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Groundwater flow modelling of main groundwater reservoirs in the Gdańsk region, Poland

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Abstract

During the last nine years, the 133 main groundwater reservoirs in Poland (MGR) have been documented; these were published last year. Some of these are situated in the coastal zone of the southern Baltic Sea. MGR numbers 111 and 112 are in the Gdańsk area and are discussed in the present paper. The study area is situated on the border region of the moraine plateau of the Cashubian Lakeland, the western part of the Vistula River delta plain and the Bay of Gdańsk. The area of the main groundwater reservoir in no. 112 is developed in Quaternary strata and referred to as Żuławy Gdańskie; it comprises predominantly the city of Gdańsk and slightly exceeds 100 km^2. There is also a Cretaceous aquifer, rich in groundwater resources, which is named MGR no. 111, beneath the Quaternary reservoir mentioned above. The area studied and modelled totalled 364 km^2, on account of the hydraulic connection between these aquifers. Methods of hydrogeological research, groundwater flow simulations, resources calculation are outlined in the present paper.

Key words: groundwater flow model, vertical circulation of groundwater

1. Introduction

The Main Groundwater Reservoirs (MGR) numbers 111 (Gdańsk Upper Cretaceous subbasin) and 112 (Żuławy Gdańskie) are located in the Pomeranian Voivodeship and in the area of the agglomeration of Gdańsk and, in part, of the Cashubian Lake District. MGR no. 111 was delimited in the Upper Cretaceous aquifer which occurs beneath the Cenozoic deposits at a depth of approximately 100 m at Gdańsk and a depth of more than 300 m in the frontal moraine belt in the southwestern part of the Lakeland upland. The area of the Vistula Delta measures 1,630 km^2, according to 1996 documentation (Kreczko et al., 1996). As a result of verification of the boundaries, the area of MGR no. 112 has been changed and now amounts to 100.4 km^2, while the study area covered a surface of 363.8 km^2 (Fig. 1).

A distinctive morphological form is seen within the agglomeration of Gdańsk. The flat surface of the Seaside Terrace and Gdańsk delta plain is contrasted with the moraine uplands of the Cashubian Lake District that spread towards the west. The morphological edge of this unit is clearly marked, reaching up to 70 m a.s.l. The Seaside Terrace with systems of inflow cones and denudative forms marked on the surface is situated along the eastern border of the Cashubian Lakeland. The third morphological unit that occurs within the agglomeration of Gdańsk is the Vistula River delta plain, named Żuławy, where in many places coastal depressions are seen. It covers part of Gdańsk and is a flat accumulation plain with surface ordinates ranging between –1 and 12 m a.s.l. A few streams (amongst others: Oliwski Stream and Strzyża Stream) flow from the marginal zone of the Cashubian Lake District through the Terrace area.

