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A groundwater flow model for the Wolin Island area, including glaciotectonic deformation

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Abstract

During the construction of mathematical models for mapping hydrogeological conditions it is necessary to apply simplifications, both in the geological structure and in hydrogeological parameters used. The present note discusses problems surrounding the mapping of glaciotectonic disturbances that occur in the northern part of Wolin Island (northwest Poland). For this part of the island, a direct outflow of groundwater towards the Baltic Sea basin has been determined on the basis of geophysical survey results. An important feature in the hydrogeological conditions here is the isolation of groundwater from both the Baltic Sea and Szczecin Lagoon by clay with a Cretaceous xenolith. Such a geological structure explains the presence of perched water at considerable heights in zones close to the cliffs, without any significant hydraulic connection with surrounding reservoirs. Hydrogeological conditions of Wolin Island have been modelled using the Visual MODFLOW package v.4.2. In the vertical section, these conditions can be simplified to one aquifer (Pleistocene-Holocene), in which two aquifers can be distinguished. In a large part of the island, these remain in mutual hydraulic contact: layer I – upper, with an unconfined aquifer, and layer II – lower, with a confined aquifer, locally an unconfined one. The schematisation of hydrogeological conditions adopted here has allowed to reproduce present groundwater dynamics in the study area.

Key words: GIS, groundwater modeling, groundwater exploitation, coastal hydrogeology, southern Baltic Sea coast

1. Introduction

The study area is situated in the northwestern part of the voivodeship of West Pomerania, and comprises the territory of the county of Kamień Pomorski and the communes of Wolin and Międzyzdroje (Fig. 1). According to the regional groundwater division by Paczyński & Sadurski (2007), the study area is located within the hydrogeological unit of the province of the Baltic Coast in the West Pomeranian region and belongs to MGR no. 102, a main groundwater reservoir.

Wolin Island is surrounded by two large bodies of water, i.e., the Baltic Sea in the north and Szczecin Lagoon in the south. The eastern and western borders of the island are formed by waters that flow from Szczecin Lagoon into the Baltic Sea; in the east it is marked by the Dziwna River, in the west by the Świna River. The surface water of Wolin Island comprises a system of canals and drainage ditches, mainly in the central and eastern regions of the island, as well as a system of drainage lakes in the eastern part, from which water flows into Kamień Lagoon via the Lewiński Stream.

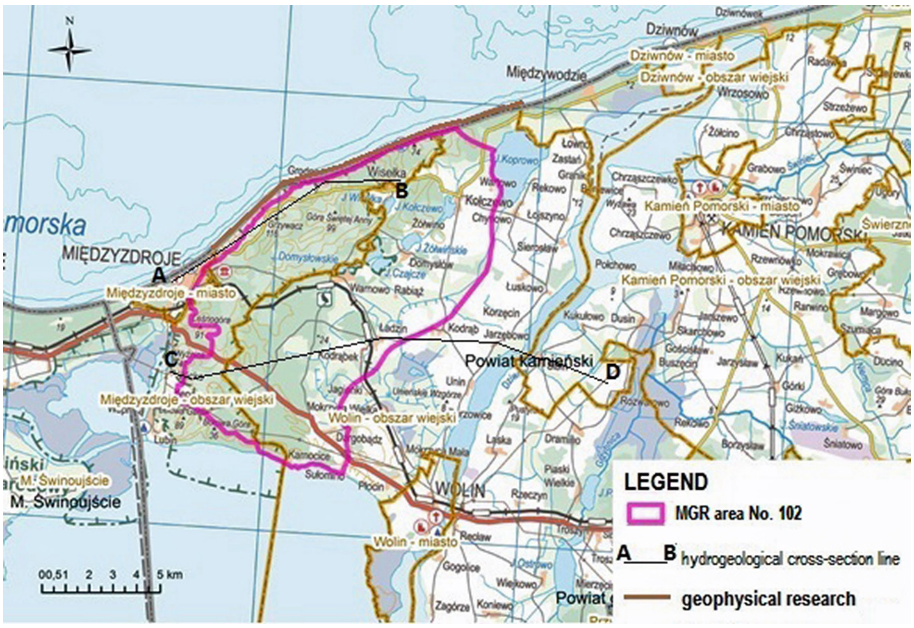

Fig. 1. The Main Groundwater Reservoir (MGR) no. 102 (Wolin Island).

2. Geological and hydrogeological outline

2.1. Geological structure

Superficial strata across the entire island comprise almost exclusively Quaternary formations; in fact, it has been claimed that the occurrence of older deposits is rather problematic. These Quaternary strata, formed in glacial, fluvioglacial and lacustrine settings, rest directly on Mesozoic level; only locally, in the southwestern part of the island are Paleogene and Neogene deposits found. Marine, fluvio-marine, aeolian and organic deposits have been categorised as formations of a Holocene date. Lithological features of these formations are incredibly diverse, being connected to their chronostratigraphical origin.

