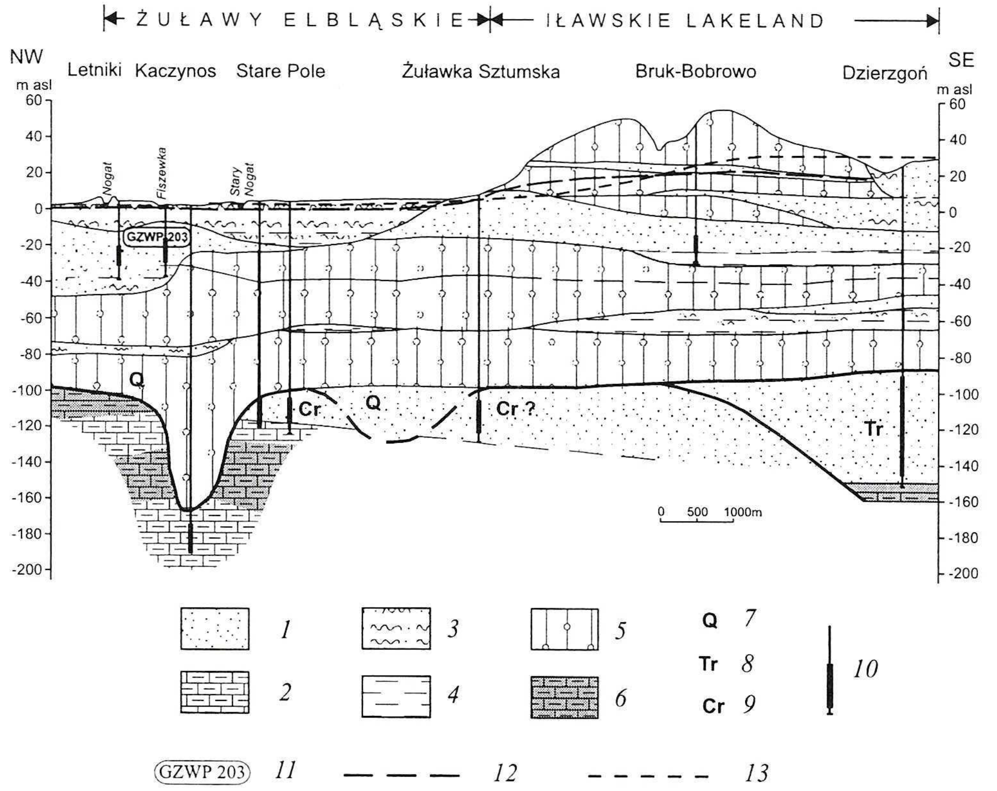

Fig. 2. Hydrogeological cross-section I—I
1, 2 — groundwater aquifers: sands (1), marl (2); 3, 4, 5, 6 — confining layers: silt (3), clay (4), till (5), marl (6); 7, 8, 9 — stratigraphy: Quaternary (7), Tertiary (8), Cretaceous (9), 10 — wells, 11 — major groundwater basin No. 203, 12 — groundwater table of Pleistocene-Holocene aquifer, 13 — groundwater table of Quaternary-Tertiary-Cretaceous aquifer

Rys. 2. Przekrój hydrogeologiczny I—I
1, 2 — utwory wodonośne: piaski (1), margle (2); 3, 4, 5, 6 — warstwy nieprzepuszczalne: mułki (3), iły (4), gliny (5), margle (6); 7, 8, 9 — stratygrafia: czwartorzęd (7), trzeciorzęd (8), kreda (9), 10 — studnie, 11 — Główny Zbiornik Wód Podziemnych Nr 203, 12 — zwierciadło wody plejstoceńsko-holoceńskiego poziomu wodonośnego, 13 — zwierciadło wody różnowiekowego (Q-Tr-Cr) poziomu wodonośnego

The Pleistocene-Holocene groundwater horizon includes mostly sands deposited during the Eemian Interval and directly overlying the Holocene deltaic sands. The caprocks are peats, muds and clays of highly variable thickness (from several to over 30 meters, Fig. 2 and 3).

Groundwater conditions are diversified. Significant thickness of Quaternary horizon (20—40 meters) is observed only in a small area close to Nogat River ("Letniki" water intake). Average thickness of this horizon in the Żuławy Elbląskie is about 22 meters. Transmissivity is usually less then 200 m^2/24 h but, under favourable conditions, it may reach even 1,000 m^2/24 h (Fig. 4).

Water table is slightly confined by low-permeable deltaic sediments and occurs at depth from about 7 meters a.s.l in the marginal parts of the Żuławy Elbląskie to below 0 meters a.s.l. in

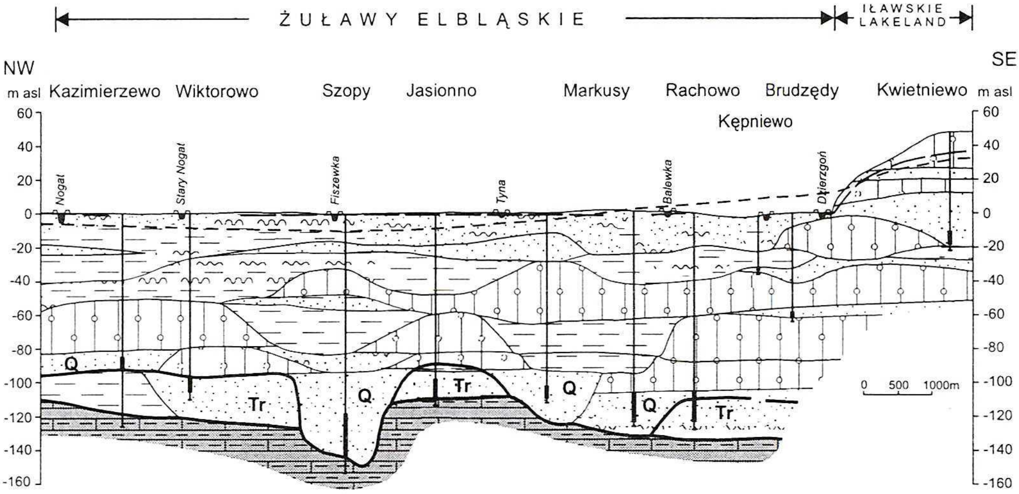

Fig. 3. Hydrogeological cross-section II—II
Explanations: as in Fig. 2.