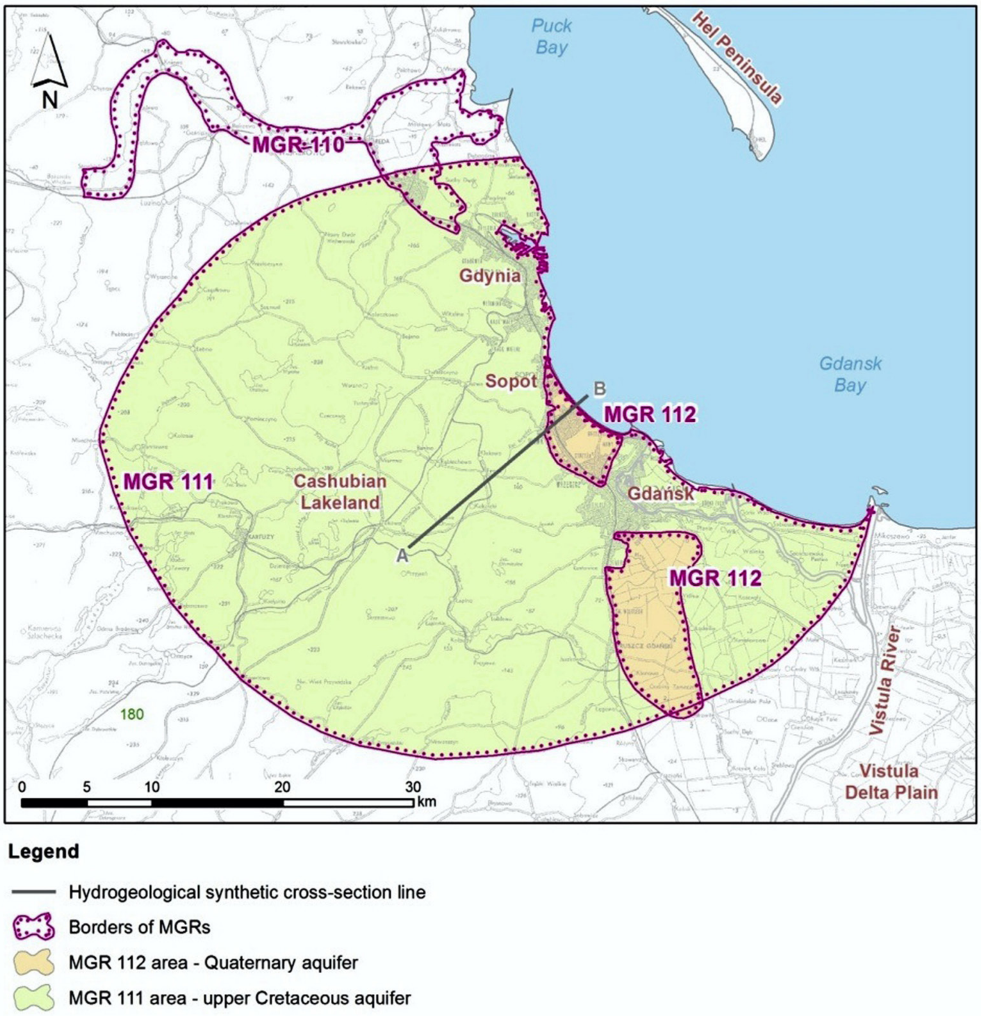

Fig. 1. Location of MGRs in the Gdańsk region, northeast Poland.

The southern part of MGR no. 112 is located in Żuławy Gdańskie. In the east it is bounded by the Vistula River bed and in the west by the margin of the moraine plateau of the Lakeland. It is a flat plain, with elevation close to sea level and local depressions, where water level is maintained through a system of drainage ditches and pumping stations.

2. Recognition of geological and hydrogeological conditions

The area of the above-mentioned MGRs is covered in rich cartographic materials related to geological and hydrogeological research and field studies. The basic knowledge of the geological structure and the occurrence of groundwater and resource calculation is provided by the sheet of the Geological Map of Poland 1:200,000 and the same map (scale 1:50,000) elaborated in 1998. Sheets of the Hydrogeological Map of Poland 1:50,000 were published a year earlier (Pikies & Zaleszkiewicz, 2013). There are other maps of this area such as the Geology-Economical Map of Poland 1:50,000, developed by Polish Geological Institute (PGI) and the Hydrographic Map of Poland 1:50,000, produced by the Head Office of Geodesy and Cartography (GUGiK). In 2001 documentation of available groundwater resources of the Vistula River delta and of the Vistula Spit (Kreczko et al., 2000) was approved by the Ministerial Hydrogeological Commission (KDH) and developed by the PGI Marine Branch and the Hydrological Company, both at Gdańsk.

Hydrogeological documentation of the Gdańsk Upper Cretaceous subbasin resources was already published in 1995 and approved in 1996 (Kreczko et al., 1996). The surface area of this subbasin is 1,630 km^2. On account of thickness of poorly permeable strata in this geological sequence, no protection zone has been designated for this MGR. In the Upper Cretaceous deposits, groundwater occurs mainly in the sandy series; the porous reservoir. Locally, at the top of Mesozoic strata, groundwater was also demonstrated in a fissure reservoir of Cretaceous limestones and marls. Over a century of groundwater exploitation (wells) of this reservoir has permitted documentation of good chemical water quality of the HCO_3-Ca-Na type. The total dissolved solids (TDS) of this water amount to about 0.5 g/l and the mean value of pH equals 7.5. This pH value of groundwater helps leaching fluorine-rich apatite as noted at the top of the Upper Cretaceous and Paleogene strata of marine origin, which explain positive anomalies of fluoride in the southern part of the Vistula River delta. Below the Cretaceous silt and loam series, there are brackish and salt waters in Jurassic strata.

