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Methods and results of groundwater vulnerability evaluation to contamination in the Kampinoski National Park, central Poland

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ABSTRACT:

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Aquifer vulnerability maps are valuable tools for communicating concerns about the level of groundwater pollution hazard to local landuse planners and to the general public. Groundwater vulnerability to contamination in the Kampinoski National Park (KNP) area in central Poland was evaluated as a basis for developing appropriate protection strategy for the groundwater resources and management in recreation areas located near Warsaw. Assessment was accomplished using U.S. EPA DRASTIC and the residence time in the unsaturated zone of a conservative pollutant. The final DRASTIC values have been grouped into medium (37 % of area) and medium high (52 %) intrinsic vulnerability categories. The residence time in the unsaturated zone is classified in 11 intervals, ranging from 30 days to 30 years, but nearly 75 % of the study area is characterized by intervals from 1 to 3 years.

Key words: Groundwater vulnerability, Intrinsic vulnerability, DRASTIC, Residence time, Kampinoski National Park

INTRODUCTION

The concept of groundwater vulnerability to contamination is now widely used in hydrogeological assessments and has become a useful tool for planners concerned with protection of groundwater and environmental resources. Groundwater vulnerability is of concern even in national parks or other protected areas, which are not isolated from "outside effects". They are often placed under increased pressure from prolonged or intermittent pollution sources from neighbouring areas and growing population.

