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DRASTIC assessment of groundwater vulnerability to pollution in the Vistula floodplain in central Poland

Ewa Krogulec and Joanna Trzeciak

ABSTRACT

Assessment of groundwater vulnerability to pollution was conducted by the DRASTIC method in central Poland, in the Vistula River valley. The results of this study have shown that 68.18% of the study area has a low pollution potential and 31.2% has a medium pollution potential. Single-parameter and map removal sensitivity analyses were conducted to evaluate the relative importance of the parameters for aquifer vulnerability. Both analyses showed that by far the most significant parameter of the DRASTIC vulnerability index in the study area is the depth to the water table. Although the water table in more than 90% of the study area is shallow, less than 3 m below ground level, the assessment shows that this does not lead to a high groundwater vulnerability.

Key words | floodplain, groundwater, groundwater-dependent ecosystems, intrinsic vulnerability, Poland

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INTRODUCTION

Groundwater vulnerability assessment is becoming an increasingly important environment management tool for local governments. Assessment of the vulnerability of groundwater to pollution can also be an element of flood risk assessment in areas where groundwater location is shallow and highly permeable sediments offer no natural protection. Such assessment is particularly important considering the EU Commission Directive dated October 23, 2007 on the assessment and management of flood risks (Directive 2007/60/Ec 2007).

The widely accepted concept of groundwater vulnerability was put forward by the US National Research Council in 1993. Groundwater vulnerability is defined as the tendency of contaminants to reach a specified position in the groundwater system after their introduction at some location above the uppermost aquifer (Worrall & Besien 2004; Rahman 2008). Vulnerability is usually considered as an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts (Bachmat & Collin 1987; Van Duijvenbooden & Waegeningh 1987; Barrocu & Biallo 1993; NRC 1993; Vrba & Zaporozec 1994). In the adopted term of vulnerability, it is assumed that pollution occurs as a result of an advective model of transport from the surface of the terrain to the groundwater. Sorption and other processes concerning the behavior of polluting substances in soils, zones of aeration, the water-bearing layer, etc., are not considered (Andersen & Gosk 1987). Various methods have been developed to estimate groundwater vulnerability and pollution risk under different hydrogeological and socioeconomic conditions (Tesoriero *et al.* 1998; Al-Adamat *et al.* 2003; Lake *et al.* 2003). One of these methods is DRASTIC, which is based on seven hydrogeological-environmental parameters. DRASTIC is the most widely used standard groundwater vulnerability assessment method, developed by the United States Environmental Protection Agency (EPA) as a method for assessing groundwater pollution potential.

This paper documents a DRASTIC assessment of groundwater vulnerability to pollution in the floodplain of the Vistula River in central Poland. The choice of the DRASTIC method was dictated by its wide application in many regions that gives the opportunity to compare obtained results.

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Two sensitivity analyses were performed to appreciate the effect of each parameter on the intrinsic vulnerability maps: the single-parameter sensitivity analysis and the map removal sensitivity analysis. Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to each parameter and helps decision-makers to judge the significance of subjective elements (Gogu & Dassargues 2000). It also allows subjectivity to be reduced to some extent (Pathak *et al.* 2009).

STUDY AREA

The study area is the floodplain terrace of the Vistula River in central Poland (Figure 1). It cover 136.2 km^2. Of this area, 7% is located within the Kampinoski National Park (KNP) and the remaining 93% is the special protective zone of the park. Development of the floodplain terrace is characterized by dense single-family housing of small towns, as well as recreational-tourism