Rys. 3. Przekrój hydrogeologiczny II—II
Objaśnienia: jak na rys. 2

depressions. Position of groundwater table is controlled by drainage system. Exploitation of the "Letniki" intake resulted in the formation of depression cone but, due to reduced withdrawal, the range and depth of the cone are recently limited (Fig. 4).

1.2. Multiage groundwater horizon (Q-Tr-Cr)

The multiage groundwater horizon includes Upper Cretaceous, Tertiary and Lower Quaternary sandy deposits. In southern and southeastern parts of the Żuławy Elbląskie this horizon comprises mostly Tertiary strata with minor younger rocks (Zwierzno-Wiśniewa area). In the northern part Quaternary sediments prevail whereas Upper Cretaceous sands are important component only in southwestern part of the study area. The multiage horizon is separated from the Quaternary one by a series of low-permeable boulder clays and clays of thickness about 60 meters (Fig. 2 and 3). Generally, the multiage horizon extends over the southern and central parts of the Żuławy Elbląskie, and continues further to the area of Iława Lake District. In the northern part of study area its thickness is reduced.

Top surface of water horizon was found at about 100 meters depth. Its thickness varies from several to several tens of meters, most commonly changing from 20 to 30 meters (Janik et al. 1996). Wide range of transmissivity values was observed: from several to over 1,000 $m^2/24$ h (Fig. 5). Most favourable hydrogeological conditions were noticed in the vicinity of Elbląg town (the "Malborska" intake) and along the narrow strip of land extending from Szopy to Zwierzno-Wiśniewo. The multiage horizon is in hydraulic connection with the underlying, fractured Cretaceous carbonates.

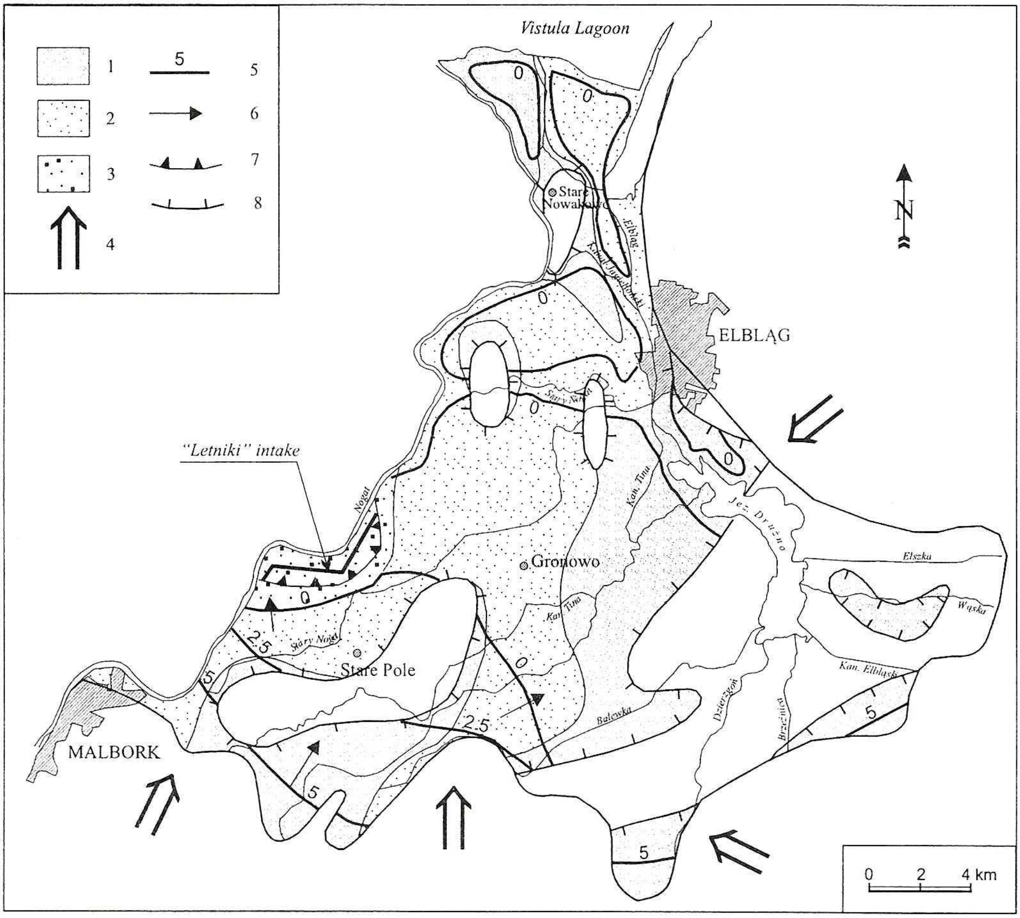

Fig. 4. Groundwater table of Pleistocene-Holocene aquifer (as obtained from modeling)
1, 2, 3 — groundwater transmissivity: < 100 m^2/d (1), 100—500 m^2/d (2), >500 m^2/d (3); 4 — lateral recharge, 5 — hydroisohypses (m. a.s.l.), 6 — groundwater flow direction, 7 — depression cone, 8 — area without Pleistocene-Holocene aquifer

Rys. 4. Zwierciadło wody plejstoceńsko-holoceńskiego poziomu wodonośnego (odtworzone na podstawie badań modelowych)
1, 2, 3 — przewodność warstwy wodonośnej: < 100 m^2/d (1), 100—500 m^2/d (2), >500 m^2/d (3); 4 — kierunki zasilania lateralnego, 5 — hydroizohipsy (m n.p.m.), 6 — kierunki przepływu wód podziemnych, 7 — zasięg leja depresji, 8 — obszar pozbawiony plejstoceńsko-holoceńskiej warstwy wodonośnej

The piezometric surface in both the multiage and the Upper Cretaceous horizons is gently inclined towards the north. Groundwater table (initially of artesian character) was found to stabilize several meters above sea level. In the area adjacent to the Iława Lakeland it occurs at elevation over 10 meters a.s.l. However, recent position of groundwater table is much lower (even –25 meters a.s.l.) due to intensive withdrawal, particularly in the vicinity of Elbląg town and Drużno Lake. The area of regional depression cone exceeds 100 km^2.