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

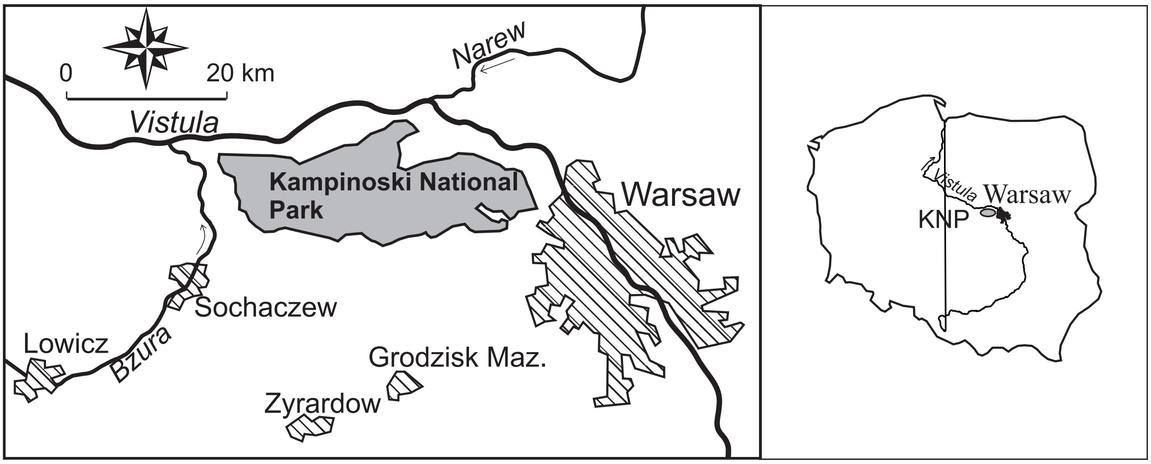

Fig.1. Localization of the Kampinoski National Park

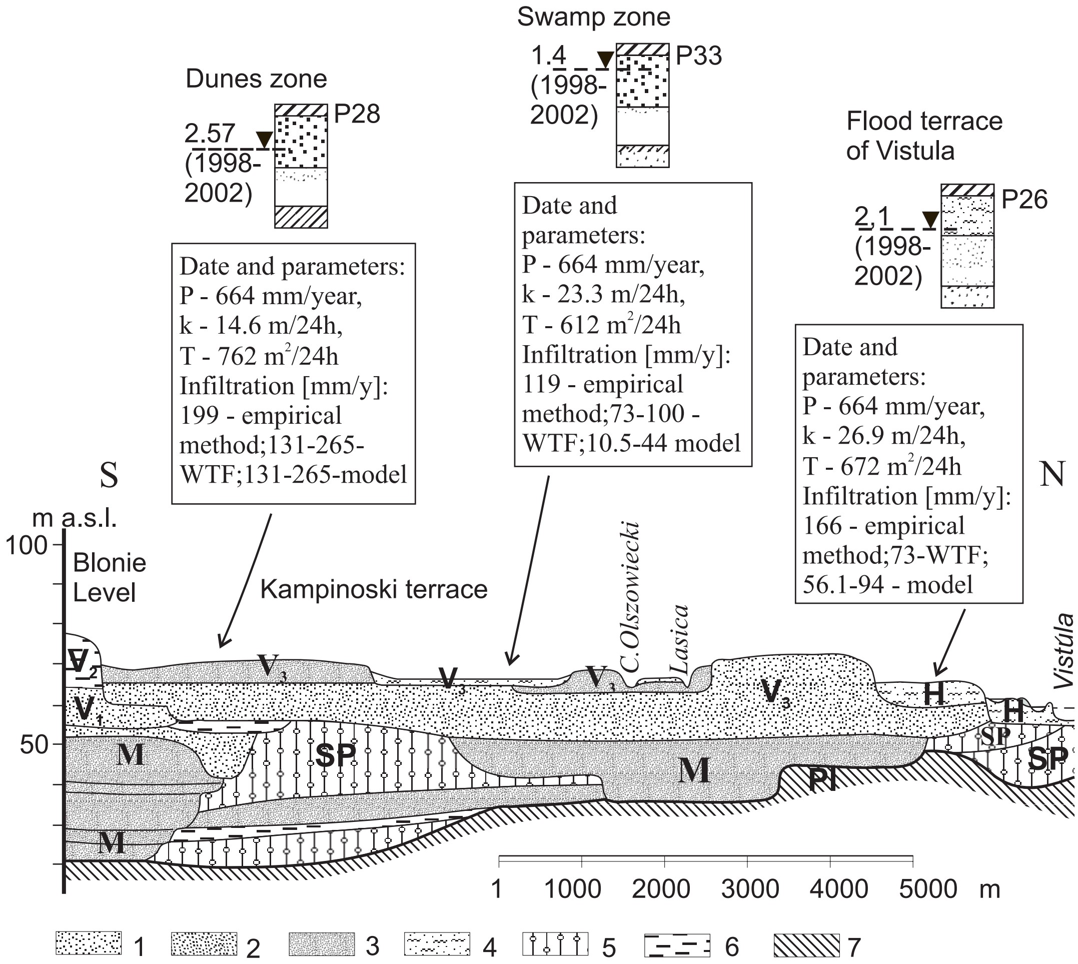

Fig. 2. Characteristic of hydrozones within the Kampinoski National Park. 1 – sand and gravel; 2 – medium sand; 3 – fine-grained sand; 4 – sand, tilly sand; 5 – till; 6 – icedammed lake clay; 7 – exposure of Pliocene deposits. P28 – profile of piezometer; parameters: P – precipitation; k – hydraulic conductivity; T – transmissivity; WTF – water fluctuation method. H – Holocene; V_1 – Lower Vistulian; V_2 – Middle Vistulian; V_3 – Upper Vistulian; E – Eemian Interglacial; MP – Middle Polish Glaciation; M – Masovian Interglacial; SP – South Polish Glaciation; Pl – Pliocene;

characterized by a diverse morphology, hydrogeological conditions, geology and vegetation, as well as infrastructure development.

HYDROGEOLOGICAL CONDITIONS OF THE KAMPINOSKI NATIONAL PARK REGION

General characteristics of the aquifer

Kampinoski National Park and its buffer zone are located in the central part of the Vistula River valley that includes the suburbs of Warsaw, a city of nearly 2 million people. In the KNP region, the main aquifer has thickness of 10 to 50 metres, and is composed of varying, fine-grained sand, in some places of till and sand. The groundwater table has an unconfined character (Text-fig. 2). In the vertical profile, two fundamental sediment series with various hydraulic parameters were determined by in-situ investigations:

- subsurface sand and gravel-sandy horizon, k_{av} – 28,2 m/d,
- horizon of medium-grained sand with numerous interbeds of washed out boulder clays with highly diverse filtration parameters; k_{av} – 20,3 m/d

Aquifer hydraulic conductivity values were also determined by statistical analysis of the hydrological data, obtained from approximately 1000 wells located within the study area (KROGULEC 2003). The arithmetic average hydraulic conductivity value for the aquifer sediment was determined from pumping test as 47.7 m/d (range of 1.2 m/d to 89.6 m/d).

The following division criteria: differences in geological structure and geomorphology, lithology of subsurface sediments and related vegetation cover, depth of groundwater table, amplitude of water level fluctuations and human economic activities were used to distinguish zones of similar hydrodynamical and environmental conditions, the so called hydrozones (KROGULEC 2004). The following zones have been distinguished: A – dune zones, B – valley (swamp) zones, C – Vistula flood plains and terraces over flood plains (Text-fig. 2), D- Blonie Level.

Groundwater monitoring network

The monitoring network consists of 56 piezometers and 25 water level gauges in seven cross sections (Text-fig. 3). The spatial distribution of the monitoring network measurement points was designed to take full advantage of hydrological and hydrogeological analysis within the enclosed surface drainage basin and the hydrogeological system (KROGULEC 2001, 2004).

