Letter to Editor

Hydrogeological Determinants of Migration of Potential Pollutants to Shallow Groundwater in the Mogilnica River Catchment

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Abstract

This study describes the hydrological conditions of migration of potential pollutants to shallow groundwater in the Mogilnica River catchment, classified as a typically agricultural lowland catchment in Poland. The assessment of vulnerability of aquifers to the inflow of pollutants from the ground's surface was conducted with the use of the GOD rank method introduced by Foster, and the method of calculation of contamination migration time through the aeration zone according to the formula of Bachmat and Collin. Using the data collected in the geographic information system, digital (screen system) maps were prepared for the catchment, illustrating the spatial distribution of the analyzed parameters. There were identified zones with different degrees of groundwater resistance, including areas that, owing to hydrological conditions, are the most vulnerable to the inflow of pollution. The collected data sets were compared with information on the method of development and use of the catchment, which was the basis for classification of the scale of hazard for groundwater from existing and potential anthropogenic activity.

Keywords: natural vulnerability, pollutants, migration, groundwater, catchment

Introduction

The dynamics and direction of change in groundwater systems depend, among other things, on their vulnerability to natural and man-made factors. These include pollutants that reach water-bearing horizons from the land surface featuring a variety of land-use patterns, and the change in the physico-chemical properties of water that they produce [1-3]. Degradation is largely a problem of shallow groundwater, but owing to hydraulic relations holding between water-bearing horizons it may involve the more extensive space in which water resources are formed [4].

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Natural groundwater vulnerability (specific, or inner, vulnerability) to the inflow of potential pollutants from the land surface is usually determined through an assessment of the hydrogeological parameters of aquifer structures and the water circulation system, including the conditions of their alimentation, flow and drainage [5]. When assessing specific vulnerability, the kinds of migrating pollutants are also described, which requires identification of their sources [6]. The contribution of the individual environmental elements to this process, however, varies greatly and is hard to interpret [7, 8].

An assessment of the natural resistance of groundwater bodies is performed at a variety of scales and for a variety of spatial units [9], including hydrogeological structures, e.g. a river valley [10, 11] and groundwater bodies; hydrographic units, e.g. a catchment [12, 13] and protected areas. Detailed analyses are also conducted on quasi-uniform surfaces, e.g. ones with similar land-use patterns, distinguished within larger spatial systems, which is especially significant with complex mathematical models and typology or regionalization tests. Diagnostic variable sets, created at each stage of groundwater system assessment, are the basis for preparation of maps and their vulnerability to anthropogenic activity. The collected geospatial data are reflected in the conceptual and mathematical models of groundwater systems that can be used on various levels of diagnostic and prognostic research [14-16].

Spatial differences in and the dynamics of processes involved in the penetration of pollutants from the land surface largely depend on the physical-geographic properties of the catchment as the basic space of formation of shallow groundwater resources. The assessment of hydrogeological conditions of migration of potential pollution to shallow groundwater was conducted for a typical lowland catchment used agriculturally. The object of research was the Mogilnica River catchment (Fig. 1) - a tributary of the Mosiński Channel (the Warta River drainage basin) located in the central part of the Wielkopolska Lowland (western Poland). This region is classified among the areas with the lowest precipitation recharge and the lowest water supplies in Poland, for which properly prepared strategies of development and water resources preservation are of fundamental significance. The assessment was carried out using Foster's GOD (Groundwater occurrence, Overlying lithology, Depth to water table) ranking method [17], and Bachmat and Collin's method [18] of assessment of the migration time of potential pollutants through the aeration zone. These methods are simplified from the point of view of the analyzed amount of diagnostic variables (3-4 diagnostic variables), but they require the application of spatial data, the obtaining and identification of which in relation to the catchment is quite a complex procedure. Hence, the reason behind this choice was, on the one hand, the access to detailed hydrological and morphological data of the catchment as the main criterion of pollution migration assessment, and on the other hand limited by the opportunity to verify the adopted models of distribution of the index of groundwater pollution vulnerability. With the use of both methods, the vulnerability index was determined and the time of migration of potential pollution to groundwater was calculated, and the interpretation of their spatial distribution was performed. At the successive stages of analysis, taking into consideration the level of human impact in the catchment, zones at the lowest and the highest risk to groundwater were identified as ones that require special care when planning new investment.

Verification of this type of model should be conducted on the basis of observation of groundwater quality in averaged time, made within a natural environment monitoring network. The Mogilnica River catchment is not sufficiently covered by environmental monitoring. There are two maps covering this area, a hydrographic and a sozological one, both at a scale of 1:50,000, which function as a database about conditions of the water cycle and also supply information about the local natural environment, level of investment, and transformation. The study indicates a possibility of adaptation of digital databases collected in GIS for spatial analysis of chosen characteristics of shallow groundwater.

Study Area

The area chosen for study was the Mogilnica River catchment (Fig. 1). With an area of 664,40 km^2, it is located in the Wielkopolska Lowland on the Poznań Upland and partly in the Warsaw-Berlin Pradolina, in the so-called Obra River Section [19].

