Assessment of groundwater vulnerability to contamination in the Kampinoski National Park, central Poland

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Abstract: Groundwater vulnerability to contamination in the Kampinoski National Park (KNP) area in central Poland was evaluated as a basic for developing appropriate protection strategy for the groundwater resources and management. The majority of studies have concentrated on detailed investigations in recreation areas located near Warsaw. Assessment was accomplished using U.S. EPA DRASTIC and the travel times to the saturated zone. Results of the study and observations made for a good data base in order to determine the role and value of individual criteria in evaluation of groundwater vulnerability. The final DRASTIC values have been grouped into themedium and medium high natural vulnerability. The travel times to the saturated zone are classified in 11 intervals, ranging from 30 days to 30 years.

1. Introduction

The concept of groundwater vulnerability to contamination is a useful tool for environmental planning, decision-making, protection of the groundwater source and of the groundwater resources. In practice in many countries the new regulations for protection groundwater often supported by groundwater vulnerability and protection zones. Groundwater vulnerability is a concern even in recreation areas such as national parks or landscape parks. Such areas, including Kampinoski National Park in Poland, that they are not isolated from "outside effects", and sometimes outright on the contrary they are a place of constant or temporary by the neighbouring inhabitants.

Kampinoski National Park (area – 385.44 km^2) with its buffer zone (area – 385.88 km^2) is a UNESCO Biosphere Reserve and it is a special protection area of NATURA 2000 network which plays an essential role in the nature conservation in the EU. KNP is located where four tributaries: the Bug, Narew, Wkra, Bzura rivers, merge with the Vistula river (Fig. 1). According to Ecological System of Protected Areas (ESPA) the valleys of these rivers are ecological corridors. The Vistula river valley in Kampinos forest is especially recognized as an important ecological area in Europe.

KNP is situated within the valley that includes the suburbs of Warsaw, a city of nearly 2 million people. The area is characterized by a diversity of morphology, hydrogeological settings, geology and vegetation as well as infrastructure development.

2. Hydrogeological conditions of KNP region

2.1. Groundwater monitoring network

The monitoring network consists of 56 piezometers and 25 water level gauges (Fig. 2). The spatial distribution of monitoring network measurement points was designed to take full advantage of hydrological and hydrogeological analysis within an enclosed surface drainage basin and hydrogeological system. The observation points for surface and groundwater monitoring network at KNP have been grouped into seven observational cross sections (Krogulec, 2001, 2004).

The general concept for location of observation points set in Kampinoski National Park local monitoring network was subordinated to meet the following goals:

- Including all existing hydrodynamic zones in observations thus enabling researches to perform full analysis of the diversified water relations in KNP area and its protection zone;
- Including the influence of anthropogenic factors on the chemical composition of groundwater and surface waters;
- Optimizing the number of groundwater and surface water observation points;
- Relating to the existing network and single observation points;
- Providing technical possibility to perform hydrogeological and hydrological observations (easy access, possibility of non-controversial point location etc.).

Measurements of surface and groundwater levels are performed in two weekly intervals from 30. 11. 1998. During the period between 1998-2004 the water table, a fundamental criteria used in evaluation of groundwater vulnerability to contamination, was at depth of 0.61 to 4.7 meters below terrain level. Water table ordinates were at a height of 65.67 to 97.53 (Tab. 1).

2. 2. Characteristics of the aquifer

Kampinoski National Park and its buffer zone are located in the central part of the Vistula river valley. This valley flood plains and a river flood terrace (Kampinos Terrace) of the Vistula and Bzura rivers. On the Kampinos Terrace, one aquifer occurs with a thickness of 10 to 50 metres. It is composed of varied, fine-grained

