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Evaluation of infiltration rates within the Vistula River valley, central Poland

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ABSTRACT:

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The Vistula river valley groundwater system has a strong hydraulic connectivity with the surface waters of the Vistula River. Typically, it is dominated by infiltration, and may at the same time represent a transitional system, in which lateral baseflow discharge takes place from surrounding units (e.g. plateau) to the river valley. A relatively simple mechanism of infiltration represents one of the elements of a complex water circulation system in the valley unit. The recognition of the entire recharge mechanism in a valley unit allows indicating a variable but significant role of infiltration.

Evaluation of the value of infiltration on a regional scale has been made for the Vistula River valley in the Kampinoski National Park (KNP) area. Data on the spatial distribution of infiltration, averaged for a particular time interval, are indispensable e.g. for balance calculations as well as for evaluation of groundwater vulnerability to contamination.

Evaluation of infiltration into the groundwater system of the KNP area was made using the following methods: meteorological and empirical methods, water table fluctuation (WTF), runoff hydrograph sub-division (BFI), and numerical simulations.

Key words: Infiltration; Groundwater recharge; River valley; Vistula River; Kampinoski National Park.

INTRODUCTION

Evaluation of the value of infiltration in the Vistula River valley was carried out in the Kampinoski National Park area (KNP). The hydrogeological and geological conditions in this area are common to the valleys of the Polish Lowlands, what allows to apply the same data set on infiltration to characterize hydrogeological water systems in any large valley having the same environmental conditions. The unique position of the Vistula River valley in the vicinity of Warsaw because of environment protection and city water supply, and its role in the system of protected areas of Poland and Europe, i.e. due to Nature 2000 natural habitats and refuges, systems Corine (CENTRE… 1998), and Econet (Liro 1998), resulted in numerous detailed hydrogeological studies of this area, including one of the most important elements of the circulation system – rates of infiltration. The Vistula River has still retained a semi-natural character for most of its length and is considered to be one of the most valuable rivers in Central Europe. International recognition of this unique river valley is reflected in the recommendation of the Contracted Parties of the Ramsar Convention on Wetlands to conserve the middle reach of the Vistula River.

This paper presents some of the most commonly applied methods of quantitative evaluation of the infiltration rates, indicating their ranges.

HYDROGEOLOGICAL CONDITIONS OF THE KAMPINOSKI NATIONAL PARK AREA

Aquifer characterization

The Kampinoski National Park (KNP) is located in central Poland, in the middle of the River Vistula valley within several geological-geomorphological units, of which the most common are Pleistocene–Holocene river terraces of up to several kilometres wide (Text-figs 1, 2). In the KNP region, the principal aquifer has a thickness ranging from 10 to 50 meters, and is composed of fine-grained sands, commonly containing silty material. The aquifer is unconfined, which causes rapid recharge after rainfall events. Vertical hydraulic conductivity values for two types of sediments were determined by in-situ investigations and represent:

- sands and sandy-gravel horizon with vertical hydraulic conductivity (kav) = 28.2 m/d; and,
- medium-grained sands horizon with numerous interbedded washed out boulder clays with vertical hydraulic conductivity (kav) = 20.3 m/d.

Aquifer hydraulic conductivity values were also determined by statistical analysis of data obtained from approximately 1,000 wells located within the study area (Krogulec 2003, 2004). The average hydraulic conductivity for this sandy aquifer was determined from pumping tests as 27.7 m/d (range of 1.2 m/d to 89.6 m/d).

The following environmental criteria: differences in geology and geomorphology, lithology of sub-surface sediments and related vegetation cover, depth to groundwater table, range of water level fluctuations and human economic activities were used to distinguish zones of similar hydrodynamic and environmental conditions, the so called hydrozones (Krogulec 2004). The following zones have been distinguished as (Text-fig. 1):

A – dune zones,
B – valley (swamp) zones,
C – Vistula River flood plains and terraces over flood plains,
D – Blonie Level (Lowicko-Blonska Plain and post-glacial plateau).

The shallow (local) and deeper (intermediate) groundwater circulation systems are of fundamental importance to the hydrogeological regime of the study area, and both receive direct infiltration. The shallow (local) circulation system is drained by smaller flows, melioration channels: Lasica, Zaborowski, Olszowiecki, as well as by evapotranspiration. The deeper (intermediate) water circulation system is linked to the Vistula River drainage system, which also plays an important role in the regional circulation system.