The research focused on shallow groundwater of the catchment's potamic zone, which occurs in Quaternary deposits forming a ground horizon and an upper inter-till horizon with an average thickness of 1-5 metres. The ground horizon has formed in the sand-gravel deposits of the pradolina terraces in the south and partly in the zone of outwash patches in the east of the catchment. The upper inter-till horizon occurs in the upland zone (the Opalenica Plain), which is a dominant unit here, the zone of end-morainic hills (the Międzyrzecz-Pniewy Hills), and older glaciotectonic structures in the western part of the area (the

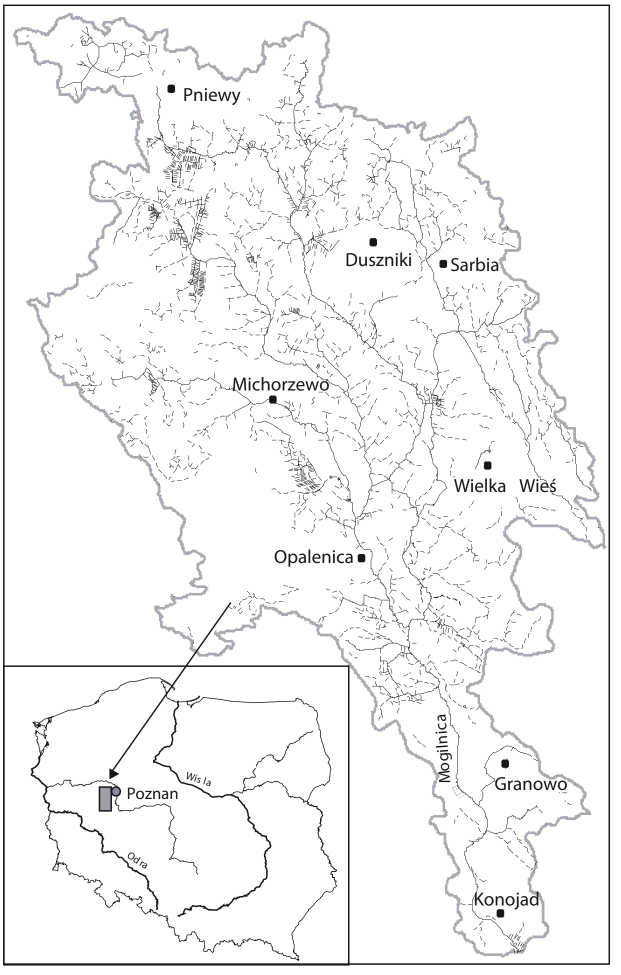

Fig. 1. Location and river net system in the Mogilnica River catchment.

Lwówek-Rakoniewice Rampart). Shallow groundwater can usually be found at a depth of up to 2 metres. The basic element in the lithology of the catchment's subsurface deposits is till (65%), which is an obstacle to alimentation of the water-bearing horizons and therefore screens them against the inflow of pollutants from the land surface. Only small fragments in the north (the Pniewy region) and west of the catchment are built of sandy deposits favourable to infiltration of precipitation, and hence to the migration of potential pollutants. The water-bearing horizon is also threatened by the inflow of groundwater from outside the study area. The degree of groundwater vulnerability to degradation is closely connected with the process of water renevability [20], which is of special importance in areas with low alimentation potential, and such is the Mogilnica River catchment.

According to A. Woś's climatic regionalization [21], almost the entire catchment lies in the Central Wielkopolska Region, which numbers among areas with the lowest rainfall in Poland which run in the range of 500-550 mm (1996-2000) and decrease towards the east. Precipitation shortage and high evaporation loss, which is proved by negative values of average annual climactic water balance, influence the runoff value [22]. Unitary runoff is below q= 3.0 $dm^3s^{-1}km^{-2}$ and counted among the lowest in Poland at the average value of q= 5.5 $dm^3s^{-1}km^{-2}$. The unfavourable structure of water balance in the area is also evidenced by the low runoff coefficient, which for the Mogilnica River catchment in the Konojad profile reaches the value of 0.14 at the average for Poland at 0.27. Predicted climactic changes indicate a real danger of further reduction of water reserves of the Central Wielkopolska region. Progressive warming has been observed, reflected in the increase of the average annual temperature, but no clear tendencies of changes have been observed in the field of precipitation. According to E. Żmudzka [23], precipitation level in lowland Poland did not show a significant change pattern in the 2^{nd} half of the 20th c.

Owing to a land-use pattern dominated by arable land and grassland (about 80%), the catchment is counted among typically agricultural areas in the Wielkopolska Lowland, the information on the formation and protection of water reserves are significant.

Research Procedure and Methods

Groundwater vulnerability to various forms of man's interference is interpreted as a natural feature of a water system describing its ability to transform [24, 25]. As to the assessment of groundwater vulnerability to pollution, several groups of methods can be distinguished, e.g. those relying on a classification of hydrogeological conditions, hydrochemical, parametric, ranking, and marker ones, those employing the calculation of migration time, digital simulation models, as well as statistical and geostatistical methods [26, 27]. Some of them have been discussed, e.g. by Krogulec [28].