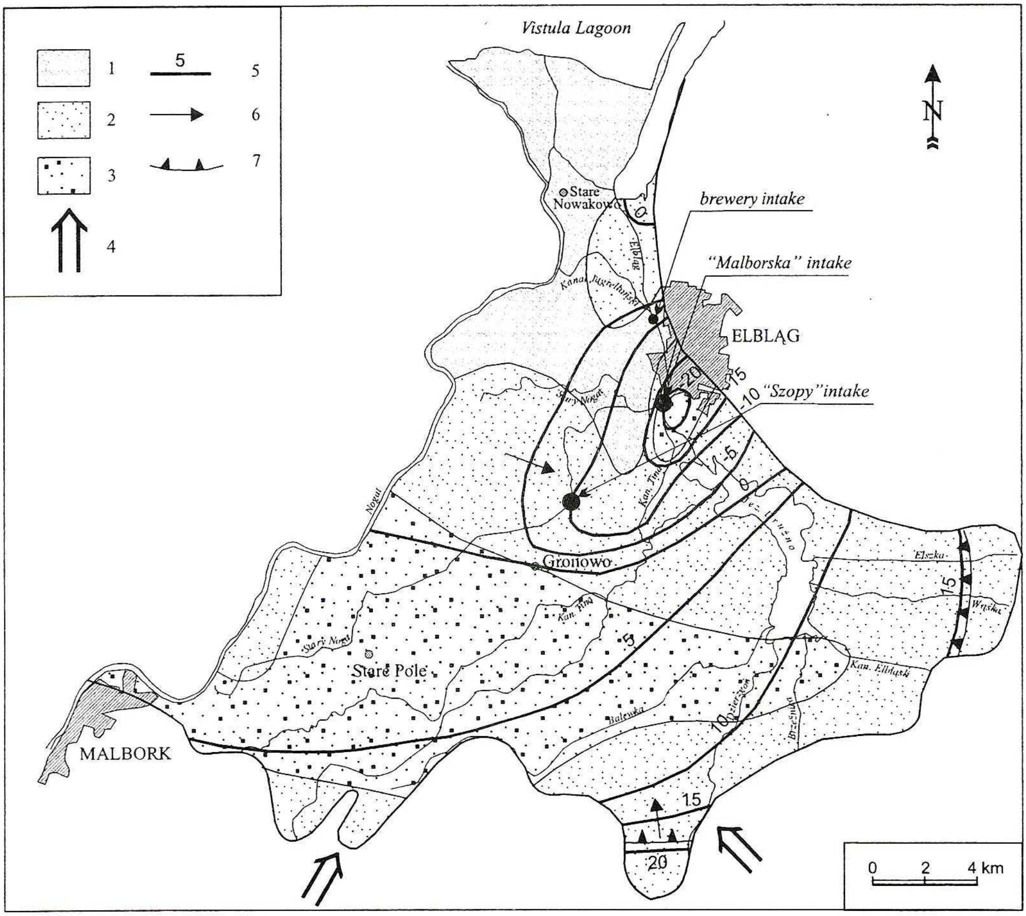

Fig. 5. Groundwater table of Quaternary-Tertiary-Cretaceous aquifer (as obtained from modeling)
Explanations: as in Fig. 4

Rys. 5. Zwierciadło wody czwartorzędowo-trzeciorzędowo-kredowego poziomu wodonośnego (odtworzone na podstawie badań modelowych)
Objaśnienia: jak na rys. 4

1.3. Groundwater withdrawal and resources protection problems

Two groundwater horizons are currently under exploitation: Pleistocene-Holocene (Q) and multiage (Q-Tr-Cr). In 1998 the withdrawal rate was 1,360 m^3/h, i.e. about 19% of approved admissible extracted volume. The most important groundwater intakes are: "Letniki", Elbląg (municipal intakes "Malborska" and "Szopy") and Ebląg brewery intake (Elbrewery).

The "Letniki" intake is located in the right bank of Nogat River, north of Malbork town. Water is produced from Quaternary and Tertiary horizons (Młyńczak, Radek 2000) and supplied to the Great Żuławy and Żuławy Elbląskie. The remaining intakes produce waters from the multiage horizon covering the demand of Elbląg town for potable and industrial waters.

The approved admissible resources in Pleistocene-Holocene horizon are 3,180 m^3/h (in which 85% in the "Letniki" intake). In 1998 this intake produced 490 m^3/h. Production rate from multiage horizon was 740 m^3/h. Its approved admissible reserves are 3,780 m^3/h.

Exploitation of larger intakes in the Żuławy Elbląskie area affects the natural environment causing deterioration of groundwater quality, changes in drainage system and decrease in farming activity (Kozerski, Kwaterkiewicz 1990). Deterioration of groundwater quality was observed in the "Letniki" intake where remarkable increase in iron, manganese and ammonia contents was reported as well as in the Elbląg one (Elbrewery and "Malborska" intakes) where ascension of groundwaters from deeper horizons resulted in the increase of chloride ion contents.

Separate problem of great importance is the protection of the Drużno Lake. Overexploitation of groundwaters may lead to the lowering of water table in the mud series and, consequently, may cause irreversible changes in the ecosystem.

1.4. The drainage system of the Żuławy Elbląskie area

Rivers, reservoirs, canals, drainage ditches and hydrotechnical constructions are components of drainage system, which controls the whole aquatic environment of the Żuławy Elbląskie. Almost whole area is protected and kept usable exclusively by land drainage.

The backbone of the Żuławy Wiślane area is the Vistula River which is protected by the Gdańsk (left bank) and the Great Żuławy (right bank) embankments. The Vistula River plays only the waterway role and is not connected to the Żuławy hydrologic system. However, the Vistula River divides the Żuławy area into the two hydrographic zones: Żuławy Gdańskie and Great Żuławy/Żuławy Elbląskie.

The left-bank polders of the Żuławy Gdańskie are directly connected to the Gdańsk Bay, i.e. water from the polders flows to the Baltic Sea through the system of embanked canals and storm gates. The right-bank polders are drained by pumping to embanked canals (which lack the storm protections), which are connected to the Vistula Lagoon (Cebulak 1991).

The hydrographic pattern of the Żuławy Elbląskie is very complicated and dominated (75% of the area) by mechanical drainage run by 62 pumping stations. Main rivers are: Nogat (with the Cieplicówka arm) and Elbląg, both connected by the Jagiellonian Canal. Both rivers are of lowland type, reveal very low gradient and channelized flow.