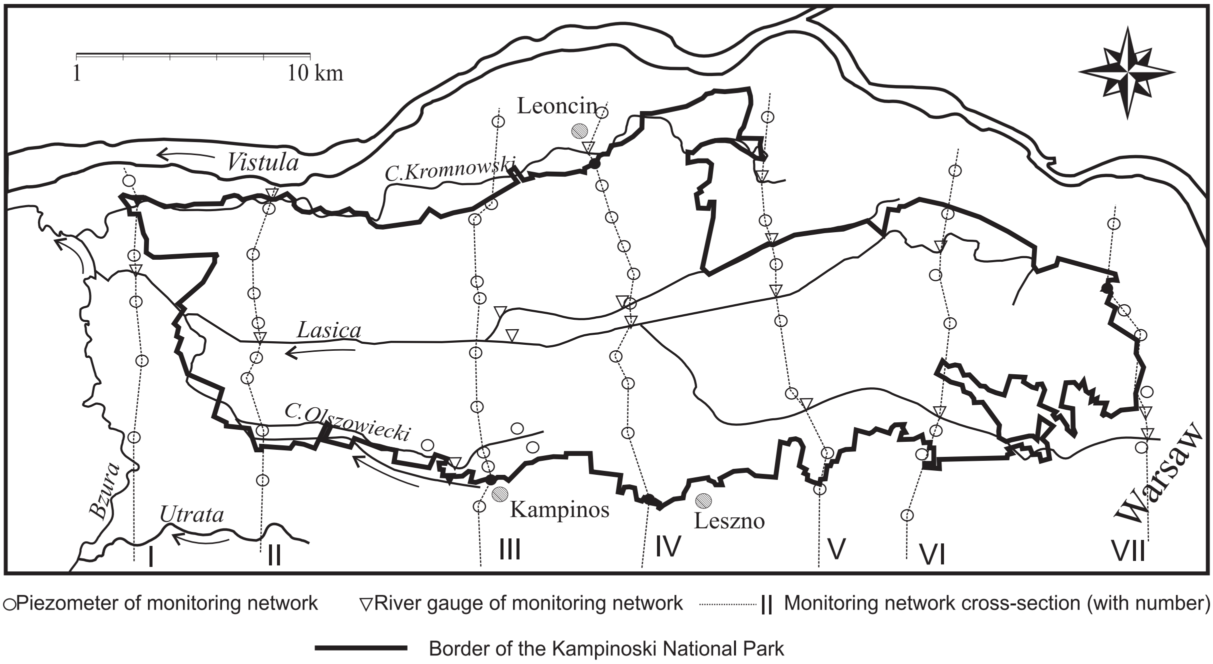

Fig. 3. Groundwater monitoring network within the Kampinoski National Park

Measurements of the surface and groundwater levels were performed at bi-weekly intervals, starting from 30.11.1998. During the period between 1998 and 2004 the water table, a fundamental criterion used in evaluation of groundwater vulnerability to contamination, was at a depth of 0.61 to 4.7 metres below terrain level. Water table hydraulic heads were at a height from 65.67 to 97.53 a. s. l. (Table 1).

Conditions of groundwater recharge and drainage

Groundwater recharge is the fundamental criterion in evaluation of groundwater vulnerability to contamination.

Groundwater recharge in the KNP area takes place almost exclusively as a result of infiltrating precipitation, but a second recharge source comes from a lower aquifer. The lower aquifer from the Blonski Level affects only the southern part of the Kampinos Terrace. During high spring runoff water from the Vistula River may infiltrate the aquifer.

The infiltration rate depends mainly on the precipitation, lithology of the subsurface and terrain afforestation ratio. The average sum of the corrected precipitation in the KNP region during the period 1951-2000 is 664 mm. In the warm half of the year (May–Oct) it reaches 399 mm and is even smaller (265 mm) in the winter season (Nov-Apr). The lithologies were evaluated through the analysis of borehole profiles and the geological mapping of the KNP region (KROGULEC 2003).

Hydrozone	Depth of groundwater table		Hydraulic head of groundwater table - average value (level fluctuation range) [m a.s.l.]
	Average value [m b.t.l.]	Level fluctuation range [m]	
Vistula flood plains and terraces over flood plains	2.13	0.35-4.65	71.19 (65.67 - 75.70)
Valley (swamp) zone	1.40	0.17-3.10	72.71 (68.19-81.81)
Dune zone	2.57	0.3-5.08	72.23 (68.04 - 77.88)
Blonie Level	2.32	1.58-3.89	86.53 (82.97 – 91.83)

Tab. 1. Characteristic of depth and hydraulic head of ground water table in the hydrozones in the KNP region

The values of infiltration were obtained by numerical modelling, hydrograph separation, watertable fluctuation (WTF) and the empirical method.

Aquifer drainage on the Kampinos Terrace takes place by a system of numerous streams, channels, rivers and melioration ditches, and partially by evapotranspiration processes in the swampy areas. The Vistula River has the strongest draining character and forms the regional drainage base. Similarly, an important role in drainage of the aquifer is played by the Bzura river, mostly in its lower section. Drainage of the aquifer also takes place through use of groundwater at many points in the study area.

Numerical modelling

The numerical model was created on the same general principle as the groundwater vulnerability model (the same study area, density of the spatial parameterization etc.). A total of 950 borehole data points allowed for building of the conceptual model. The basis for accepting the parameter values and the hydrogeological parameters (coefficient of permeability for: aquifers, low permeability sediments and near riverbed layers; effective infiltration coefficient; evapotranspiration volume, hydraulic head) was detailed by a hydrogeological survey of the research area.

Model calculations were performed with VisualMODFLOW 2.20 software, which uses the method of finite differences. Model simulations were carried out using the Strongly Implicit Procedure Package – SIP (MCDONALD & HARBAUGH 1988; MCDONALD & *al*. 1988) digital method.

The space domain was discretized in two stages. In the first stage, the model area was divided into calculation cells of 100 m x 100 m. In the second stage of simulation, the model grid was refined by reducing the cell size in the region of the Blonie Level slope, rivers and canals. Digitisation performed in this way allowed for a more accurate representation of the terrain surface and provided a better means for describing the borders of all the geological formations. It also allowed for precise assignment of surface flows in the model. Model simulations were performed for steady state conditions, giving an average value of river water levels taken from more than 6 years of monitoring observations conducted in the KNP monitoring network. Calculation results in the form of groundwater levels are also given as an average for the period of time in question.