A significant group of methods employed in the system of assessment of groundwater vulnerability to pollution is that of ranking methods (of parameter indexation), which include the GOD, DRASIC, DIVERSITY and GPSRI methods as well as those (empirical formulae) calculating the time of water migration through the aeration and saturation zones [29]. In those methods the number of input elements is variable, and the hydrogeological criteria usually include: depth to the groundwater table, soil water permeability, degree of isolation of the body of groundwater, and filtration parameters of the water-bearing structures. These data are supplemented by climatic criteria and characteristics of the use and level of development of the study area. The above methods do not accommodate the type and properties of the polluting substances, nor the hydrogeochemical processes that can occur during the migration of the pollutants.

In the assessment of vulnerability of groundwater to pollution in the Mogilnica catchment, the GOD rank method suggested by Foster was used. The flow time of water through the aeration zone, determined with the use of the empirical formula by Bachmat and Collin, was used to assess the scale and degree of shallow groundwater hazard from migration of potential pollution originating from the surface of the ground. The assessment of vulnerability of groundwater to contamination was conducted in several stages. The preparatory stage, with determining the so-called "Input" (a term introduced by Foster) to the assessment system, involves the obtaining and preparation of data sets pertaining to selected features and their schematization. At the stage of "Output" from the assessment system, they are processed into the form of vulnerability index or groundwater hazard value. The vulnerability indices (measures) employed often accommodate the total interactive effect of the most crucial environmental parameters of groundwater susceptibility to external influences. In the final result, based on the adopted concepts, there are prepared area distributions (in the form of a screen or vector map) of the susceptibility degree and classes of groundwater hazard from pollution.

In the analysis use was made chiefly of the sets of data collected in a geographic system of spatial information, including hydrographic and sozological databases as well as the hydrographic and sozological maps of Poland at a scale of 1:50,000 each, prepared on their basis. The material was supplemented with data obtained from geological, geomorphological, soil and land use, and other thematic maps. The selected characteristics of a shallow groundwater system were taken using the cartographic research method. In the procedure a raster data structure was adopted based on a local discretization grid with 2,870 calculation blocks and an area of 0.25 km^2 in which isotropic conditions were assumed while not excluding a variability of parameters among them. For every assessment field, the values of entry parameters were selected and then the exit index in the form of vulnerability degree and pollution migration time, which was in turn the basis for the assessment of the degree of groundwater hazard.

Table 1. Diagnostic variables (1-3) of the space of migration of potential pollutants and the index of vulnerability and scale of risk to shallow groundwater (4-5) in the Mogilnica River catchment.

(1) Isolation of water-bearing horizons			**(2) Lithology of subsurface deposits**			**(3) Depth to the groundwater level**		
Degree of screening	Area [km^{-2}]	%	Kind of deposits	Area [km^{-2}]	%	Depth zones	Area [km^{-2}]	%
Isolating	248.5	37.4	Till	439.2	66.1	< 2	378	56.9
Partly isolating	233.8	35.2	Organic soil (Peats)	183.4	27.6	2-5	227.9	34.3
Partly exposed	82.4	12.4	Fluvioglacial sands and gravels	5.3	5.5	5-10	41.9	6.3
Variable isolation (organic soil)	69.1	10.4	Dune sands	36.5	0.8	10-20	10.6	1.6
Exposed deposits	30.6	4.6				20-50	6	0.9

(4) Vulnerability of groundwater to pollution			**(5) Risk to groundwater resulting from the time of migration of pollutants**		
GOD index	Area [km^{-2}]	%	Risk /Time	Area [km^{-2}]	%
High	4	0.6	High / < 5 years	129.6	19.5
Moderate	25.2	3.8	Modereate / 5-25 years	368.7	55.5
Low	108.3	16.3	Low / 25-100 years	152.8	23
Very low (variable)	526.9	79.3	Practically no risk / > 100 years	13.3	2

In the GOD procedure an assessment is made of three elements: degree of isolation of the water body (Input 1), type of subsurface deposits (Input 2), and depth to the groundwater table (Input 3). Those characteristics are each assigned a multiplier value which differentiates the rank of the given characteristic in the inflow of pollutants from the surface. The index of groundwater vulnerability to pollution (Output) is calculated as a product of the three multipliers (GOD = I_1 x I_2 x I_3) and assumes values between 0 and 1. According to the GOD formula, vulnerability can be classed as very low (0-0.1), through low (0.1-0.3), moderate (0.3-05) and high (0.5-0.7), to very high (0.7-1.0).

The level of isolation of the water-bearing horizons was determined through the analysis of the lithological properties of soils and their permeability. Using the hydrographic database, at the preliminary stage, there were indicated soils with varying permeability degrees: average, poor, very poor and variable (organic soils), and diversified (anthropogenic soils), which were then assigned the proper isolation degree. In this procedure a hydrogeological classification of deposits by the criterion of water permeability was performed. There were distinguished in the Mogilnica River catchment five groups of deposits with different screening properties (Table 1): exposed deposits (regolith, gravels, sands of various grain sizes), partly exposed, partly isolating, and isolating (packed soils, tills, silts, and man-made soils). Organic soils, whose permeability varies owing to periodic changes in humidity, were put in the class of those with temporally variable isolating properties. The analysis showed those partly and fully isolating to be dominant; they occupy a total of 72.6% of the catchment area. The least extensive (about 6%) are exposed soils, which can largely be found in the watershed zones.