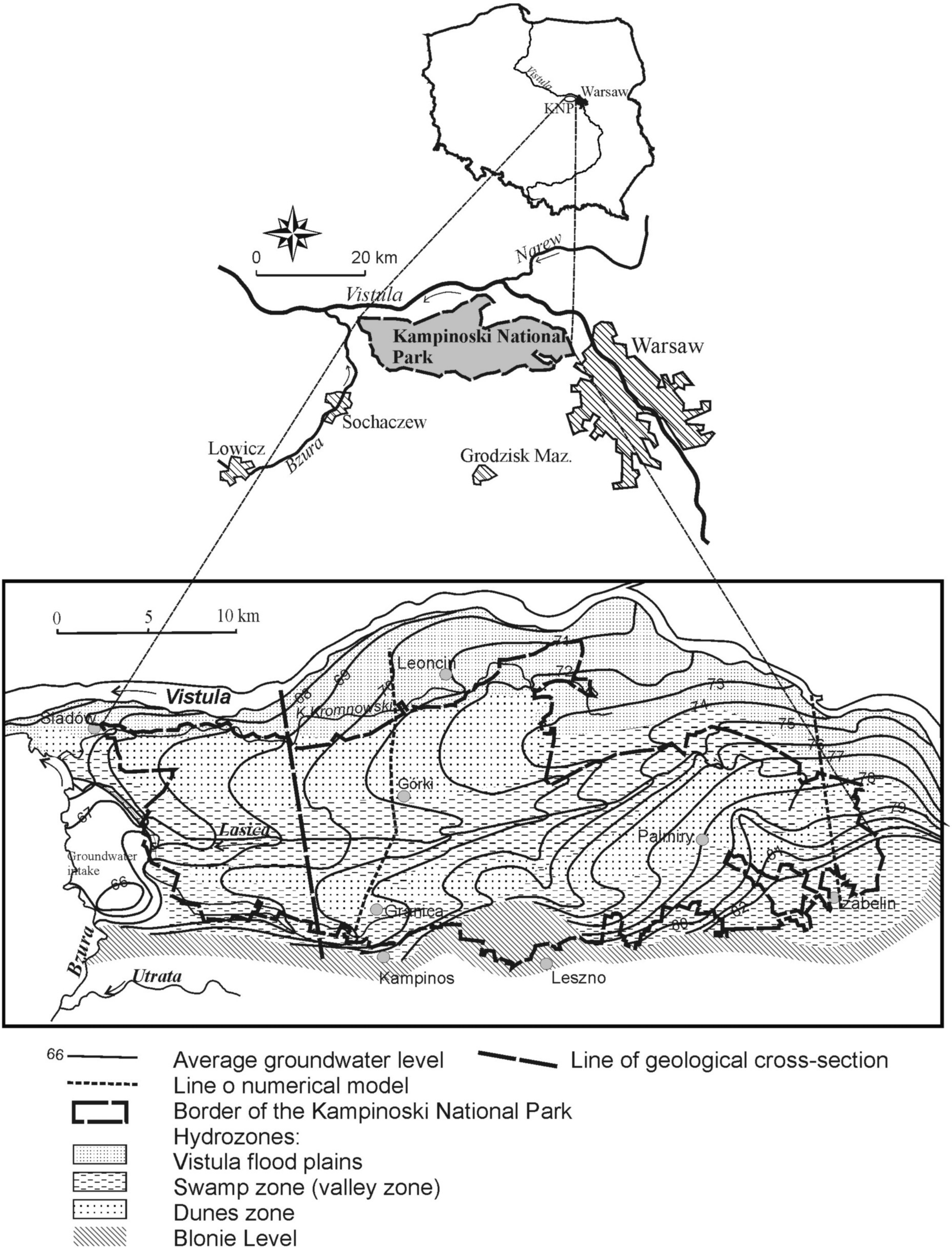
Boundaries between hydrogeological units and their role in groundwater inflow from surrounding units are important factors determining the mechanism of recharge to the KNP area. The boundaries, within which the hydrogeological units are located in the KNP and their protection zones, are typical of Polish river valleys. The southern boundary is formed by the margin of the glacifluvial deposits of the ice-dammed plain (Blonie Level) and a small part of the post-glacial plateau (Rawa Plateau); the northern and eastern boundaries by the Vistula River and partly by the Warsaw agglomeration, and the western boundary by the Bzura River. Simulation studies indicate insignificant lateral baseflow discharge from the ice-dammed plain and post-glacial plateau to the Vistula valley that is of some significance only in the southern part of the valley unit.