The standard error of the calculated and observed groundwater heads is smaller than 10 cm and satisfies a compatibility test. In addition, an error analysis (ANDERSON & WOESSNER 1992) was performed. The mean error between the computed and measured heads was found to be close to zero. The mean absolute error and the root mean square error were also low, which indicates that the model was well calibrated.

The model was calibrated and verified in two steps: as a steady state model representing quasi-natural conditions, by reproducing average natural heads from before well exploitation, and as a steady state model by reproducing the current, stationary, abstraction-influenced flow system condition, characterized by a constant pumping rate.

In the abstraction-influenced simulation, not only the heads but also the stream flow measurements were used to verify the model. In this regard, the river base flow estimates were compared with the appropriate model results.

The values of the average infiltration calibrated by the modelling calculations are:

- in the southern dune zone – 186 mm/y
- in the northern dune zone – 332 mm/y
- in the Vistula River flood plain – 55,5 mm/y

Analysis of the balance elements on the numerical model shows that the Kampinos terrace is recharged from the south 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, 2004).

The numerical model research confirmed the prevailing role of the Vistula River in the formation of the hydrodynamic regime in the valley unit analysed. The river is a regional drainage base, recharged by the groundwater volume of 0.55 m^3/d for 1 m of the river length. The remaining watercourses drain the aquifer with the following volumes: Olszowieckie Canals A & B – 0.29 m^3/d, Lasica River – 0.34 m^3/d, Kronowski Canal - 0.12 m^3/d. The groundwater drainage in the research area is also related to the evapotranspiration process which is significant only in the area of the valley depressions and the Vistula River flood plain where the groundwater table is less than 1.5 m b.t.l. (below terrain level). In the northern swamp zone the evapotranspiration value is 0.31 m^3/d, in the southern swamp zone – 0.16 m^3/d, in the Vistula River flood plain – 0.084 m^3/d (KROGULEC 2004).

Hydrograph separation method

The quantitative evaluation of the baseflow for the Lasica river – the main river in the Kampinoski National Park – depends mainly on the intensity and the volume of precipitation, which entitles us to state that it plays an important role in the lowland drainage basin with swamps and the forest cover.

The basis for the baseflow calculations for the Lasica river was the hydrological profile at Władysławowo (area of catchment = 441.0 km^2). Series of daily discharges in the period 1951-2000 were used. The runoff calculation by hydrograph separation to the surface and underground components, was done using an automated method called **B**ase **F**low **I**ndex (MAGNUSZEWSKI 1990; TOMASZEWSKI 1998). In the period 1951-2000, the river baseflow varied considerably, from 163 mm in 1967, to barely 43 mm in 1952 and 1992 (SOCZYŃSKA & *al*. 2003)

Water table fluctuation method

The water table fluctuation (WTF) method is a conventional method for quantifying groundwater infiltration recharge by multiplying the specific yield by the water level rise (HEALY & 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 analyze the effects of the water level depth and the soil properties on the recharge estimate using the WTF method. The values of infiltration obtained by the WTF method using observation from the KNP monitoring network range from 73 mm/year in the flood terrace of Vistula and the swamp areas to 265 mm/year in the dunes areas.

Empirical method

The empirical method offers a quick assessment of infiltration recharge as a proportion of precipitation in terms of climate (generally corrected atmospheric precipitation), land use, terrain and geology (PAZDRO 1983). Results of infiltration using the empirical method in the KNP area are from 119 in the swamp areas to 199 mm/year in the dunes.

GROUNDWATER VULNERABILITY

According to the conclusions of the international conference on „Vulnerability of Soil and Groundwater to Pollutants", held in 1987 in The Netherlands (DUIJVENBOODEN & WAEGENINGH 1987), groundwater vulnerability to contamination is defined as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of 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 the type of hazardous substance, its amount, and its location with respect to the aquifer (DUIJVENBOODEN & WAEGENING 1987; VRBA & ZAPOROZEC 1994; WITCZAK & ŻUREK 1994).

For the central area of KNP located in the Vistula River valley, the intrinsic vulnerability of the groundwater was determined by means of two methods:

- U.S. EPA DRASTIC model (ALLER & *al*. 1987),
- residence time in the unsaturated zone of a conservative, non-absorbable and non-adsorable pollutant.

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 & *al.* 1987). It is one of the most popular ranking methods developed especially for evaluation of vulnerability in particular hydrogeological regions. The classification system of vulnerability in the DRASTIC method is a standard tool used by many countries in the 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 the Ścianawka catchment, with an area of 595 km^2, located in Lower Silesia (LIMISIEWICZ 1998) and the Upper Silesia catchments (WITKOWSKI & *al*. 2003), and also was used in some studies for various types of water-bearing reservoirs, mostly porosity-fracture type, undertaken by the Academy of Mining & Metallurgy (WITCZAK & ŻUREK 1994).

DRASTIC is an acronym for the variables that control the groundwater pollution potential: **d**epth to the water level, net **r**echarge, **a**quifer media, **s**oil types, **t**opography, **i**mpact of vadose zone, and hydraulic **c**onductivity.