The main recharge area of the Gdańsk Upper Cretaceous subbasin occurs in the western part of MGR no. 111 on the Cashubian Lakeland, while the discharge zone includes the area of the Seaside Terrace and the Vistula River delta plain at Gdańsk. The margin of the Lakeland upland belongs to discharge zone and from this place groundwater flows directly into the Bay of Gdańsk and is, in part, drained by numerous valleys of streams and ditches.

The limits of MGR no. 112 and its protection area at Gdańsk have been defined in detail in a hydrogeological elaboration by Szelewicka et al. (2015). The most important criterion for determining the limits of this reservoir was the quality of groundwater and the risk of salt water encroachment to the Quaternary aquifer from the Dead Vistula at Gdańsk and from the Gulf of Gdańsk. The area of changes identified in the water quality in the central part of the study area was so extensive that it was necessary to divide the reservoir into two parts: a northern one (mainly the Seaside Terrace) and a southern, i.e., the western part of the Vistula River delta (Burzyński et al., 1999; Szelewicka & Kordalski, 2013). However, in the southern part of MGR no. 112, near the village of Suchy Dąb, a large concentration of fluoride ion was found in groundwater drawn from the limestone and marls aquifer that belongs to the Upper Cretaceous, as well as from the overlying Quaternary aquifer. This area was also excluded from the reservoir area.

3. Sketch of the geological structure of the study area

The structure and origin of the sea shore are related to the last glacial period (end of the Pleistocene and beginning of the Holocene), when the Baltic Sea developed. Similarly to the Cashubian Lake District, the coastal zone is composed of Quaternary strata on the surface, such as glacial tills, boulders and coarse-grained sands, clays and sands of cattle hole sediments and crevice-glacial accumulation. Mio-