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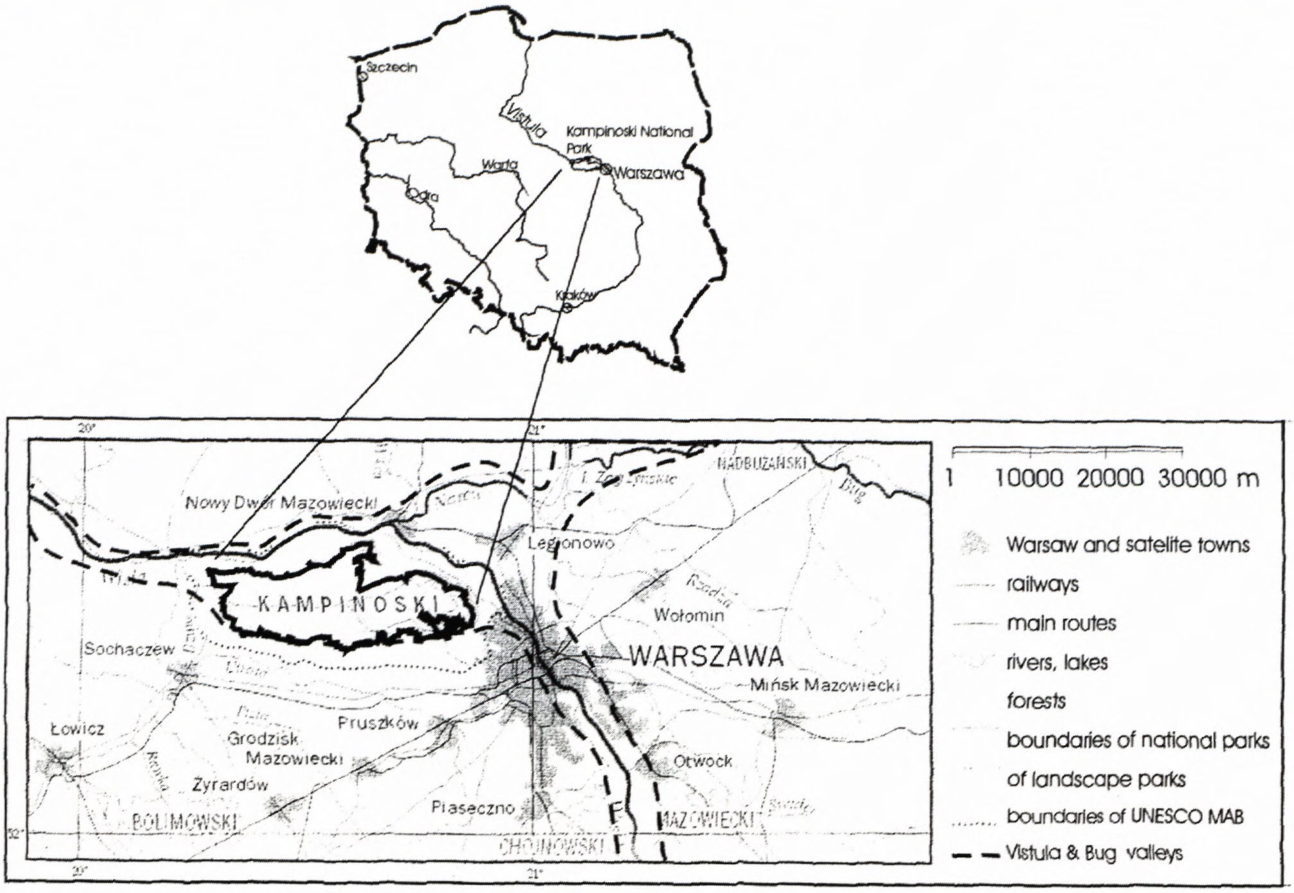

Fig. 1. Location of the Kampinoski National Park.