Each variable is assigned a different degree of importance on a scale of 1 to 5, the most significant factors have weights of 5; the least significant a weight of 1. Each criterion also possesses a suitable value of the coefficient and is given a rank, on a 1 to 10 scale, depending on the local conditions (Table 2). High values correspond to high vulnerability. The index of vulnerability DRASTIC IPZ_Σ corresponds to the weighted average variable rank:

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

No	Criterion	Class	Weight of criterion	Rank
1 D	**D**epth to groundwater water table [m]	<1 - >5	5	7 - 10
2 R	Net **R**echarge [mm/y]	50 - >50	4	2 - 6
3 A	Lithology of **A**quifer	sand, gravel - sandy clay, loam, loam and sand	3	2 - 8
4 S	**S**oil media	loam, sandy loam, shrinking clay, peat, anthropogenic and absent	2	5 - 10
5 T	**T**opography (slope) [%]	0,0 - 3,9	1	7.5 - 10
6 I	**I**mpact of vadose zone	clay, sand, silty loam, loam, gravel	5	2 - 8
7 C	Hydraulic conductivity of aquifer [m/24h]	<4 – 80		- 8

Tab.2. Rating of DRASTIC criteria with assigned weights (after ALLER & *al*. 1987 – modified for the KNP area - KROGULEC 2004)

Initial data for DRASTIC model values of basic data and hydrological parameters in the region of the middle part of the Vistula valley suggest heavy diversification of the area. Parameters such as the properties of the vadose zone, the soil layers and the depth of the water table, have to be characterised quantitatively.

One of the most precisely defined criteria – 1 (Table 2), the depth to the water table, was extracted from a long-term monitoring study, with piezometers located over the entire study area. It allowed the determination of median values, with the data collected verified with the modelling results. The water table in the Vistula valley region is found at shallow depths, because in 79% of the blocks (area of more than 480 km^2) in the DRASTIC method the depth to the water table does not exceed 1.5 m below terrain surface, and only 9% of all blocks are areas where the water table is situated much deeper, reaching more than 5 m below terrain surface (Text-fig. 4).

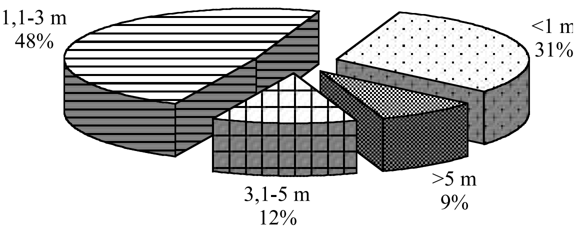

Fig. 4. Depth of groundwater table in the KNP - criterion 1 of DRASTIC method

Criterion 2 – the variable net recharge was calculated by the method presented in the above section. The infiltration changes in the range from 50 to 250 mm/year (Table 2). The highest infiltration, over 250 mm/year, occurs in 94 computational cells, which account for less than 1% of the research area (Text-ig. 5). The average value of infiltration index is between 150 to 250 mm/year.

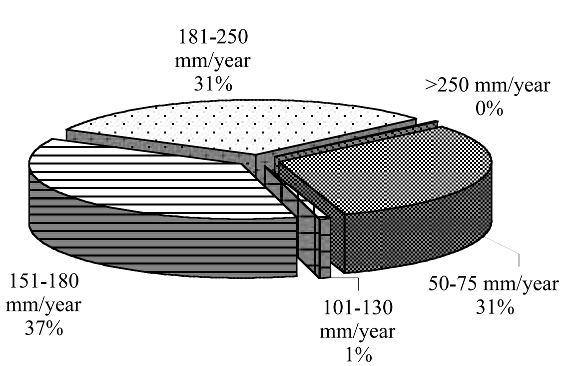

Fig. 5. The recharging infiltration in KNP - criterion 2 of DRASTIC method

Aquifer lithology (criterion – 3) was derived from a detailed analysis of borehole profiles. The database for the study region comprises of 978 boreholes (observational and well type); the research was supplemented with geophysical probing (KROGULEC & POMIANOWSKI 2001). For the requirements of the DRASTIC model six classes were separated. The largest area was occupied by river and fluvioglacial sand (39%), eolian sand (31%), river mud and oozes (25%). The remaining separations played a limited role in aquifer formation (Text-fig. 6).

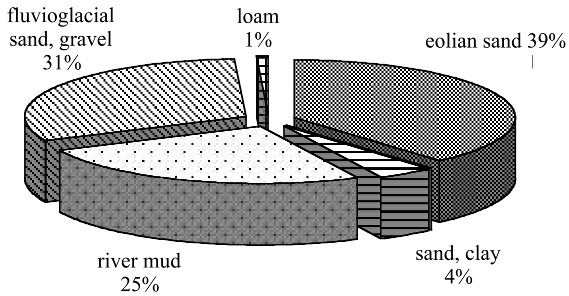

Fig. 6. Aquifer lithology in KNP - criterion 3 of DRASTIC method

Soil media (soil cover; criterion 4) in the study area is highly diverse; it was examined thoroughly in order to preserve and re-naturalize habitat plants in the park territory. Basic data on the types and characteristics of the soil cover were gathered from a 1:5 000 pedological map and pedological profiles. For the requirements of the DRASTIC model, generalization was performed and the separations, with the exception of podsol, eolic-eroded soil and anthropogenic soils, occupied about 92% of the area, which accounted for over 560 km^2 (Text-fig. 7).

