METHODS AND RESULTS OF GROUNDWATER RECHARGE ASSESSMENT IN THE KAMPINOSKI NATIONAL PARK, CENTRAL POLAND

METÓDY A VÝSLEDKY HODNOTENIA DOPĹŇANIA PODZEMNÝCH VÔD V KAMPINOSKOM NÁRODNOM PARKU V CENTRÁLNOM POĽSKU

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ABSTRACT
Scope, methodology and results of hydrogeological modelling of recharging infiltration are performed in in the Kampinoski National Park (KNP). Park – a UNESCO Biosphere Reserve (an area of about 800 km^2) is located within hydrological valley unit in the middle part of Vistula River valley. The values of infiltration were obtained by numerical modelling, hydrograph separation, water table fluctuation (WTF) and empirical method. The calculation results indicate that the effective infiltration in the KNP region is particularly strong in the dune areas where it ranges from 74.0 to 169.6 mm/year.

KEY WORDS
River valley, infiltration recharge, groundwater vulnerability, Kampinoski National Park

KĽÚČOVÉ SLOVÁ
údolie rieky, dopĺňanie infiltráciou, zraniteľnosť podzemných vôd, Kampinoski národný park

INTRODUCTION

The assessment of the volume of the infiltration recharge in the Vistula valley was carried out in the region of the Kampinoski National Park (KNP). The hydrogeological and geological conditions in the area are typical for the valleys in the Polish Lowlands, which means that the obtained results for the infiltration volumes and the approach can be applied to calculations in other valley units.

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 NATURA 2000 network which plays an essential role in nature conservation in the EU. The park is located where tributaries: the Narew and 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 the Kampinoski National Park is especially recognized as an important ecological area in Europe.

River valleys, including the Vistula valley are the concentrations of the largest groundwater intakes. The exceptional significance of the Vistula valley in the economy and its paramount role in the system of protected areas encouraged detailed hydrogeological research, including one of the key elements of the circulation system – the volume of infiltration.

HYDROGEOLOGICAL CONDITIONS OF THE KNP REGION

Kampinoski National Park is located in the central part of the Vistula River valley that includes the suburbs of Warsaw (Fig. 1), 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 tilly sand.

In the vertical profile, two fundamental sediment series with various hydraulic parameters were determined by in-situ investigations: subsurface sand and gravel-sandy horizon, kav – 28.2 m/d (T: 226 - 846 m^2/d) and horizon of medium grained sand with numerous interbeddings of washed out boulder clays with very diversified filtration parameters; kav – 20.3 m/d (T: 304 - 568 m^2/d).