The Żuławy Elbląskie area is drained to the Vistula Lagoon by the extended system of the Elbląg River which includes two basic drainage patterns connected to the Drużno Lake and to the Fiszewka River (Cebulak 1991). The Drużno Lake (area: 14.5 km^2, maximum depth: 3 m) collects waters migrating from the northern slope of the Iława Lake District and southwestern part of the Elbląg Upland as well as flowing through the canal system from 20 polders located in the eastern part of the Żuławy Elbląskie. The western path of the Żuławy Elbląskie area extending from the upland margin to the Jagiellonian Canal is connected to the Fiszewka River (left-bank tributary of the Elbląg River). Waters from the northern part of the Żuławy Elbląskie is drained to the Nogat River and directly to the Vistula Lagoon.

The total volume of water drained from the Żuławy Elbląskie system reaches about 140 Mm^3/year which is an equivalent of about 8.7 $dm^3/s \cdot km^2$. This volume is controlled by precipitation in the Żuławy area and in surrounding uplands, by water levels in the Vistula

Lagoon and the Gdańsk Bay as well as by the land drainage base imposed by agriculture and industry.

1.5. Lateral flow as a principal water resources control

Results of current hydrogeological studies support the general opinion (Burzyński, Sadurski 1980; Kozerski 1988; Zaleski 1988; Kozerski, Kwaterkiewicz 1990) that the groundwater horizons of the Żuławy Elbląskie are significantly recharged by lateral flow from surrounding uplands. It is confirmed by continuity of filtration flow enabled by numeorus hydraulic contacts and by stable directions of groundwater flow on both sides of Vistula River delta margin. Considering the water balance, it can be demonstrated that external areas must contribute to the inflow of fresh waters as the migration of meteoric waters is limited (Kulma et al. 2002).

The lateral recharge is diversified in various groundwater horizons and at upland margins. The recharge volumes were preliminary determined in hydrogeological assessments (Kreczko et al. 2002). The zone of intensive exchange of waters migrating laterally from the uplands to the Quaternary horizon forms a narrow strip along the delta margins. The width of this strip depends mostly on the flow rate and hydraulic contacts with groundwater horizons in the uplands.

Groundwaters of the Żuławy Elbląskie area are recharged by filtration from the Iława Lakeland and the Elbląg Upland. The recharge area in this part of the Vistula River delta is about 1,400 km^2 for Quaternary horizon and nearly 4,000 km^2 for older horizons. Most part of the filtration area is covered by low-permeable sediments (boulder clays of bottom moraine), which hampers the surficial recharge of groundwater horizons. Sediments of high and very high filtration parameters — fluvio-glacial sands of sandur plains and sandurs accompanying the river valleys — cover about 25% of the area. Decisive for the Żuławy Elbląskie recharge are groundwater horizons hosted in sandy sediments deposited during Mid-poland Glacial Period and the Eemian Interval as well as the Tertiary strata (mostly Miocene and Oligocene sands, and Paleocene sediments).

In the Iława Lake District the main, Quaternary groundwater horizon is located usually at 15—50 meters depth. Its thickness does not exceed 30 meters and transmissivity of waterbed varies from 100 to 500 m^2/24 h. Groundwater table is inclined northward and occurs at elevations from 10 to 100 meters a.s.l. This groundwater horizon is in hydraulic contact with Pleistocene-Holocene horizons of the Żuławy Elbląskie area but the character of contacts is very diversified: direct in the area between Malbork and Żuławka Sztumska and limited in the remaining area due to the poorly developed waterbeds.

Hydraulic connection between groundwaters in the Elbląg Upland and the Żuławy Elbląskie is limited due to the presence of low-permeable sediments which separate both geomorphological units.

Tertiary groundwater horizon has been recognized only in the border zone of the Iława Lakeland. It occurs at elevation about –90 meters a.s.l. and reaches considerable thickness. Transmissivity of waterbed varies from 50 to 500 m^2/24 h. Groundwater table occurs at elevations from 10 to 50 meters a.s.l. In the Elbląg Upland the Tertiary groundwater horizon is very poorly known. However, the multiage horizon of the Żuławy Elbląskie area is hosted in Tertiary strata.

The Żuławy Elbląskie area reveals unfavourable conditions of groundwater exchange in the shallowest, Quaternary horizon. Lateral recharge was observed in southwestern and northern parts but lower inflow rates result from the dominance of impermeable sediments in the upland area and from unfavourable hydrogeological conditions of Pleistocene-Holocene formation.

Dynamics of groundwater in the multiage horizon is controlled also by lateral migration from the uplands. In the Żuławy Elbląskie area intensive lateral recharge was found along the southern border with the Iława Lakeland. Recharge is here facilitated by the presence of erosional structure deeply cutting the Cretaceous bedrock. This structure is filled with sands and is in direct contact with groundwater horizons of the Iława Lakeland.

The estimated lateral recharge of the Żuławy Elbląskie area by groundwaters migrating from the surrounding uplands was about 910 m^3/h under "natural" conditions (without withdrawal) which makes about 18% of total lateral recharge of the whole Żuławy Wiślane area. Main groundwater flow directions in this part of the Vistula River delta are from the south (Sztum, Stary Targ and Dzierzgoń areas) to the north (towards Stare Pole, Letniki, Szopy and Zwierzno) and from the southeast (Pasłęk) towards Elbląg town intakes.

1.6. Groundwater quality

Groundwater quality problem is more important in the Żuławy Elbląskie than in the surrounding uplands. Unfavourable hydrochemical parameters show variable distribution and spatial extent.

In southwestern part of the study area chemical composition of groundwaters from the Pleistocene-Holocene horizon is similar to that of waters from the uplands. With the distance from marginal parts of the Vistula River delta the hydrochemistry changes and groundwater quality deteriorates.

In the marginal areas groundwaters from the first horizon belong to bicarbonate-calcium or bicarbonate-calcium-magnesium types (if enriched in Mg^{+2} ion). Towards the delta center the volume of waters migrating from the deeper levels increases which results in dominance of bicarbonate-calcium-sodium and bicarbonate-sodium water types. Usually, in the depressions (northern deltla margins) groundwaters are additionally enriched with young fossil waters of marine origin. Thus, in such areas waters reveal complicated hydrochemical composition (HCO_3-Cl-Ca-Na) or belong to chloride-sodium type.

