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The FEM model of groundwater circulation in the vicinity of the Świniarsko intake, near Nowy Sącz (Poland)

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Abstract

Modern hydrogeological research uses numerical modelling, which is most often based on the finite difference method (FDM) or finite element method (FEM). The present paper discusses an example of application of the less frequently used FEM for simulating groundwater circulation in the vicinity of the intake at Świniarsko near Nowy Sącz. The research area is bordered by rivers and watersheds, and within it, two well-connected aquifers occur (Quaternary gravelly-sandy sediments and Paleogene cracked flysch rocks). The area was discretized using a *Triangle* generator, taking into account assumptions about the nature and density of the mesh. Rivers, wells, an irrigation ditch and infiltration of precipitation were projected onto boundary conditions. Conditions of groundwater circulation in the aquifer have been assessed based on a calibrated model, using water balance and a groundwater level contour map with flow path lines. Application of the program based on FEM, using smooth local densification of the discretization mesh, has allowed for precise mapping of the location of objects that significantly shape water circulation.

Key words: groundwater flow model, numerical modelling, FEFLOW, recharge area

1. Introduction

Solving complicated hydrogeological problems requires the use of research methods that enable precise mapping of groundwater circulation and formulation of reliable predictions. Meeting these requirements, numerical modelling offers speed and accuracy of calculations, as well as versatility of possible application results. Modelling of filtration processes uses a mathematical description of groundwater flow on the basis of assumed parameter values and boundary conditions. Most often, Modflow simulators are used, based on the finite difference method (FDM). As an alternative, the finite element method (FEM) is being used increasingly more often and more widely, due to the possibility of more accurate determination of complex geometries of aquifers and important objects (Zdechlik, 2016).

The use of numerical methods does not guarantee a reliable result. The essence of model research is proper recognition and understanding of reality, combined with making good use of the possibilities of programs. Only a correctly prepared and calibrated model can be used to predict the behaviour of the real system reliably, taking into account different conditions, for instance when assessing and optimising groundwater exploitation (Treichel et al., 2015; Haładus et al., 2017), analysing mining activities (Luo et al., 2014; Sinton et al., 2015; Juśko et al., 2018) or modelling the migration of pollutants in groundwater (Pietrucin & Czop, 2015).

The present article outlines the process and results of model tests, specifying the conditions of groundwater circulation in the area of medium-sized water intakes. The research covered the area of groundwater intakes near the village of Świniarsko. The aim of the present study was to characterise groundwater flow using a method that enables existing elements that shape water circulation (wells, irrigation ditch and rivers) to be mapped with very high precision. The numerical model was prepared in FEFLOW 7.1 (www.mikepoweredbydhi.com) based on FEM. After model calibration, a hydrodynamic field system was obtained, recharge areas for the groundwater intakes analysed were determined and also quantitative water circulation characteristics were presented.

2. Methodology of model research used

Numerical modelling of groundwater flow consists of solving a differential equation of filtration, the overall form of which for flow in heterogeneous and anisotropic porous aquifers with transient flow conditions have been presented in numerous publications (e.g., Dąbrowski et al., 2011). In the case of complex geometry of aquifers and boundary conditions and in order to obtain results with satisfactory accuracy, it is necessary to apply advanced computational modelling, which includes numerical methods such as FDM or FEM. The essence of these methods is to obtain approximate functions describing the values searched (which are continuous in time and space) on the basis of discrete values, i.e., those whose location in time and space are strictly defined (Diersch, 2014).