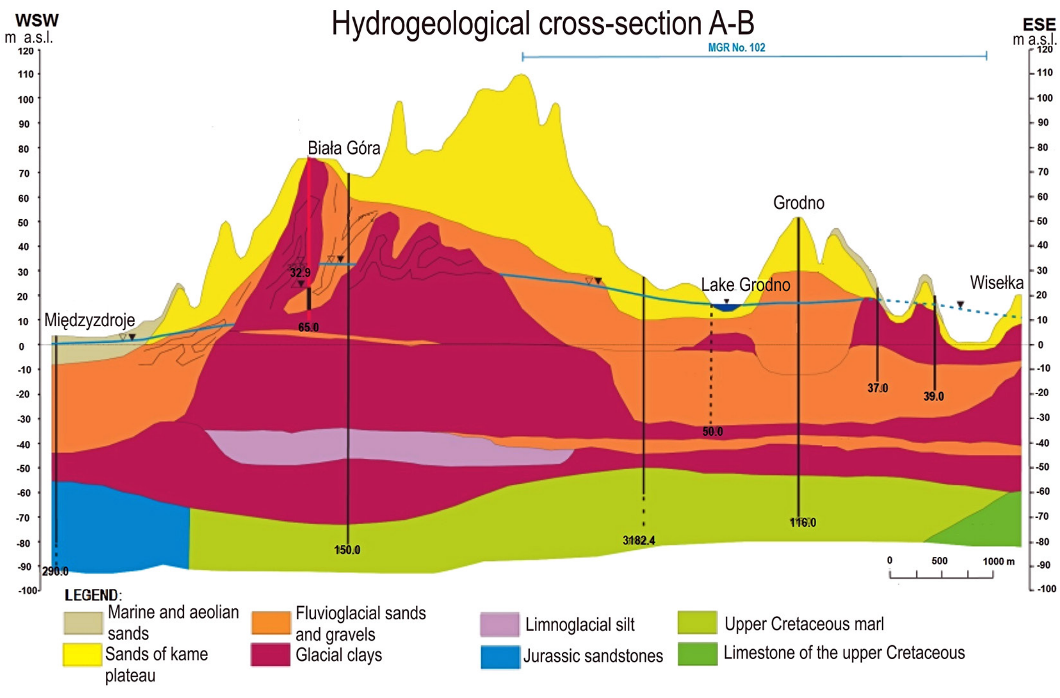

Fig. 2. Hydrogeological cross section across Wolin Island from Biała Góra to Grodno (after Wiśniowski, 2012).

Upper Pleistocene formations of the last glaciation prevail in Wolin Island; the following glacial levels have been documented: strata assigned to the Elsterian and Vistulian glaciations near the surface rest on levels dated as the Holstein interglacial. These levels are comprised mainly of fine-grained sands with gravels, with cobbles and boulders; silts, tills, dusts and dammed clays occur locally. The thickness of these Quaternary sediments varies, the maximum thickness of 140 metres having been recorded on the kame plateau in the northern (Grodno-Wisełka area) and northwestern parts (Biała Góra-Międzyzdroje area) of this island (Fig. 2). This is connected to the morphology of this area and the sub-Cenozoic relief. A slightly lesser thickness has been recorded in the southeastern part of the island, in the vicinity of the town of Wolin. Fluvioglacial sands and gravels with cobbles form a level of variable grain sizes; coarser deposits with gravel and cobbles can also occur in the form of a panel on moraine sediments. Fluvioglacial sediments were probably formed under different conditions during the retreat of the continental ice sheet. Amongst these, outwash sand covers can be found, as well as deposits that formed under conditions of stagnant or dead ice and in ice sheet fractures.

The youngest levels, of Holocene age, play a significant role in the geological structure of the study area, and include marine, fluvial and fluvio-marine sediments, aeolian and organogenic sediments as well as muds of diverse structure and grain size. The Holocene levels fill numerous closed drainage depressions, beds and shores of overgrown lakes, banks of the River Dźwina, river valleys and intra-dune lows. These strata also occur in the form of dunes. The thickness of these formations is rather limited, ranging from one to several metres. However, in the case of dunes, it may exceed ten metres.

2.2. Hydrogeological conditions

In the proximity of cliff zones, the geological structure explains the presence of perched water at considerable depths, without any significant hydraulic connection with surrounding water bodies. This is well documented on the hydroisohypse sheets of the Hydrogeological Map of Poland (scale 1:50,000; Międzyzdroje and Wolin; see Matkowska, 1990, 1997a, 1997b). The geological structure and hydrogeological conditions in the Wolin cliff zone are illustrated in a hydrogeological cross section (Fig. 3).