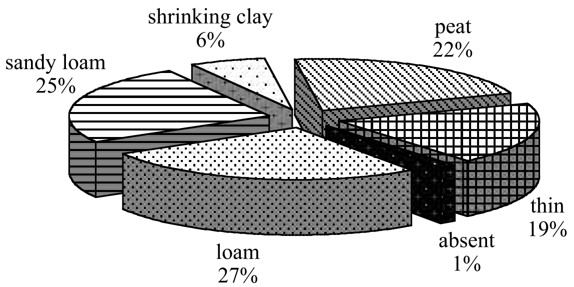

Fig. 7. Soil media in the KNP - criterion 4 of DRASTIC method

Criterion 5, terrain slope, plays a smaller role in the evaluation of the vulnerability of groundwaters to contamination. The study area, in spite of being situated in the river valley, is morphologically diverse with frequent occurrence of sand dunes (hills) and valley depressions. Calculations of slopes were performed using a 1:50 000 Digital Elevation Model (DEM) of the area. Although about 94% of the terrain is characterized by small slopes, from 0 to 0.2%, approximately 1% of the area has relatively steep slopes from 0.4 to 3.8%. The lithology of the subsurface formations (criterion 6) is variable, similarly to the aquifer lithology. It was investigated in detail by analysis of the borehole profiles. For the requirements of the DRASTIC model 6 separations were isolated (Table 2).

Hydraulic conductivity value (criterion 7) for the aquifer was determined similarly to the lithology of the aquifer, using the database of borehole profiles, piezometers and geological surveys. Furthermore, hydraulic conductivities were derived from mathematical modelling. It was found that 48% of the study area was characterised by high hydraulic conductivities ranging from 13 to 28 m/d, while much lower values of 4 m/d occurred only in approximately 4 % of the study area (Text-fig. 8).

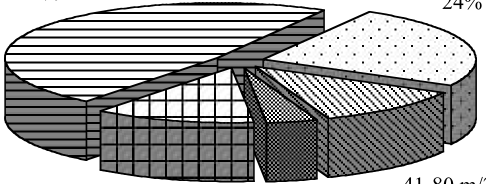

Fig. 8. Hydraulic conductivity of aquifer in the KNP - criterion 7 of DRASTIC method

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. Each criterion (hydrogeological data, soil categories, and topography) was plotted on several maps at a scale of 1:50 000[1]. Modelling called for all criteria to be brought into a form of pseudo-continuous distributions, expressed in a form of nets of a natural mesh with a resolution of 100 m x 100 m (cells 100x100 m, more than 65 000 cells).

Based on the DRASTIC method, slightly modified, classification of groundwater vulnerability was adopted, dependent on the variation range of the IPZ index. The following types of groundwater vulnerability were assigned: very low (IPZ<100), low (IPZ from 100 to 125), medium (IPZ from 126 to 150), moderately high (IPZ from 151 to 175), high (IPZ from 176 to 200), very high (IPZ>200) – Table 3.

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 km^2 – evaluated area**		**100 %**

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

The region of the middle Vistula valley is characterized by medium (37% of the area – 228 km^2) and medium high (52% of the area that is over 318 km^2) vulnerability to contamination. In the study region, an area of approximately 12,5 km^2 is classified as highly vulnerable. The remaining vulnerability classes occur on a considerably smaller area (Table 3). The DRASTIC evaluation produces a map that shows the distribution of values of the vulnerability index IPZ_{Σ} (scheme of map – Text-fig. 9).

Residence time as a criterion of vulnerability

Residence time in the unsaturated zone of a conservative, non-absorbable and non-adsorbable pollutant is typically described as the travel time (infiltration time) from the terrain surface to aquifer. It is a key factor in determining the vulnerability of groundwater to contamination. Approximate travel time can be determined from the time of water exchange in a rock formation assuming the piston-flow model.

Travel time through the vadose zone was calculated with the use of the following formula (WOSTEN & AL. 1986; HAITH & LADEN 1989; WITCZAK & ŻUREK 1994; KROGULEC 2004):

[1] ARC/INFO 8.0.1, ArcView 3.2, AVSpatialAnalist 1.1, AVArcPress 2.0 produced by ESRI, were used to prepare maps and perform relevant spatial computations in PGNiG Poland.