Groundwater monitoring network

The ground and surface water monitoring network consists of 56 piezometers. The spatial distribution of the monitoring network was designed to take full advantage of hydrological and hydrogeological analysis within the enclosed surface drainage basin and the hydrogeological flow system (Krogulec 1997, 2001, 2004). Measurements of groundwater levels were performed manually at fortnightly intervals, starting from 30 November 1998 (Text-fig. 1). The hydrogeological and statistical characterization of the hydrozones distinguished, including mean, yearly fluctuation, maximum, minimum and standard deviation, is shown in Table 1.

Due to the shallow position of the groundwater table in the valley units (Text-fig. 1), the reliability of manual monitoring measurements taken fortnightly in order to evaluate the infiltration was analyzed statistically. In seven selected piezometers considered representative of particular hydrozones, electronic sensors were installed in 2001 (continuous data acquisition) and set on per-hour measurement of the groundwater level. Analysis of basic statistical parameters was made for data obtained from manual and continuous measurements during the period 2001 to 2004 (Table 2).

Analysis of the results showed small differences in the mean annual values between the different measurement techniques. The largest differences were obtained for the maximum value, which reached, e.g., 4.5 cm in the case of piezometer P33. It is important to note the small scale of the error, being less than 4% of the amplitude of annual water level oscillations (Table 2). The results of automatic data acquisition are obviously important in evaluation of changes in the recharge process and analyses for particular ecosystems (generally wetland areas). In the case of the evaluation of average in-



Text-fig. 1. Location of the Kampinoski National Park

Hydrozone (see Text-fig. 1 for location)	Mean depth for winter half year (November-April)	Mean depth for summer half year (May-October)	Average depth	Yearly fluctuation	Maximum depth	Minimum depth	Standard deviation
Vistula flood plains	2.16	1.01	2.33	1.43	2.42	0.99	1.11
North swamp area	2.43	1.14	2.38	1.72	2.67	0.95	1.14
South swamp area	0.62	0.88	0.77	0.98	1.33	0.35	0.88
South dunes area	2.42	0.96	2.38	1.12	3.43	2.31	0.96
North dunes area	2.40	0.86	2.28	1.00	3.18	2.18	0.86
Blonie Level	2.88	1.63	2.87	1.97	1.99	3.96	1.63

Table 1. Basic statistic measures of groundwater depth in KNP for the period 1998–2002 [m]

filtration the results of manual readings represent a sufficient database (Krogulec and Andrzejewska 2005).

RECHARGE RATES INTO THE KAMPINOSKI NATIONAL PARK AREA

Definition and methodology of infiltration evaluation

Effective infiltration is defined as the flow of water downward from the land surface into and through the upper soil layer that recharges groundwater, excluding the volume linked with surface run-off, evapotranspiration and other processes and man-made factors that decrease the volume of infiltrating water.

The recharge rate into the river valley with respect to resource objectives and assessment of the natural vulnerability to contamination may be evaluated on variable time scales – from single precipitation "events" to seasonal and annual studies (Simmers 1990; Stephens 1996; Learner 1997; Learner *et. al.* 1998). However, in regional analyses the recharge evaluation typically requires mean values from a longer time period because it is difficult from a technical point of view to prepare and interpret several seasonal groundwater level maps.

The selection of the method of evaluating infiltration depends on climatic conditions, time-scale and spatial distribution of measurements, the study aim (research, water supply, commercial), and the range and character of research (for example, preliminary reconnaissance, etc.).

General methods

Classification of the KNP with its protection area into one of the hydrogeological units recognized in Poland allows an indirect estimated method of evaluating the value of infiltration. The most typical subdivision into hydrogeological regions has been applied in the Hydrogeological Atlas of Poland, and includes macro-regions, regions, sub-regions and regions connected with water management units (balance units) (Paczyński 1995); it is based on hydrostructural (geological, geomorphological and tectonic) criteria. The KNP is located within: the north-eastern macro-region (a), Mazovian region (I), central sub-region (I_1), within the Warsaw Basin and Mazovia-Podlasie region, covering an area of 1900 and 2100 km^2, respectively. The rate of infiltration depends here largely on groundwater renewal and reaches from 50 to 100 m^3/24h m^2 (137–274 mm/year). Renewal is understood as the inflow of water to the sat-

Year	Measurement	Mean depth	Maximum depth	Minimum depth	Standard deviation	Median
Piezometer P33 (swamp area)						
2001–2004	continuous	1.40	2.04	0.86	0.30	1.36
	manual	1.40	2.03	0.91	0.32	1.36
Piezometer P34 (swamp area)						
2001–2004	continuous	2.09	2.64	1.37	0.28	2.10
	manual	2.09	2.63	1.38	0.29	2.09

Table 2. Basic statistical data of groundwater depth in KNP obtained from manual and continuous measurements in piezometers: P33 and P34 for the period 2001–2004 [m]

uration zone where, in the case of shallow groundwater, the most important role is played by infiltration of precipitation.