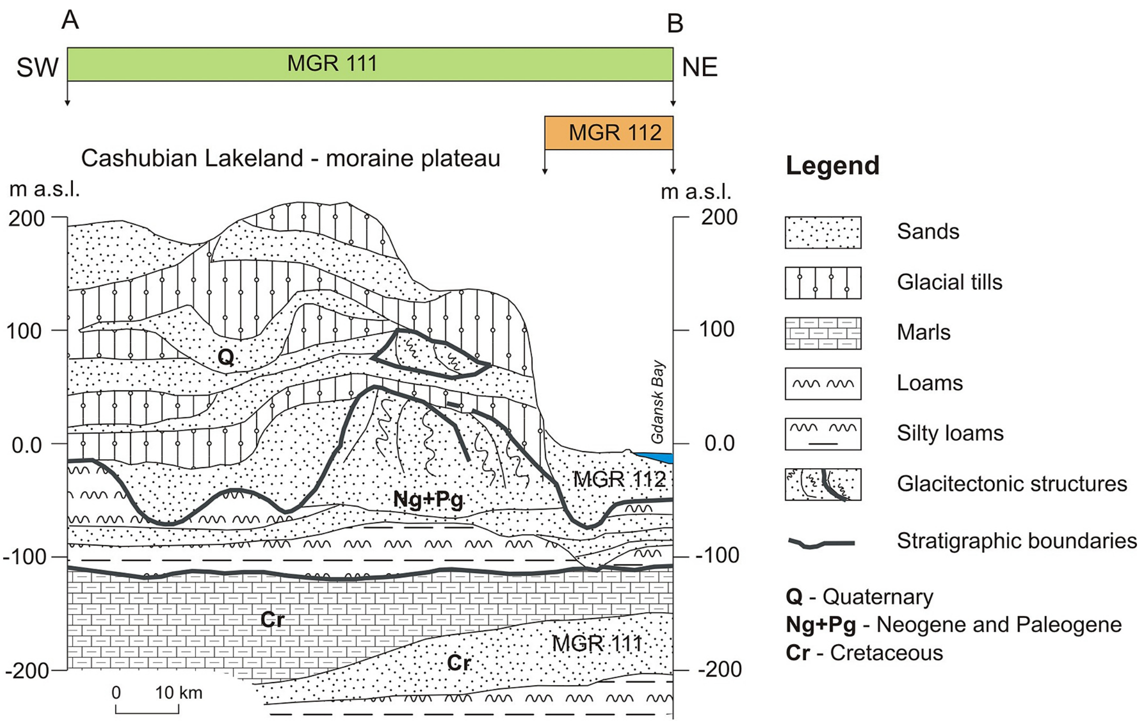

Fig. 2. Synthetic hydrogeological cross section of the Gdańsk region; the cross section line is shown in Figure 1.

cene sands and loams appear in small places on the surface of the Lakeland upland; locally, these are found in glacial floats entrapped amongst Pleistocene strata. A layout of Pleistocene, Neogene, Paleogene and Upper Cretaceous strata is shown in the synthetic hydrogeological cross section of Figure 2.

Miocene sands, silts and muds are of terrestrial origin, and are completely destroyed in the Vistula River delta plain and strongly reduced by glacial erosional processes during advance of the Scandinavian ice sheets and also during long interglacial periods. However, Paleogene deposits are of marine origin, analogous to the Upper Cretaceous, and contain glauconite – and fluorine-rich apatite.

4. Hydrogeological conditions

Fresh groundwater is found mainly in Quaternary, Miocene and Oligocene formations and these resources are exploited in municipal water works of the Gdańsk region. Moreover, fresh groundwater occurs in Upper Cretaceous aquifers at a depth of several hundred metres. Detailed characteristics of MGR no. 111 and 112 were published in a reference book of the Polish Hydrogeological Survey last year (Mikołajków & Sadurski, 2017).

Conditions of occurrence and circulation of groundwater in the coastal areas show specific features that distinguish them from other hydrogeological regions in the country. The sea is a regional drainage base for all aquifers and groundwater flow systems. Along the shoreline, there is also contact of salt sea water with fresh groundwater that flows from the inland. These waters remain in a state of natural balance which, when violated, results in quick and undesirable effects, manifested by an increase in chloride ion concentrations and, consequently, degradation of fresh water resources (Burzyński et al., 1999). For the Vistula River delta at Gdańsk, the geological structure of sediments lying at the top of the aquifer is characteristic. These are loams, silty fine-grained sands and peats of Holocene age, as documented in descriptions of geological logs of wells. The thickness of the Holocene strata does not exceed a few metres in the southern part of the Vistula River delta, but exceeds 30 m in the northern zone of that delta. A characteristic feature in this zone is that these fine-grained sands are rich in organic matter. Holocene strata directly overlie Pleistocene sands and create a common Pleistocene-Holocene aquifer. In places, silts and loams are found directly on Pleistocene sands that create aquifer. Glacial tills from older glaciations, occurring in the study area, constitute a conventional boundary that divides the Quaternary aquifer into two layers, an upper and a lower. They do not show a continuous distribution due to hydrogeological windows, as a consequence of glacial erosional processes. Therefore, in many places the upper and lower layers are combined and form a common Quaternary aquifer with a thickness between 40 and up to 70 m in a buried valley structure, e.g., along the western border of the Vistula River delta, where the higher levels of Neogene and Paleogene age were eroded (Szelewicka & Kordalski, 2013). The Cretaceous aquifer belongs to the regional groundwater circulation system, extending from the recharge area on the Cashubian Lakeland to the Seaside Terrace and Vistula River delta plain at Gdańsk.

The Cretaceous aquifer is well recognised in the Gdańsk area; it was widely used for water supply during the last century. A significant reduction in water well exploitation, screened in this aquifer caused a return of the hydraulic head to its state in recent years. This is observed at present in the coastal belt and close to the Dead Vistula River.