On the basis of the available data and thematic maps, the types of deposit and the thickness of the aeration zone were described. The area distribution of subsurface formations relates directly to the distribution of the isolation degree and soil permeability classes. The result indicates that the area considered is dominated by morainic upland tills (Table 1), together with those of the end-morainic zone they cover most of the catchment area (66%). The smallest area is covered with dune sands that occurs in the south-western part of the catchment. Fluvioglacial sands and gravel spread in the eastern part of the catchment, mainly from the northwest to southeast and organic soil (peats) occurs mainly along basic watercourses.

The distribution of depths to the groundwater table in the catchment was obtained from the pattern of hydroisobaths, which is entered in a hydrographic database under a concrete date of field mapping. To obtain comparative data and determine boundary values for the groundwater system under study, this information was supplemented with regime characteristics, which allowed a verification of the depth distribution of the groundwater table, and hence of the thickness of the aeration zone under average and extreme conditions. An analysis carried out for average conditions revealed that the groundwater table of the first water-bearing horizon in the Mogilnica River catchment occurred at a depth of 0.5 m to 25 m below ground level, but in most of the area (48.2%) it could be found at a depth of 1-2 m b.g.l. Together with the zones of the shallowest groundwater occurrence (0-1 m b.g.l.), they occupy more than 50% of the total catchment area (Table 1).

The prevalence of areas with a shallow-lying groundwater table can be a factor favourable to the supply of pollutants from the land surface, in the absence of an isolating surface.

However, in the case of the Mogilnica River catchment, this situation can only affect local zones where the subsurface structure of tills has been transformed, e.g. there has appeared a crack or a flattening. Zones with an elevated filtration coefficient developing in till covers are privileged places in groundwater alimentation.

The calculation of the time of water infiltration through the aeration zone (t) according to Bachmat and Collin's formula (t= dMv/EI) requires the following variables: thickness of the aeration zone - depth to groundwater (d), average moisture by volume of deposits in the aeration zone (Mv), and index of annual effective infiltration of precipitation (EI). On the basis of the estimated migration time, groundwater bodies are classed from ones at practically no risk (time in excess of 100 years), through those for which the risk is low (25-100 years), moderate (5-25 years), high (2-5 years), to very high (below 2 years).

In a part of the assessment of migration of potential pollution originating from the surface of the area, there were data sets collected at the stage of the GOD index component analysis. It concerned mainly the types of formations and the thickness of the aeration zone. In the study, at the stage of entry data preparation, land (soil) groups were selected, with different degrees of influence on local water circulation (soil maps), and also on the process of rainwater infiltration into shallow groundwater. The basis was the identification of homogenous zones of the water regime and then the use of these data in the spatial variability analysis of the time of pollution migration through the aeration zone. The migration time of water (pollution) through the aeration zone, estimated on the basis of the formula used, refers to the hydrological cycle occurring at average conditions of recharge and loss of water from the water-bearing system; therefore, it is also dependent on the humidity degree of subsurface soil. In determining the volumetric moisture of the aeration zone soil, there were adopted values suggested by S. Witczak and A. Żurek [30]. The effective infiltration index of precipitation, which is also taken into account in an empirical formula, was taken from E. Gawron [31]. There is a predominance of areas (67%) in which effective infiltration was less than 50 mm per year (5% of annual rainfall). The highest effective infiltration figures exceeded 150 mm and were calculated for areas with a favourable type of groundwater alimentation and the effective infiltration index even amounting to 20-30% of annual rainfall.

The information about the vulnerability (the GOD index) and class of risk to groundwater posed by the migration of

