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Modelling groundwater flow and nitrate transport: a case study of an area used for precision agriculture in the middle part of the Vistula River valley, Poland

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Abstract

The present paper discusses studies related to the preparation of a hydrogeological model of groundwater flow and nitrate transport in an area where a precision farming system is applied. Components of water balance were determined using the UnSat Suite Plus software (HELP model), while the average infiltration rate calculated for the study area equalled 20 per cent. The Visual MODFLOW software was used for the purpose of modelling in the saturated zone. Hydrogeological parameters of the model layers, inclusive of hydraulic conductivity, were defined on the basis of results of column tests that were carried out under laboratory conditions (column experiment). Related to the dose of mineral nitrogen used in precision fertilisation (80 kg N/ha), scenarios of the spread of nitrates in the soil-water environment were worked out. The absolute residual mean error calculated for nitrate concentrations obtained from laboratory and modelling studies equalled 0.188 mg/L, the standard error of the estimate equalling 0.116 mg/L. Results obtained were shown graphically in the form of hydroisohypse maps and nitrate isolines. Conclusions were drawn regarding the possibility of using numerical modelling techniques in predicting transport and fate of nitrates from fertilisers applied in precision agriculture systems.

Keywords: hydrogeological modelling, agricultural pollution, mineral nitrogen, precision farming

1. Introduction

River valleys of lowland areas are often developed for agricultural purposes. Requirements related to the fulfilment of notions of sustainable development have an impact on the necessity of expanding tools and solutions in support of agricultural economy in protected areas. With reference to hydrogeological conditions of valley areas that generally play a role as drainage zones for the longest part of the hydrogeological year (besides the period of overbank flow when their infiltrative character is demonstrated), issues related to protection of groundwater and surface water resources deserve special attention in quantitative and qualitative aspects. In the area of the Polish Lowlands, the specificity of the geological structure of individual valley sections results from their morphogenetic immaturity. Sandy layers deposited by the river can constitute a privilege zone for groundwater filtration, and hence the riverbed can be highly susceptible to pollution. It is also worth noting that rivers carry a significant load of agricultural pollution (nitrogen and phosphorus compounds) to the Baltic Sea, this being the real cause of its degradation. One of the methods for limiting the negative impact of agriculture on the water quality is the increasingly frequent application of precision-farming tools in agricultural practice (Baum et al., 2012).

The occurrence of several sources of contaminants (i.e., agriculture, industry, landfills, sewage systems) and their possible negative impact on the environment and human health should persuade researchers to carry out works related to augmenting current knowledge with respect to the migration of pollutants in the soil-water environment. The nature of the relationship between groundwater and surface water is crucial in understanding pathways through which contaminants may be exchanged between these two systems and how this could affect exposure of humans and aquatic biota to contamination (Ritter et al., 2002). In order to imitate the nature of the migration of contaminants, especially within the context of self-purification processes that may occur in a porous medium, it appears to be particularly important to determine the parameters that describe the migration environment, and processes occurring in this, correctly and reliably.

Mathematical modelling tools facilitate solving problems related to groundwater flow dynamics, balancing water resources and characteristics of the hydrodynamic field to a significant extent (Koda, 2012). In the case of conservative tracers, the correctness of the model design is limited to verification of the groundwater level in wells and piezometers, while filtration parameters are defined through measurement of hydraulic conductivity in field or laboratory tests. When taking into account other compounds, impacted by sorption or biodegradation in the soil-water environment, it is necessary to specify a number of additional parameters that correspond to the kinetics of these processes (Sieczka & Koda, 2016a, 2016b; Sieczka et al., 2018).

Taking into account these issues, the main objectives of the present study were twofold: 1) to estimate the possible concentration of nitrate in groundwater, deriving from agricultural fields within a precision agriculture system, using numerical modelling techniques, and 2) to simulate the spread of nitrate in groundwater, with regard to parameters responsible for their migration, as obtained from column studies.

2. Characteristics of the study area

The study area lies in the Konstancin-Jeziorna commune (Masovian Voivodeship). According to the physico-geographical regionalisation of Poland (Kondracki, 2002), this area is located in the mesoregion of the Middle Vistula River valley (macroregion of the Middle Masovian Lowland). Relatively shallowly lying deposits (clays) of Pliocene age that limit the free exchange of waters with deeper aquifers have been observed in this region. The succession of alluvial strata starts with sands of the channel facies of a braided river, overloaded with debris. These sands are medium- and coarse-grained and well-sorted (Sarnacka, 1976) and are characterised by a proper filtration parameters. These deposits constitute the main exploitable aquifer, which is part of a major groundwater basin, numbered 222 (Middle Vistula River valley – Warsaw-Puławy).