In the Żuławy Wiślane area, along the margin of the Iława Lake District, fresh waters were found of chloride content 75 mg Cl/dm^3, total hardness 6 $mval/dm^3$ and dry residue 550 mg/dm^3. With the distance from marginal zone the chloride content in Quaternary groundwaters increases up to 500 mg/dm^3 in the Nowakowska Island. Apart from chloride, the components which limit utilization of Quaternary waters are: iron, manganese and ammonia. Particularly high iron and manganese concentrations were detected in northern, right-bank part of the Vistula River delta. Iron contents reach 40 mg Fe/dm^3 and manganese ones are up to 1.8 mg Mn/dm^3. It must be emphasized that Fe and Mn contents increase during exploitation of intakes. Moreover, groundwaters in this area reveal high ammonia contents, intensive colour and high oxygen consumption. Highest ammonia contents (13.3 mg NH_4/dm^3) were analyzed in the vicinity of Drużno Lake but average content does not exceed 5 mg NH_4/dm^3.

Quality of groundwaters from multiage horizon is controlled by composition of waters migrating from the Iława Lakeland and from greater depths (regional circulation system, Kozerski, Kwaterkiewicz 1990). In the marginal zones waters belong to bicarbonate-calcium and bicarbonate-calcium-sodium types or, if enriched in chloride ion, to bicarbonate-calcium-sodium one. Mineralization is variable, as revealed by chloride contents, total hardness and dry residue. Lowest contents of chloride ion were found in southern part of study area (10—50 mg Cl/dm^3). Northward chloride content increases up to 600 mg Cl/dm^3 in the Nowakowska Island. Unfortunately, the area of high chloride contents (over 250 mg Cl/dm^3) includes also the northern quarters of Elbląg town.

Iron contents oscillate around 1.5 mg/dm^3 and are higher in southern part of the Żuławy. Manganese contents in the whole study area are somewhat higher than permissible values for potable waters. Contents of nitrogen compounds are low. Average ammonia concentration is about 1.0 mg NH_4/dm^3.

2. Remarks on hydrogeologial model of the Vistula River delta

The filtration area subjected to modelling (Fig. 1) was selected using the hydrogeological and geomorphological factors. The model of waterbeds (Kulma et al. 2000) which includes Pleistocene-Holocene and multiage (Quaternary-Tertiary-Cretaceous) horizons as well as top and bottom sealing strata was based upon the current state of geological recognition. Direct modelling was applied to the area of 1,954.56 km^2. This area was divided into the calculation blocks (Δx = 800 m). The Quaternary horizon includes 2,749 blocks and the multiage one — 2,770 blocks. This division system appeared to be sufficient for schematic projection of important details of geological structure, hydrogeological and hydrologic conditions, and technical/exploitation parameters of the intakes.

The hydrogeological model of the Vistula River delta was constructed with the Processing Modflow (PM5) software. The following assumptions were made:

— practically all boundaries providing the outer contour of the model are natural. The northern boundary is the Gdańsk Bay shoreline (from Sopot to Kąty Wrocławskie). The remaining boundaries are the edges of uplands: Kaszuby Lakeland from the west, Iława Lakeland from the south and Elbląg Upland from the east. Only in the northeastern fragment the boundary is conventional. Two arbitrary lines: meridional and parallel provide the conventional boundaries of a part of Vistula River Lagoon which was included into the model;

— in the whole modelling area two groundwater horizons (two modelling layers) are separated by impermeable sediments:

- Pleistocene-Holocene horizon (Layer I) of confined table hosted in sand-gravel strata. In the top the confining, low-permeable layer occurs (Fig. 2 and 3),
- multiage horizon and Upper Cretaceous fissure-type series (Layer II) which includes sandy strata (Tertiary, Oldest Pleistocene) and Upper Cretaceous carbonate-siliceous series (Fig. 2 and 3). This horizon is most important water source in the Żuławy Elbląskie area;

— natural boundary which determines the depth of regional exchange of fresh waters in the delta area and in surrounding uplands is the impermeable Upper Cretaceous mudstone-claystone series;

— the main recharge areas for Cretaceous and Cainozoic aquifers are uplands of the Kaszuby and Iława lake districts as well as the Elbląg Upland. The Żuławy Wiślane area provides the regional drainage base in which waters migrate to surface flows and reservoirs. Local drainage bases form in the vicinity of groundwater intakes and land drainage systems;

— surface recharge for the Quaternary groundwater horizon was deduced from precipitation rates and lithology of aeration zone. The value of infiltrational recharge was determined from distribution of average values of annual precipitation — 520—640 mm/year (Malicki, Miszke 1990). Despite very favourable morphology of the area (low relief) low infiltration rates predominate as a result of low permeability of strata overlying the water table (in aeration zone) of the Layer I and intensive drainage provided by very dense network of canals and draining ditches;

— for modelling purposes the lateral recharge of Quaternary and multiage horizons was based upon the software option which enables the application of shifted model boundaries. The values of lateral infiltration taken for the model purposes vary from 360 to 1,450 m^3/day/block for Layer I in the area of Żuławy Elbląskie and 35—1,350 m^3/day/block for Layer II. Both layers include fragments in which the impermeable sediments preclude the lateral groundwater migration within the area of Vistula River delta;

— the main rivers: Vistula and Nogat and their tributaries provided model's outer boundary condition. The same role was played by system of draining ditches and canals. Calculation blocks in which such conditions were applied constitute 91.1% of the total number of blocks;

— in the Żuławy Wiślane area surface flows and reservoirs play only a minor role in development of groundwater resources. Most of them are isolated by low-permeable sediments (muds) and direct hydraulic contacts of ground- and surface waters are scarce. Projection of land drainage system required significant simplifications due to relatively sizeable calculation blocks (Δx = 800 m) and dense network of trenches and canals;

— groundwater horizons are exploited in numerous intakes located mostly in the marginal zone of the Żuławy, close to the surrounding uplands. In the Żuławy Elbląskie area the Quaternary horizon is drained by the "Letniki" intake at the rate of about 12,000 m^3/24 h. The multiage horizon and Upper Cretaceous fissure aquifers are exploited by a dozen of wells at total rate 21,000 m^3/24 h. Discharges of intakes utilizing both groundwater horizons in the Żuławy Elbląskie area make 15% and 21% of approved admissible resources (data for 1990);

— groundwater table in the Żuławy Wiślane area was positioned basing upon hydrogeological assessment reports and current (1999) measurements made in the observation wells (Kreczko et al. 2000). In the Quaternary horizon hydraulic elevations vary from –2.5 to +13 meters a.s.l. (under general flow direction towards the northeast) and in the multiage one these values change from –23.0 to +24.0 meters a.s.l. (with the well-visible drainage center in Elbląg area, Fig. 5).