Near the coast of the Baltic Sea and in the cliff zone of Szczecin Lagoon in the southern part of the island, the groundwater table is located quite high, as a result of hindered outflow in the direction of surface water reservoirs. The occurrence of a peak piezometric surface has been recorded in the Biała Góra area (formerly Janogród) and at Grodno (33.5 m a.s.l.).

The main directions of the groundwater flow in Wolin Island result from flow systems that are recharged on the hills and discharged by ditches and swamps and water drainage by the Lewiński Stream, as well as a system of drainage channels (Ładziński and Mokrzycki channels) used by the pumping station at Darzowice.

The water-bearing horizon occurs mainly within Quaternary strata at a depth between 20 to 80 metres. The lower aquifers in the Pleistocene strata are

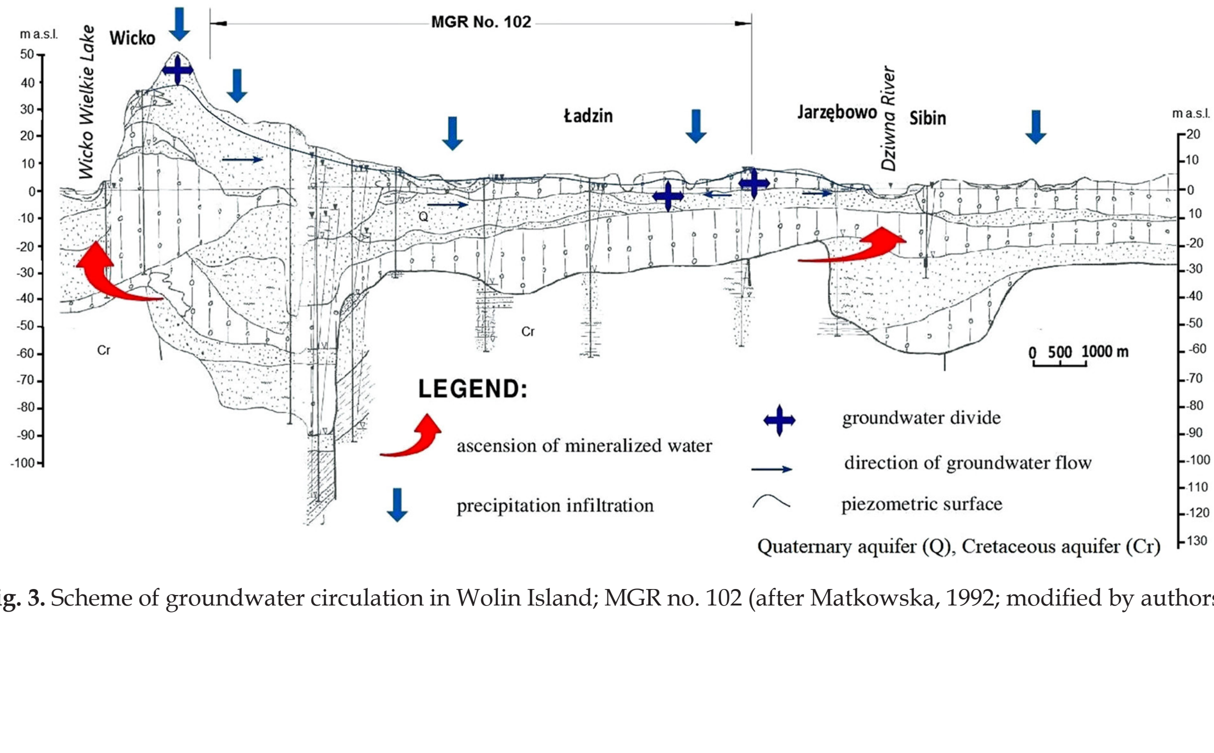

Fig. 3. Scheme of groundwater circulation in Wolin Island; MGR no. 102 (after Matkowska, 1992; modified by authors).

separated from the multi-aquifer formation in the Mesozoic layers by a discrete layer of boulder clays which have their origin in earlier glaciations.

2.3. Aquifers in the study area

In this area both local and regional groundwater circulation systems can be identified. The former are connected with gravity-driven flow to lakes in the northeastern part of the island, as well as to depressions occupied by peat plains. These systems most frequently include aquifers which occur at shallow depths below the surface and which have an unconfined groundwater table. On a regional basis, groundwater flow lines within the hydrogeological system of Wolin Island are of a radial character. The outflow in the regional aquifer system is perturbed due to the occurrence of moraine strata that had previously been glaciotectonically disturbed (Wolin terminal moraine), which impedes water runoff in northwesterly, westerly and southwesterly directions. Research conducted along the seashore, using electrical resistivity tomography, has confirmed that quantitatively substantial groundwater outflow into the Baltic Sea occurs to the east of Grodno (Kłyza, 1988; Kucharski & Tkaczyk, 1997; Mieszkowski, 2015). The most important elements of the aquifer system in the study area are presented in condensed form below.