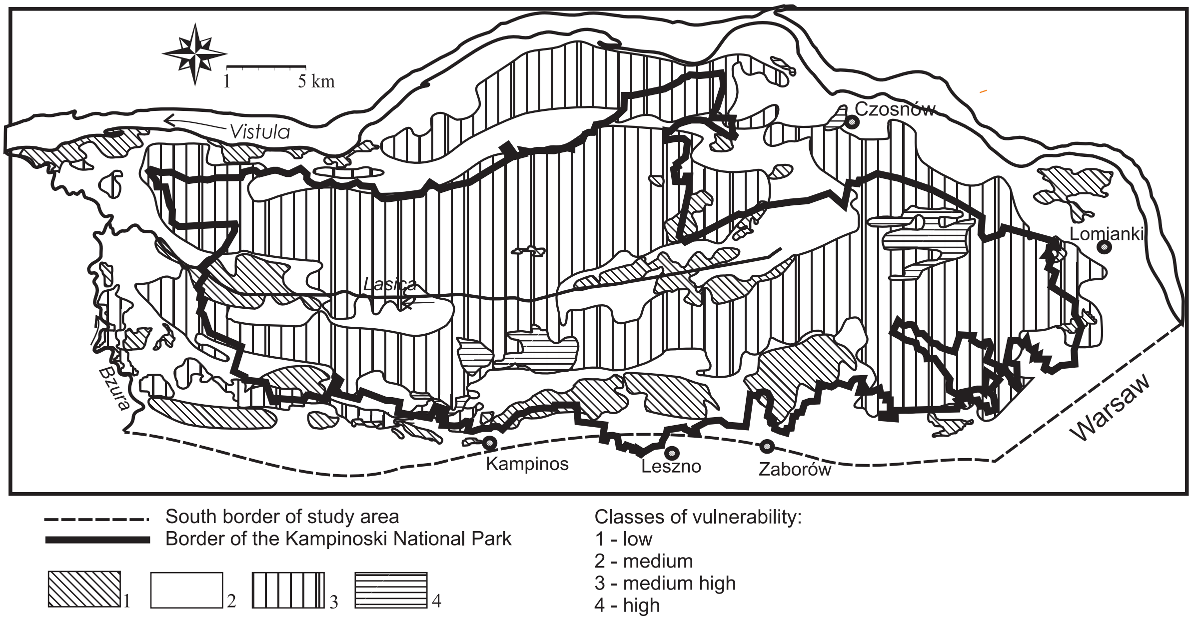

Fig. 9. Groundwater vulnerability map of the Kampinoski National Park - DRASTIC method

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

where:

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

w_o- storage capacity of vadose zone [-]

I_e - infiltration recharge in the soil profile [m/ y]

The thickness of successive layers of the vadose zone, the storage capacity of the vadose zone and value of infiltration was plotted on maps at a scale of 1:50 000 and then were divided into calculation blocks with a resolution of 100 m x 100 m in the same way as in numerical modelling and the DRASTIC method.

Vulnerability classes	Travel time of conservative pollutant [year]	Percentage share of classes [%]
Very low	>30	0.6
Low	20-30	1.2
Medium	10-20	8.2
Medium high	3-10	10.7
High	0.5-3	74.7
Very high	<0.083 (30 days)[1)]-0.	.6

Tab. 4. Travel time of conservative pollutant in the Vistula River valley (area of the Kampinoski National Park), percentage share of classes

Travel time determined by the above formula is from 0.5 to 10 years, but almost 75% of the study area is characterized by infiltration time from 0.5 to 3 years (high class of vulnerability) – Table 4.

CONCLUSIONS AND DISCUSSION

The results of the comprehensive hydrogelogical assessment presented in the context of local topography and soil layering provided the basis for creating a reliable and precise environmental database of the KNP region. Use of GIS techniques during the development of the vulnerability map made possible a more precise assignment of the parameter values and enabled a more accurate distinction of vulnerability types. The use of extensive data series comprising long-term hydrogeological measurements resulted in better determination of groundwater horizons in all the hydrozones defined within the KNP area.

The DRASTIC method enabled creation of a general classification and map of intrinsic vulnerability for the study area, based on calculated values of the IPZ index. This type of enhancement of the basic DRASTIC model can be carried out for the entire KNP region or just for selected parts, characterized by high intrinsic vulnerability, or perhaps only in cases where there are planned changes in development. The maps of groundwater vulnerability developed using DRASTIC show that the river valley region, which covers nearly 90% of the study area, represents medium and medium-high vulnerability (nearly 90% of the study area). The analysis of residence time, expressed as travel times, proved to be one of the most important factors in determining groundwater vulnerability. This is particularly the case in the areas of shallow groundwater table in sandy sediments not isolated from the terrain surface by low permeability sediments.. Travel time in the KNP area is from <30 days to 30 years but almost 75% of the study area is characterized by travel times from 0.5 to 3 years - which shows high vulnerability.

Because evaluation methods of groundwater vulnerability to contamination are not standardised, it is difficult to compare results and conclusions between studies (Table 5).

Classes of the groundwater vulnerability	Percentage share of classes – DRASTIC method [%]	Percentage share of classes – travel time method [%]
Very low	<1	<1
Low	8.63	1.2
Medium	37.25	8.2
Medium high	52.08	10.7
High	2.05	74.7
Very high	<1	4.6

Tab. 5. Distribution of percentage share of vulnerability classes: DRASTIC and travel time methods

It is important to understand that the key factors in the evaluation of vulnerability - depth to groundwater and value of infiltration - are useful but do not characterize the vulnerability on their own (tab. 6).

Some of the systems for evaluation of vulnerability and for hazard ranking include a vulnerability index which is computed from hydrogeological, morphological and other aquifer characteristics in a clearly defined way. In principle, the adoption of an index has the advantage of eliminating or minimising subjectivity in the ranking process. Such a standardised DRASTIC index, developed by ALLER & *al*. (1987), regardless of its limitations, is currently used in many countries. This index is simple to use and effective.

All vulnerability maps consider more and less vulnerable categories (e.g. high, medium and low vulnerability categories) but the key parameters selected and the criteria used in the ranking may differ. The limitations and uncertainties of individual vulnerability assessments must be clearly acknowledged in order to avoid misuse.