In a significant portion of the Vistula River floodplain terrace, the layer of permeable sandy material formed on an alluvial subsoil (Falkowska&-Falkowski, 2015). On the basis of *in-situ* tests, it has been shown that the groundwater level is stabilised in these deposits (1st aquifer). This aquifer is also characterised by the highest susceptibility to pollution.

The study area is strongly transformed by contemporary overbank flows. Locally, a layer of poorly permeable alluvial soils was eroded and replaced by younger deposits which are characterised by

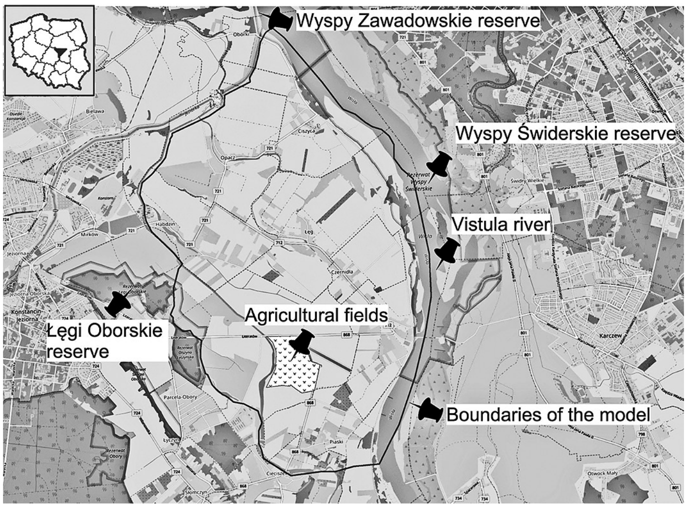

Fig. 1. Location of the study area.

good filtration parameters and constitute 'hydrogeological windows', thus combining the shallow aquifer with deeper-lying, usable one.

The modelled site covers an area of *c.* 17.5 km^2. From the north, east and west, it is surrounded by the following nature reserves, respectively: Wyspy Zawadowskie, Wyspy Świderskie and Łęgi Oborskie (part of the Chojnowski Landscape Park). Within the study area, two fields of winter wheat crop production are found (Fig. 1).

The research was conducted in the period from 2013 to 2014 when winter wheat was cultivated in two selected fields, both of them within the framework of precision farming. The application of principles of precision farming was basically associated with limiting the excessive use of mineral fertilisers and reducing the loss of unused fertiliser compounds into the environment. The most important idea of this system is using the least possible amount of fertilisers in a timely manner.

Agricultural fields of 40 hectares lie approximately 88 m above sea level, while the average precipitation for this region is 550 mm per year (period 2011–2015). The rate of nitrogen application through fertilisation varied between 55 and 105 kg N/ha. The main fertiliser used here was ammonium nitrate.

3. Material and methods

As a first step, particular attention has been paid to proper determination of factors that influence the water balance within the study area. For this purpose, the WHIUnSat Suite Plus software was used, with emphasis on the model HELP and its application. The scheme of the modelling approach is presented in Figure 2.

Information on average precipitation and temperature characteristics for the study area were taken from the National Institute of Meteorology and Water Management – National Research Institute. Moreover, meteorological data from the Okęcie station were taken into account using the HELP model that implements a weather generator.

Soil properties concerning effective porosity and saturated hydraulic conductivity were measured under laboratory conditions. Six undisturbed soil samples were taken from the vicinity of piezometers located in agricultural fields, by using a stainless steel tube sampler (diameter 89 mm, length 600 mm). Saturated hydraulic conductivity was measured according to the ASTM D5084-00 (2001) procedure. The effective porosity was calculated with reference to the formula presented by Marciniak et al. (2006), concerning flow rate, time required for exchange one pore volume of flow, length and diameter of the soil sample, registered during the column studies. Field capacity and wilting point were calculated based on contents of clay, silt and sand fraction and organic matter, characteristic of soils taken from the vadose zone. The calculations were made using the SPAW (Soil-Plant-Air-Water) model (Saxton & Willey, 2006). The thickness of the vadose zone layers were defined on the basis of shallow wells performed in the study area. In total, twenty-two wells (up to 1.2 m in depth) were drilled (ten of these within the field analysed in 2013 and twelve within that studied in 2014). The average slope of the study area was calculated with reference to digital elevation model data. Plant characteristics were set in the HELP model, as based on data on plants cultivated in the study area.