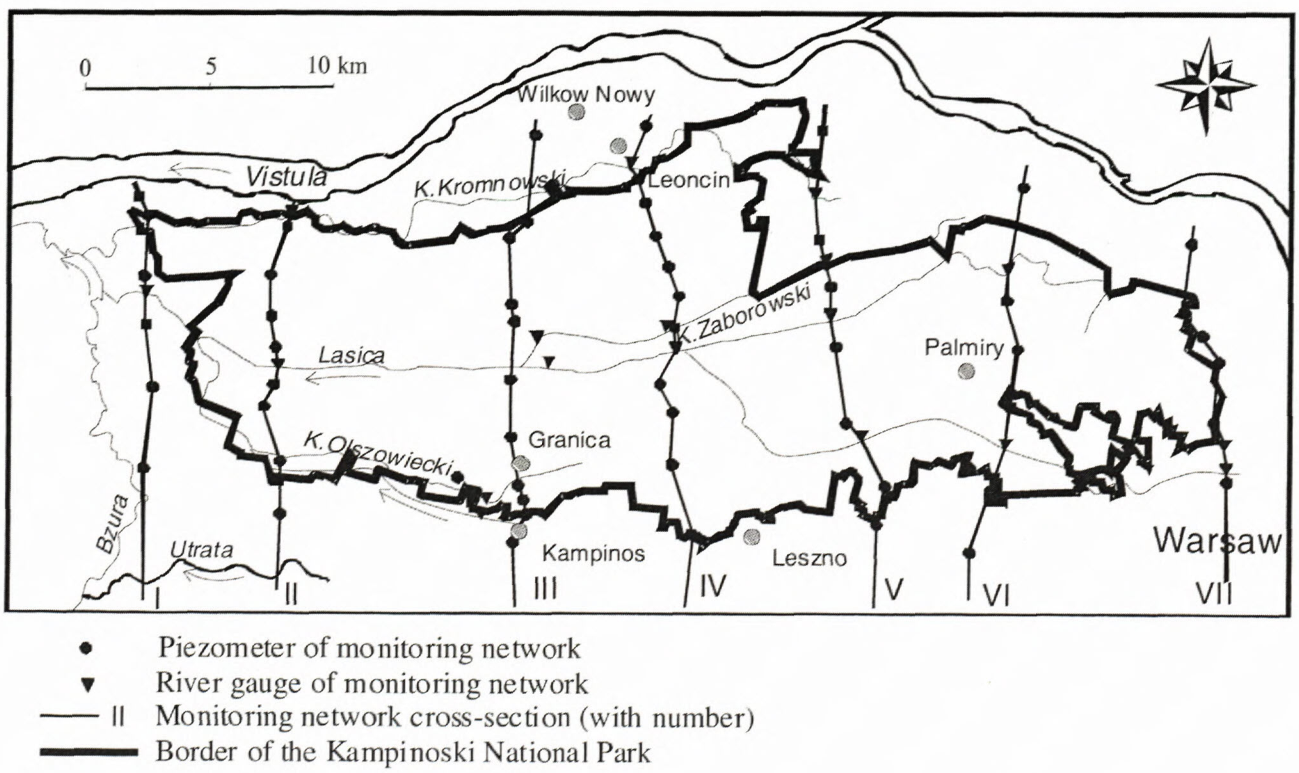

Fig. 2. Monitoring network in the Kampinoski National Park.

Tab. 1. Hydrogeological characteristic of hydrodynamic zones in the KNP.

Hydrodynamic zone	Average depth /ordinate of groundwater table [m b.t.l.] / [m a.s.l.]	Level fluctuation range [m]	Hydraulic conductivity [x10^{-5} m/s]
Northern dune zone	1.30 – 4.49 / 68.04 – 73.44	0.6 – 1.76	12.21
Southern dune zone	1.27 – 4.38 / 68.60 – 77.88	0.85 – 1.18	5.57
Northern swampy zone	0.86 – 1.74 / 68.19 – 73.93	0.85 – 1.67	7.39
Southern swampy zone	0.61 – 2.48 / 69.05 – 81.81	0.64 – 1.5	5.32
Vistula flood plains	0.89 – 4.33 / 65.67 – 75.70	0.58 – 1.93	19.38
Bzura terrace	2.57 – 4.70 / 66.63 – 68.19	0.98 – 1.23	12.75
Warsaw suburbs	1.33 – 3.30 / 78.01 – 97.53	0.81 – 1.92	6.38
Blonie Level	1.87 – 3.27 / 82.97 – 91.83	1.2 – 2.09	3.85

sands, in some places silty. The groundwater table has an unconfined character.