Hydrozone	IPZ_ - DRASTIC method and vulnerability class	Travel time [y] and vulnerability class	Average depth of groundwater [m b.t.l.]	Infiltration [mm/y]
Vistula flood plains and terraces	131 medium	0.083-5 very high, high, medium high	2.13	90.4
Swamp zone	100-114 medium	1-10 high, medium high	1.40	48.5
Dune zone	165 medium high	1 – 5 high, medium high	2.57	98.9
Blonie Level	140-151 medium, medium high	1-10 high, medium high	2.57	67.5

Tab. 6. Characteristics of dominant IPZ value and vulnerability classes in selected hydrozones and average values of key factors in evaluation of groundwater vulnerability

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REFERENCES

ALLER, L. BENNETT, T. LEHR, J.H. PETTY, R.J. & HACKETT, G. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings, 1-238. *Ada*; Oklahoma.

ANDERSON, M. & WOESSNER, W. 1992. Applied groundwater modelling and avective transport, 1-456. *Academic Press, Inc*.; London.

DUIJVENBOODEN, W. & WAEGENINGH, H.G. 1987. Vulnerability of Soil and Groundwater to Pollutants, Proceedings and Information. No.38. International Conference held in Netherlands, 1987, TNO Committee on Hydrological Research, Delft, 1-114, The Netherlands.

HAITH, D.A. & LADEN E.M. 1989. Screening of groundwater contaminations by travel-time distributions.

Journal of Environmental Engineering, *ASCE*, **115** (3), 497-512.

HEALY, RW. & COOK, P.G. 2002. Using ground water levels to estimate recharge. *Hydrogeol. J.V* **10** (1), 91-109.

KROGULEC, E. 1997. Numeryczna analiza struktury strumienia filtracji w strefie krawędziowej poziomu błońskiego, 1-79. *Wydawnictwa Uniwersytetu Warszawskiego*; Warszawa.

— 2001. Monitoring shallow groundwater within protected areas – an example of local groundwater monitoring network in Kampinos National Park (Poland). Conference Hydrogeochemia 2001, 117-123. Bratislava.

— 2003. Hydrogeological conditions of the Kampinos National Park (KNP) region. *Ecohydrology and Hydrobiology*, **3** (3), 257-266.

— 2004. Ocena podatności wód podziemnych na zanieczyszczenia w jednostce dolinnej w aspekcie warunków hydrodynamicznych, 1–177. *Wydawnictwa Uniwersytetu Warszawskiego*; Warszawa.

KROGULEC, E. & POMIANOWSKI, P. 2001. Warunki hydrogeologiczne Kampinoskiego Parku Narodowego – nowe dane z badań geofizycznych. *Przegląd Geologiczny* **4**, 312-316.

LIMISIEWICZ, P. 1998. Ocena podatności wód podziemnych na zanieczyszczenie w wybranych zlewniach Dolnego Śląska, Uniwersytet Wrocławski, unpublished Ph.D. thesis; Instytut Nauk Geologicznych, Zakład Hydrogeologii, Wrocław.

MAGNUSZEWSKI, A. 1990. Zautomatyzowany sposób obliczania charakterystyk niżówkowych. *Przegląd Geofizyczny*, **1-2**.

MCDONALD, M. & HARBAUGH, A. 1988. A modular three-dimensional finite-difference ground-water flow model, 1-223. *U.S. Geological Survey*; Washington.

MCDONALD, M. HARBAUGH, A. BRENNON, R. & ACKERMAN, D. 1988. A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model, 1-147. *U.S. Geological Survey*; Washington.

PAZDRO, Z. 1983. Hydrogeologia ogólna, 1- 576. *Wydawnictwa Geologiczne*; Warszawa.

SOCZYŃSKA, U. GUTRY-KORYCKA, M. POKOJSKA, P. & MIKOS, D. 2003. Bilans potamologiczny jako metoda oceny zmienności obiegu wody w dorzeczu Łasicy (Kampinoski Park Narodowy). *Ecohydrology and Hydrobiology*, **3** (3), 291-309.

TOMASZEWSKI, E. 1998. Zastosowanie zmodyfikowanego algorytmu FRIEND do oceny wielkości podziemnego zasilania rzek. *In*: A. MAGNUSZEWSKI & U. SOCZYŃSKA *(Eds)*, Hydrologia u progu XXI wieku. Komisja Hydrologiczna PTG, pp. 34-68. *Wydawnictwa Uniwersytetu Warszawskiego*; Warszawa.

VRBA, J. ZAPOROZEC, A. (*Eds*) 1994. Guidebook on mapping groundwater vulnerability, IAH, 1-246, *International Contributions to Hydrogeology*, **16.** *Heise Verlag*; Hannover.

WITCZAK, S. & ŻUREK, A. 1994. Wykorzystanie map glebowo-rolniczych w ocenie ochronnej roli gleb dla wód podziemnych. 1-22, *AGH*; Kraków.

WITKOWSKI, A. RUBIN, K. KOWALCZYK. A. RÓŻKOWSKI, A. & WRÓBEL J. 2003. Groundwater vulnerability map of the Chrzanów Karst-fissured Trassic aquifer (Poland). *Environmental Geology*, **44** (1), 59-67.

WÖSTEN, J.H., BANNINK, J.J. DE GRUIJTER, J. & BOUMA, J. 1986. A procedure of identify different groups of hydraulic conductivity and moisture retention curves for soils horizons. *Journal of Hydrology*, **86**, 133-145.

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