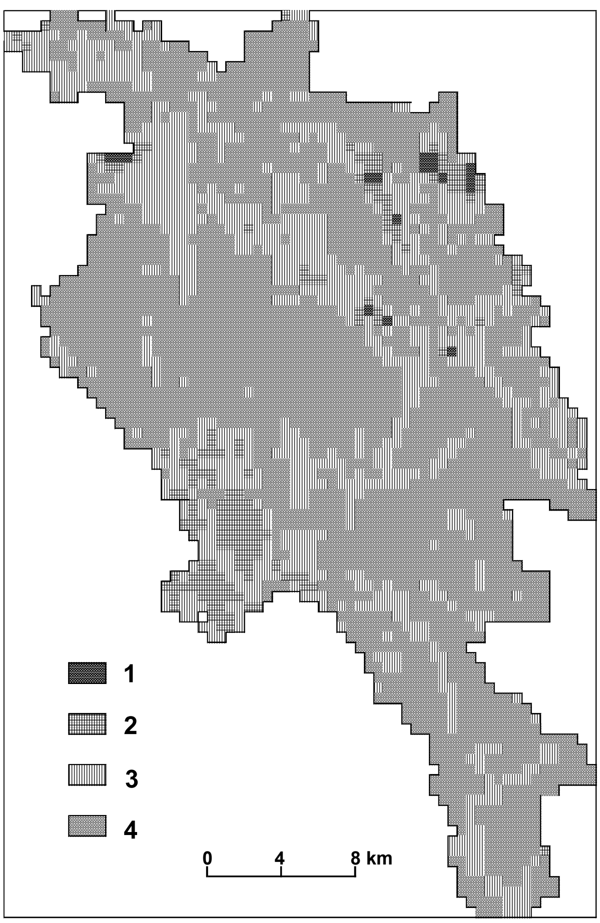

Fig. 2. Vulnerability of groundwater to pollution from the land surface (the GOD method) – an Output stage: 1- high, 2- moderate, 3- low, 4- very low (variable).

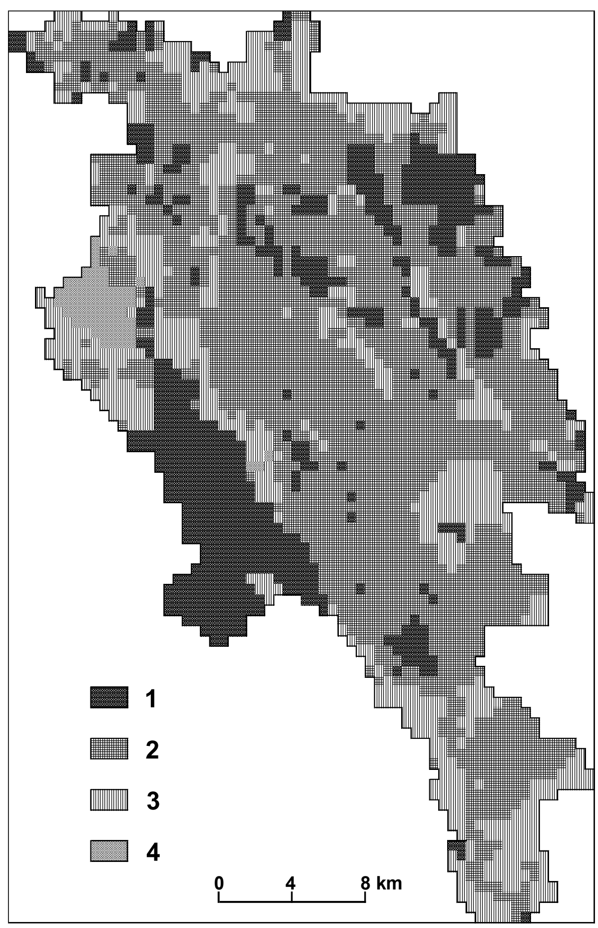

Fig. 3. Risk to groundwater resulting from the time of migration of water through the aeration zone – an Output stage: 1- high (<5 years), 2- moderate (5-25 years), 3- low (25-100 years), 4- practically no risk (> 100 years).

potential pollutants in the Mogilnica River catchment was compared with data on the land-use pattern in the catchment and the spatial distribution of point pollution sources in the form of storage yards of raw materials and fuels, and municipal refuse tips. In addition, using the sozological database, those ventures were located in a catchment that may significantly affect the environment, including the ecological state of the groundwater system, e.g. chicken or pig farms.

Discussion of Results

Using the assumptions of the adopted methods of assessment of groundwater vulnerability, an analysis was made of the spatial distribution of basic hydrogeological parameters controlling the conditions of alimentation and the possibility of pollutants penetrating along this pathway from the land surface to the aquifer systems. The parameters included in this group were quasi-stationary and variable in time, e.g. depth to the groundwater table, which depends among other things on the frequency of humid and dry periods determining the alimentation potential of the water-bearing horizons.

Because of the type of subsurface formations (moraine tills) and their isolating character, it was assumed in the initial stage of the analysis that vulnerability of groundwater to contamination, mainly of the area type, should be low and the degree of hazard from external influences - insignificant. In the zones where organic formations occur, it was assumed that the degree of groundwater vulnerability to the inflow of pollution is highly dependent on the degree of soil humidity. In periods of high humidity, organic soil is the zone limiting precipitation infiltration and in dry periods, the coefficient of hydraulic conductivity for peats can reach 10^{-3} ms^{-1}.

When analyzing the distribution of the GOD vulnerability index, only four out of the five degrees of groundwater vulnerability to pollutants from the land surface were identified in the Mogilnica River catchment (Fig. 2). The groundwater was found to show a low degree of vulnerability, at 0.1, with very low (0-0.1) and high (0.5-0.7) as the extreme degrees. Values describing the degree of vulnerability as very high (0.7-1.0) were not recorded. Groundwater with very low, though variable, vulnerability could be found in 80% of the area, while zones where groundwater was at high risk occupied a mere 0.6% (Table l). This follows from the fact that most of the catchment area is covered with till, which screens the shallow groundwater from the inflow of pollution. High vulnerability was determined in the north of the catchment, while zones where groundwater was found to be moderately vulnerable were identified mainly in the southwestern and northeastern parts of the catchment.