On this basis it was possible to determine the value of groundwater recharge characteristic of the study area, which, in the next step, was applied as a value of *Recharge* variant in a model of hydrodynamics of groundwater flow and nitrate transport, created using the Visual MODFLOW software (version 2009.1). The input data for modelling in the

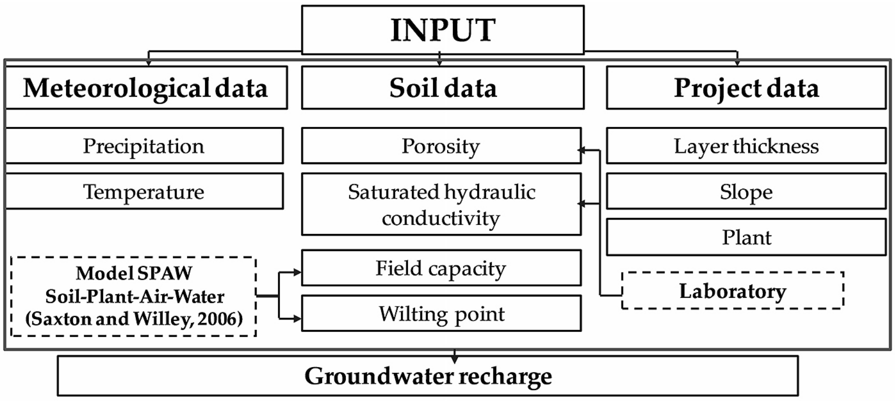

Fig. 2. Scheme of the methodological approach applied in determining groundwater recharge.

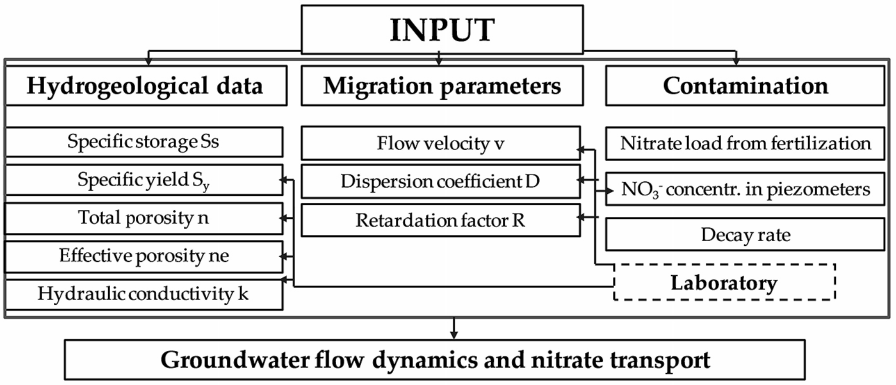

Fig. 3. Scheme of the methodological approach applied for the purpose of modelling in the saturated zone.

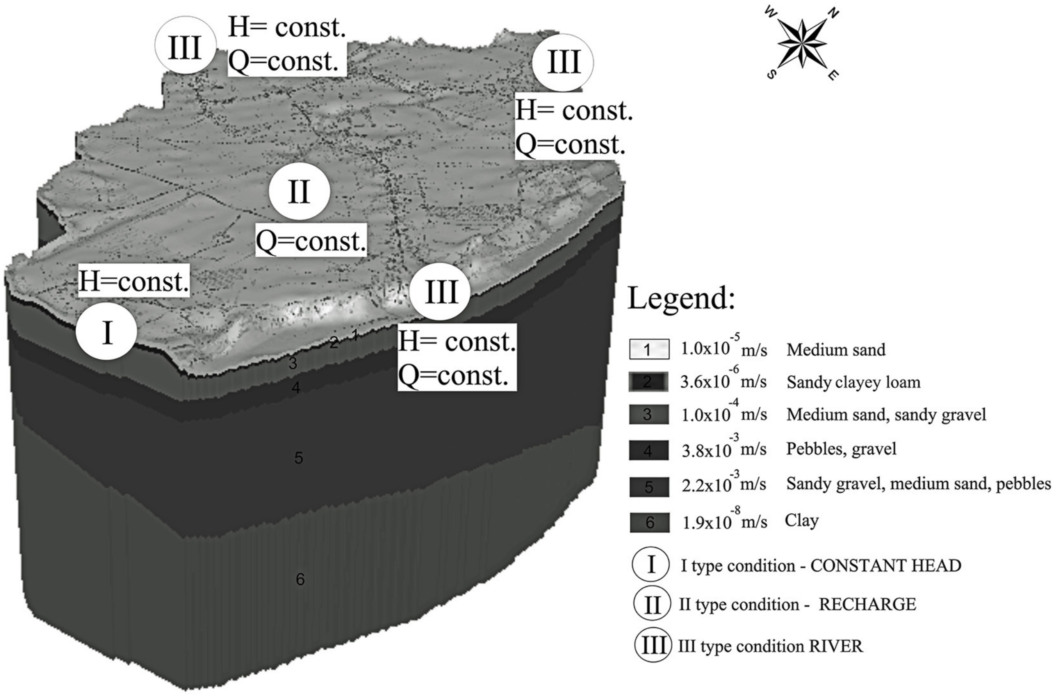

Fig. 4. The model body and its boundaries (Sieczka et al., 2018).

saturated zone were subdivided into three groups (Fig. 3): (a) hydrogeological data, (b) migration parameters and (c) contamination.