The groundwater level and upper interclay level occur across the entire study area. These levels are separated by clays, the thickness of which ranges from several to over a dozen metres. In hydrogeological windows they create a single level in mutual hydraulic connectivity. Their thickness ranges from several to 40 metres, whereas their transmissivity (T) amounts to 10–20 m^2/h. The aquifer generally is unconfined, except in some places where it is confined. Aquifer recharge occurs by means of direct rainwater infiltration into the shallower aquifer, whereas in deeper aquifer seepage from the first aquifer occurs.

For the purpose of schematisation of hydrogeological conditions, results of research conducted by means of the following methods have been used:

- geoelectrical resistivity tomography,
- hydrogeological mapping,
- laboratory isotopic tests: $^{16}O/^{18}O$, $^{32}S/^{34}S$,$^{1}H/^{2}H$, and chemical tests of water composition.

Geoelectric cross sections, produced on the basis of results from geoelectrical resistivity sounding, has provided data on sites of freshwater runoff from the plateau into the sea. The runoff occurs in those zones that offer favourable conditions in terms of water conductivity and flow. In the cliff zone, the runoff is blocked over a substantial length by poorly permeable glaciotectonically disturbed strata, which formed the cliff. The zones in question are shown in Figure 2.

One of the most important elements in the construction of the model was to determine land development of the study area in order to allocate effective infiltration to model's blocks. Wolin Island is primarily agricultural and has a touristic and spa natural values. The western and central parts of the island are overgrown with forests, while the eastern part has an agricultural character.

These data of land cover, according to Corine Land Cover and surface geology, have been used to determine the value of effective infiltration. A similar recharge was implemented to the groundwater flow model elaborated by Gurwin & Krawiec (2010, 2012).

3. Groundwater flow model of Wolin Island

3.1. Boundary of modelling of the study area

The central part of Wolin Island can be divided into two sub-areas, which differ considerably from each other, in terms of location in the groundwater flow system:

- recharge zone – devoid of surface waters, covered by forests, having good infiltration conditions (area of Wolin Terminal Moraine – Dargobądz Plain, Mokratz Hills),
- discharge zone – morphological depressions, where groundwater is drained and flows out (Kodrąbek Depression, Wolin Lake District).

The central and eastern parts of the island comprise extensive wetland depressions with a complex system of channels and drainage ditches. This is a zone of intensive groundwater drainage, which includes the area of the Wolin Lake District, where the local water drainage is based on channels, drainage ditches and lakes.

3.2. Schematisation of the hydrostructural model and groundwater circulation

In the area of an unconfined groundwater table, below the surface, a vadose zone can be found, whereas in the area of a perched groundwater table, an insulating layer consisting of poorly permeable moraine clays, loams and peats is located.

The hydrogeological system of the study area creates a diversified model of aquifers – the Quaternary aquifer is constrained by its geological structure and glaciotectonic discontinuities in the area. Within Cretaceous and Jurassic strata, salt- and brackish water has been found, whereas fresh groundwater occurs only locally and lacks usable properties for water supply.

The water flow on a set level in the aquifer system of Wolin Island results from a balance between: the value of precipitation infiltration recharge, impact of surface-water fluctuations on the intensity of groundwater outflow in the drainage zones and the amount of exploitation of water intakes. The greatest changes in the water circulation system occur as a result of the exploitation of municipal groundwater intakes at Wolin and Międzyzdroje, as well as the impact of drainage systems connected with the Darzowice pumping station.

In the vertical section, the hydrogeological conditions of the island can be simplified to the occurrence of two aquifer levels, as described above. For a large proportion these levels of the island remain in mutual hydraulic connection.

In the moraine hill zone, due to the presence of the vadose zone, the thickness of which can locally reach even 50 metres, perched aquifers may occur. In this zone accumulations of glacial deposits and exceptionally high hydraulic gradients have been recorded, which can be explained by the occurrence of structural barriers in groundwater flows.

3.3. Discretisation of the study area and boundary conditions

The discretisation of the aquifer systems has been conducted by means of the Visual MODFLOW program, using a uniform orthogonal grid for all layers, consisting of a clearly defined number of computational blocks. In the area covered by the groundwater flow model there are 54,636 computational blocks. Each of the three model layers has been simulated by the same number of active computational blocks.

The boundaries of the model have been marked by the following water bodies: the rivers Świna and Dźwina, the Baltic Sea and Szczecin Lagoon. Hydrogeological parameters, as well as other information assigned to particular computational blocks, formed the input of tables of data, needed to conduct simulation calculations.

In terms of aquifer filtration properties, the values adopted are based on field pumping test results of wells, laboratory test results as well as literature data which especially refer to model layer II (Gurwin & Krawiec, 2012).