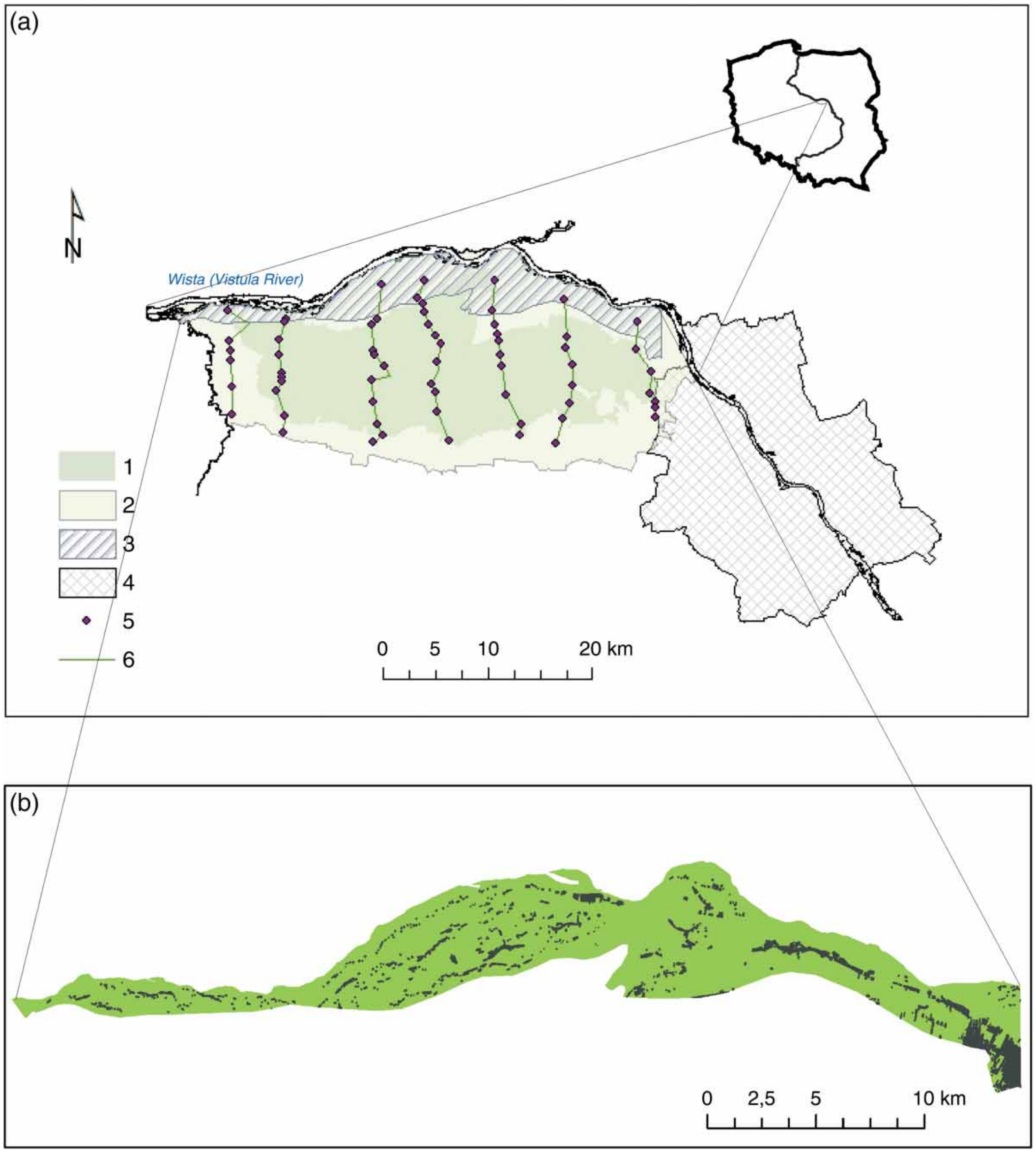

Figure 1 | Location of the study area. (a) 1, Kampinos National Park; 2, protective zone of the Kampinos National Park; 3, Vistula River floodplain terrace; 4, city of Warsaw; 5, piezometers of the KNP groundwater monitoring system; 6, lines of the monitoring system and line of schematic cross-section (Figure 2). (b) Residential and service buildings within the Vistula River floodplain terrace.

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and farming activities, especially ecological farming (Krogulec 2004).

Quaternary sediments occur in the entire area of the KNP and its protective zone, and are a collector of groundwater. A schematic south to north geological cross-section of these Quaternary sediments is shown in Figure 2. The top of tertiary loams forms the base of the quaternary water-bearing layer and occurs in the range of 2 to 54 m above sea level (a.s.l.). A clear dichotomy of this unconfined aquifer, of a total thickness up to 50 m, is connected with its lithological shape. The top part of the aquifer has a sandy and sandy-gravel character; the bottom is created by sandy-silt sediments, in places changing to sandy clay, clay and till. The higher part of the water-bearing layer (thickness from 8 to 17.5 m) is characterized by a value of the coefficient of permeability within the range of 30 to 71 m/d. For the bottom part of the layer (thickness from 18 to 36 m), the coefficient of permeability is clearly lower and amounts to under 30 m/d (Krogulec 2004).

On the floodplain terrace of the Vistula River in the KNP area, the top layer is created by sandy silts, fine-grained sands lie below, while hiatal sands constitute the lowest layer. The surface of the aquitard created by glacial tills and more often Pliocene loams, constitutes the floor of the Quaternary aquifer (Krogulec 2011).

DRASTIC METHOD: APPLICATION OF THE DRASTIC METHOD TO THE STUDY AREA

DRASTIC (Aller *et al.* 1987) is a method used to assess groundwater vulnerability to a wide range of potential contaminants and it is a standard tool applied in many countries (Rosen 1993; Vrba & Zaporozec 1994; Witczak *et al.* 2007). DRASTIC is an overlay-and-index method that was developed for the US Environmental Protection Agency by the American Water Well Association (Aller *et al.* 1987). Specific parameters considered in the DRASTIC method are analyzed as spatial information, which can be obtained directly or indirectly from many sources.

Calculations of the DRASTIC index are conducted according to the following formula (Aller *et al.* 1987):

$$\mathrm{DI} = D_{\mathrm{RA}}D_W + R_{\mathrm{RA}}R_W + A_{\mathrm{RA}}A_W + S_{\mathrm{RA}}S_W + T_{\mathrm{RA}}T_W + I_{\mathrm{RA}}I_W + C_{\mathrm{RA}}C_W \quad (1)$$