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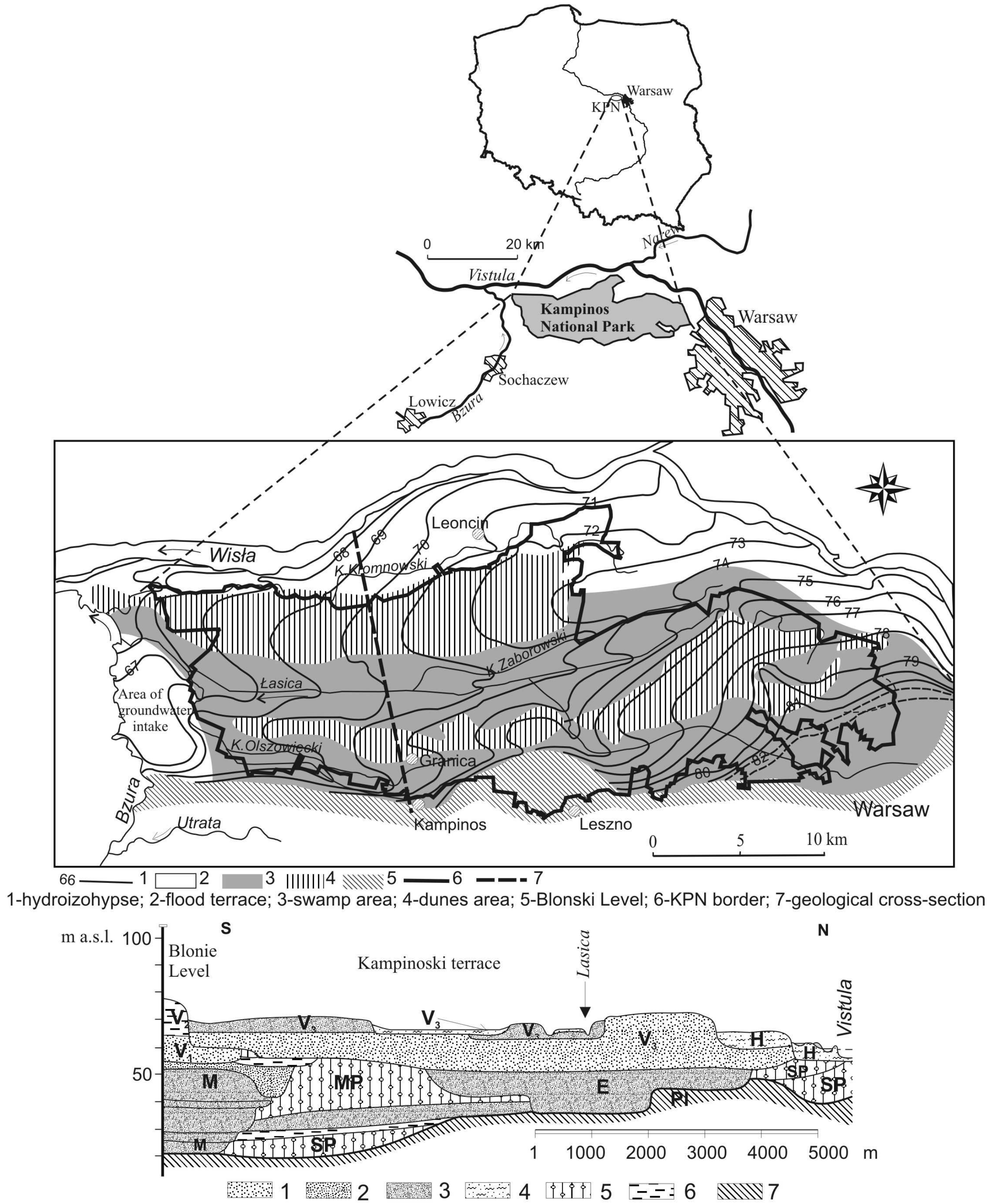

1 - sand and gravel, 2 - medium sand, 3 - fine-grained sand, 4 sand, tilly sand, 5- till, 6 - icedammed lake clay, 7 - exposure of Pliocene deposits

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

Fig. 1: Lokalization and characteristic of hydrozones within Kampinoski National Park

The groundwater table has an unconfined character. Measurements of the surface and groundwater levels were performed in bi weekly intervals starting from 30.11.1998. The monitoring network consists of 56 piezometers and 25 water level gauges in seven cross sections. During the period between 1998 and 2006 the water table was at a depth of 0.61 to 5.2 meters below terrain level; average: 1.4 m b.t.l. – swamp areas; 2,1 m b.t.l. – Vistula flood terrace and 2.57 m b.t.l. – dunes area. Water table hydraulic heads were at a height from 65.67 to 97.53 m a. s. l.

The following division criteria: differences in geologic structure and geomorphology, lithology of sub-surface sediments and related vegetation cover, depth of ground water 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, D- Blonie Level (upland level) (Fig. 1).

GROUNDWATER RECHARGE IN KAMPIOSKI NATIONAL PARK

Effective infiltration also referred to as the infiltration recharge is defined as that part of the precipitation, which is charged to the groundwater, after diminution by the volume of the surface run-off, evapotranspiration and other processes that diminish the water quantity and occur in the aeration zone. The most important factors determining the recharge volume in the river valleys are:

- precipitation,
- vertical value of the filtration coefficient of the subsurface beds and the contact zone with the subsurface waters,
- conductivity within the neighbouring groundwater systems which determine the possibility of water flow from the feeding zones,
- depth groundwater table,
- anthropogenic factors.

Other factors, such as terrain morphology (terrain inclination), vegetation, temperature, saturation deficit and the height of the capillary lift are also taken into account, yet indirectly, in case of the analysis of the recharge volumes in hydrogeological valley units, specifically on regional level, although they do not play a primary role.

In assessment of the intrinsic groundwater vulnerability to contamination and other hydrogeological problems, the recharge volume can be estimated in different scales. For regional analyses, however, the recharge volume estimation will most frequently involve averaging of values for a longer period due to technical difficulties with creation and interpretation of multiple different seasonal maps, which are or will be useful e.g. for land development guidelines.