Two main stages are highlighted in the process of creating a numerical model: (1) simplifying, describing the modelled reality and presenting it in the form of a hydrogeological (conceptual) model, and then (2) converting this model into a mathematical model. The conceptual model is based on a schematic representation of the hydrogeological conditions of the aquifer. The transformation into a mathematical model is done by discretization – the conversion of continuous functions occurring in the equation, to discrete functions, defined only for specific points of the area, so-called nodes. One of the features that characterises FEM is the possibility of selecting the shape of the discretization mesh, which provides precise and clear mapping of important elements of the geological structure or other objects that affect water circulation. The area can be divided into elements of any shape, most often prismatic solids with triangular bases. It is possible to increase the density of the mesh in any part of the area, without modifying other areas. The shape of the mesh is matched to previously defined limits of the area and other characteristic elements (e.g., groundwater intakes). The grid nodes are the vertices of the calculated blocks. Individual parameters and boundary conditions of the model are assigned directly to nodes or to fields limited by nodes (Zdechlik & Partyka, 2018).

3. Characteristic of the study area

3.1. Location and environment conditions

The object of research is the aquifer structure located in the vicinity of the village of Świniarsko near the city of Nowy Sącz, in the Małopolska voivodeship. Limitations of the study area are (Fig. 1): the River Dunajec (to the east and southeast), the River Brzeźnianka (to the southwest), the surface watershed (to the west, northwest and north) and the River Biczyczanka (to the north). The total area of the region studied is 29.75 km^2. Within the structure, groundwater exploitation is carried out by three complexes: (1) Świniarsko, (2) Mała Wieś and (3) Biczyce Dolne. Within the boundaries covered by the study area, there are recharge areas for all three intakes (Jaskulska, 2018).

Morphology reflects the nature of physical and geographical units in the area – this is the Carpathian region, the province of the Western Carpathians. The eastern part, where the intakes occurs, is located in a flat valley of the River Dunajec (275–300 m a.s.l.). This is distinguished by two terraces of Holocene age, standing flat with a slight inclination towards the river. The western part is formed by the valley of the River Niskówka, with a varied landform (elevation 310–540 m a.s.l.), resulting from erosion of Eocene sandstones and shales.

Hydrographically, the area belongs to the Dunajec catchment. There are smaller streams, tributaries of the River Dunajec: the rivers Brzeźnianka, Niskówka and Biczyczanka, which are separated by third-order watersheds. The main drainage base of the study area is the River Dunajec, with an average annual flow of 60 m^3/s and a hydraulic drop of approximately 0.7%. Flowing centrally through the area, the River Niskówka is about 8.5 km long, with an average annual flow of about 0.05 m^3/s, its catchment area being 15.8 km^2.