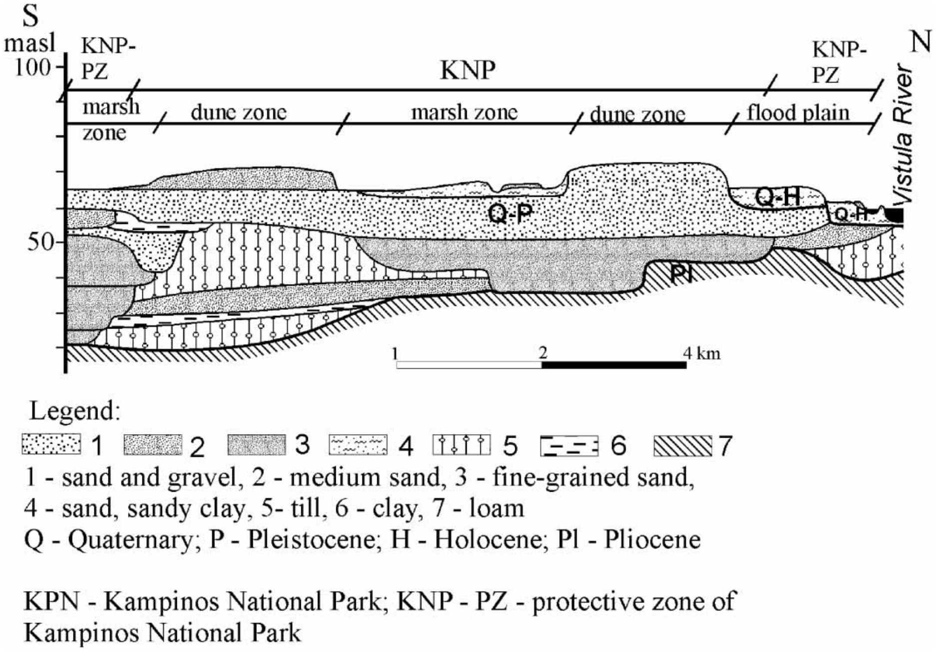

Figure 2 | Schematic cross-section of Quaternary sediment in central part of the Vistula valley.

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where, DI = DRASTIC index; RA = parameter rating; W = parameter weight; D = depth to groundwater; R = net recharge; A = aquifer media; S = soil media; T = topography; I = impact of vadose zone; C = hydraulic conductivity of the aquifer.

The seven intrinsic parameters are rated from 1 to 10. Each parameter is then weighted from 1 to 5. The rates and weights are multiplied for each parameter and added together to produce a so-called 'intrinsic' DRASTIC index (Equation (1)). The advantage of the DRASTIC method is that it uses a relatively small number of parameters to compute the index. This makes the method suitable for producing comparable vulnerability maps on a regional scale (e.g., Secunda *et al.* 1998; Kim & Hamm 1999; Al-Adamat *et al.* 2003; Babiker *et al.* 2005; Rahman 2008; Saidi *et al.* 2011).

The study area was digitized by adopting a discretization space step size (grid size) of 0.01 km^2 (100 m × 100 m), which was divided into 13,620 blocks. The analysis was performed for active blocks with annual recharge infiltration (R), thus the 12,071 blocks of the discretization grid were obtained. The step size corresponds to the accuracy of the digital elevation model, hydrodynamical model, and the accuracy of hydrogeological (Figure 3), geological (Figure 4), and environmental reconnaissance (Figure 5).

The DRASTIC parameters were obtained from data sources as listed in Table 1. All parameters were manipulated as raster maps in an ArcGIS environment (Ver. 10.1). The vulnerability index for each block was then calculated (Equation (1)).

Parameter 1: depth to groundwater (D)

One of the most exactly defined parameters of the DRASTIC system is the depth to water. The monitoring system of groundwater in the KNP region is based on manual measurements in 56 piezometers (points of monitoring system) located along the seven lines (Figure 1). A set of data was collected from the multiyear period (1999–2014) in the floodplain terrace where nine points were located, providing a database of over 3,500 observations. Statistical analysis of groundwater level enabled a determination of the scope of the groundwater level changes in the multi-year period, and in the annual period. The spatial interpretation of the hydrogeological data was carried out using the GIS software. The analysis was conducted with the kriging method, which involved data derived from the monitoring system. The groundwater level within the floodplain terrace was shallow; on 10% of the area it occurred less than 1 m below the surface and on 82.9% of the floodplain terrace area it occurred at a depth not exceeding 3.0 m below the surface (Figure 3(a)); average depth-to-water over a multiyear period 1999–2014 ranges from 0.83 m to 4.33 m across the study area.

Parameter 2: net recharge (R)

The mean value of infiltration recharge was determined using groundwater flow model-based research that has been presented in several publications (Gruszczyński & Krogulec 2012; Krogulec & Zabłocki 2015).

The groundwater flow model enabled the calculation of the groundwater balance of the hydrogeological system – KNP area. The balance consists of the total inflow and outflow throughout the KNP area and delimited parts of KNP like the floodplain terrace of the Vistula River.

The result of the model calculations was the water balance for KNP area and delimited area like the floodplain terrace of the Vistula River (Table 2). The result of the model calculations was also an infiltration grid, which, in a discrete way, represents the spatial distribution of infiltration recharge of the aquifer system (average annual recharge). Average annual recharge for the area of floodplain terrace is approximately in the range 0–80 mm/year (Figure 3(b); Table 3). Nearly 60% of the terrace is characterized by infiltration in the range 60–80 mm/year.

Parameter 3: aquifer media (A)

Aquifer media has been widely recognized on the basis of direct studies and interpretations of drilling profiles. The database for the KNP region contains 978 drillings (studies and wells); a supplementation of the recognition was by geophysical polls (Krogulec *et al.* 2009, 2010). For the needs of the DRASTIC method, four classes were generated in the floodplain terrace (Figure 4(a); Table 3). Most of the area is taken up equally by river and fluvioglacial sands (43.2%) and hiatal sands with inlays of rinsed clay (42.7%).