The choice of the method of infiltration volume estimation depends on the climate conditions, the time and area covered by the surveys, the purpose of the survey (scientific research, assessment of water resources, etc.) and the level of detail (preliminary or detailed surveys).

Groundwater recharge in the Kampinoski National Park area takes place almost exclusively as a result of infiltrating precipitation; however, a second recharge source comes from a lower aquifer. The lower aquifer from Blonie Level only affects the southern part of KNP.

Aquifer drainage on the KNP takes place by a system of numerous streams, channels, melioration ditches, rivers 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 plays Bzura River, mostly in its lower section. Drainage of the aquifer also takes place through use of groundwater in many points in the study area.

NUMERICAL MODELLING

A total of 950 borehole data points allowed for building of the geological 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. The model was constructed on a 16 km cross section in the central part of the KNP and its protection zone. The cross section line, running north south starts from the Blonski Level and ends on the Vistula river.

Model calculations were performed with VisualMODFLOW 2.20 software (McDonald, Harbaugh, 1988, McDonald et al., 1988), which uses the method of finite differences.

The space domain was performed in two stages. In the first stage the model area was divided into calculation cells (blocks) of 100 m x 100 m. In the second stage of simulation of stressed hydrodynamic conditions, 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 llowed for a more accurate representation of the terrain surface and provided a better means for describing the borders of all geological formations. It also allowed for precise assignment of surface flows in the model. The following border conditions were provided for the model borders: Vistula river from the north, III-rd type condition was assumed for the block including the river, for remaining blocks within this border the II-nd type condition was taken (type Q = 0);from south watershed zone, in subsurface aquifer and marginal lake clays, border the II-nd type condition was taken. The volume of flow from the lower Blonie Level horizon aquifer to Kampinos terrace was modelled by border condition of II-nd type Q = 0.248 m^3/d (Krogulec, 2004). Bottom model border was taken as the floor of the aquiferous layers, the top border was surface level and was given the II-nd type condition was modelling the volume of infiltration supply and evaporation.

Model simulations were performed for steady state conditions, giving an average value of river water levels taken from more than 8 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 mentioned period of time.

The standard error of the calculated and observed groundwater heads is smaller than 15 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 groundwater exploitation, and as a steady state model by reproducing 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 and in the Vistula River flood terrace – 55.5 mm/y (Tab. 1).

Tab. 1: Value of infiltration recharge – method of modelling

Hydrozones in KNP	Infiltration recharge [mm/year]
Flood terrace of Vistula River	46.1- 94.5
Swamp areas – north part	10.5-43.9
Swamp areas – south part	33,2
Dunes areas – north part	82.2-348
Dunes areas – south part	74.0-199.9

Analysis of the balance elements on the numerical model shows that the Kampinos area 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 analysed valley unit. 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 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 terrace 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 terrace – 0.084 m^3/d (Krogulec, 2004).

HYDROGRAPH SEPARATION METHOD

The runoff separation to surface and underground component was made using automated method of the series processing developed by UK Institute of Hydrology, Wallingford. The, so called, **B**ase **F**low **I**ndex performs hydrograph separation (Magnuszewski, 1990, Tomaszewski, 1998). Similarly like in the case of the hydrogram genetic split the method has an automatic assumption that after the freshet wave passes there is a gradual decrease of river flow intensity with simultaneous increase of groundwater inflow to the water course beds. The runoff separation to surface and underground component for the Lasica river the main river in the Kampinoski National Park (area of catchment = 441.0 km^2) was made using **B**ase **F**low **I**ndex. Series of daily discharges in the period of 1951 – 2000 were used. The runoff separation by hydrograph separation to the surface and underground components – baseflow, was done using an automated method (Soczyńska et al., 2003).

The conversion of river discharge to runoff layer has been done using an effective catchment area responsible for formation of the surface runoff. Excluded without drained (areas without outflow) areas cover 32 % of the catchment, and are located within the dune zones where there is an intensive infiltration.