According to the 1:50 000 Hydrogeological Map of Poland (Cygański, Woźniak 1997; Rudzińska-Zapaśnik 2000), 15 hydrogeological units are located within the KPN area. The value of groundwater renewable resources is from 4 to 110 mm/year. The value of groundwater renewable resources in the unit analyzed depends mostly on infiltration rates of precipitation.

Runoff hydrograph sub-division (BFI)

The study was carried out in the Lasica catchment, situated within the boundaries of the KPN (Text-fig. 1). The total area of the Lasica River catchment to the mouth of the Bzura River is 551.4 km^2. This area is used as forest or forest-agricultural land and only in some parts is suburban settlement (urban) and estate development (villa) present.

The hydrograph separation was computed using the automated series processing method developed by the UK Institute of Hydrology, Wallingford (Magnuszewski 1990; Tomaszewski 1998). The so called **B**ase **F**low **I**ndex (BFI) performs hydrograph separation (Magnuszewski 1990; Tomaszewski 1998). Series of daily runoff during the period 1951–2000 have been used. The average discharge of the Lasica River in 1951–2000 is 1.13 m^3/s (minimum 0.016 m^3/s, maximum 8.36 m^3/s); runoff from the mouth of the catchment is 121 mm, but it can change by a factor of four – from 242 mm (1967) to 52 mm (1991). The highest value occurs during the spring thaw (19–20 mm), the lowest in summer and autumn from June to October (4–6 mm).

In certain years of the long-term period analyzed, the river baseflow varied considerably: from 163 mm in 1967 to barely 43 mm in 1952 and 1992. A much larger baseflow (60 mm) occurred in the winter half of the year (November-April). The seasonal distribution shows that the most efficient baseflow is from snowmelt and spring precipitation (March and April) (12 mm) while the lowest accompanies recharge is observed in the summer–autumn period (3 mm) (Soczynska *et. al*. 2003).

The results obtained reflect the typical seasonal character of the baseflow, depending on the recharge into the Lasica River catchment, and probably do not correspond entirely to the infiltration of the aquifer system in the KNP area, which is linked, for example, with the catchment area, groundwater basin area, baseflow discharge and water withdrawal.

In the period 1998–2002 the river baseflow reached 102.1, 89, 49.8, 56 and 72 mm/year respectively.

Meteorological method

The most important element of evaluating infiltration into a river valley, besides the lithology of the surface deposits, is the amount and rate of precipitation which, due to its variability in time, are parameters that are difficult to take into account in hydrogeological analysis.

The mean sum of real precipitation in the drainage basin during the long-term period (1951–2000) calculated using the Thiessen polygons method is 664 mm. In this 50-year period, the yearly total precipitation in the Lasica drainage basin show significant variability from 952 mm in 1970 to 487 mm in 1951. In respect of the yearly total precipitation, we can distinguish humid years with precipitation $\geq$ 800 mm (1962, 1967, 1970, 1977, 1994, 1995), average years $\approx$ 664 mm (1975, 1983, 1987) and dry years with precipitation $\leq$510 mm (1951, 1959). The monthly, seasonal and yearly precipitation values are characterized by great non-uniformity and distribution irregularity in time (years and seasons). The higher monthly precipitation values include the summer months (May–October, with the maximum in July reaching 89 mm) while the smaller values ($\leq$51 mm) appear in winter (February 38 mm). In the warm half of the year (May–October) total precipitation reaches 399 mm, with even smaller values (265 mm) in the winter season (November–April) (Soczyńska *et.al*. 2003).

In the period 1998–2002, the value of the mean annual precipitation was 589.4 mm, thus 74.6 mm lower than the analogous value for the period 1951–2000. Daily (24 hours) measurements of the sum of precipitation indicate that in the study area precipitation up to 3mm/24h mm predominates (a precipitation input of 3 mm/24h is considered to be sufficient to influence groundwater recharge) (Małecki 1998).