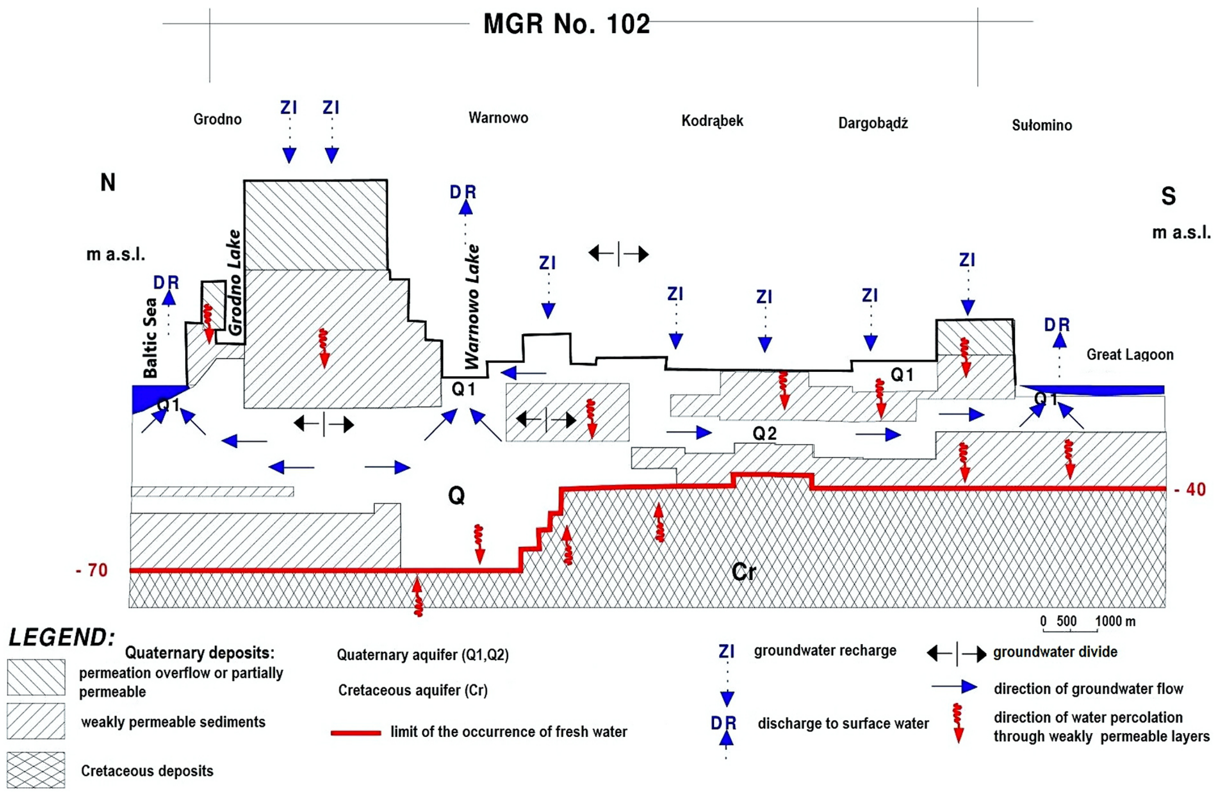

Fig. 4. Conceptual groundwater flow model of Wolin Island.

3.4. Division into layers

As already mentioned above, the existing groundwater circulation in the model area has been put in a suitable conceptual model to a three-layer system which constitutes a starting point for further work:

- layer I – permeable $Q_{h/p}$ – continuous, formed by Pleistocene and Holocene formations. The thickness of the near-surface layer $Q_{h/p}$, along with the vadose zone, ranges from 0 to 10 metres (mainly fine-grained sands occurring superficially in the island).
- layer II – poorly permeable $Q_{p/1}$ – discrete, formed by Pleistocene formations, the thickness of which does not exceed 10 metres (loams and clays). In the areas where the $Q_{p/1}$ layer does not occur, aquifer levels of thicknesses reaching up to 10 metres, have been simulated. The calculation programme requires the continuity of simulated layers within the entire model, as a consequence of which aquifer parameters have been