Hydrogram separation shows that the direct runoff is only 29 % of the Lasica total runoff reaching 36 mm/year in the period 1951 – 2000. The amplitude of direct runoff is 66 mm, in 1952 it reaches only 10 mm, while in the humid year of 1978 it is seven times bigger (70 mm). In the analysed period the river baseflow varied considerably: from 163 mm in 1967 to barely 43 mm in years 1952 and 1992 (Soczyńska et al., 2003). Definitely bigger base runoff (60 mm) occurs in the winter half of the year (XI-IV).

The seasonal distribution shows that the most efficient groundwater recharge is from snowmelt and spring precipitation III, IV (12 mm) while the lowest recharge is observed in the summer-autumn (3 mm).

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.

Infiltration recharge was calculated with the use of the following formula (Healy, Cook, 2002):

$$R = \frac{S_y dh}{dt} = \frac{S_y \Delta h}{\Delta t}$$

where:
R – infiltration recharge [mm/y]
S_y - specific yield [1]
h – water table hydraulic head [mm]
t – time [year]

The values of infiltration obtained by the WTF method using groundwater table observation from the KNP monitoring network are from 73 mm/year in the flood terrace of Vistula and the swamp areas to 265 mm/year in the dunes areas (Tab. 2).

Tab. 2: Value of infiltration recharge – WTF method; specific yield: Sy=0,0826 (flood terrace and swamp areas), Sy =0,1731 (dunes areas, Somorowska, 2003)

Hydrozones in KNP	Infiltration recharge [mm/y]
Flood terrace of Vistula River (4 piezometers*)	73
Swamp areas (5 piezometers)	73-100
Dunes areas (5 piezometers)	131-265
Kampinoski National Park	**143 mm/year**

* - piezometers of KNP monitoring network

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). 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 multi-year period (1951 – 2000) is 664 mm. The evaluation of lithology was well researched through drilling profiles analysis and from the geological and soil mapping of the KNP region (Krogulec, 2003).

Results of infiltration using the empirical method in the KNP area taking into consideration geological maps in scale 1:50 000 are from 119 in the swamp areas to 199 mm/year in the dunes (Tab. 3).

Tab. 3: Value of infiltration recharge [mm/year] – empirical Metod

Hydrozones in KNP	Lithology (geological maps)	Interpretation of soil maps
Flood terrace of Vistula River	166.0	132.8
Swamp areas	119.5	99.6
Dunes areas	199.2	199.0
Kampinoski National Park	159.4	126.2

RESIDENCE TIME AS A CRITERION OF 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). An investigated quantity of groundwater recharge is the fundamental criterion in evaluation of groundwater vulnerability to contamination.

Residence time in the unsaturated zone of a conser-vative, non-absorbable and non-adsorbable pollutant is typically described as the travel time (infiltration time) determining the vulnerability of groundwater and one of rational criteria used in evaluating groundwater vulnerability. 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 et al., 1986, Haith, Laden, 1989, Witczak, Żurek, 1994, Krogulec, 2004):

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

where:

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

wo- storage capacity of vadose zone [-]

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

Thickness of successive layers of vadose zone, storage capacity of vadose zone and value of infiltration was plotted on maps at a scale 1:50 000 and than were dividend into calculation blocks with a resolution of 100 m x 100 m pseudocontinous distributions; 65 000 calculation blocks).

One of the most precisely defined criteria thicknesses of successive layers of vadose zone profile was extracted from a long term monitoring study, with piezometers located over the entire study area. It allowed to determine median values, with the data collected verified with the modelling results. Water table in the Vistula valley region is found at shallow depths, because in 79 % of the calculation blocks does not exceed 3 m below terrain surface and only 9 % of all blocks are areas were water table is situated much deeper, reaching more than 5 m below terrain surface (Fig. 2). Storage capacity of vadose zone was obtained according to Wilun (1987).

Value of infiltration recharge obtaining by empirical method have been 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. The highest rate of infiltration, over 250 mm/year, occurs in 94 calculation blocks that account for less than 1% of the research area. The average volume of recharging infiltration index is between 150 to 250 mm/year – Fig. 3 (Krogulec, 2006).

Travel time determined by the mentioned 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) – Fig. 4.