The results obtained with the help of the GOD method follow from the criteria and assumptions adopted, hence there is a strong dependence of the vulnerability index on the kind of subsurface deposits and depth to the groundwater table, i.e. elements relating to the structure and state of the aquifer system. Studies of groundwater dynamics in the Mogilnica River catchment have shown there to be significant variations in the position of the water table at a given stage of resource formation, especially in zones of its shallowest occurrence, i.e. to a depth of 2 m, significant changes in the position of the water table in a particular phase of resources formation, which may influence the variation in the index of vulnerability of water to pollution. Vulnerability of shallow groundwater to anthropogenic influences will increase during replenishing of water resources, when rising of the water table is usually registered, which means the decrease of the depth of its occurrence. In the conditions of limited recharging or its absence, when water resources are drawn in, the lowering of the water table lengthens the path of potential pollution from the soil surface.

The assessment of the degree of risk to groundwater in the Mogilnica River catchment resulting from the migration time of water through the aeration zone showed more than half of the area (about 56%) to be at moderate risk and nearly 20% at high risk (Fig. 3). This means that the migration of potential pollutants can take from 5 to 25 years and from 2 to 5 years, respectively (Table 1). The remaining groundwater is generally at low risk (23%) or at no risk at all (2%). Highly threatened areas were found mostly in the southwestern and fragments of the northeastern and central parts of the catchment. No zones were identified in which groundwater would be very strongly (< 2 years) susceptible to the migration of potential pollutants. In this case the elements modifying the conditions of inflow of pollutants to groundwater from the land surface are the pathway (thickness of the aeration zone) and the speed of vertical migration, which are considered parameters variable in time.

The groundwater bodies most vulnerable to pollution were those in sandy zones devoid of an isolating overlay, and hence of a protection against the inflow of polluting substances. These zones roughly coincide with areas for which the calculated pollution migration time was shorter than 5 years. This land is largely covered with woodland complexes showing (15%) a low level of transformation and development, hence the human impact on the groundwater environment here is only slight. However, one cannot rule out a situation when the inflow of pollutants to groundwater will form outside the zone of its occurrence.

In river valleys the element making groundwater highly vulnerable to degradation is a small thickness of the aeration zone, about 1 m, and often an absence of deposits screening it from the surface. Besides, river valleys as zones of concentration of groundwater flow can be places of accumulation of groundwater-borne pollutants [32, 33].

Given the agricultural use of the catchment, one should first of all consider an areal inflow of pollutants [34], especially to groundwater, whose table lies at a depth of no more than 2 m b.g.l. In the study area elevated levels of nitrogen compounds were recorded in groundwater, which puts the communes of Buk, Duszniki and Opalenica situated in the Mogilnica River catchment in the class of zones at special risk, ones in which the outflow of nitrogen from agricultural land should be reduced. Besides, the threat to groundwater in the catchment is amplified by point sources of pollutants in the form of storage yards of raw materials and fuels, and municipal refuse tips (more than 100 objects), which were identified using the sozological database. There are also other kinds of activity found in the Mogilnica River catchment that may significantly affect the hydrosphere, including the ecological state of the groundwater system, e.g. chicken or pig farms (Sarbia, Michorzewo). Another problem is the lack of sewage in many scattered settlement units, which enhances the risk of shallow groundwater being contaminated with household sewage.

The use of the GOD ranking method and the method based on the pollution migration time to assess the vulnerability of shallow groundwater in the Mogilnica River catchment to pollutants, made it possible to distinguish zones showing various degrees of resistance to man-made factors. In evaluating the vulnerability of shallow groundwater to the inflow of potential pollutants from the land surface and the risk this posed, account was taken mainly of hydrogeological determinants of the migration process: the degree of isolation of the water-bearing horizons, kinds of subsurface deposits, and depth to the groundwater table. However, there are also many other natural and man-made factors which greatly affect the movement and accumulation of water-borne compounds. Hence the results obtained with the help of the above methods should be treated as approximate estimates, owing to the incomplete knowledge of the aquifer system as well as several simplifications and the schematisation of data. The results of modelling of potential groundwater vulnerability based on ranking and matrix methods are usually interpreted in terms of a tendency or probability, which requires their verification through the monitoring of groundwater quality [35]. A similar inverse relation between the results of vulnerability indices (e.g. DRASTIC) and the real groundwater pollution was observed by, among others, the authors of the EPA [36] and GAO/PEMD [37] reports. In order to compare the (temporary) results of groundwater quality measurements with the results of the vulnerability model, the conditions of introduction of pollution into the environment should be taken into consideration, or it should be assumed that it was introduced evenly on the entire tested area. Such data are possible to obtain only in experimental catchments. In addition, in the case of verification of vulnerability models, there often appears the problem of representativeness of point measurements in the assessment of the quality of the spatial model.