In the vertical profile, three fundamental sediment series with various filtration parameters determined by in-situ investigations:

- horizon of medium grained sands, in some roof places passing into silty sands, with numerous interbeddings of washed out boulder clays, gravel with very diversified permeability parameters ($k = 0.9 \div 19$ m/d, $k_{av} = 6.3$ m/d) with a thickness of 10 to 15 m,
- middle horizon, gravel-sandy ($k = 1.3 \div 19.8$ m/d, $k_{av} = 8.5$ m/d) with a thickness of 8 to 15-20 m,
- subsurface sand horizon ($k = 0.4 \div 20$ m/d, $k_{av} = 18$ m/d) with a thickness of 3 to 6 m.

Aquifer hydraulic conductivity values were also determined by statistical analysis of hydrological data, obtained from approximately 980 wells, located within the study area (Krogulec, 2003). Average hydraulic conductivity value for the aquifer sediment was determined from pumping test results to be 47.7 m/d (range of 1.2 m/d to 89.6 m/d).

2.3 Conditions of groundwater recharge and drainage

Groundwater recharge takes place almost exclusively as a result of infiltrating precipitation but a second recharge source comes from a lower aquifer. The lower aquifer from Blonski Level only affects the southern part of Kampinos Terrace. During high spring runoff, water from the Vistula river may infiltrate the aquifer. Water also infiltrates from the Bzura river in the south-western part of study area.

The infiltration value depends mainly on the lithology of the subsurface and terrain afforestation ratio. The values of infiltration were obtained by mathematical modelling, hydrograph separation and table fluctuation (WTF) method.

Modelling calculations were performed using VisualMODFLOW 2.20 software; simulations have been made with the use of the Strongly Implicit Procedure Package – SIP (McDonald and Harbaugh 1988) digital method. The values of infiltration obtained by modelling calculation are:

- in the southern swampy zone – 332 mm/year
- in the northern swampy zone – 186 mm/year
- in the Vistula river flood plain – 55.5 mm/year

The runoff separation to surface and underground component by hydrograph separation was made using automated method so called, **B**ase **F**low **I**ndex (Magnuszewski, 1990; Tomaszewski, 1998). The quantitative evaluation of Lasica base runoff (catchment located in KNP area – 441.0 km^2) depends on the intensity. Volume of precipitation entitles us to state that it plays an important role in the lowland drainage basin with swamps and forest cover. Series of daily discharge in have been used. In the period 1951-2000 the river base runoff varies considerably: from 163 mm in 1967 to barely 43 mm in years 1952 and 1992 (Soczyńska et. al., 2003).

Water table fluctuation (WTF) method is a conventional method for quantifying groundwater infiltration recharge by multiplying the specific yield to the water level rise (Healy and Cook, 2002). Based on the van Genuchten model, an analytical relationship between groundwater recharge and the water level rise is derived. The equation is used to analyse the effects of the depth to water level and the soil properties on the recharge estimate using the WTF method. The values of infiltration obtained by WTF method (observation from KNP monitoring network) are from 73 mm/year in flood terrace of Vistula and in swamp areas to 265 mm/year in dunes areas.

Empirical method offers a quick assessment of infiltration recharge in terms of climate, land use, terrain and geology. Results of infiltration using empirical method in KNP area are from 119 in swamp areas to 199 mm/year in dunes.

Analysis of the balance elements on numerical model shows that from the south of the Kampinos Terrace is recharge by water from the deeper aquifer of the Blonie Level. The supply value in the study area is 0.2 m^3/d for 1 m of slope width (Krogulec, 1997).