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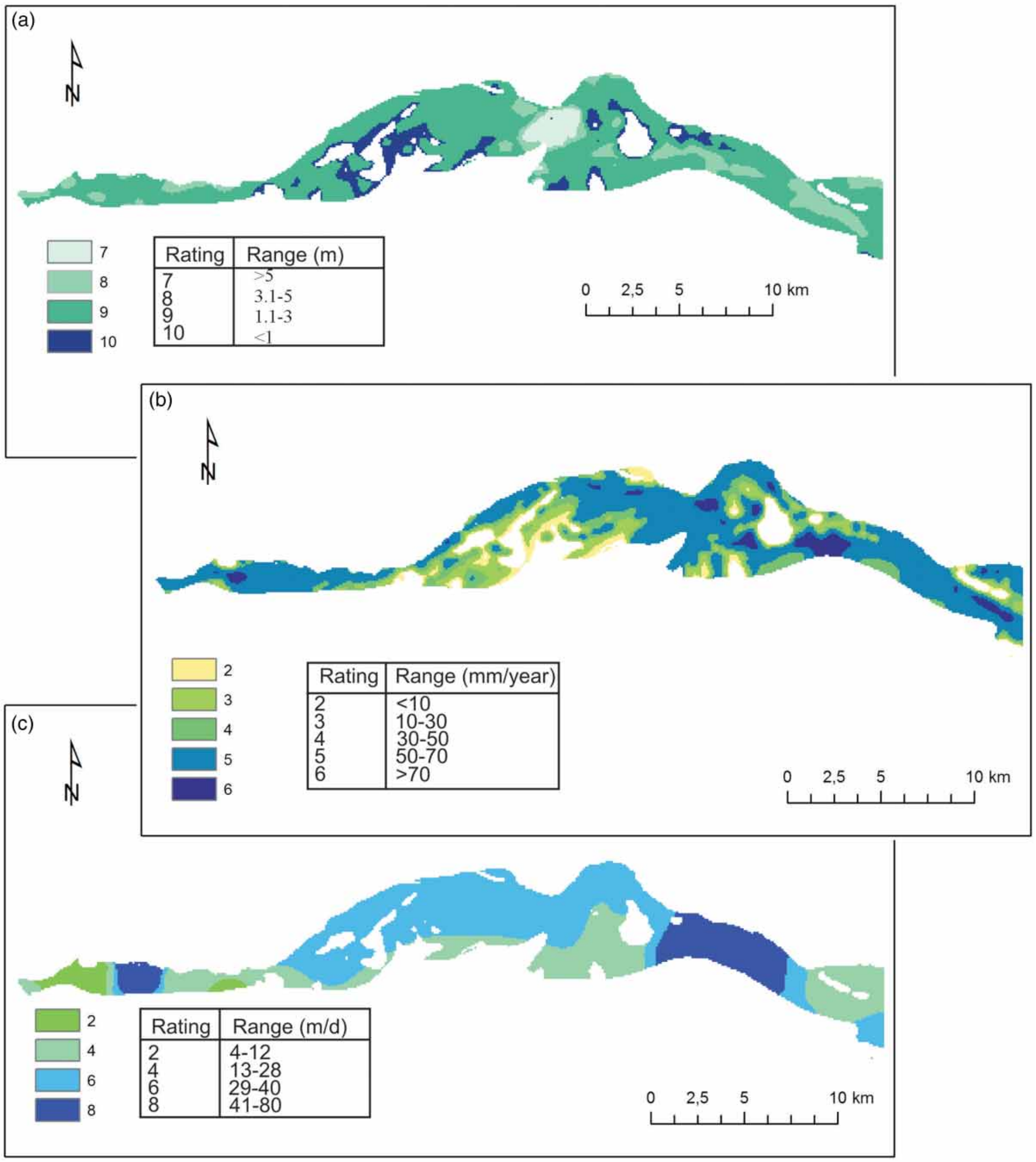

Figure 3 | (a) Depth to water of floodplain terrace; (b) net recharge of floodplain terrace; (c) hydraulic conductivity of the aquifer.

Parameter 4: soil media (S)

For the purpose of the DRASTIC method, a generalized map of soil was used (Wicik 1995; Piórkowski *et al.* 2011) (Figure 5(a)). The soil cover is very diverse; it has been studied in detail for the needs of maintaining and renaturalizing plant habitats in the KNP (Wicik 1995). For the DRASTIC method, the soil was characterized through references to primary types as classified by US SCS (Soil Conservation Service–American Office of Soil Protection). The choice of the appropriate rating of the soil requires consideration of the characteristic features of the soils; this can be obtained by identifying not only the most important soil types, but also the layers occurring in the soil profile that have the greatest influence on the filtering of water and transport of contamination. The largest area is covered by silty, mineral-muck soils, and alluvial muds – 50.5% (northern part – developed on poorly sorted sands near the river valley and in valleys of small streams). Brown