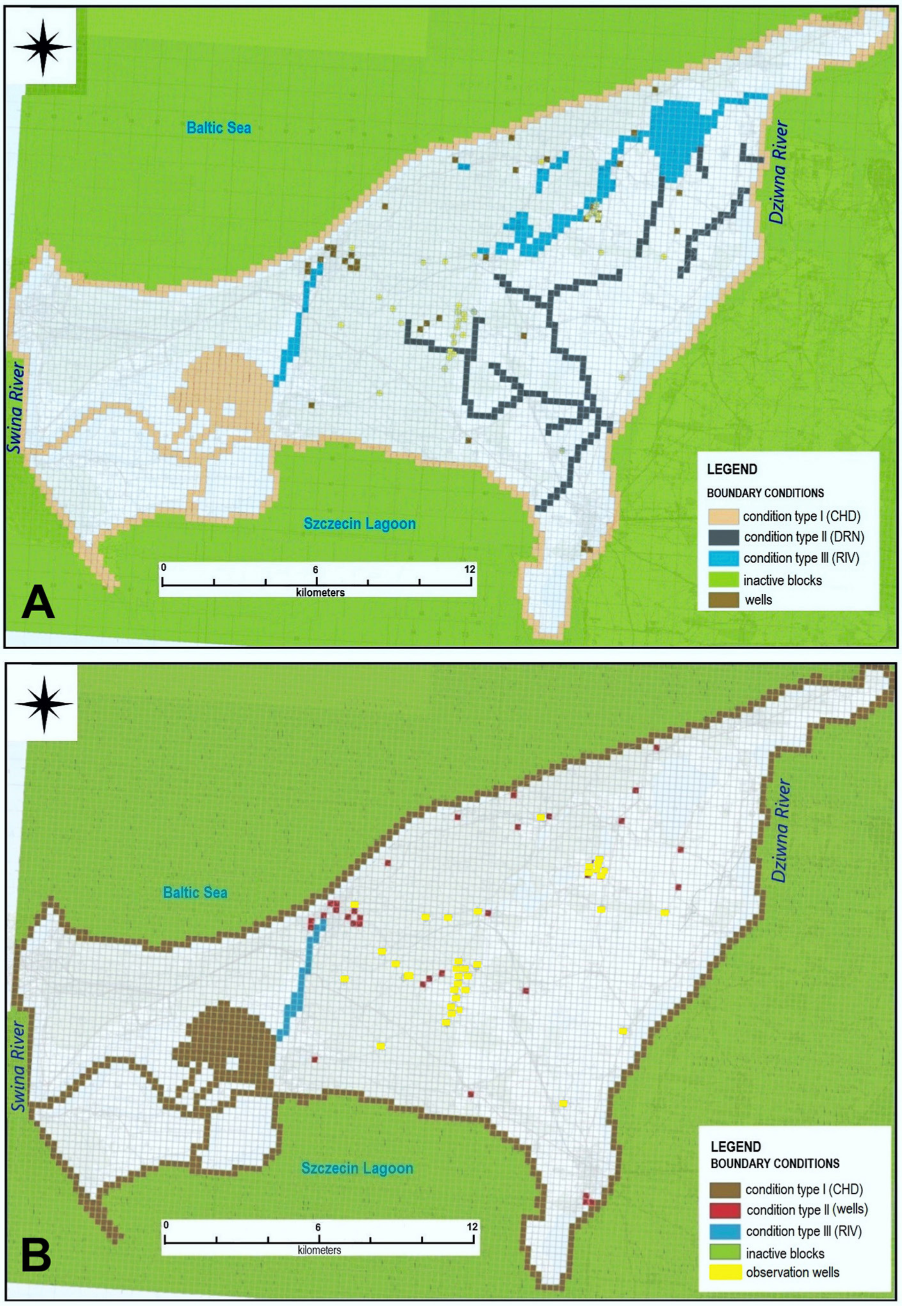

Fig. 5. Boundary conditions of the groundwater flow model: **A –** layer I; **B –** layer III.

simulated in areas where the $Q_{p/1}$ layer does not occur.

– layer III – aquifer $Q_{p/2}$ – continuous, formed by variously grained sands and gravel, the thickness of which locally exceeds 30 metres. These sediments cover clays, but locally can be found on top of Cretaceous strata.

The model comprises a geological section from a depth of 40.0 metres below sea level to over 70.0 metres on the kame plateau (Fig. 4).

3.5. Boundary conditions

In specific computational blocks, the ordinates of the groundwater table have been adopted, as calculated on the basis of measurement data from drilled wells and piezometers as well as surface-water level of water courses. In the model, boundary conditions have been applied (Fig. 5) as follows:

– first-type boundary condition – this condition has been applied to the border of two main surface-water reservoirs: the Baltic Sea and Szczecin Lagoon. The same boundary condition has been applied along the rivers Świna and Dźwina.

– second-type boundary condition – this boundary condition has been applied in order to simulate precipitation infiltration recharge into the first water-bearing aquifer layer as well as groundwater intakes exploiting aquifer layers of a specific capacity. This condition has also been applied to simulate drains in the northeastern and central parts of the model.

– third-type boundary condition – this boundary condition has been applied in simulations of lakes of the Wolin Lake District and of the Lewiński Stream.