Aquifer drainage on the Kampinos Terrace takes place by rivers and canals and partially with evapotranspiration processes in the swampy areas. The Vistula river has the strongest drainage character and is the regional drainage base. Similarly an important role in

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drainage of aquifer fulfils Bzura, mostly in its lower section. Drainage of the aquifer also takes place through production of groundwater in many points in the study area.

The numerical model research confirmed the prevailing role of the Vistula river in forming of the hydrodynamic regime in the analysed valley unit. The river is a regional drainage base, supplied by groundwater volume of 0.55 m^3/d for 1 m of river length. The remaining water flows drain the aquifer with the following volumes: Olszowieckie A and B canals – 0.29 m^3/d, Lasica river – 0.34 m^3/d, Kronowski canal – 0.12 m^3/d. The groundwater drainage in the study area is also related to the evapotranspiration process which is significant only in the depressions and on the flood plain where the groundwater table not exceeds 1.5 m below terrain level. In the northern swampy zone the evapotranspiration value is 0.31 m^3/d, in the southern swampy zone – 0.16 m^3/d, in the Vistula river flood plain – 0.084 m^3/d (Krogulec, 2004).

Annual average sum of potential evaporation in the Lasica catchment in the period of 1951-2000 calculated by the Penman method is 722 mm. Prevailing part (76 %) occurs in the warm half-year (546 mm), while 176 mm (24 %) represents cold half. Average monthly sums are from 15 mm in January and December to nearly 10 times bigger (121 mm) in July (Soczyńska et. al., 2003).

3. Groundwater vulnerability

In this article groundwater vulnerability to contamination is understood to be a natural characteristic of the aquifer system. It describes the risk of migration of hazardous substances from the surface to the aquifer. Intrinsic vulnerability is determined only by hydrogeological conditions (recharge conditions, discharge, formation conditions including degree of groundwater isolation). Specific vulnerability also takes into consideration type of hazardous substance, its amount, and its location with respect to the aquifer (Duijvenbooden and Waegening, 1987; Vrba and Zaporozec 1994; Witczak and Żurek, 1994).

For central area of KNP located in Vistula river valley, natural vulnerability of groundwater was determined with application of two methods:

- U.S. EPA DRASTIC Model (Aller et al., 1987),
- travel time of conservative contamination from the terrain surface (percolation time through aeration zone).

3.1 DRASTIC model

One of the most widely used groundwater vulnerability methods is DRASTIC, developed by the United States Environmental Protection Agency (EPA) as a method for assessing groundwater pollution potential (Aller et al., 1987). As was mentioned above, it is one of the most popular ranking methods developed especially for evaluation of vulnerability in the particular hydrogeological regions. Classification system (evaluation) of vulnerability in the DRASTIC method is the standard tool used by many countries in management of water resources, water legislation and controlling. In Poland DRASTIC was used to evaluate vulnerability of geological variability (porosity reservoir, porosity-fracture, fracture) of Ścianawka catchment, with the area of 595 km^2, located in Lower Silesia (Limisiewicz, 1998) and Silesia catchment (Witkowski et al., 2003), and also was used in some studies for various types of water bearing reservoirs, mostlyof porosity-fracture type, done by Academy of Mining & Metallurgy (Witczak and Żurek, 1994).

In the DASTIC method is an acronym for the variables that control the groundwater pollution potential (depth to the water level, effective infiltration, aquifer media, type of soil, topography, impact of vadose zone, has the permeability coefficient of aquifer). Each variable are assigned different degree of importance on a scale of 1 to 5. Each criterion also possesses suitable order of value of the used coefficient and is credited with a rank, in other words a rank on 1 to 10 scale (Tab. 2). Vulnerability index IPZ_Σ that is the sum of the multiplication of variable rank and weight of individual criteria is the final evaluation of groundwater vulnerability.