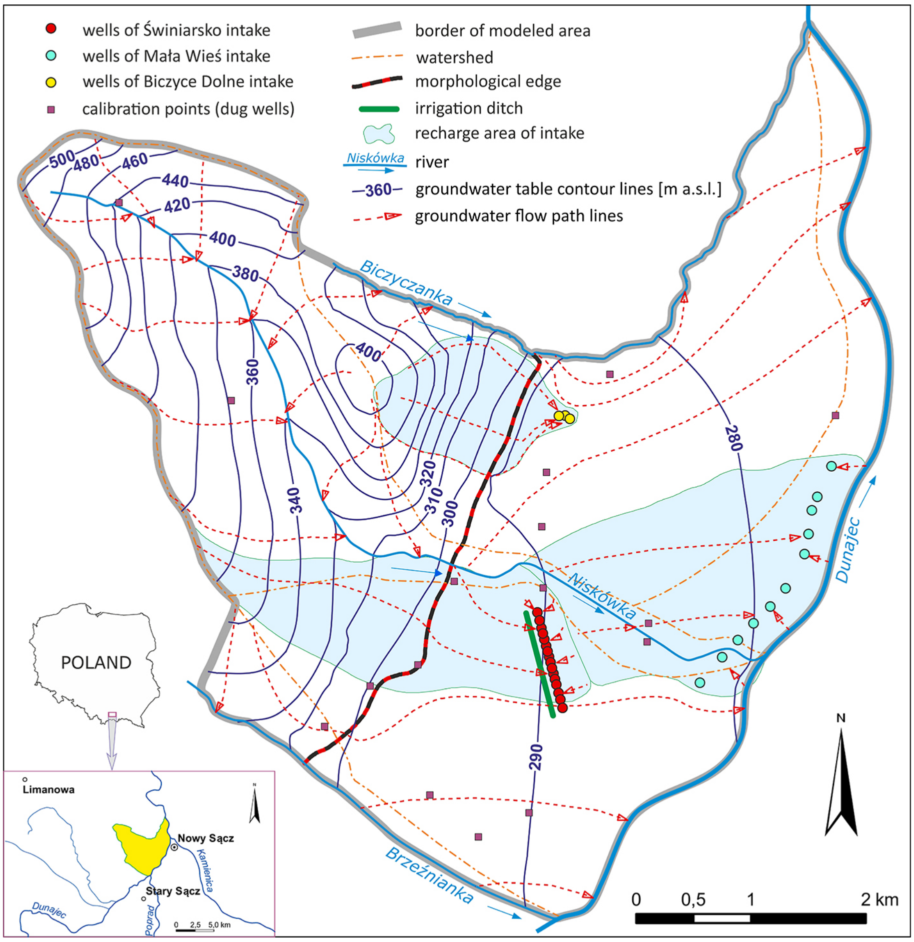

Fig. 1. Documentation map of the study area

Land-use in the area is agricultural and there are small forested areas on the hills. There are numerous urbanised areas. Precipitation is relatively high; the meteorological station at Nowy Sącz having documented an average precipitation in the years 2001–2010 of 806 mm/year (Dmochowska, 2016).

3.2. Geological structure

Geological strata occurring within the research area represent three separate structural stages. The oldest stage consists of deposits, of Cretaceous to Paleogene age. To the middle stage belong Middle Miocene deposits, while the youngest stage is represented by Quaternary sediments (Oszczypko & Wójcik, 1993). The basal strata in the research field consist of sedimentary rocks of the Magura Series: sandstones, shales and marls. The younger stage comprises Neogene deposits, especially of Miocene age (silts, clay shales, sands and sandstones). The youngest structural stage, the shallowest and thinnest, comprises Quaternary formations (rock erosion, landslide, clay and weathered rock). The Holocene is represented by river sediments (gravels and boulders, sands and clays and silts).

The main tectonic unit in the vicinity of Nowy Sącz is the Magurian Mantle, and a separate tectonic element, imposed on the mantle, is the Sądecka Valley.

3.3. Hydrogeological conditions

The southeastern part of the area is situated within the limits of Major Groundwater Reservoir (GZWP) No. 437 – Valley of the River Dunajec (Nowy Sącz). This is a porous reservoir, directly connected with the surface water of the rivers Dunajec, Poprad and Kamienica (Gryczko-Gostyńska & Olędzka, 2009; Mikołajków & Sadurski, 2017). The whole study area belongs to Groundwater Body (JCWPd) No. 166 of a porous or fissure-pore nature, where water-bearing deposits are Quaternary sands and gravels and Paleogene sand-slate packages of the Carpathian Flysch (www.pgi.gov.pl).

There are two areas of groundwater occurrence. In the eastern part lies the Quaternary aquifer of the Nowy Sącz Basin, connected hydraulically with the River Dunajec. This comprises alluvial gravelly-sandy sediments, in part with clay, reaching a thickness of up to approximately 10 m, on top of Miocene clays and silts. Recharge of this aquifer takes place through direct infiltration of atmospheric precipitation, partly by surface runoff. The groundwater table is unconfined, locally slightly confined, usually at a depth of 4 m. Hydraulic conductivity values are in the range of 10^{-4} to 10^{-2} m/s. In the western part of the region is situated a Paleogene aquifer (sandstones of the Maguran layer), associated with the broken-up top part of flysch rocks, represented by coarse- and medium-grained sandstones with slate insertions. The average hydraulic conductivity value is 1 m/d (Gryczko-Gostyńska & Olędzka, 2009). Studies of flysch formations (Oszczypko et al., 1981) indicate the permeability of the Magura sandstones in a zone at a depth of 80–90 m. The most favourable conditions for groundwater flow are seen in a subsurface zone with a thickness of 30–40 m. This aquifer is recharged by infiltration of precipitation directly on outcrops or through a thin layer of Quaternary formations. The groundwater table is located at a depth of about 4 m; flow occurs towards the River Dunajec.