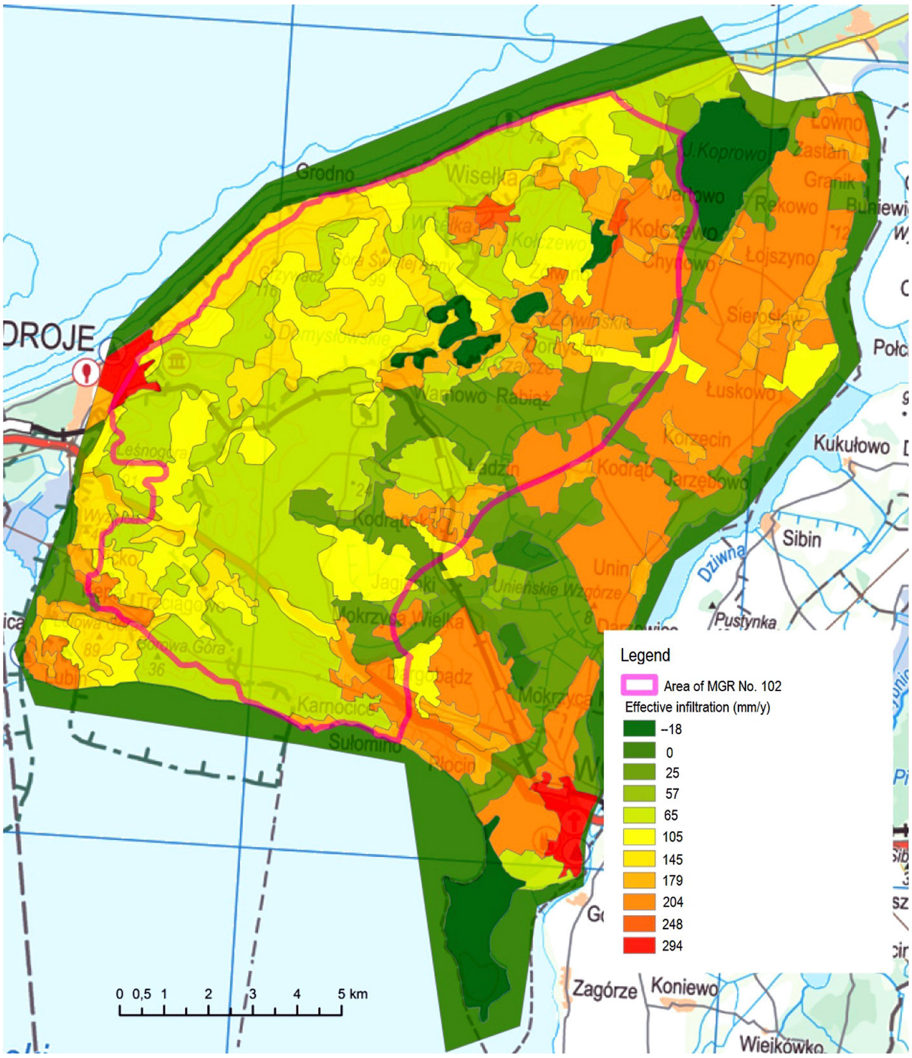

Fig. 6. Effective infiltration ratio distribution in the study area.

On balance, 14 surface water courses, lakes and other surface-water reservoirs have been simulated by means of first-type and third-type boundary conditions. These water courses have been taken into consideration in the first, second and third layer of the simulated model.

3.6. Coefficient of permeability

The values of the permeability coefficient (*k*) for aquifer and poorly permeable layers which have been applied in the model have ranged as follows:
– layer I ($Q_{h/p}$) – fine-grained sand/clays; *k* from 1.0×10^{-6} to 8.0×10^{-4} m/s (average 1.22×10^{-4} m/s = 10.52 m/d),
– layer II ($Q_{p/1}$) – sandy sludge and clays, sands; *k* from 1.0×10^{-7} to 8.0×10^{-4} m/s (average 2.91×10^{-5} m/s = 2.51 m/d),
– layer III ($Q_{p/2}$) – medium- and variously grained sand; *k* from 1.0×10^{-8} to 1.75×10^{-3} m/s (average 2.12×10^{-4} m/s = 18.4 m/d).

The bottom limit of the model in the study area has been adopted at the boundary of occurrence of fresh and salty groundwater, as stated previously by Matkowska (1992), Krawiec et al. (2000), Krawiec (2013) and Mieszkowski (2015).

3.7. Infiltration recharge

For the first water-bearing layer mapped in the model, an infiltration recharge value (I_e) has been adopted, taking into account the lithology of rocks in the vadose zone, precipitation values (*P*) and land development. In order to specify the precipitation infiltration coefficient (*w*), geological maps with Quaternary strata on the scale 1:50,000 have been used.

Infiltration conditions are particularly good in areas of dune sands, meadows on sands, arable lands on sand and clay soils. In areas with a thick cover of coniferous and mixed forests, near ground surface, morphologically diversified sands of kame formations occur. Precipitation infiltration conditions in this area are considerably less favourable and much more diverse in terms of their lithology (Fig. 6).

The least favourable infiltration conditions are known in areas where organic sediments occur at the surface and the groundwater table is at shallow depths (0–1 metre below ground surface). In such areas a negative value of the effective infiltration coefficient has been adopted because water outflow prevails over precipitation.