The monitoring network of groundwater level and its quality consisted of twelve wells and six observation piezometers located within the fields used for precision agriculture. All of the monitoring points were connected to the National Geodetic Network. The co-ordinates were set in reference to the PUWG 1992 geodetic system using the GPS-RTK equipment. Drops of water level were determined to set boundary conditions of the study area. Using the GIS tools, the concept of the system modelled and its boundaries has been defined. The model extent was imitated in a horizontal plane (X,Y) using a square mesh of a 200-m-dimension. Discretisation on the vertical axis (Z) was performed by dividing this into layers with different filtration parameters (Fig. 4). As an effect, six separated layers were created (Table 1).

The morphology of the first layer was defined on the basis of resources of the Digital Elevation Model (DEM) taken from the Geodetic and Cartographic Documentation Centre. The thickness of the model layers was determined on the basis of hydrogeological cross sections prepared as part of the development of the conceptual model. The morphology of the 6th layer, which was also an impermeable boundary in the model, was interpolated using the kriging method, as linked to data from logs of

Table 1. Characteristics of model layers.

Layer	Description
1st	Top soil and subsoil deposits – medium-grained sands
2nd	Holocene deposits – sandy clayey loams
3rd	Holocene medium-grained sands and sandy gravels
4th	Pleistocene deposits – pebbles and gravels
5th	Pleistocene sandy gravels, medium-grained sands and pebbles
6th	Clay layer – the impermeable bottom boundary of the model

deep boreholes collected by the Central Geological Archive of the Polish Geological Institute-National Research Institute. The assumed homogeneity and isotropy of the separate layers of the model was also taken into account.

Based on the experiment under laboratory conditions, the parameters of advection, dispersion and sorption were determined and then were applied as input data to the model of the saturated zone. For the purpose of model preparation, the results of column studies of ammonium nitrate transport through soil samples taken from analysed agricultural fields were applied. Retardation of nitrate ions during their migration in soils was expressed using retardation factors R, calculated on the basis of the formula presented by Macioszczyk (2006). By analysing the results of column studies (breakthrough curves) and comparing the time period required to reach the maximum concentration of nitrate (reactive marker) and chloride (non-reactive marker) in the experiment, it was possible to define the intensity of ion retardation in the selected soil samples. Then, the distribution coefficients K_d were calculated using the formula concerning dry bulk density, effective porosity and the retardation factor obtained for the soils tested (Zhu & Anderson, 2002). Parameters occurring in the equation of advective-dispersion transport were calculated based on results of the column experiment, using the CXTFIT software (Toride et al., 1999). Values of specific storage were taken from Batu (1998), whereas specific yield values were calculated using the formula presented by Bieciński (1960).

When modelling nitrate migration, a nitrate load from fertilisation was used as a *Recharge Concentration* variant. Nitrate load treated as input data for numerical simulation was calculated on the basis of the average dose of ammonium nitrate applied during precise fertilisation equal to 80 kg N/ha. The conversion of nitrate dose applied during fertilisation (kg/ha) into their concentration (mg/L) was performed following Duda et al. (2011).

For calibration of the model of nitrate transport, the values of nitrate concentration measured for water samples taken from six piezometers were applied. As a measure of nitrate decomposition during the denitrification process, the half-life $t_{1/2}$ was used. With reference to the half-life time of nitrates, the first-order decay coefficient was calculated using the formula presented by Almasri & Kaluarachchi (2007). Compared to research studies by Kozlovsky (1988), Frind et al. (1990), Herbert & Kovar (1998) and Uffink (2003), it has been revealed in our study that the best model fitting was obtained for the $t_{1/2} = 3.7$ years. Taking into account this assumption, the first-order decay coefficient equalled 5.13×10^{-4} 1/d.

The boundary conditions were set by the *River* and *Constant Head* variants, respectively. Steady-state modelling was considered in the present study. The morphology of the area was identified with the use of satellite images and elevation data obtained from airborn laser scanning (ALS) within the ISOK project (IT System of the Country's Protection against Extreme Hazards).

The calibration of the created model was run on the basis of data obtained from the monitoring network of wells and piezometers. More precisely, the groundwater level and concentration of nitrates in piezometers was the subject of interest during the calibration process.

4. Results and discussion

On the basis of calculations performed for a period of 5 years using the HELP model, the average infiltration value was determined at the 20 per cent level (Table 2).