Calculations of the Żuławy Wiślane model included three variants, which allowed to evaluate principal factors influencing the aquatic environment in this filtration area. Variant 0 aims to reconstruct the "natural" position of groundwater table if water withdrawal from all wells is stopped. Variant I aims to reconstruct current (data for 1999) hydrodynamic conditions in order to verify the model. Variant II is the hydrodynamic prognosis under optimum exploitation conditions of existing groundwater intakes.

3. Groundwater balance

Results of simulations allowed to construct the groundwater balance of the Żuławy Elbląskie area and to analyze in details the factors controlling these resources. Such attempt should provide the rational basis for water management in the study area. Particularly useful is here the prognostic version, which enables the determination of hydrodynamic conditions at the optimum withdrawal rates of admissible reserves by the existing or designed groundwater intakes. In details, the prognostic version determines:

— volume of waters recharging or draining the waterbeds through the outer boundaries of filtration area assumed in the model,

— volume of waters infiltrating the Quaternary groundwater horizon due to precipitation or migration between horizons,

— volume of recharge and drainage of the filtration area by main surface flows and polder system, if present within the modelled area.

3.1. Layer I — Pleistocene-Holocene groundwater horizon

Total amount of groundwaters taken into consideration in the water balance of quarternary horizon varies from 21,000 $m^3/24$ h under "natural" conditions (Variant 0) to about 35,000 $m^3/24$ h at the maximum withdrawal (Variant 2).

The principal controlling factor of water resources is the lateral migration, particularly from the south (Iława Lake District) and the east (Elbląg Upland). The flow rate changes from 11,840 $m^3/24$ h (56.2% of balance total) under reconstructed "natural" conditions to 18,260 $m^3/24$ h (52.1%) for the forecasted maximum withdrawal. In the each considered variant recharge from the south is significant and constitutes from nearly 26% (Variant 2) to over 35% (Variant 0) of the balance total.

Infiltration of meteoric waters plays minor role in the recharge of Quaternary horizon. The effective contribution from this source is about 4,350 $m^3/24$ h which constitutes 12.4% (Variant 2) or 20.6% (Variant 0) of the total amount of groundwaters considered in the balance calculations.

Attention should be paid also the remaining recharge sources. Under "natural" conditions (Variant 0) migration from the multiage horizon (Layer II) becomes important. This vertical filtration reaches about 4,900 $m^3/24$ h. Under such condition the recharge from rivers and reservoirs is practically absent.

With the increasing exploitation of groundwater intakes the recharge of Quaternary horizon by vertical migration becomes less important at the expense of increasing inflow from rivers and polders. At the maximum withdrawal rate from intakes and wells this recharge amounts 12,380 $m^3/24$ h.

In the vicinity of the "Letniki" intake particularly important for groundwater resources control in Quaternary horizon are Fiszewka and Nogat rivers. At withdrawal rate of 11,840 $m^3/24$ h recorded in 1998 (Variant 1) the contribution of infiltration from both rivers was about 21.9% (2,590 $m^3/24$ h). If the increase of well discharges up to 23,040 $m^3/24$ h is considered the contribution from rivers will rise up to 35.9% (8,250 $m^3/24$ h).

The discharge from the modelled area is dominated by drainage systems. Under "natural" conditions (Variant 0) the drainage by polder system reaches 10,300 m^3/24 h (48.9%). Drainage by rivers and reservoirs is comparable — 9,050 m^3/24 h (42.9%). These values must be supplemented by outflow through the outer boundaries of study area, mostly to the north, towards the Vistula River Lagoon.

Decisive changes in groundwater balance and hydrodynamic pattern (Fig. 6) must be expected under the conditions of maximum permissible withdrawal rate (Variant 2) which may reach about 23,200 m^3/24 h, i.e. 66.3% of balance total. Under such circumstances the drainage volumes will be much decreased: polders — to 4,280 m^3/24 h (12.2%), rivers — 1,860 m^3/24 h