3.8. Groundwater exploitation at water intakes

Groundwater intakes have been simulated using a mathematical model by means of second-type boundary condition $Q = const.$ Groundwater exploitation at intakes has been determined as average annual groundwater intake flow.

3.9. Model verification

Model verification has been carried out by analyses of formerly known changes in the position of the hydrodynamic field, as well as by comparisons of water balance results with corresponding balance components of adjacent aquifer systems, in this case, Uznam Island. The model created has additionally undergone a sensitivity analysis of the previously weighed set of input parameters, including the infiltration recharge, which in fact means that the influence of minor parameter changes on the result obtained in model simulation has been assessed. The results obtained from the groundwater flow simulation on the flow model are illustrated in Figure 7.

4. Conclusions

The results obtained indicate that the authors have been primarily concerned with infiltration water that recharged Holocene deposits. The results of chemical analyses clearly indicate that the water from the upland part of Wolin Island is of short flow and residence time and has no traces of sea water ingression. This corroborated former results as published by Krawiec et al. (2000) and Krawiec (2013). Geophysical surveys have provided approximate data on the location of freshwater runoff from the plateau to the sea. These sites have been included in the present hydrogeological model.

The numerical model was subordinated mainly to piezometric pressure mapping in order to calculate reservoir recharge as a result of precipitation infiltration. The model has also enabled us to verify the adopted concept of water circulation within a multi-aquifer system and to estimate groundwater balance of the area. The model maps groundwater circulation in two aquifer layers, which are hydrodynamically or hydrostructurally limited by a drainage base, implying that the circulation of balance areas, separated on the basis of the course of watersheds, has been mapped.

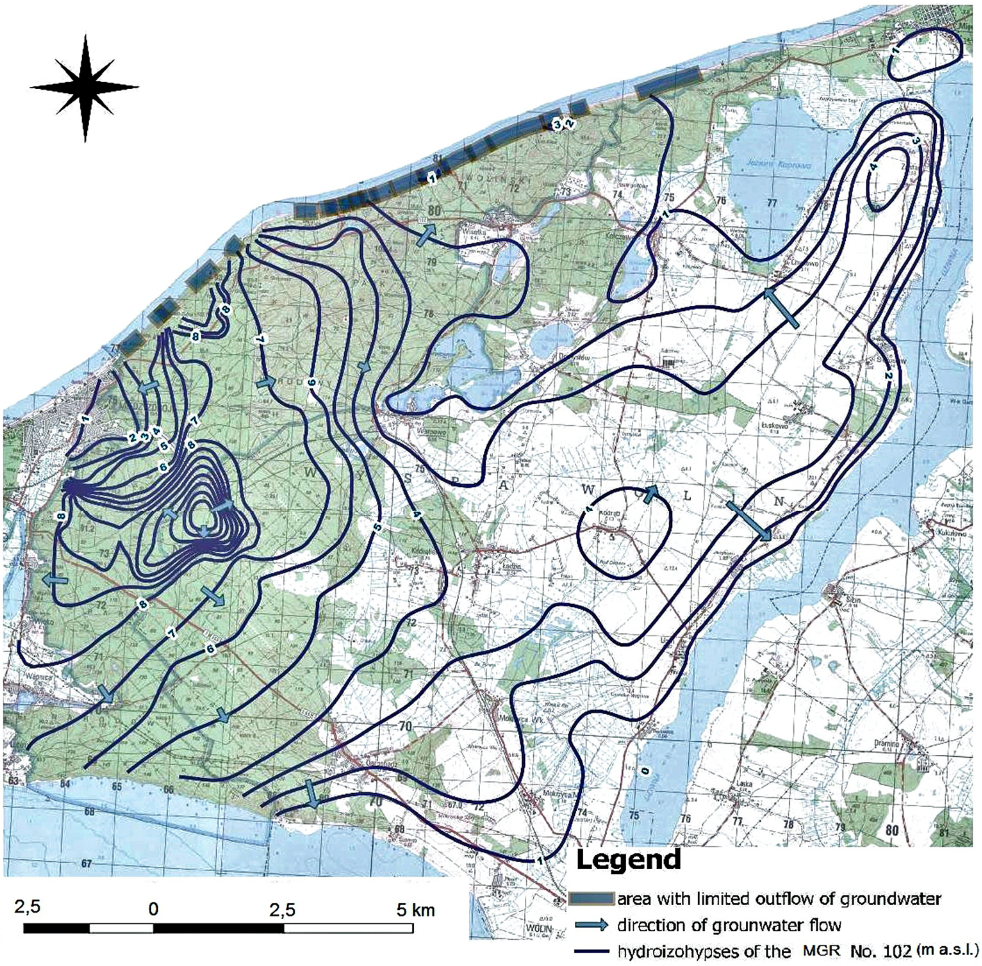

Fig. 7. Piezometric pressure contour lines of the modelled aquifers on Wolin Island.

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