5. Hydrogeological regime in the coastal zone

Closer to the shoreline, a stronger impact of the Baltic Sea on climate and on the state of the water table, but a decrease in the impact of land is observed (Kordalski, 2013). Factors affecting groundwater conditions here are changes in atmospheric pressure and storm surges. Damming or lowering of sea level throughout the year ranges between –1 and +1 m a.s.l. in relation to the mean annual value. In the delta plain, low water levels or floods caused by the Vistula River and its tributaries, as well as drainage ditches on polders, have a marked impact on the groundwater table.

The hydrogeological regime of groundwater additionally complicates the multi-level aquifer system (Kozerski, 2007). In addition to the Quaternary aquifer beneath the surface there are deeper-lying aquifers of Miocene, Oligocene and Cretaceous age.

6. Conceptual model of the study area

For the construction of the numerical model of groundwater flow it is necessary to know the extent and thickness of the aquifers and of strata separating them, hydrogeological parameters of these layers, the intensity of water flow on the boundary of the model, the states of surface and groundwater in the area of the model and its balance sheet area. It

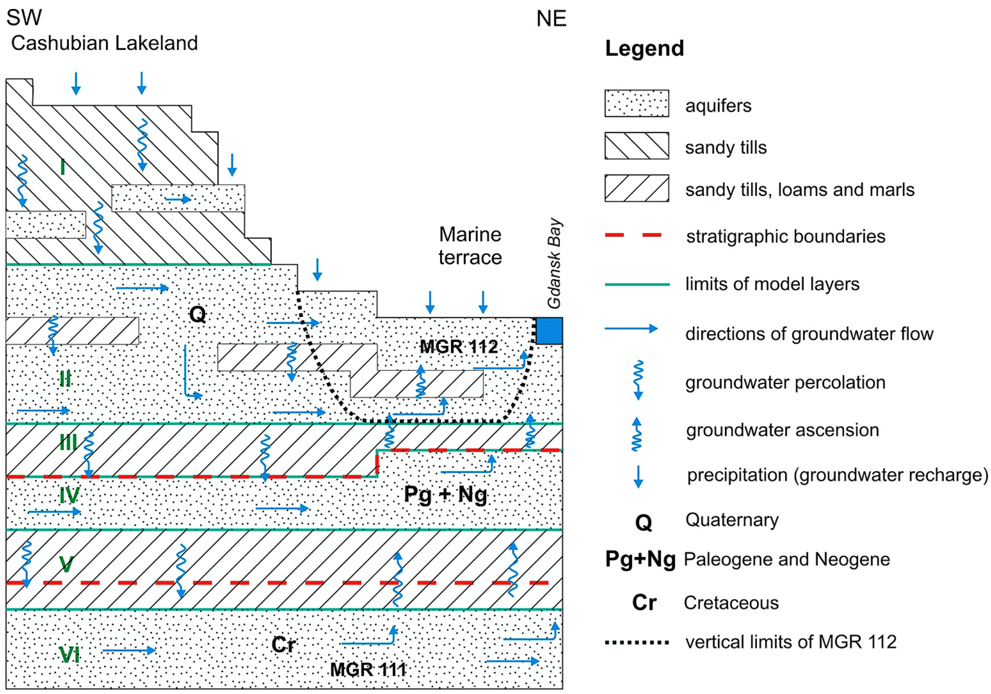

Fig. 3. Conceptual model of the groundwater flow system in the Gdańsk area.

is also necessary to determine circulation groundwater systems in the vertical sections, groundwater abstraction and hydraulic head in the wells and water well fields.

A sketch of the conceptual model is given in Figure 3. Water-bearing layers, weakly permeable layers, their range and flow directions, as well as seepage of groundwater have been marked on it. The choice of the area subjected to detailed model tests was significantly influenced by specific hydrogeological conditions that distinguish the Gdańsk and Sopot area from other regions of the Baltic coastal zone. Ground waters occur at shallow depths below the surface, whereas sandy, sand and gravelly strata predominate at the surface. This situation leads to increased infiltration of rainwater and recharge of the aquifers. As a result, aquifers are not isolated from anthropogenic hazards. This situation is reflected in the vulnerability of aquifers to pollution. An additional factor that threatens groundwater is the proximity of salt waters of the Gulf of Gdańsk (Kordalski, 2013). Brackish water can migrate to intensively exploited aquifers and disturb the hydrodynamic equilibrium between fresh and salt interface along the shore.