It is important that the key factors in evaluation of vulnerability: value of infiltration and depth to groundwater are useful but do not characterize the real vulnerability and variability of this process (Tab. 4).

from the terrain surface to aquifer. It is a key factor in

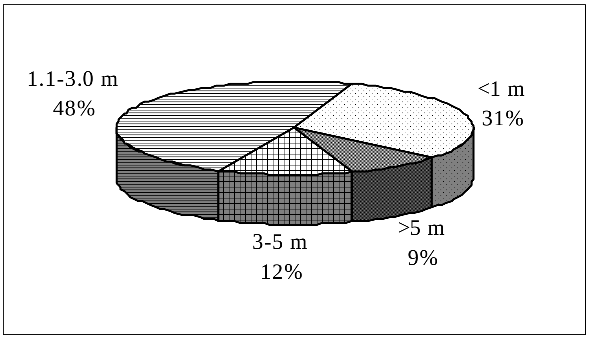

Fig. 2: Depth of groundwater table in the KNP

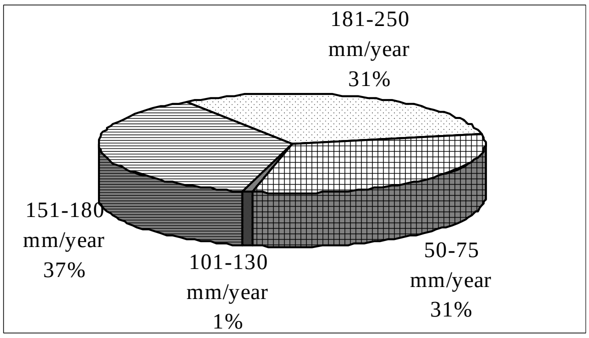

Fig. 3: Infiltration recharge in the KNP

CONCLUSIONS

The volume of infiltration recharge in the Vistula River is the key element for the assessment of groundwater resources and the level of hazard to the groundwater quality. In the KNP region, the assessment of infiltration was carried out using a range of different methods, including those based on observations of the climate, surface waters (runoff hydrograph separation), groundwater (water table fluctuation method), empirical calculations (index method) and numerical modelling. The obtained infiltration feed volumes vary, which not confirms the dynamics of the process over time and space but also the estimated character of the regional assessment.

Modelling can be used to characterise the feed volume throughout the entire hydro-geological unit in question, as well as specific regions within such unit, and to perform a wide range of forecasting calculations. The calculation results indicate that the effective infiltration in the KNP region is particularly strong in the dune areas.

The infiltration feed volumes derived based on average precipitation and the infiltration coefficient which are representative in the regional level, have been adjusted and supplemented with results obtained with other methods, which define more accurately the feed volumes in specific hydrozones.

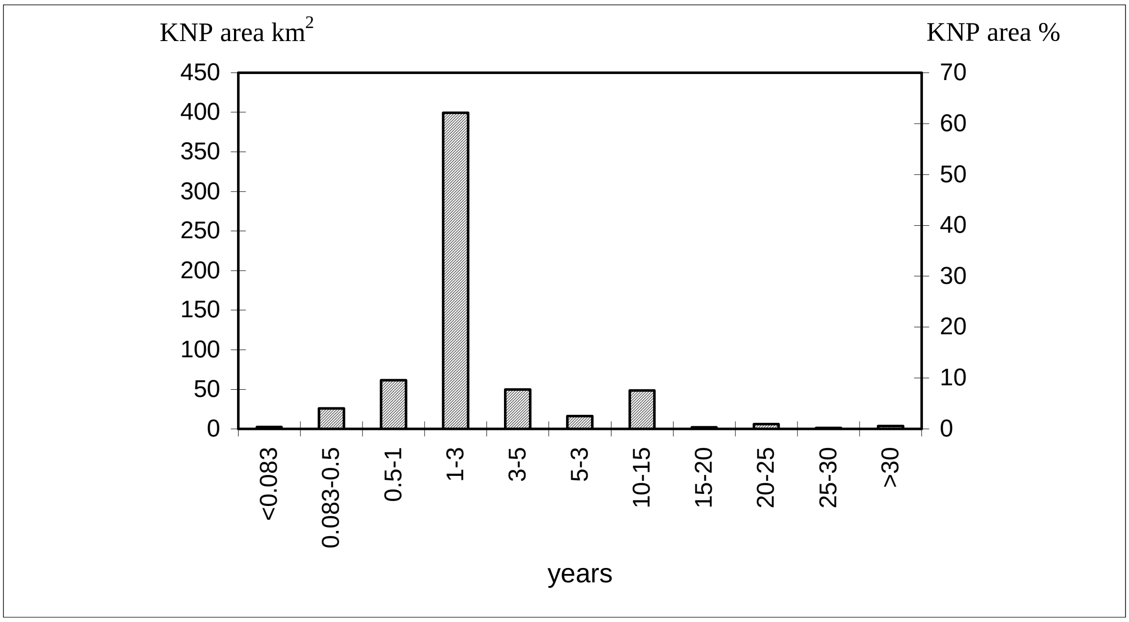

Fig. 4: Residence time in the unsaturated zone (criterion of vulnerability) – KNP area