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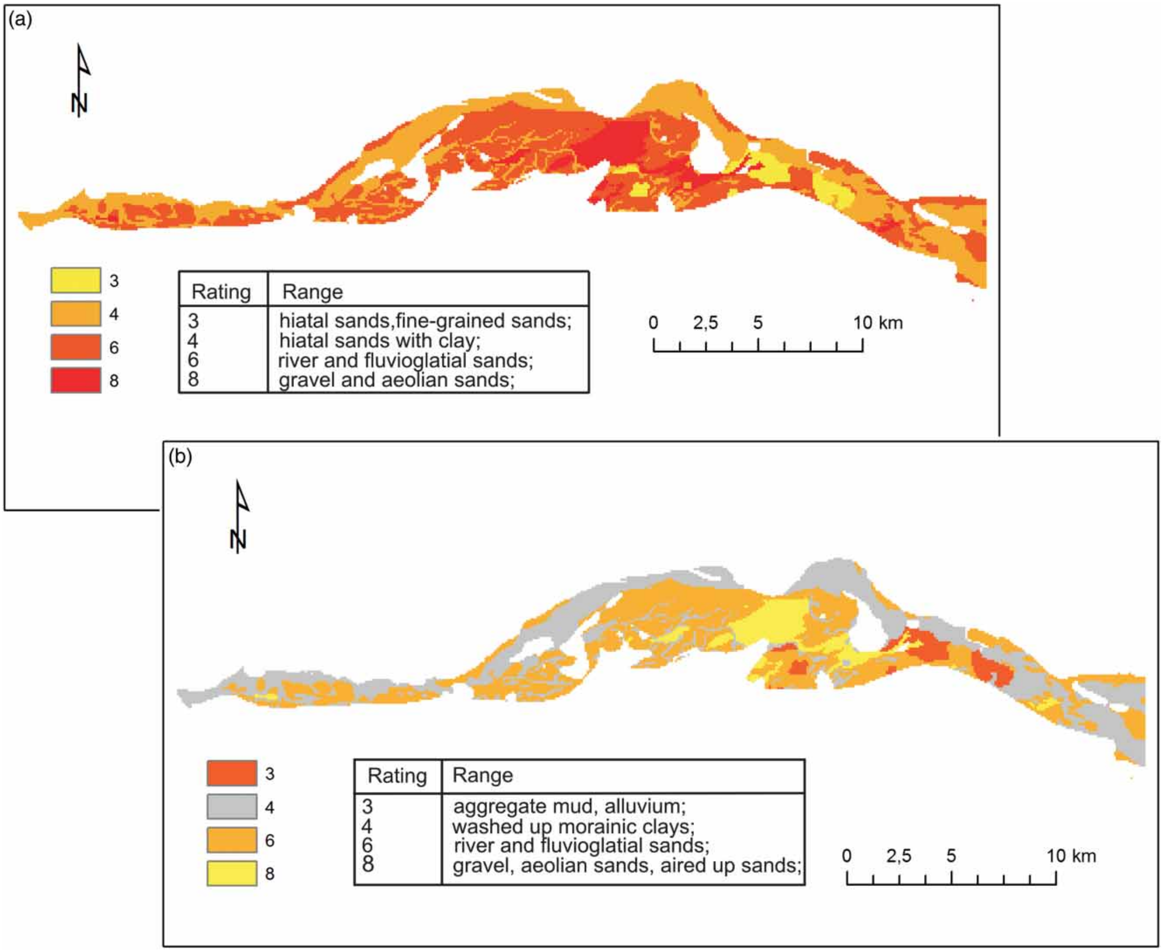

Figure 4 | (a) Aquifer media of floodplain terrace; (b) impact of vadose zone of floodplain terrace.

soils and black earth also cover a large area – 44.5% (southern part of the area – developed on fluvial and fluvioglacial sands). Much rarer are rusty, peat-muck, and mucky soils. Podzols and eolian-eroded soils occur sporadically (Figure 5(a); Table 3).

Parameter 5: topography (T)

The slope of the land surface in the study area plays a smaller role in assessing vulnerability of groundwater to pollution (weight 1; Table 3). Despite small hypsometric differences, the slope of the terrain shows a changeability resulting from microsculptures and changes of declines of an anthropogenic character. Approximately 94% of the territory's surface is characterized by small slopes, from 0% to 0.2%; only less than 1% of the area has a slope from 0.4% to 2.8% (Figure 5(b); Table 3).

Parameter 6: impact of vadose zone (I)

The lithology of subsoil deposits, zones of aeration, has been widely recognized in the study area on the basis of geophysical studies and the analysis of drilling profiles of mainly shallow piezometers of the monitoring system of the KNP. The greatest area (nearly 86% of the terrain) of subsoil deposits is taken up by washed up morainic clays and river and fluvioglacial sands. Much less common are gravel, aeolian sands, and aired up sands (Figure 4(b); Table 3).

Parameter 7: hydraulic conductivity of the aquifer (C)

On the basis of the analysis of values from sample pumping conducted at different times in 186 well holes located in the

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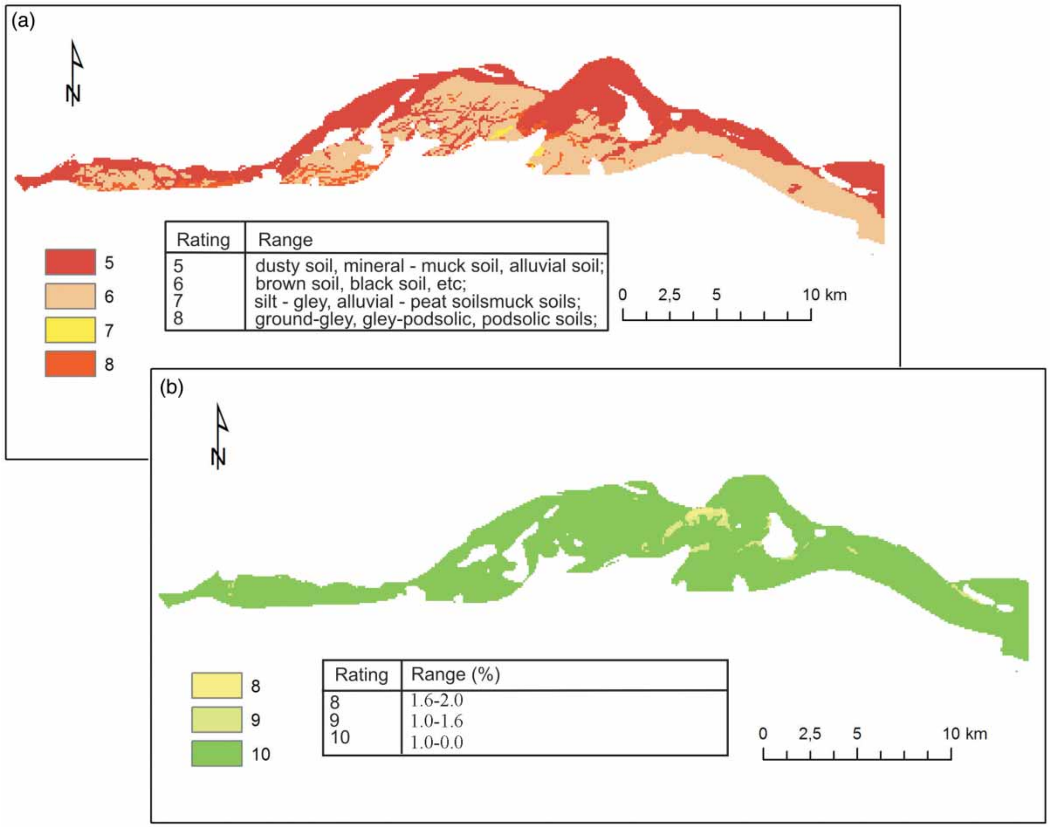