Conclusions

The obtained picture is exclusively a product of the criteria adopted, dominant among which is a group of selected hydrogeological parameters. In the methods employed, the analysis focuses on the spatial variability of the parameters rather than on the hydrodynamic state of the groundwater table and relations between the zones of its alimentation and drainage. In the method of calculating the migration time of pollutants, taking into consideration elements connected with the infiltration type of alimentation improves the amount and quality of information, which allows a more detailed analysis of factors controlling the process in question. Of crucial significance for the protection of groundwater against pollution are zones of its direct alimentation, which are also privileged areas in the migration of potential pollutants. Besides, the stream of groundwater moving to the drainage zones can also form of waters from regions where the groundwater regime largely depends on alimentation from neighbouring areas. In the Mogilnica River catchment it was found that shallow groundwater could be nourished by confined water, and that the Wielkopolska Buried Valley, the chief exploitation level, could be nourished by waters of the ground horizon, especially in the zones of hydrogeological windows [38].

A quantitative expression of the characteristics of individual catchment subsystems, including shallow subsurface water, is a starting point for conducting spatial analysis of variability of individual parameters and comparative analyses between various units, e.g. catchments or groundwater reservoirs. Apart from that, characteristics of the shallow groundwater system are used to prepare conceptual models and mathematical models of water filtration or pollution transport [39, 40], that are created for uniform groundwater bodies, according to the guidelines of the Framework Water Directive. The results of analyses of the degree of groundwater vulnerability and hazard from pollution will be a fundamental element in determining the strategy of balanced use of water resources in agriculturally used catchments.

References

1. ŁUCZKIEWICZ A., QUAN B. Soil and Groundwater Fecal Contamination as a Result of Sewage Sludge Land Application. Polish Journal of Environmental Studies **16**(4), 587, **2007**.
2. POLKOWSKA Ż., ZABIEGAŁA B., GÓRECKI T., NAMIEŚNIK J. Contamination of Runoff Waters from Roads with High Traffic Intensity in the Urban Region of Gdańsk, Poland. Polish Journal of Environmental Studies **14**(6), 799, **2005**.
3. TALALAJ I. A., DZIENIS L. Influence of Leachate on Quality of Underground Waters. Polish Journal of Environmental Studies **16**(1), 139, **2007**.
4. SEILER K-P., LINDNER W. Near- surface and deep groundwater. Journal of Hydrology **165**(1-4), 33, **1995**.
5. ROBINS N.S. Groundwater pollution, aquifer recharge and vulnerability. Geol. Soc. Lond Spec. Publ. 120, **1998**.
6. ŻUREK A., WITCZAK S., DUDA R. Vulnerability assessment in fissured aquifers. Groundwater quality and vulnerability. Rubin H., Rubin K., Witkowski A.J. (ed.). Studies of the Department of Earth Sciences of the Silesian University, Sosnowiec, **22**, 241, **2002** [In Polish].
7. WINTER T.C. Relation of the streams, lakes and wetlands to groundwater flow systems. Hydrogeology Journal **7**, 28, **1999**.
8. SCANLON B.R., GOLDSMITH R.S. Field study of spatial vulnerability in unsaturated flow beneath and adjacent to playas. Water Resources Res. **33**, 2239, **1997**.
9. ZIJL W. Scale aspects of groundwater flow and transport systems . Hydrogeology Journal **7**, 139, **1999**.