Both aquifers are treated separately because they differ significantly in their characteristics. However, considering the circulation of water in the area analysed, they are aquifers that remain generally in hydraulic connection (Fig. 2).

3.4. Groundwater intakes

An infiltration intake, consisting of 16 wells, with depths of 10 to 12 m, is situated near the village of Świniarsko. In 2015, average exploitation of water was 1,966.46 m^3/d. The wells are located in the immediate vicinity of the irrigation ditch that supplies the aquifer, to which surface water drawn from the River Dunajec is supplied (2,065 m^3/d in 2015). The intake in Mała Wieś consists of 11 wells, with depths from 8 to 11 m, and location on the left bank of the River Dunajec. Wells exploit water to the amount of 710.38 m^3/d (average for 2015). The groundwater intake at Biczyce Dolne consists of three wells, with depths from 11 to 15 m. These wells exploit a Quaternary aquifer (gravel with pebbles), with an average water consumption of 206.4 m^3/d (2015).

4. Hydrogeological model

4.1. Conceptual model

The subject of the present research is a hydrogeological structure that include two aquifers which remain in hydraulic connection: Paleogene (flysch) and Quaternary (gravel-sand). Groundwater flow takes place under unconfined conditions. The boundaries of the model were determined along fragments of watersheds and the rivers Dunajec, Biczyczanka and Brzeźnianka (Fig. 1). Within the area covered by the model flows the River Niskówka, which, together with the rivers Biczyczanka and Brzeźnianka, have limited contact of surface water and groundwater. The River Dunajec remains in good hydraulic connection with an aquifer. Terrain elevation within the boundaries of the model varies from 269 to 555 m a.s.l. The thickness of the aquifer ranges from 70 m in the flysch zone, to 10 m in the area of Quaternary gravels and sands. Within the boundaries of the model there are 30 wells that exploit water, with a total average expenditure of

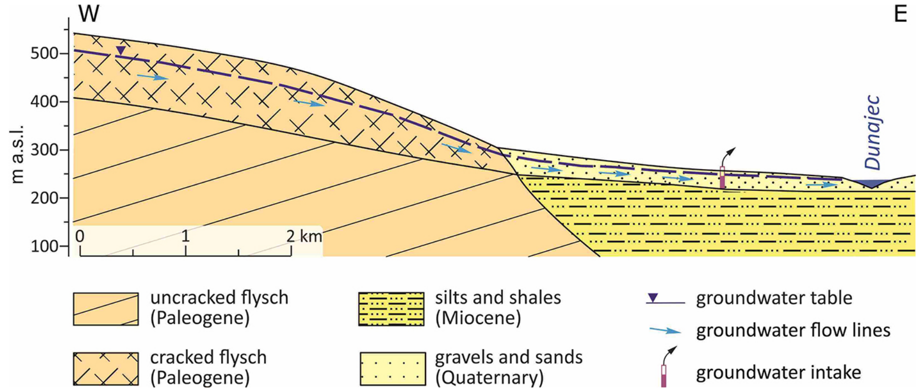

Fig. 2. Schematic diagram of groundwater circulation in the study area

2,883.24 m^3/d (2015). An important role in groundwater flow is played by the irrigation ditch, which supplies the structure with surface water drawn from the River Dunajec.

4.2. Numerical model

The construction of the numerical model using the FEFLOW 7.1 program proceeded in several basic stages: discretization of the area, setting of boundary conditions, determination of layer parameters, and configuration and launch of the calculation process.