$$IPZ_\Sigma = \sum_{n=1}^{7} \text{(variable rank x weight of criterion)}$$

The DRASTIC method assumes that the flow of the groundwater is linear. This assumption is fully acceptable for the porous media in the aquifer of the central Vistula river valley. Final evaluation of vulnerability depends on the precision and accuracy of hydrological character, which is very high for KNP region. Assignments of each criterion (hydrogeological data, soil assignments, and topography) were plotted on several maps (scale 1 : 50 000) with the use of vectoring, calculations and visualizations in the following computer programs: ARC/INFO 8.0.1, ArcView 3.2, AVSpatialAnalist 1.1, AVArcPress 2.0 produced by ESRI, operating on Sun Solaris and Win NT platforms. Modeling called for all criteria to be brought into a form of pseudo-continuous distributions, expressed in a form of nets of natural mesh with a resolution of 100 m x 100 m (block 100 x 100 m, more than 65 000 blocks).

Basing on the initial data and calculations conformable with DRASTIC methods slightly modified but conforming to the specifics of the study area, classification of groundwater vulnerability was obtained, dependent on the range of the IPZ index. The following types of groundwater vulnerability were assigned: very low (IPZ_Σ <100), low (IPZ_Σ from 100 to 125), medium (IPZ_Σ from 126 to 150), moderately high (IPZ_Σ from 151 to 175), high (IPZ_Σ from 176 to 200), very high (IPZ_Σ >200).

The middle Vistula river valley is characterized by moderate (37 % of the area or 228 km^2) and moderately high (52 % of the area or over 318 km^2) vulnerability to contamination. In the study area about 12.5 km^2 is an area of high vulnerability. Remaining vulnerability classes are located on considerably smaller areas (Tab. 3).

The DRASTIC evaluation produces a map that shows the distribution of values of the vulnerability index IPZ_Σ (scheme of map - Fig. 2).

Tab. 2. Rating and weight of criterion for DRASTIC criterions with assigned weights (after Aller, et al., 1987 – modified for KNP area - Krogulec, 2004).

No	Criterion	Classes of criterion	Weight of criterion	Rank
1 D	**D**epth to groundwater water table [m]	>5 m 3.1-5 m 1.1-3 m <1 m	5	7 8 9 10
2 R	Net **R**echarge [mm/year]	50-75 101-130 151-180 181-250 >250	4	2 3 4 5 6
3 A	Lithology of **A**quifer	sandy clay, loam, loam and sands sandy loam, sands sands, sandy loam sands sands, gravel	3	2 3 4 6 8
4 S	**S**oil media	loam sandy loam shrinking clay peat thin anthropogenic absent	2	5 6 7 8 9 10
5 T	**T**opography (slope) [%]	2.9-3.9 2.5-2.9 2.0-2.5 1.6-2.0 1.0-1.6 1.0-0.0	1	75 8 8.5 9 9.5 10
6 I	**I**mpact of aeration zone	clay silty loam loam sands sands, gravel	5	2 3 4 6 8
7 C	Permeability **C**oefficient of aquifer [m/day]	<4 4-12 13-28 29-40 41-80	3	1 2 4 6 8

Tab. 3. Distribution of the vulnerability classes – DRASTIC model.

IPZ_{Σ}	Classes of the relative vulnerability	Area [km^2]	Percentage share of classes
<100	very low	0.01	0.002
100-125	low	52.82	8.63
126-150	medium	228.05	37.25
151-175	medium high	318.86	52.08
176-200	high	12.53	2.05
>200	very high	0.03	0.005
Σ	**612.3 km² – area of hydrogeological unit**		**100 %**

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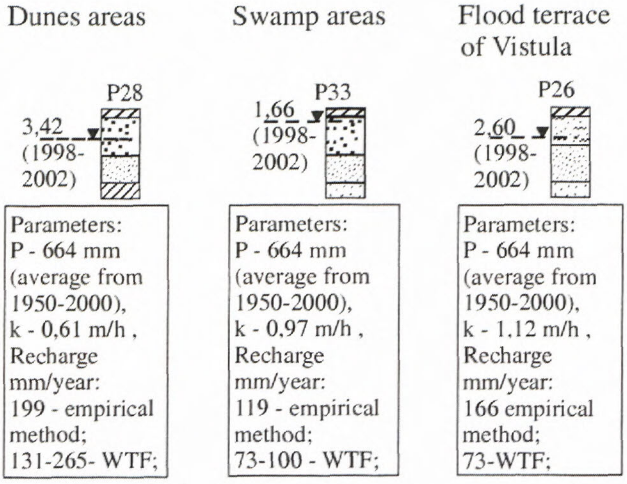