7. Software used for modelling

The program used to prepare the model of aquifers and to perform simulation calculations was the Groundwater Modelling System (GMS). GMS uses MODLOW code (McDonald & Harbaugh, 1996) for groundwater flow calculations and ZONE BUDGET code to calculate water balance. This software is an advanced graphic environment for modelling groundwater flows and the migration of pollution. GMS also has tools for model calibration – it was possible to optimise model parameters using PEST or UCODE programs automatically.

8. Hydrogeological scheme and boundary conditions

Based on the conceptual model adopted for modelling purposes, the entire aquifer of the study area has been schematised. The occurrence and lithology of the aquifers and mutual hydraulic relationships between low permeable layers and aquifers and circulation in groundwater systems have been included in the construction of the model. The impact on the hydraulic schematisation had also led to selection of a method of calculations, assuming three-dimensional parameterisation of space filtration. In the process of aquifer aggregation, flow directions of groundwater and differences of hydraulic head were taken into account. Six model layers have been distinguished for the simulation of groundwater flow:

– Layer I – the upper Quaternary level, in which the groundwater flow was simulated in the plateau area of the Cashubian Lake District. It consists mainly of sands, sandy tills and gravels of inlet cones. This layer occurs on the plateau of the lake district and its marginal zone.

- Layer II – the main Quaternary aquifer. It was deposited in the form of fluvioglacial sands and Pleistocene gravels. Locally, this aquifer includes also sandy sediments of the delta series, aeolian and marine sands accumulated during the Holocene. This aquifer is substantial for the Gdańsk water supply and municipal water work construction (Kozerski, 2007). It is the richest aquifer of MGR no. 112.
- Layer III – low permeable sediments, comprising silt, loams and glacial tills, which separate the Quaternary aquifer from the Paleogene and Neogene ones. It separates locally also the Quaternary aquifer at depth in buried valley structures.
- Layer IV – situated low in the section in the Quaternary aquifer and Paleogene and Neogene aquifers. They have essential significance from the point of view of lateral groundwater flow and ascension recharge of MGR no. 112.
- Layer V – combines semi-permeable strata that separate the Quaternary and Paleogene aquifer from a water-bearing series occurring at the top of the Upper Cretaceous. It comprises low-permeable sediments such as limestones and marls at the top of the Mesozoic sequence.
- Layer VI – modelled as water-bearing deposits of the Upper Cretaceous, developed mainly as quartz sand with glauconite; the main aquifer of MGR no. 111.

The study area delimited for groundwater flow model simulations contains portions of the cities of Gdańsk and Sopot and the commune of Pruszcz Gdański. This area was divided into computing blocks with a dimension of 200 x 200 m, containing 124 columns and 153 rows (18,972 blocks per layer and 113,832 blocks in total). In the calculation process 53,801 blocks were involved. Other, inactive, blocks were used in the procedure of data input. This means that the modelling area covered a surface of 363.8 km^2. The adopted discretisation of the groundwater flow system was completely sufficient for schematic mapping of hydrogeological conditions, model construction and acceptable boundary conditions.

The external boundary conditions of the groundwater flow model were based on the contractual beginning of the marginal zone of the moraine plateau, the Baltic shoreline, the Dead Vistula River and the current flux of groundwater from the plateau towards the sea. The boundary conditions of the 1st type (*Constant Head Boundary*) were assigned in all layers along the western boundary of the model. In addition, in layers I, II, V and VI, with condition of type I, the discharge of groundwater to the sea and the Dead Vistula River was simulated. The segment of the model boundary along the flow line (groundwater watershed) was assigned to the second type boundary without flux (*No Flux Boundary*). The boundary conditions of type III were assigned to the remaining boundaries of layers I–VI as *General Head Boundary*. The boundary conditions of the 1st and 3rd type were determined on those segments where a flow beyond the model limits or an inflow from outside of the area of model was found. The exploitation wells and recharge of the first or second model layer were simulated by the condition type II (*Well*, *Recharge*).