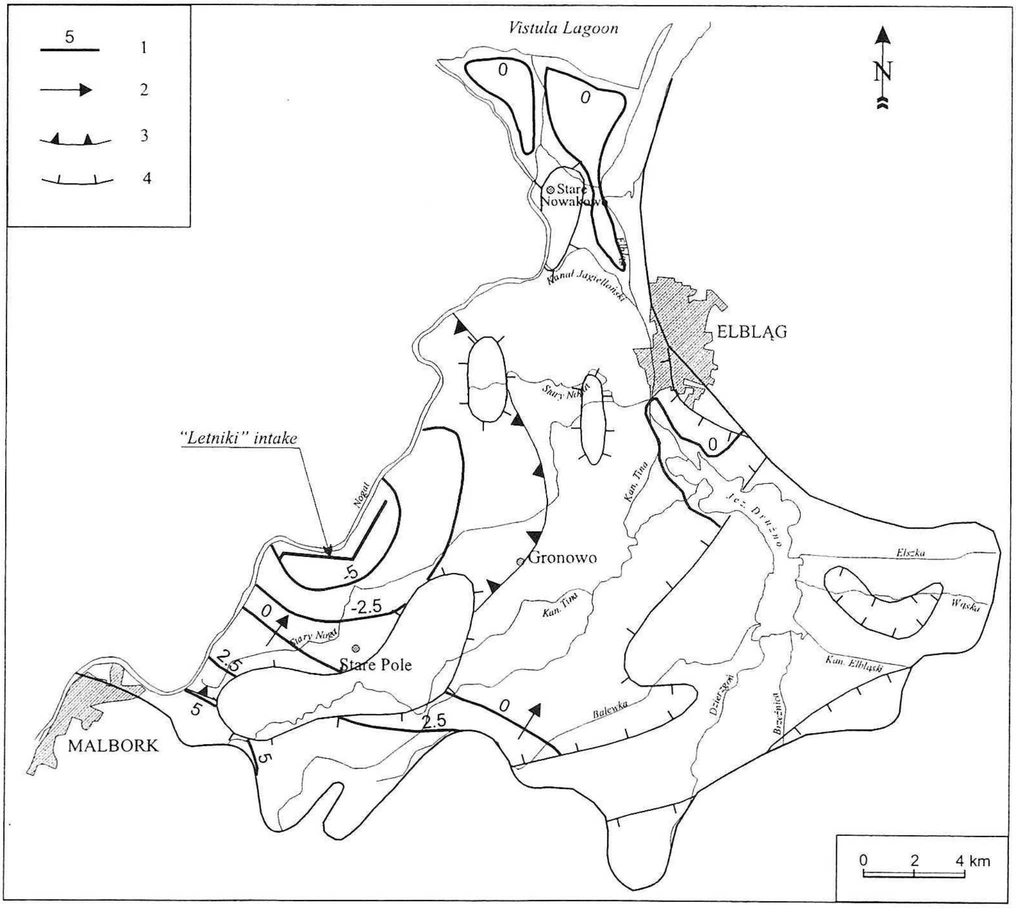

Fig. 6. Groundwater table of Pleistocene-Holocene aquifer — model predictions
1 — hydroisohypses (m. a.s.l.), 2 — groundwater flow direction, 3 — depression cone of "Letniki" intake, 4 — area without Pleistocene-Holocene aquifer

Rys. 6. Zwierciadło wody plejstoceńsko-holoceńskiego poziomu wodonośnego — stan prognozowany na modelu hydrogeologicznym
1 — hydroizohipsy (m n.p.m.), 2 — kierunki przepływu wód podziemnych, 3 — zasięg leja depresji ujęcia „Letniki", 4 — obszar pozbawiony plejstoceńsko-holoceńskiej warstwy wodonośnej

(5.3%) and Vistula River Lagoon — to 1,330 m^3/24 h (3.8%). On the contrary, migration to the multiage horizon will increase to about 4,340 m^3/24 h (12.4%).

3.2. Layer II — multiage groundwater horizon

Groundwater balance of the multiage horizon is controlled by external factors: lateral recharge and discharge as well as vertical exchange of waters with the overlying Quaternary horizon. Under "natural" conditions (Variant 0) total amount of circulating groundwaters is 8,440 m^3/24 h and increases 5 times (up to 43,900 m^3/24 h) at the maximum permissible withdrawal rate (Variant 2).

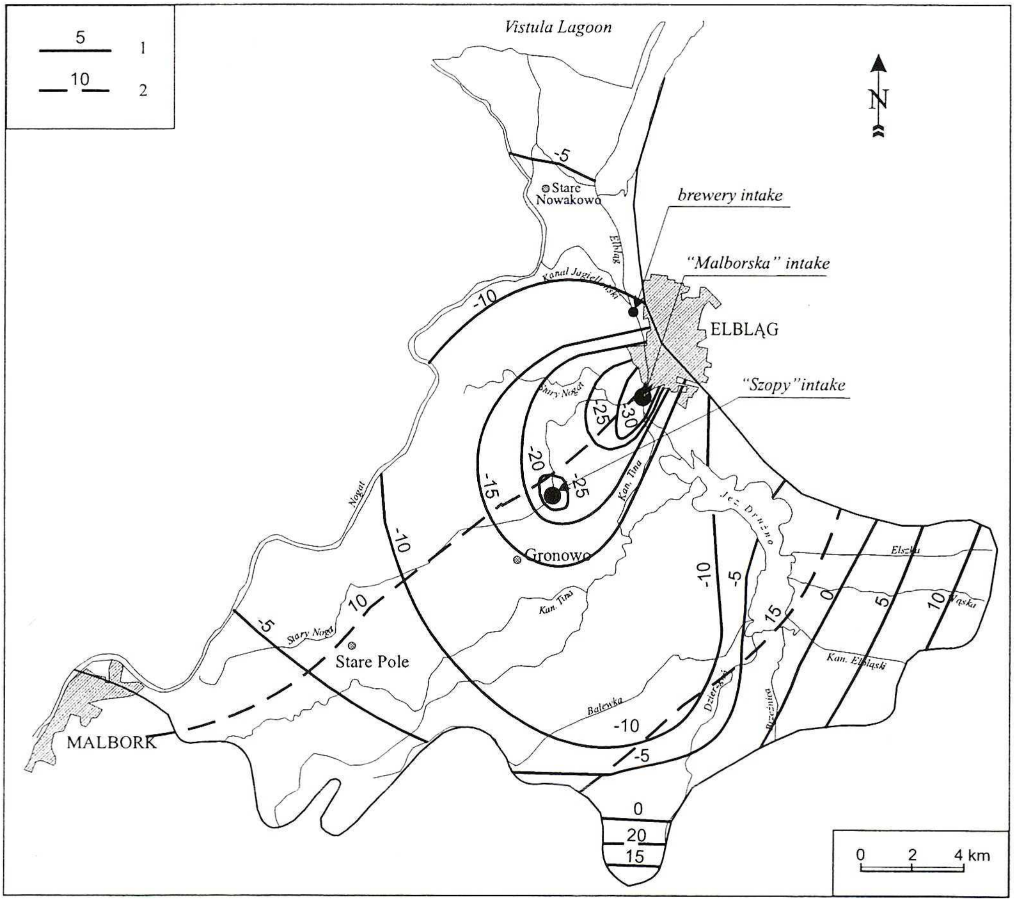

Fig. 7. Groundwater table of Quaternary-Tertiary-Cretaceous aquifer — model predictions
1 — hydroisohypses (m. a.s.l.), 2 — original water table contours (m.a.s.l)

Rys. 7. Zwierciadło wody czwartorzędowo-trzeciorzędowo-kredowego poziomu wodonośnego — stan prognozowany na modelu hydrogeologicznym
1 — hydroizohipsy (m n.p.m.), 2 — położenie zwierciadła wody w warunkach naturalnych (m n.p.m.)

Under "natural" conditions the principal recharge of the multiage horizon is provided by migration from the south, i.e. from the Iława Lakeland (7,180 m^3/24 h, 84.7% of balance total). It is supplemented by migration from the east, from the Elbląg Upland (1,290 m^3/24 h, 15.3%). Discharge is dominated by migration to Quaternary horizon (nearly 4,900 m^3/24 h, 84.7% of balance total) and by filtration towards the west, to the Great Żuławy (3,090 m^3/24 h, 36.6%).