Tab. 4: Characteristics of travel time and vulnerability classes in selected hydrozones and average values infiltration recharge and depth of groundwater table as the key factors in evaluation of groundwater vulnerability

Hydrozones in KNP	Average value of infiltration recharge (all methods) [mm/y]	Average depth of groundwater table / level fluctuation [m]	Travel time [y] and vulnerability class
Vistula flood plain and terraces	90.4	2.1 / 0.35-4.65	0.083-5 high, medium high
Swamp areas	48.5	1.4 / 0.17-3.10	1-10 high, medium high
Dune areas	98.9	2.57 / 0.3-5.08	1-5 high, medium high
Blonie Level	67.5	2.88 / 1.58-3.89	1-10 high, medium high

The application of other methods is limited:

- water table fluctuation method characterises the recharge in zones beyond the impact of anthropogenic factors,
- runoff hydrograph separation, carried out based on automated calculation of baseflow characteristics in accordance with a modified FRIEND-BFI algorithm covers only a part of KNP (Lasica River catchment). It can be assumed that thus separated underground runoff, due to the nature of river value recharge, represents the infiltration volume.
- index calculations, which are of estimate nature, are useful in regional surveys, e.g. assessment of the groundwater vulnerability to contamination.

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METÓDY A VÝSLEDKY HODNOTENIA DOPĹŇANIA PODZEMNÝCH VÔD V KAMPINOSKOM NÁRODNOM PARKU V CENTRÁLNOM POĽSKU

SÚHRN

Množstvo infiltrovanej vody z rieky Vistula je kľúčovým prvkom pre hodnotenie zdrojov podzemných vôd a úrovne ohrozenia kvality podzemných vôd. Metodika a výsledky hodnotenia dopĺňania podzemných vôd infiltráciou boli aplikované na území Kampinoského národného parku (KNP). Park, Biosférická rezervácia UNESCO (s plochou cca 800 km^2) je lokalizovaná v rozsahu hydrologickej jednotky v strednej časti rieky Vistula (centrálne Poľsko). V regióne KNP má hlavná zvodnená vrstva hrúbku od 10 do 50 m, jej zloženie je premenlivé, od jemne zrnitého piesku až po miesta s morénovým materiálom (tillom). Dopĺňanie podzemných vôd v Kampinoskom národnom parku je výhradne výsledkom infiltrácie zrážkových vôd; hoci druhým zdrojom dopĺňania je nižší zvodnený horizont (v južnej časti KNP).

Hodnoty množstva infiltrovaných vôd boli získané numerickým modelovaním, separáciou hydrogramu, zo zmien hladiny podzemnej vody (metóda WTF) a empirickými metódami. Hodnoty priemernej infiltrácie získané modelovaním sú od 55,5 mm/rok v údolných terasových sedimentoch do 332 mm/rok v severných dunových zónach. Separáciou hydrogramu sa preukázalo, že celkový odtok dosiahol 36 mm/rok v perióde rokov 1951 až 2000 v povodí rieky Lasica (hlavný tok KNP). Hodnoty infiltrácie vypočítané zo zmien hladiny podzemnej vody, získané z monitoringu hladín podzemných vôd KNP dosahujú od 73 mm/rok na údolných terasách rieky Vistuly do 265 mm/rok v oblastiach dunových sedimentov. Hodnoty infiltrácie z empirických metód sú od 119 mm/rok v močaristých oblastiach do 199 mm/rok v oblastiach dunových sedimentov.

Empirické výpočty sú užitočné v regionálnych prieskumoch, resp. v hodnotení zraniteľnosti podzemných vôd, ale získané výsledky môžu byť upravené a doplnené výsledkami ďalších metód, ktoré presnejšie definujú množstvo zásob podzemných vôd v špecifických častiach KNP (zvodnené horizonty).