Figure 5 | (a) Soil of floodplain terrace; (b) terrain slope classes of floodplain terrace.

Table 1 | Data sources of DRASTIC parameter

Parameter	Data sources
D	Statistical analysis based on measurements in the monitoring system – analysis of the nine points of monitoring system (>3,500 observations)
R	Hydrodynamical model assessment (Gruszczyński & Krogulec 2012; Krogulec & Zabłocki 2015)
A	Data obtained from the geophysical data, bore logs, geological map at scale 1:50,000–(978 drillings)
S	Soil map of the study area 1:50,000 (Wicik 1995)
T	Numerical model of terrain
I	Data obtained from geophysical data, bore logs, geological map at scale 1:50,000, analysis of drilling profiles of mainly piezometers of the groundwater monitoring system of KNP
C	Data obtained from geophysical data, bore logs, geological map at scale 1:50,000, 186 well holes located in the study area or in its direct neighborhood

Table 2 | Water balance in Vistula floodplain terrace

Element of the balance	Supply (m^3/d)	Discharge (m^3/d)
Exploitation of groundwater	0.0	1,932.5
Watercourses	583.8	24,193.0
Underground evaporation	0.0	7,540.2
Infiltration recharge	19,517.0	0.0
Supply from other areas	14,770.5	1,365.2
Total	34,871.0	35,030.0

study area or in its direct neighborhood, the average value of the coefficient of permeability amounts to 23.59 m/d. Most of the floodplain terrace (75% of area) consists of deposits with the permeability coefficient in the range of 13–40 m/d. Smaller areas consist of deposits with permeability coefficient in the range of 41–80 m/d (16.7%) (Figure 3(c); Table 3).

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Table 3 | Theoretical weights and rating of the parameter in the DRASTIC method (Aller *et al.* 1987)

No.	Parameter	Range	Weight	Rating	Distribution in Vistula floodplain (%)
1	D (m)	>5	5	7	3.5
		3.1–5		8	13.7
		1.1–3		9	72.1
		<1		10	10.8
2	R (mm/year)	<10	4	2	6.7
		10–30		3	14.9
		30–50		4	18.6
		50–70		5	54.3
		>70		6	5.5
3	A	Hiatal sands, fine-grained sands with silt	3	3	4.3
		Hiatal sands with inlays of rinsed up clay		4	42.7
		River and fluvioglacial sands		6	43.2
		Gravel and aeolian sands		8	9.4
4	S	Dusty soil, mineral-muck soil, alluvial soil	2	5	50.5
		Brown soil, black soil, etc.		6	44.5
		Silt-gley, alluvial-peat soils muck soils		7	0.4
		Ground-gley, gley-podsolic, podsolic soils		8	4.6
5	T (slope) (%)	1.6–2.0	1	8	0.4
		1.0–1.6		9	2.4
		1.0–0.0		10	97.2
6	I	Aggregate mud, alluvium	5	3	4.3
		Washed up morainic clays		4	42.7
		River and fluvioglacial sands		6	43.2
		Gravel, aeolian sands, aired up sands		8	9.4
7	C (m/d)	4–12	3	2	8.3
		13–28		4	27.6
		29–40		6	47.4
		41–80		8	16.7

RESULTS AND SENSITIVITY ANALYSIS

In the first phase of the analysis, the DRASTIC intrinsic vulnerability index was calculated. Within the floodplain terrace, almost the entire characterized area has low (68.18% of the surface) or medium (31.2% of the surface) vulnerability of groundwater to pollution, with only minimal parts having very low (0.46% of the surface) or moderately high (0.16% of the surface) vulnerability (Figure 6; Table 4).

In the second phase, two sensitivity tests were performed: the map removal sensitivity analyses introduced by Lodwick *et al.* (1990) and the single-parameter sensitivity analysis introduced by Napolitano & Fabbri (1996). Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to each parameter and helps the decision-maker to judge the significance of subjective elements (Napolitano & Fabbri 1996; Gogu & Dassargues 2000; Babiker *et al.* 2005).