P33 - number of piezometer in KNP monitoring network;
P - precipitation; k - coefficient of permeability

Fig. 3. Characteristic of hydrodynamic zones within the Kampinoski National Park.

$$t_a = \sum_{i=1}^{n} \frac{m_i \cdot (w_o)_i}{I_e}$$

where:

m_i - thickness of successive layers of aeration zone profile [m]

w_o - average volumetric moisture of successive layers of aeration zone [-]

I_e - infiltration of atmospheric precipitation deep into the soil profile [m/year]

Travel time of conservative contamination through aerated zone ($t = t_a + t_p$) is a sum of infiltration through aerated zone (t_a) and eventual percolation through deeper cover (t_p). This is the reason why separate calculations were performed for the soil layer cover (average thickness in the studied area = 35 cm) and for the remaining aerated zone thickness. The result is the sum of flow time through both zones.

Infiltration time, determined by mentioned formula is from 0.5 to 10 years, but almost 75 % of the study area is

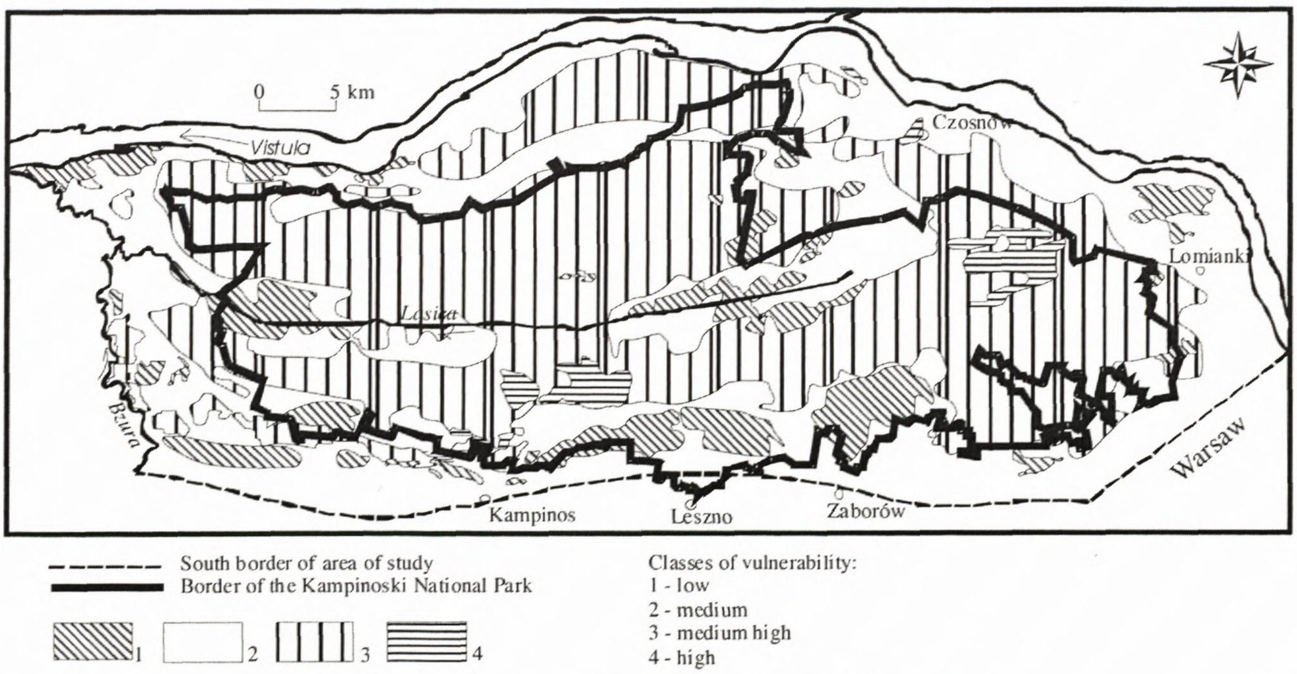

Fig. 4 Groundwater vulnerability map of the Kampinoski National Park based of DRASTIC method.