Discretization of the area was carried out on the basis of model boundaries as well as thematic layers containing well locations and the course of the River Niskówka. The structure of the *Layered 3D mesh* model was assumed, in which the adopted horizontal division is preserved on all layers, and the blocks in space have the shape of triangular prisms. A so-called *supermesh* was prepared – a set of polygons, lines and point objects, which map the essential elements that shape the model, on the basis of which discretization was carried out. The nodes of the loaded objects are the basic elements for the created mesh, while the walls of triangles are placed on the sides of the polygons and along the defined lines.

The mesh generation is based on the selected algorithm, which determines the method of geometry mapping. The mesh (Fig. 3A) was constructed using a *Triangle* generator. The following assumptions were made:

– minimum angle of triangles forming the mesh: 30° (avoidance of triangles with small angles; this results in an even distribution of nodes in the mesh);
– lack of anisotropy of triangle dimensions (striving to create an irregular mesh of triangles of shapes that are as homogeneous as possible, without clear directionality);
– densification of the mesh in the area of linear objects (rivers, watersheds) with a 3-step gradation of triangle size (Fig. 3B);
– densification of the mesh in the area of point objects (wells) with a 4-step gradation of triangle size (Fig. 3C).

In the northwestern part (cracked sandstones and shales) the thickness of the layer is assumed to be 70 m, which corresponds to the approximate depth of the active groundwater exchange zone in flysch deposits (Oszczypko et al., 1981). In the southeastern part of the valley, the thickness of the aquifer was assumed to be 10 m. The boundary conditions (BC) represent (Fig. 1):

– the River Dunajec – as *Hydraulic-head BC* (1st type BC);