The single-parameter and DRASTIC index sensitivity analysis

The single-parameter sensitivity measure was developed to evaluate the impact of each of the DRASTIC parameters on the DRASTIC index. The single-parameter sensitivity compares ‘effective’ and ‘theoretical’ weights of parameters (Napolitano & Fabbri 1996; Al-Adamat *et al.* 2003; Babiker *et al.* 2005). The ‘effective’ weight of a parameter is obtained with regard to the other parameters of DRASTIC assessment. The ‘effective’ weight of a parameter (W_E) in each of the 12,071 active blocks of the discretization grid was

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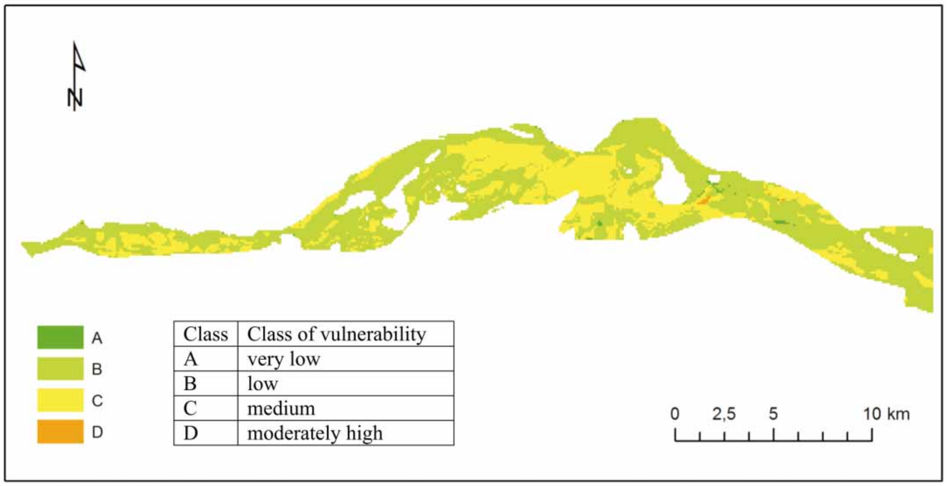

Figure 6 | Classes of vulnerability: results of intrinsic vulnerability assessment using the DRASTIC method. A, very low; B, low; C, medium; D, moderately high.

Table 4 | Result intrinsic vulnerability assessment using the DRASTIC method in the study area

DRASTIC index	Class	Area (km^2)	Proportion of study area (%)
100	Very low	0.60	0.46
100–125	Low	88.13	68.18
126–150	Medium	40.33	31.20
151–175	Moderately high	0.20	0.16

calculated by the following equation:

$$W_E = \left(\frac{P_{RA}P_W}{DI}\right) \times 100 \tag{2}$$

where, W_E = 'effective' weight of parameter P (%); P_{RA} P_W = rating and weight of parameter P, respectively, of the discretization grid; DI = DRASTIC index as computed in Equation (1).

The effective weights of the parameters shown in Table 5 indicate that the parameter D dominates the DRASTIC index with an average 'effective' weight for 12,071 active blocks of 31.67% ('theoretical' weight 27.74%). Also, the 'effective' weight of topography (7.10%) exceeds the 'theoretical' weight (4.35%). The 'effective' weights of impact of the vadose zone remain high but not as high as the 'theoretical' weights. Aquifer media, soil media, impact of vadose zone, and the hydraulic conductivity reveal lower 'effective' weights. The DRASTIC index was calculated with Equation (1), calculation assumes 'effective' weight of parameters obtained through Equation (2).

Recalculation of the DRASTIC index by Equation (1) using the 'effective' weights determined by Equation (2) raised the DRASTIC index everywhere in the study area. The increase ranged from 2.06 to 20.72 (Figure 7). The average increase across the study area was 12.27.

Map removal sensitivity analysis

Map removal sensitivity analysis describes the sensitivity of the vulnerability map when one or more parameters are removed from the suitability analysis (in this case, single parameters at a time) and it is calculated with the following formula (Farjad *et al.* 2012):

$$S = \left(\frac{|V/N - V'/n|}{V}\right) \times 100 \tag{3}$$

where, S = sensitivity measure expressed in terms of variation index (%); V = unperturbed vulnerability index; V′ = perturbed vulnerability index; N = number of data layers used to calculate V; n = number of parameters used to calculate V′.

In Equation (3), the unperturbed vulnerability index represents vulnerability calculated using all seven parameters. The perturbed vulnerability index is calculated using fewer parameters.

To perform a sensitivity analysis, all seven parameters were removed from the model one by one. The significance of each parameter was indicated by the mean variation index after that parameter's removal. Table 6 shows the

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Table 5 | Single-parameter sensitivity analysis in blocks of the discretization grid

				'Effective' weight (%)			
Parameter	**'Theoretical' weight**	**'Theoretical' weight (%)**	**'Effective' weight**	**Mean**	**Minimum**	**Maximum**	**Standard deviation**
D	5	21.74	7.28	31.67	21.47	43.10	3.06
R	4	17.39	2.85	12.37	5.00	19.67	2.81
A	3	13.04	2.51	10.93	6.48	16.16	2.12
S	2	8.70	1.83	7.95	5.78	13.45	1.10
T	1	4.35	1.63	7.10	5.51	9.01	0.59
I	5	21.74	4.19	18.21	10.79	26.94	3.53
C	3	13.04	2.71	11.77	3.85	19.28	3.09
Total	23	100	23	100			