3.2 Travel time of conservative contamination from the terrain surface (percolation time through aeration zone) as a criterion of vulnerability

Estimation of travel time of conservative contamination from the terrain surface - infiltration time is a key factor in determining the vulnerability of groundwater. It is one of rational criteria used in evaluating groundwater vulnerability. Approximate determination for travel time can be achieved by the time of water exchange in a rock formation assuming piston - flow model.

Infiltration time through the aerated zone was calculated with the use of following formula (Wosten *et. al.*, 1986; Haith and Laden, 1989; Witczak and Żurek, 1994):

characterized by an infiltration time from 0.5 to 3 years (high class of vulnerability).

Because evaluation methods of groundwater vulnerability to contamination are not standardized, it is difficult to compare results and conclusions between studies potential impacts (Tab. 4).

4. Conclusion

Detailed hydrological recognition and also data relating to topography and soil layering of KNP region become the basis for compiling reliable and precise database. Use of GIS techniques during creation of vulnerability map, made it possible for much more precise assignment of data (value) to each criterion, more precise division of

Tab. 3. Travel time of conservative contamination in Vistula River valley (area of the Kampinoski National Park), percentage share of classes.

Vulnerability classes	Migration time of conservative contamination [year]	Percentage share of classes
Very low	>30	0.6
Low	25-30	0.2
	20-25	1.0
Medium	15-20	0.3
	10-15	7.9
Medium high	5-10	2.6
	3-5	8.1
High	1-3	64.7
	0.5-1	10.0
Very high	0.083-0.5	4.2
	<0.083 (30 days)[1)]	0.4

[1)] – according to Polish Low (till 2001 year) – range of intake protection zone

Tab. 4. Distribution of percentage share of vulnerability classes: DRASTIC and travel time methods.

Classes of the groundwater vulnerability	Percentage share of classes – DRASTIC method	Percentage share of classes – travel time method
Very low	0.002	0.6
Low	8.63	1.2
Medium	37.25	8.2
Medium high	52.08	10.7
High	2.05	74.7
Very high	0.005	4.6

vulnerability types depending on IPZ value. Method used, even though it might bring on some mistakes, seems to be correct in case of hydrological unit of valley type. Special attribute of the surveyed area are a long-term hydrological recognition, which in effect yields data regarding positioning of groundwater layer in all assigned zones within KNP area.

DRASTIC method enabled creation of general classification as well as map of natural vulnerability for the study area, based on calculated values of the IPZ index. This may be useful tool for environmental management. For areas where groundwater table in porous medium is shallow – river valley, and not isolated by low permeability natural from the terrain surface, for example in river valleys, an additional method to use is the migration time of conservative contamination from the terrain surface. Supplementing the base DRASTIC model can be conducted for an entire study area of study or selected parts, characterized by high natural vulnerability or perhaps in cases where there are planned changes in development. The resulting maps of groundwater vulnerability, obtained from U.S. EPA DRASTIC, show that in river valley - area of study is generally characterized by medium and medium high vulnerability (nearly 90 % of study area). The travel time of conservative contamination from terrain surface is an important factor for quantifying the groundwater vulnerability. Travel time in KNP area is from <30 days to 30 years but almost 75 % of the study area is characterized with the time from 0.5 to 3 years. It shows the high class of vulnerability.

Calculations performed with different methods; in this case using different parameters (in consequence different maps) can become basis for scenario maps showing varying concepts for protection of groundwater depending on terrain development.

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