Table 2. Components of water balance calculated using the HELP model.

Component	Unit	Year 1	Year 2	Year 3	Year 4	Year 5	Average
Precipitation	mm	463	540	563	507	478	510
Evapotranspiration	mm	366	370	398	376	321	366
Surface runoff	mm	10	30	30	50	70	40
Infiltration	mm	51	124	143	93	103	102
	%	11	23	25	18	22	20

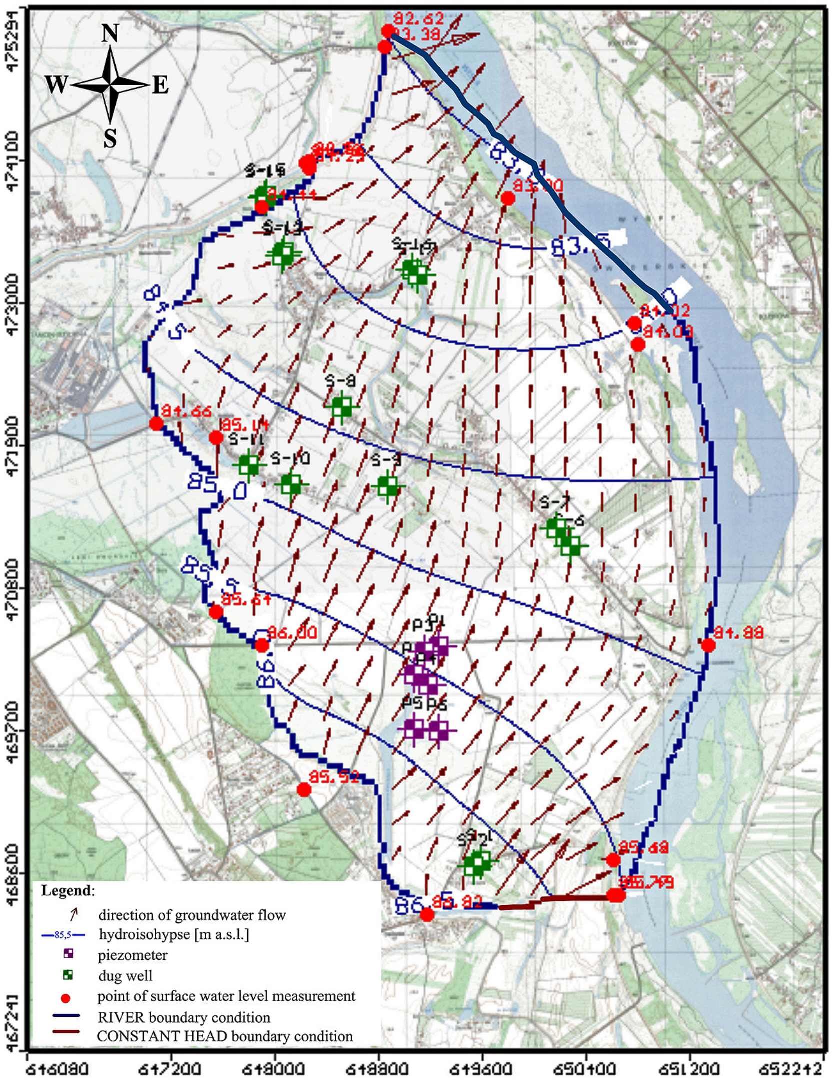

Fig. 5. Visualisation of the modelling area extracted from the Visual MODFLOW.

The infiltration rate obtained from the HELP model corresponds to the average infiltration rate that is characteristic of Poland. According to Witczak et al. (2013), for Polish conditions, the infiltration rate is equal to 100 mm/year and the velocity of vertical infiltration is equal to 3.2×10^{-9} m/s. Several researchers have reported that the infiltration of rainfall depended on properties of the material composing soil layers (e.g., Diamond & Shanley, 2003; Cesnulevicius, 2011) and had a significant impact on the replenishment of the groundwater level (Gworek et al., 2016; Koda et al., 2016).

A visualisation of the modelling area and its boundaries is presented in Figure 5. The *River* boundary condition was set around the entire area, with exception of the southern part where the *Constant Head* variant was applied. The model results show that the direction of groundwater flow is from south to north and the major portion of the study area is drained by the Vistula River.

The simulation of nitrate transport, with reference to doses of nitrogen applied with ammonium fertiliser, shows that nitrate concentrations in groundwater one year after fertilisation are lower than 0.2 mg/L (Fig. 6).