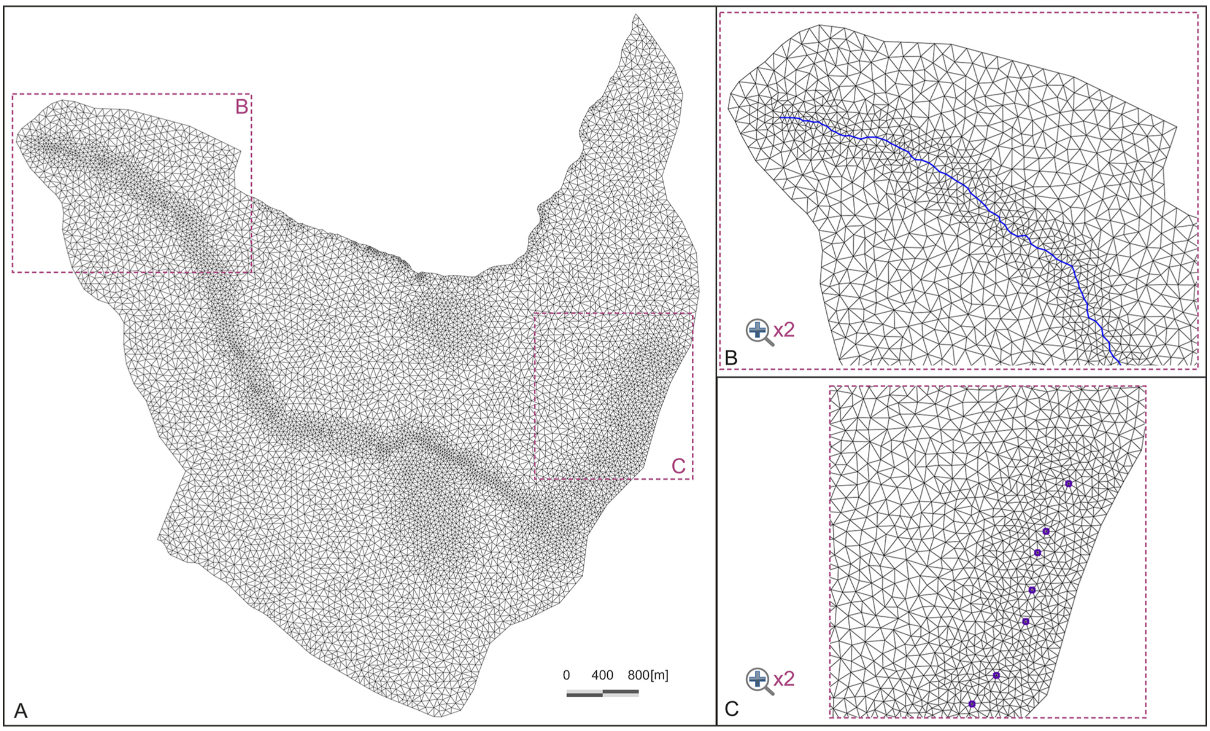

Fig. 3. Discretization mesh of the model: **A –** study area; **B –** mesh densification in the northern area of the River Niskówka; **C –** mesh densification in the area of the well of the Mała Wieś complex

- the rivers Niskówka, Biczyczanka and Brzeźnianka – as *Fluid-transfer BC* (3rd type BC);
- exploitation wells – as *Multilayer Well* (2nd type BC);
- irrigation ditch and recharge from effective infiltration of precipitation – expressed in mm/year the inflow value in the *In/outflow on top/bottom* table (2nd type BC).

Parameters and recharge of the aquifer (Table 1) were entered into tables from the *Material Properties* group. Values for hydraulic conductivity in the valley were determined on the basis of borehole data, and for the flysch data from the literature were used (Duda et al., 2013). Effective porosity was determined as the average value within two areas (valley and flysch). Recharge from effective infiltration was determined on the basis of the effective infiltration index and amount of precipitation in 2015 for the meteorological station at Nowy Sącz. In the blocks immediately adjacent to the wells of the Świniarsko complex on the western side, additional supply of the aquifer was simulated (surface water of the River Dunajec introduced into the irrigation ditch).

Simulation solutions were carried out for steady-state conditions, assuming the unconfined nature of the aquifer. The PCG solver was used in the calculation process, with a convergence criterion of numerical calculations at 0.005 m.

Table 1. Aquifer parameters adopted for the model

Areas	Hydraulic conductivity	Effective porosity	Recharge
	m/d	–	mm/y
Flysch	0.1–2.0	0.1	16–97
Valley	70-100	0.25	161

4.3. Model calibration

In order to minimise differences between results obtained in the calculation process and real values, the model was calibrated. The calibration consisted in adjusting the hydrodynamic field obtained from the model to the hydrodynamic field obtained from point measurements of groundwater level and surface water ordinates on the rivers. The model has been calibrated to the average state of 2015. Data for model calibration were adopted as in previous model tests (Morański, 2016; Zdechlik & Morański, 2017). The adjustment was carried out by manual introducion of changes to parameter values set on the model. During this process, the distribution of hydraulic conductivity in the flysch and near the River Dunajec was changed, as was the recharge from infiltration of precipitation in the flysch.

To assess the correctness of calibration, measurements of groundwater level at 16 points (dug wells), located mostly in the valley part (Fig. 1), were used. The validity of model calibration was assessed both qualitatively (calibration graph, residual water table histogram) and quantitatively, determining the average error *MAE* (Kulma & Zdechlik, 2009). The calculated *MAE* value is 1.783 m, which is less than 1% of the amplitude of the water table in the area considered.

5. Results of model studies

The calibrated model was used to evaluate the circulation conditions of groundwater in the aquifer in the region analysed. The water balance obtained (Table 2) indicates that:

- the main source of recharge is atmospheric precipitation (nearly 34% of resources);
- the main drainage base is the River Dunajec, which receives 64% of circulating groundwater;
- smaller rivers (Biczyczanka, Niskówka, Brzeźnianka) constitute a significant source of recharge to the structure, which results mainly from the specific system of water courses and the location of wells;
- the River Dunajec supplies an aquifer with a small extent, which may be forced by functioning of the intake at Mała Wieś;
- wells are responsible for receiving about 9% of the circulating water in the structure;
- recharge from the irrigation ditch fully covers the water exploitation of the Świniarsko intake.