The next basic climatic factor influencing the assessment of groundwater recharge in valley units is the rate of evaporation (various evaporation processes), known in some cases as “negative” groundwater recharge.

In this research, the land evaporation was calculated using potential evaporation estimated as a function of hydroclimatologic elements (wind speed and air humidity deficit). The mean annual potential evaporation in the Lasica catchment in the period 1951–2000 calculated by the Penman method is 722 mm. The greater part of this relates to the warm half of the year (May–October), when it reaches 546 mm, while values less than 200 mm are found in the winter season (November–April). The annual totals of land evaporation in the 50-year period investigated vary from barely 413 mm (in 1980) to 632 mm (in 1971). In the warm half of the year (May–October) land evaporation reaches 365 mm and is even less (178 mm) in the winter season (November–April) (Soczyńska *et.al*. 2003).

Value for KNP area	Mean precipitation 1951–2000 [mm/year]	Mean evaporation 1951–2000 [mm/year]	Infiltration [mm/year]
Mean annual value	664	543	121
Mean value – Summer season (May–October)	399	365	34
Mean value – Winter season (November–April)	265	178	87

Table 3. Value of infiltration of the Vistula River valley in the KNP area estimated on the basis of the difference between precipitation and evaporation

The difference between precipitation and evaporation is the basis for evaluating the volume of infiltration for the time interval 1951–2000, reaching 121 mm/year (rainfall runoff = 0; Table 3). During the summer season, infiltration is low, reaching 34 mm/year on average, whereas in the winter season it reaches 87 mm/ year. For the shorter period between 1998 and 2002, with mean annual precipitation of 589 mm and mean annual evaporation reaching 482 mm, the estimated infiltration value reaches 107 mm/year.

Infiltration recharge using empirical method (infiltration rate)

The empirical method offers a quick assessment of infiltration as a proportion of precipitation in terms of climate (generally atmospheric precipitation), land use, terrain and geology (Table 4; Pazdro 1983). The infiltration rate depends mainly on the precipitation, lithology of the subsurface zone and terrain forestation ratio.

The value of infiltration determined by the empirical method (as a proportion of precipitation and lithology) that is commonly applied in many Polish reports reaches 161 mm/year, taking into account the average sum of precipitation as 664 mm/year for the period 1951–2000 and 143 mm/year as the mean precipitation for the period 1998–2002 (Tables 3, 4); in selected hydrozones infiltration ranges from 110.4 to 170.1 mm/year (Table 5).

Water-table fluctuation method (WTF)

The water table fluctuation (WTF) method is a conventional method for quantifying groundwater infiltration by multiplying the specific yield by the water level rise. Based on the van Genuchten model (Healy and Cook 2002), an analytical relationship between groundwater recharge and water level rise is derived. The equation is used to analyze the effects of water level depth and soil physical properties on the recharge estimate using the WTF method.

Infiltration was calculated using the following formula (Healy and Cook 2002):

$$R = S_y dh/dt = S_y \Delta h/\Delta t$$

where:

R – infiltration [mm/y]

S_y - specific yield [percentage by volume]

h – water table hydraulic head [mm]

t – time [year]

Lithology	Area [km^2]	Infiltration rate [%]	Infiltration 1951–2000/1998–2002 [mm/year]
sand and gravel	192.38	30	199.2/176.7
sand, medium sand, sandy-till	237.56	25	166.2/147.2
sandy-till	155.53	20	132.8/117.8
till	25.38	5	33.2/29.4
glacialfluvial lake clay deposits	5.65	5	33.2/29.4
Sum or average values	Sum 616.50	18	161.3/143.0

Table 4. Value of infiltration in the KNP area computed as proportion of precipitation and lithology

Hydrozones	Infiltration [mm/year]
Vistula flood plains	136.0
Swamp areas	110.4
Dunes areas	170.1
Area of KNP, average value	141.2

Table 5 Value of infiltration for the period 1998–2002 computed as a proportion of precipitation and lithology in selected hydrozones in the KNP

Application of this equation requires the assumption that water reaching the saturation zone is stored instantly, and that other factors of the balance equations during recharge are equal to zero. This method gives the most precise results for short observation periods in areas where the groundwater table is shallow, which guarantees significant fluctuation in time (Scanlon *et al*. 2002).