Compared with the groundwater quality standard presented in the Regulation of the Minister of the Environment of Poland (Rozporządzenie, 2016), it can be stated that the groundwater environment in the study area is of a good chemical status. With reference to the values of nitrate concentration in groundwater, the quality of groundwater can be defined as first class (concentration of nitrates lower than 10 mg/L). The results of modelled nitrate concentrations are also convergent with concentrations determined on the basis of laboratory measurements conducted for samples taken from piezometers located within the field of winter wheat production. The concentrations of nitrate in groundwater samples taken from piezometers located within agri-

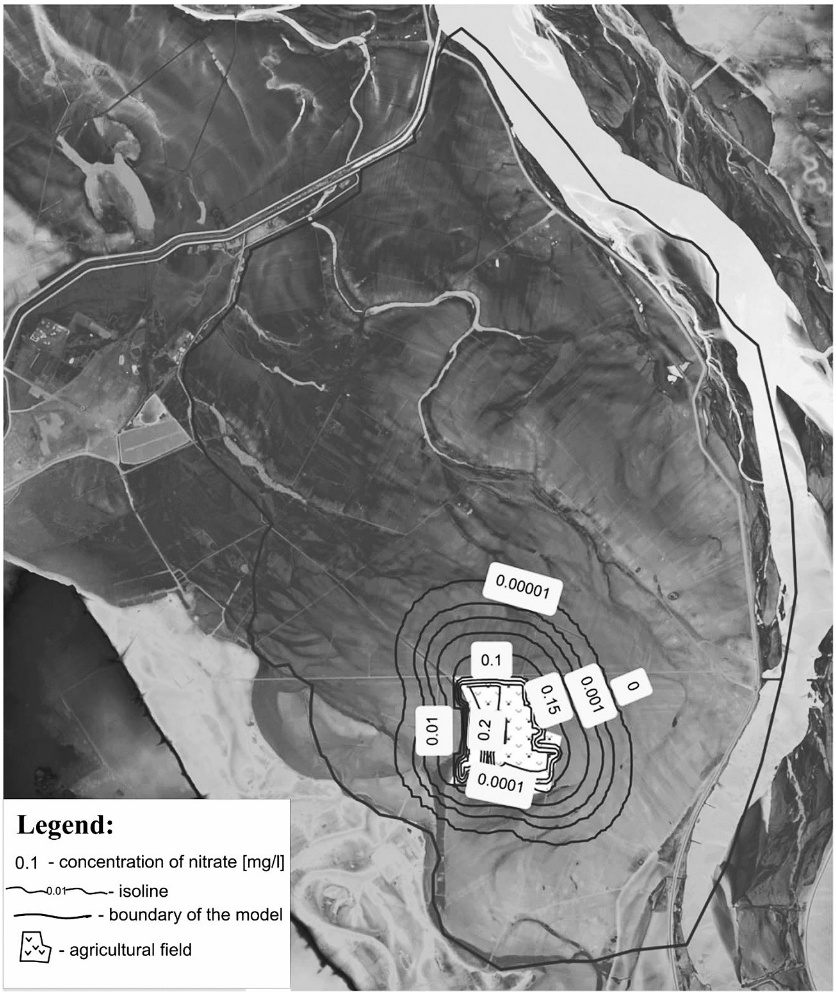

Fig. 6. Isolines of nitrate concentration in groundwater after one year of simulation.

cultural fields were in the range of 0.10–0.30 mg/L. The prediction of nitrate concentration with the use of the Visual MODFLOW software indicated concentrations of 0.21–0.38 mg/L. An absolute residual mean error calculated for values obtained from laboratory and modelling studies equalled 0.188 mg/L, the standard error of the estimate equalling 0.116 mg/L.

The extent of nitrate movement in groundwater was modelled in a 20-year-interval (Fig. 7). The results show a considerable decrease of nitrate concentration in groundwater, which is an effect of several processes that take place in the saturated zone. It was stated in our previous study (Sieczka et al., 2018) that nitrate transport was subjected to advection, hydrodynamic dispersion, sorption and biodegradation. The combination of these processes is a key factor in changes of nitrate concentration in the soil-water system.

Aljazzar & Al-Qinna (2016) reported that nitrate transport in coarsely textured soils was dominated by advection supported by low sorption capacity, while nitrate transport in loamy soils was primarily through diffusion. Moreover, it was detemined in our laboratory studies that cohesive soils tended to adsorb nitrate onto their surface. Where a cohesive layer occurs in the top part of a soil sequence, nitrate transport may be delayed. For example, for a silty loam the retardation of nitrate ions expressed by the value of retardation factor *R* equals 11, which means that the nitrate can be transferred in this soil more than ten times more slowly than the conservative marker (e.g., chlorides). Some results of retardation factors of nitrate compared to retardation factors of ammonium, obtained from our laboratory studies for various agricultural soils, are presented in Figure 8.