10. MAGNUSZEWSKI A. Geographical information systems in ecohydrological studies. Case study of Vistula River near Plock. Warsaw University. Faculty of Geography and Regional Studies. Warsaw, pp. 113, **2002** [In Polish].
11. MĄDRALA M. Hydrogeochemical valuation of river valley environment apply for groundwater exploitation. Contemporary problems of hydrogeology, Sudety Annexe Publishing , Wroclaw, **10** (1), 357, **2001** [In Polish].
12. GRAF R. Assessment of the susceptibility of shallow-lying groundwater to pollution as a basis for protective measures in a catchment. Environmental assessment in physical planning. Kistowski M. Korewl-Lejkowska B. (ed).The Problem of Landscape Ecology. Gdansk- Warsaw **19**, 297, **2007** [In Polish].
13. SUCHOŻEBRSKI J. Assessment of conditions for migration of pollutants to groundwater in upper Wilga basin. Geographic research and studies, Warsaw, **31**, 153, **2002** [In Polish].
14. SOKOL G., LEIBURGIT C., SCHULZ K. P, WEINZIERL W. Mapping procedures for assessing groundwater vulnerability to nitrates and pesticides in Application of Geographic Information System in Hydrology and Water Resources Management. International Association of Hydrological Sciences **211**, 80, **1993**.
15. DALY D., DASSARGUES A., DREW D., DUNNE S., GOLDSCHNEIDER N., NEALE N., POPESCU I. C., ZWAHLEN F. Main concepts of the European approach for karst groundwater resource assessment and mapping. IAH Hydrogeology Journal **10**, 340, **2001**.
16. DALY D., WARREN W. P. Mapping groundwater vulnerability: the Irish perspective. Geological Society Special Publication **130**, 179, **1998**.
17. CHEŁMICKI W. Water - resources, degradation, preservation. Scientific Publishing (PWN). Warsaw, 306, **2001** [In Polish].
18. MARCINIAK M., PRZYBYŁEK J., HERCIG J., SZCZEPAŃSKA J. Research of coefficient of hydraulic conductivity of aquiotards. Sorus Publishing. Poznan – Cracow, pp. 101, **1999** [In Polish].
19. KONDRACKI J. Regional geography of Poland. Scientific Publishing (PWN). Warsaw **1998** [In Polish].
20. LERNER D.N. Groundwater recharge [w] Geochemical processes, weathering and groundwater recharge in catchments. Saether O.M, de Caritat P (Ed) AA Balkema, Rotterdam, pp. 109-150, **1997**.
21. WOŚ A. The climate of the Wielkopolska Lowland. Adam Mickiewicz University Publishing. Poznan, **1994** [In Polish].
22. KOWALCZAK P., MAGER P., KĘPIŃSKA-KASPRZAK M. An assessment of water resources in the context of predicted climate changes in the Wielkopolskie District area. Climate changes - opportunities, risks, adaptations. Materials of Conference. Poznan, pp. 70, **2007** [In Polish].
23. ŻMUDZKA E. On the variability of precipitation in lowland Poland in the 2nd half of the 20th century. Institute of Meteorology and Water Management Messages. Warsaw, **25**, 4, **2002** [In Polish].
24. VRBA J., ZAPOROZEC A. eds.: Guidebook on mapping groundwater vulnerability. IAH, "International Contributions to Hydrogeology". 16, Heise Verlag, Hannover, **1994**.
25. GRAF R. The use of Poland's Hydrographic Map of scale 1: 50,000 in the evaluation of groundwater susceptibility to pollution. Thematic cartography in geographical environment planning. Materials of National Cartographic Conference. Adam Mickiewicz University, Bogucki Publishing, Poznan **25**, 219, **2004** [In Polish].
26. MAXE L., JOHANSSON P.O. Assessing groundwater vulnerability using travel time and specific surface area indicators. Hydrogeological Journal **6**(3), 441, **1998**.
27. WITCZAK S., ŻUREK A., DUDA R. Methodology of determining zones susceptible to nitrate leaching. Materials of Conference Hydrochemistry. Bratyslawa, pp. 12-16, **2003**.
28. KROGULEC E. An assessment of groundwater susceptibility to pollution in river valleys on the basis of hydrodynamic factors. Warsaw University Publishing, Warsaw, pp. 176, **2004** [In Polish].
29. ARTUSO E., OLIVEIRA M. M., LOBO FERREIRA J.P. Assessment of Groundwater Vulnerability to Pollution using six different Methods: AVI, GOD, DRASTIC, EPPNA and SINTACS. Application to the Evora Aquifer. LNEC, Rel. 184/02- GIAS, **2002**.
30. WITCZAK S., ŻUREK A. The use of soil maps in the assessment of protective part of soils to groundwater. Methodical bases of protection of groundwater, Kleczkowski A.S. (ed). AGH-University of Science and Technology Publishing, Cracow, **1994** [In Polish].
31. GAWRON E. Susceptibility of shallow groundwater to pollution migration in the Mogilnica catchment Department of Hydrology and Water Management. Adam Mickiewicz University. (Archive- typescript). Poznan, **2006** [In Polish].
32. BOSZKE L., SOBCZYŃSKI T., GŁOSIŃSKA G., KOWALSKI A., SIEPAK J. Distribution of Mercury and Other Heavy Metals in Bottom Sediments of the Middle Odra River (Germany/Poland). Polish Journal of Environmental Studies **13**(5), 495, **2004**.
33. KOWALSKI A., SIEPAK M., BOSZKE L. Mercury Contamination of Surface and Ground Waters of Poznań, Poland. Polish Journal of Environmental Studies, **16**(1), 67, **2007**.
34. FOSTER S. S. D., CHILTON P. J., STUART M. E. Mechanisms of groundwater pollution by pesticides. Journal of Institution of Water and Environmental Management **5**, 186, **1991**.
35. BURMASTER D., Learh J. It's time to make risk assessment a science. Ground Water Monitoring and Remediation **11**(3), 5, **1991**.
36. EPA. Another Look: National Survey of Pesticides in Drinking Water Wells. United States Environmental Protection Agency, **1992**.
37. GAO/PEMD General Accounting Office, Program Evaluation and Methodology Division. Differential Groundwater Protection Strategy. Washington, **1992**.
38. DĄBROWSKI S. Hydrogeology and groundwater protection conditions of the Wielkopolska Buried Valley. Agricultural Academy Publishing. Warsaw, **1990** [In Polish].
39. MARTIN P. J., GOMES D. C., IRITANI M., GUIGUER N. An Integrated Groundwater Management Using Modeling and GIS. Proceedings of the Groundwater in a Watershed Context Symposium, Canada Centre for Inland. Waters, Burlington, Ontario **3**, 137, **1998**.
40. KAZIMIERSKI B. The description versus the conceptual model of the Groundwater Body (GWB). Geologos **10**, 131, **2006**.