Under the prognozed conditions of maximum withdrawal of the Żuławy Elbląskie groundwater resources (Variant 2) all the outer boundaries will provide recharge at the total rate 39,560 m^3/24 h (90.1% of balance total). Although proportions will be changed, the main recharge will originate from the Iława Lake District (24,710 m^3/24 h, 56.3%) and from the Elbląg Upland (10,980 m^3/24 h, 25.0%). Additional volumes will migrate from the Quaternary horizon (4,340 m^3/24 h, 9.9%) and from the Great Żuławy (3,520 m^3/24 h, 8.0%). The discharge will be dominated by prognozed high withdrawal from the intakes (43,850 m^3/24 h, 99.9% of balance total). Such high rates will result in significant changes of hydrodynamic pattern (Fig. 7).

4. Disposable resources of groundwater horizons

The disposable resources can be estimated exclusively by methods which consider the spatial variability of all elements of the aquatic, geological and even economic environments (Paczyński et al. 1996). Therefore, only the modelling methods meet the criteria resulting from the assessment principles of groundwater resources. Disposable reserves are determined by means of optimization of groundwater withdrawal from the existing or designed intakes preceded by analysis of "natural" (pseudonatural) conditions (without exploitation) and current development of the resources. The resulting recommendations were verified by the simulations run on hydrogeological model of the Vistula River delta.

Separate problem which had to be considered during evaluation of groundwater resources of the Żuławy Elbląskie area was the quality deterioration. Even recently a part of groundwater resources in this area had to be abandoned due to exceeded permissible contents of various components (as provided by the Regulation of the Minister of Health, Dz.U. No. 82, item 937 issued on 4.09.2000) or requirements for groundwater quality categories after the State Institute of Environment Protection. The presence of areas of degraded groundwater quality is supported by the observed zonality of chloride concentrations (Kozerski, Kwaterkiewicz 1984, 1990).

The permissible values were exceeded for chlorides ($Cl^- > 250$ mg/l), iron ($Fe^{+2} > 0.2$ mg/l), ammonia and anthropogenic pollutants. The reasons of groundwater quality changes are probably related to the ingression of salted waters from the Vistula River Lagoon or to the ascension of brines from deeper horizons (Sadurski 1986). Especially endangered is the Quaternary-Holocene horizon in the depressions where land drainage proceeds. The results of overexploitation are visible also in the lower, multiage waterbed.

The final optimizatiom of groundwater withdrawal from horizons was run under the general rule that discharge of wells located in the quality hazard areas was only insignificantly increased or left unchanged. Partial increase in an intake discharge within the range of approved admissible resources may occur only for intakes localized where the proper quality of waters is guaranteed and where environmental impact is eliminated.

Finally, the disposable resources in the study area are: for Pleistocene-Holocene horizon — 24,000 m^3/24 h and for multiage horizon — 38,400 m^3/24 h.

Summary

The numeric model of the Vistula River delta includes an area about 1,955 km^2 in which the Żuławy Elbląskie constitute 510 km^2. Practically all the outer boundary conditions resulted from hydrogeological and geomorphological premises. The external conditions were: natural and artificial hydrographic network, recharge from precipitation and water production from wells exploiting the specific groundwater horizons and hydrotechnical systems of the polders.

The principal recharge of groundwaters in the Żuławy Elbląskie area is provided by lateral migration from the areas of Iława Lakeland and Elbląg Upland. This recharge amounts from 20,285 m^3/24 h (38.7% of balance total) under reconstructed "natural" conditions up to 57,816 m^3/24 h at the maximum permissible production from the wells.

Surface recharge of the Quaternary horizon caused by infiltration of meteoric waters becomes important only in limited areas of the filtration zone. Effective infiltration of meteoric waters in the whole area reaches from 20.6% under "natural" conditions to 12.4% during exploitatiom of groundwaters with the permissible prodution rate.

Simulations made on hydrogeological model under "natural" conditions point to the importance of surface flows (particularly the land drainage). Despite the natural migration to the north (towards the Gdańsk Bay), the study area was the main receiver of waters flowing from the Quaternary horizon at the rate of 19,359 m^3/24 h (91.8% of balance total). Especially important for drainage of groundwaters was the polder system of discharge rate 10,305 m^3/24 h (48.8%).

The disposable resources determined from modelling are: 24,000 m^3/24 h for Pleistocene-Holocene horizon and 38,400 m^3/24 h for multiage horizon. Taking into account the recent exploitation rate (data for 1998), the amount of 62,400 m^3/24 h (2,600 m^3/h) is still available in the Żuławy Elbląskie area.

The principal factor limiting the volume of disposable resources is low quality of groundwaters which results from excessive chloride content, high concentrations of iron and manganese and increased amount of ammonia.

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ZASILANIE I DRENAŻ WÓD PODZIEMNYCH NA ŻUŁAWACH ELBLĄSKICH

Słowa kluczowe

Hydrogeologia, zasoby wód podziemnych, badania modelowe

Streszczenie

Żuławy Elbląskie położone są we wschodniej części delty Wisły. Jest to płaska, aluwialna równina, w znacznej części zdepresjonowana. Spływ wód powierzchniowych odbywa się w kierunku północnym do Zalewu Wiślanego. Przestrzeń Żuław Elbląskich w znacznej części utrzymywana jest dzięki zabiegom wodno-melioracyjnym.

Użytkowe znaczenie dla zaopatrzenia w wodę pitną i na potrzeby gospodarcze mają dwa poziomy wodonośne: plejstoceńsko-holoceński — w piaszczystych utworach czwartorzędu i różnowiekowy — obejmujący najstarsze ogniwa plejstocenu, piaszczyste osady trzeciorzędu i węglanowo-krzemionkowe utwory kredy górnej. Żuławy Elbląskie są zasilane przede wszystkim poprzez dopływ boczny z otaczających je wysoczyzn.

Czynnikiem w znacznym stopniu ograniczającym zasoby wód podziemnych jest ich jakość. Wielkość zasobów dyspozycyjnych, ustalona na podstawie badań modelowych, wynosi: dla poziomu plejstoceńsko-holoceńskiego 24 000 m^3/d i dla poziomu różnowiekowego 38 400 m^3/d.