It was assumed that the occurrence of landforms characterised by different filtration parameters has a significant impact on groundwater flow in the floodplain area. These forms recognised in the study area concerned crevasses and zone of transformed floodplain (Bujakowski & Falkowski, 2017). It was also reported in our previous research (Sieczka et al., 2018) that in a situation of low and medium precipitation, these landforms, clearly visible

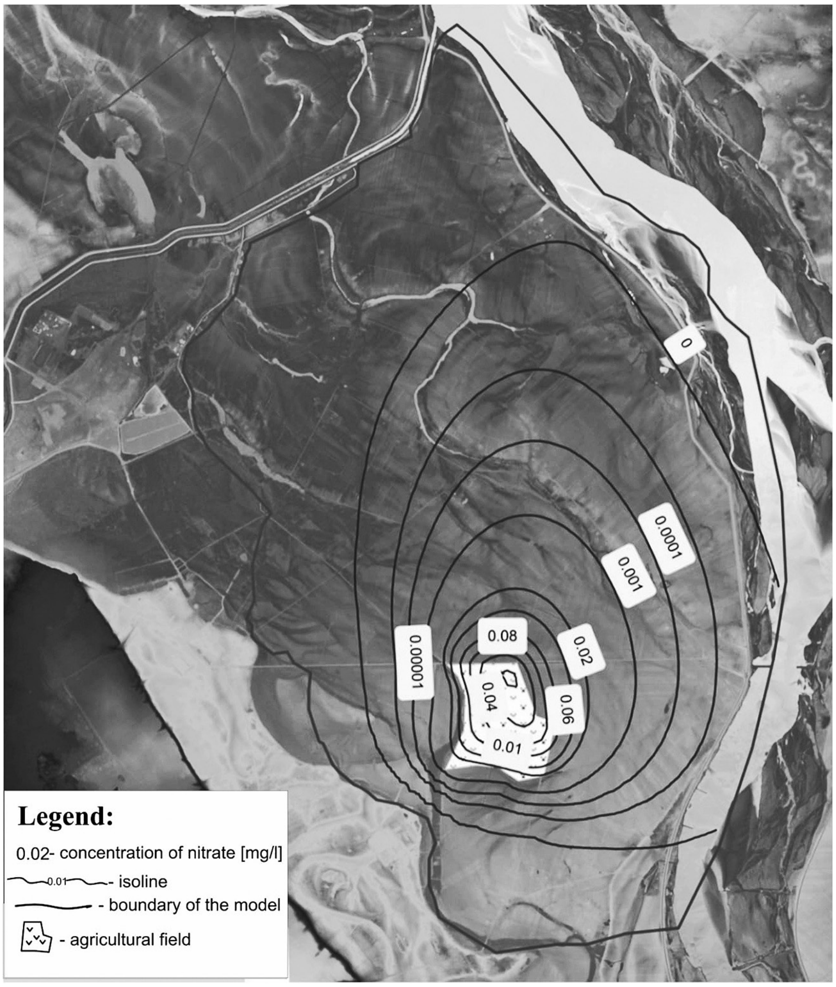

Fig. 7. Isolines of nitrate concentration in groundwater after twenty years of simulation.

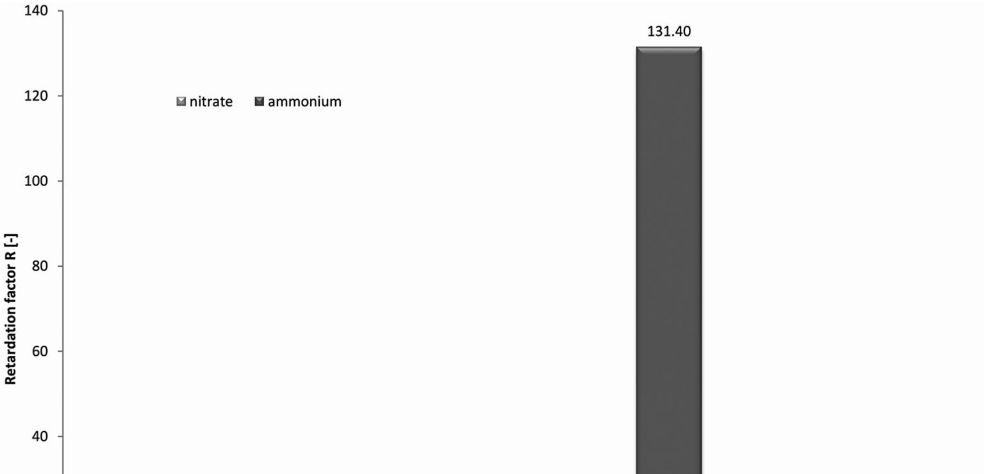

Fig. 8. Nitrate and ammonium retardation on various types of soils.