9. Model identification

The effect related to the model identification should be recognised as satisfactory and in the area of MGR no.112 highly so. The average absolute error for all points of the observation network amounted to 0.64 m. The calculated and observed depth of the groundwater table differed for more than 2 m only in the case of two points located in the Cashubian Lake District, the moraine upland beyond the area of MGR no. 112. Differences were probably caused by way of layer I of the model secretion. Inside this MGR area differences do not exceed 1 m.

Results of calculations after corrections were sufficiently convergent with archive data and those obtained via numerical model simulation. The procedure checking the principality of the model ended the process of their identification. The mathematical model of groundwater flow obtained was sufficiently reliable and became the basis for groundwater resource estimation and delineation of the protection area of MGR no. 112.

10. Results of numerical simulations

Modelling research allowed to determine groundwater flow conditions in the area of MGR no. 112, with a subdivision into a northern and a southern part of the reservoir. Assuming the groundwater well exploitation (1,496 m^3/h) of model layer II (richest in water resources), values of components of groundwater balance were obtained (Table 1). The inflow due to ascension from Cretaceous aquifers, i.e., from MGR no. 111, was taken into account. The piezometric contour lines obtained sep-

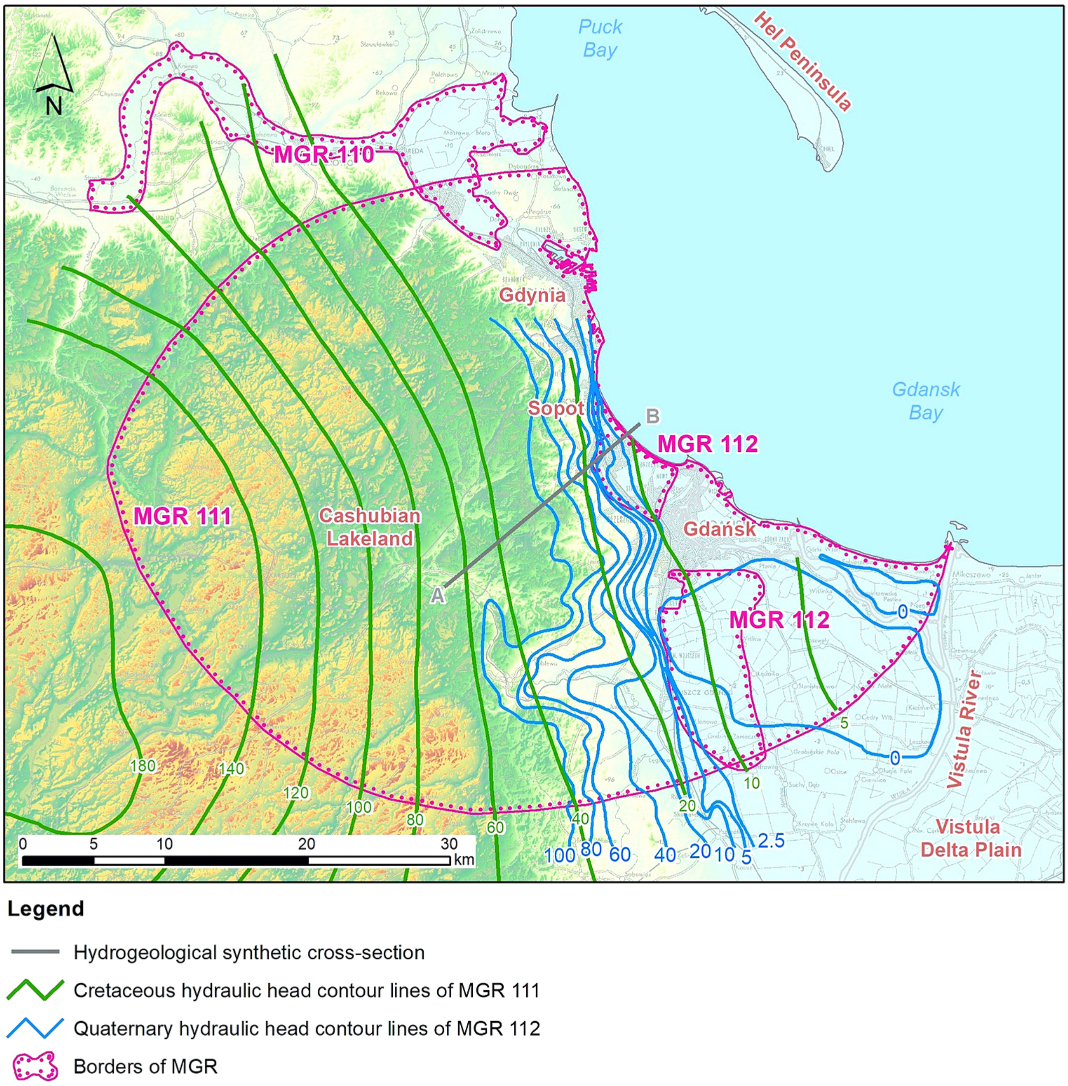

Fig. 4. Calculated piezometric contour lines obtained in the groundwater flow model for Quaternary and Cretaceous aquifers in the Gdańsk area.

Table 1. Groundwater balance sheet components of MGR no. 112.

Components	MGR no. 112 (II model layer)		
	Northern part	Southern part	Total
	Inflow (m³/d)		
Recharge	14915	–	14915
Infiltration from rivers	–	143	143
Inflow from I layer	–	14863	14863
Lateral inflow	39187	12262	51449
Inflow from III layer	6744	11616	18360
Sum	60846	38884	99730 (4155 m^3/h)
	Outflow (m³/d)		
Wells	20800	14270	35070
Rivers and ditches	28	18220	18248
Outflow to I layer	–	3974	3974
Lateral outflow	40018	2297	42315
Outflow to III layer	–	123	123
Sum	60846	38884	99730 (4155 m^3/h)

arately for Quaternary and Cretaceous aquifers and marked by different colours are shown in Figure 4.