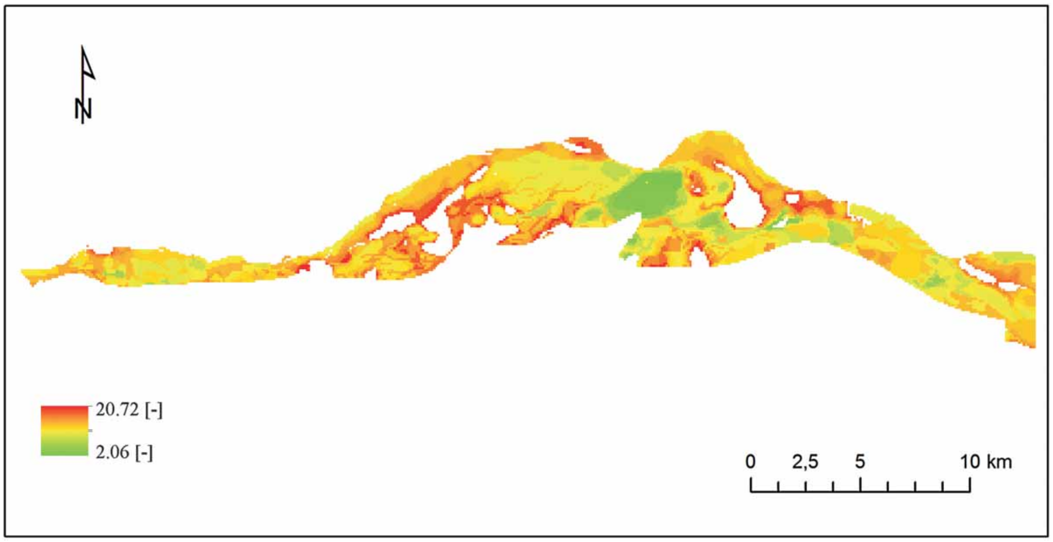

Figure 7 | Difference of DRASTIC index after using the effective weight (DRASTIC index modified and 'theoretical' weights).

results. A relatively high variation index was obtained upon the removal of the depth to water parameter (mean variation index 2.90%). Also, the vulnerability seems to be sensitive to the removal of the data layers for impact of vadose zone, aquifer media, hydraulic conductivity of the aquifer, and recharge.

DISCUSSION

This study was done in the area of a shallow aquifer. Within the floodplain terrace the vulnerability of groundwater to pollution varies from very low to moderately high and is mostly low (68.18% of the study area) or medium (31.20% of the study area). Only 0.16% of the study area (0.2 km^2) has moderately high vulnerability, the highest vulnerability calculated for the area. The zones with this vulnerability are in the center and southern parts of the study area.

Single-parameter sensitivity analysis indicates that parameter D dominates the DRASTIC index in the study area. Its 'effective' weight is 7.28 (31.67%), significantly greater than the 5 (21.74%) for the 'theoretical' weight. Similarly, map removal sensitivity analysis confirms that the vulnerability index is most sensitive to the removal of the depth to groundwater parameter. The mean variation index for this parameter is 2.90% and is much higher than for the other

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Table 6 | Statistics of the one-map removal sensitivity analysis

	Variation index (%)			
Parameter removed	**Minimum value**	**Maximum value**	**Mean**	**Standard deviation**
D	1.20	4.80	2.90	0.60
R	0.00	1.55	0.42	0.38
A	0.00	1.30	0.58	0.32
S	0.14	1.42	1.05	0.18
T	0.13	1.46	0.85	0.24
I	0.02	2.11	0.70	0.53
C	0.00	1.74	0.54	0.38

parameters. Thus, parameter D can be considered the most important in the groundwater vulnerability assessment in the study area. The depth to the water table is also the most precisely defined parameter in the study area which raises the credibility of the vulnerability assessment. The water table here is shallow – it is less than 3.0 m below the surface over 92.9% of the area. Remarkably, despite this, 68.18% of the area belongs to the class of low vulnerability.

The largest difference between the DRASTIC index obtained from 'theoretical' and 'effective' weights was 20.72, which may result in the change of vulnerability assessment by one vulnerability class (Figure 7). The research shows that the DRASTIC index possesses a high degree of effective weight in assessing vulnerability.

CONCLUSIONS

Identification of groundwater vulnerability to pollution in areas of shallow groundwater in river valleys should be an element in the management and protection of flood risk maps. This study presents the assessment of groundwater intrinsic vulnerability in the Vistula floodplain terrace using the DRASTIC method. The DRASTIC method is widely used, therefore the results of the studies can be compared with assessments for other regions. Groundwater vulnerability to pollution in the central part of Vistula floodplain terrace, characterized by a shallow water table, varies from very low (0.46% of the study area) to moderately high (0.16% of the study area), with almost the entire area characterized by low (68.18% of the study area) or medium (31.2%) vulnerability. The single-parameter sensitivity analysis has revealed that the 'effective' weights for each parameter in the DRASTIC method differ from the 'theoretical' weights. The depth to groundwater dominates the DRASTIC index with an average 'effective' weight of 31.67% and a 'theoretical' weight of 21.74%. The depth to the groundwater is not only the most important parameter in the DRASTIC method, but also it is the most precisely defined parameter based on measurements in points of monitoring system in the study area. The vulnerability map using the calculated 'effective weight' demonstrates that the majority of the floodplain terraces is medium vulnerable. When using 'effective weights', the DRASTIC index shows that local vulnerability changes by one class, which points to the need to analyze vulnerability by the applied susceptibility assessment method. The map removal sensitivity analysis has also indicated that the DRASTIC index is much more sensitive to the depth to water than to the other parameters.

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