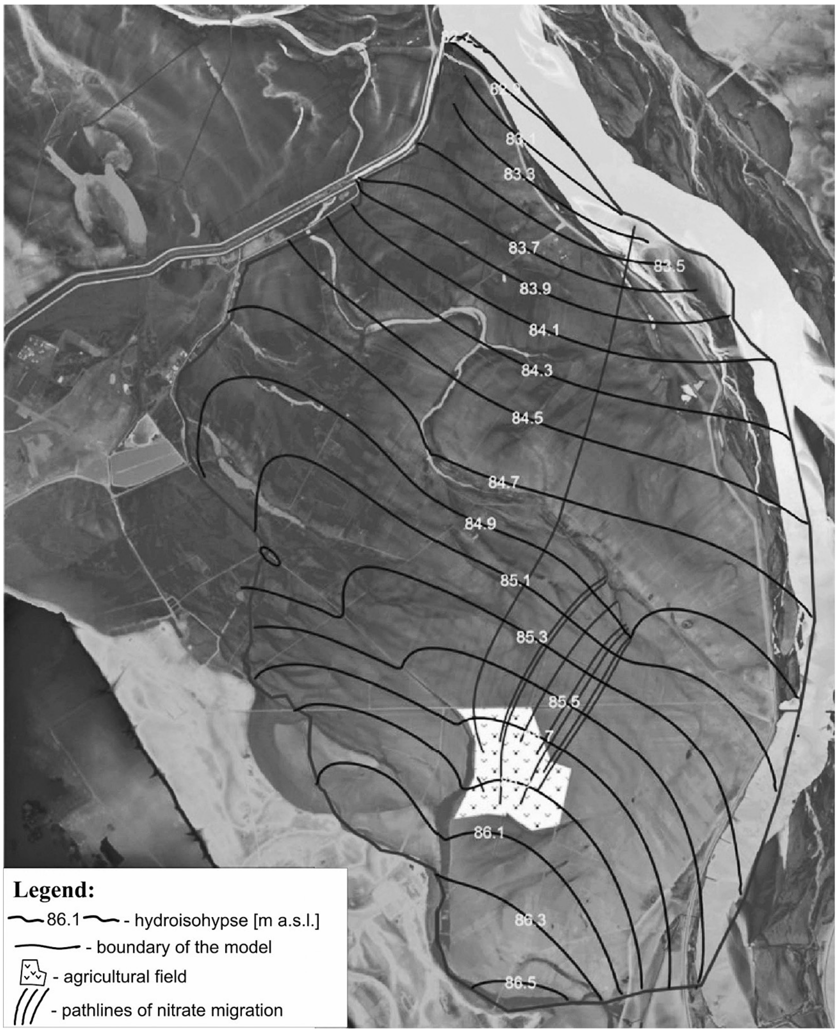

Fig. 9. Scenario of groundwater flow in periods of intense precipitation.

in the numerical terrain model (ALS data), have no impact on conditions prevailing at the first aquifer level. However, the zones mentioned are activated during high precipitation, creating a local drainage base. As a result, it may have a significant impact on a shortening of the time residence of water affected by nitrogen compounds in the aquifer. Moreover, it can limit the possibility of self-purification of the soil-water environment. A consideration of morphogenetic effects of a contemporary overbank flow can have an impact on calibration results of the hydrogeological model created (Bujakowski & Falkowski, 2017).

Several days with intense rainfall contribute to full saturation of the study area. The zone of the transformed floodplain, both those constituting a combined system of surface water courses as well as those masked in the landscape due to secondary filling with sediments, become zones of intense drainage (Fig. 9).

The present study has provided valuable information on the possible susceptibility to water pollution in the zone of the transformed floodplain. In practice, it may be a valuable premise in designing additional monitoring points to follow groundwater quality at that site, especially vulnerable to contamination at times of intense precipitation.

5. Conclusions

Optimisation of fertilisation techniques with the use of precision farming tools allows to reduce the doses of substances delivered to the environment and maintain a high production. Modelling of processes related to nitrate migration in groundwater allows for estimates of the amount of doses that have no negative impact on the soil-water environment. It also enables the identification of groundwater flow directions and makes an important contribution to the identification of drainage zones. The outcomes presented have revealed that using remote sensing starts to be an effective tool in identifying zones that are susceptible to pollution. Additionally, the outcomes of column studies performed for nitrate ions can be implemented as input data for hydrogeological modelling of migration of these compounds in the soil-water environment. The present study has revealed that the application of numerical modelling techniques for mapping the transport and fate in the unsaturated and saturated zone can be effectively performed using the HELP and Visual MODFLOW software for areas located in an agriculturally rich valley of a lowland river.

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