The main reservoir layer of MGR no.112 is mainly recharged laterally from the west, from the moraine upland of the Cashubian Lake District (52 per cent). Direct effective infiltration of rainfall precipitation into this layer takes place only in the northern part, e.g., on the Seaside Terrace, where the 1st model layer does not occur and accounts for about 15 per cent of the balance sum in total. The southern part of this MGR is recharged by rainfall precipitation and then through layer I, which in the area of the Vistula River delta consists of sandy loam. The percolation from layer I to the main aquifer of MGR no. 112 is less than 15 per cent of the balance sum in total. The inflow, due to ascension, from more deeply situated levels (Cretaceous aquifer), which can be identified from MGR no. 111, is about 18 per cent.

The total groundwater flow rate through the aquifer system analysed is 223,362 m^3/d during groundwater exploitation. The main factor affecting water resources of MGR no. 112 is the lateral inflow from the side of the Cashubian Lake District and amounts to 61 per cent of the balance sheet in total. An important role in the recharge of the aquifers is effective infiltration caused by atmospheric precipitation – about 39 per cent, while inflows from surface water courses in the aquifer are negligibly small. The outflow side of the water balance equation is dominated by groundwater outflow, mainly to the Baltic Sea in the value of *c*. 45 per cent and significant groundwater exploitation on the water wells, up to 29 per cent. Drainage through rivers and ditches accounts for 26 per cent of the balance sheet in total.

11. Summary

During numerical simulations of groundwater flow and assessment of groundwater resources, vertical flows between aquifers of the MGR 112 and 111 reservoirs were considered. It reflects the hydrodynamics of the Gdańsk hydrogeological system (Kozerski, 2007). The estimated renewable groundwater resources determined by flow modelling simulation of MGR no. 112 are 4,155 m^3/h. Available groundwater resources were estimated as 2,701 m^3/h, which is about 65 per cent of the amount of renewable resources. Due to the risk of deterioration of water quality in the Seaside Terrace area, these reserves are better accessible in the southern part of the reservoir, e.g., in the Lipce well field.

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