The distribution of the hydrodynamic field is shown in the form of a groundwater level contour map (Fig. 1). The aquifer is drained mainly by the River Dunajec, as well as by exploitation wells. Groundwater from the valley and flysch parts is drained into the intakes, locally aided by infiltration from rivers. In general, groundwater runoff takes place in easterly and northeasterly directions, and locally in the direction of smaller rivers. The rivers modelled by the third-type boundary, in particular the River Niskówka, intensively recharge the aquifer. It is noticeable that on the morphological edge the area is divided into two separate parts: flysch, strongly drained by the river, and the valley part, in which the character of rivers changes into infiltration or mixed. Groundwater flow path lines in the vicinity of Biczyczanka are directed mainly to the River Dunajec. In the valley part, the River Niskówka has a very variable nature: in a significant part of the river drainage takes place through its right bank with simultaneous infiltration to the aquifer

Table 2. Water balance of the aquifer structure under consideration, obtained in the model

Balance component	In		Out	
	m^3/d	%	m^3/d	%
Rivers	18506.90	59.46	28238.60	90.73
Dunajec	624.00	2.00	20073.00	64.50
Biczyczanka	4756.20	15.28	3129.20	10.05
Niskówka	8327.90	26.76	4003.20	12.86
Brzeźnianka	4798.80	15.42	1033.20	3.32
Irrigation ditch	2064.78	6.68	–	–
Recharge	10551.22	33.86	–	–
Intakes	–	–	2883.80	9.27
Mała Wieś	–	–	710.35	2.28
Świniarsko	–	–	1966.45	6.32
Biczyce Dolne	–	–	207.00	0.67
SUM	31122.90	100.00	31122.40	100.00

through its left bank. The River Brzeźnianka in its valley section supplies the aquifer. The groundwater flow path lines in the median section of the River Dunajec indicates a small infiltration to the aquifer from the river, which is the result of functioning of intakes and the presence of a small damming step in the river.

On the basis of the groundwater flow path lines obtained, areas of water runoff to the intakes (recharge area, RA) were determined as follows:

– for the Świniarsko intake, the RA covers 2.95 km^2 and spreads into the northwestern part of the research area; the northern border is partly along the River Niskówka, which has in this fragment an infiltrating nature (Fig. 1); the course of the borders of the RA indicates that the water exploited originates from both flysch and valley gravels;

– the RA of the Mała Wieś complex, with an area of 3.81 km^2, is directly bordered by the RA of the Świniarsko wells; the eastern border of the Mała Wieś complex RA is based on the River Dunajec; the RA spread indicates that the water exploited originates from gravel deposits;

– the RA for the complex at Biczyce Dolne covers a small area (1.36 km^2); the majority are in the flysch area; the water comes from the Magura sandstones.

6. Conclusions

A prepared numerical hydrogeological model for the Świniarsko intake region was used to determine water circulation conditions in detail. Application of the program using the finite element method allowed precise mapping of the location of objects that significantly shape water circulation (wells, watercourses, irrigation ditch), through the smooth local densification of the discretization grid (gradation of block sizes), which is noticeable in comparison to previous studies that used the finite differences method (Morański, 2016; Zdechlik & Morański, 2017). The advantage of this method is the high precision of hydrodynamic field projection, especially in regions where grid densification was applied. This way of model design allows for detailed determination of flow conditions, enabling unequivocal separation of simulated water streams. This is particularly important in zones where the areas of water runoff to different intakes are directly adjacent to each other (to the east of the Świniarsko intake), or in groundwater flow path where there are water courses in which drainage takes place through one bank with simultaneous infiltration to the aquifer through the other, or groundwater flow may take place under the riverbed.

The results obtained also indicate that the actual water discharge by intakes is many times smaller than the total amount of water that circulates in the aquifer. This suggests that the environmental potential of groundwater exploitation is greater than the current exploitation. The answer to the question what possibilities of receiving water under specific location and technical conditions of wells are, can be obtained by model optimisation tests, covering the hydrogeological structure within the recharge area of the intakes.

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