Due to its basic assumption and the possibility of evaluating groundwater level changes based on regular monitoring measurements, this method has been applied to evaluate infiltration in the Vistula River valley in the KNP area. The WTF method is precise enough for regional hydrogeological analyses, although it is worth remembering its oversimplification, influencing the results of calculations.

In calculations (Table 6), the following values of the storage coefficient for deposits building the aquifer horizon in the KNP area (Somorowska 2003) were adopted:

- 0.0826 for areas of very shallow groundwater level (up to 1.5 m in the KNP area);
- 0.1731 for shallow groundwater level (more than 1.5 m in the KNP area).

The monitoring database for the period 1998–2002 enables recharge for different time intervals to be calculated. For example, the recharge value for the period with the smallest precipitation during the winter season reached a mean of 90.5 mm/year, which is about 10% of the mean annual precipitation.

During the highest precipitation in July, infiltration reached 207 mm, i.e., about 30% of the average sum of precipitation and 40% higher than the mean annual recharge.

Hydrozone	General groundwater level	Infiltration [mm/year]	Area* [km^2]
Vistula flood plains – central part	Partly very shallow groundwater level	73	120.48
Swamp areas – south part	Very shallow groundwater level	100	47.88
Swamp areas – south part		94	
Swamp areas – north part		89	107.04
Swamp areas – north part		73	
Dunes areas - south part	Shallow groundwater level	131	87.12
Dunes areas - south part		265	
Dunes areas - north part		193	90.12
Dunes areas - north part		207	
Blonie Level (central part)		207	90
Blonie Level (central part)		137	
KNP area	Very shallow and shallow groundwater level	143	542.64

*land surface, for which the groundwater level measured in piezometers, is representative (areas where the groundwater level dynamics linked with factors other than climatic have been omitted)

Table 6. Value of infiltration [mm/year] – WTF method

Numerical simulation

To compare results obtained from different monitoring and computation methods, a numerical model was applied to simulate recharge into the Vistula valley groundwater system. The model was constructed using ca 12–18 km cross-sections in the central and eastern part of the KNP and its protection zone (Text-fig. 1). The cross-section lines, running N–S, start from the Blonie Level and end on the Vistula River. Simulation studies have allowed proper water balance calculations using modelling on hydrozones distinguished in KNP area (Krogulec 2004).

Modelling simulations have been made for steady state flow conditions; the model was calibrated taking into account the mean groundwater level measured in piezometers and other monitoring and observation points for the period 1998–2002.

Model calculations were performed with Visual MODFLOW 2.20 software, which uses the finite differences method. Model simulations were done with the Strongly Implicit Procedure Package – SIP digital method (Harbaugh *et. al*. 2000; McDonald and Harbaugh 1988). Infiltration recharge of the system was modelled through the combination of the II- and III-type conditions. The II-type condition was set as fixed for the entire area of the recharge size. The III-type condition was used to calculate evapotranspiration. *Evapotranspiration* package (Visual MODFLOW program) was applied for this, which enables to calculate the amount of losses in the depth function of the depth to groundwater occurring. Combining II-and III-type conditions, together with applying the numeric model of the territory's area allows determining the net recharge as one of the result maps of the model.

Space discretization of models in the KNP area took place in two stages. In the first stage, the area was subdivided into blocks characterized by Δx = 500 m (Δy = 1 m – models in vertical 2D space), whereas Δz was applied to the evaluated geological conditions. In the following stage, the blocks were fused, mainly at the contact zone of the valley with the glacifluvial plain and glacial plateau as well as in the vicinity of smaller flows in the study area (Text-fig. 2).

The standard error of the calculated and observed groundwater heads was compared and calculated to be smaller than 10 cm, which satisfies compatibility test requirements. In addition, an error analysis (Anderson and Woessner 1992) was performed. The mean error between the computed and measured heads was found to be negligible. The mean absolute error and the root mean square error were also low, which indicates that the model was properly calibrated.

The relation of the model with the surrounding was determined using the II- and III-type border conditions. For boundaries passing through the Vistula River channel, the type III condition was applied (the RIVER packet was used in this case in all models), based on data referring to the surface water state. In blocks with condition III, values of transmissivity of the bottom deposits measured during model calibration were applied. On the south border along margin of the glacifluvial deposits of the ice-dammed plain and the post-glacial plateau, the III type condition was set (GHB). The lower boundaries of the models were restricted by the base of the aquifer horizontal position, whose basement was considered as practically impermeable, thus this boundary was described by condition type II (type Q = 0).

The most optimal values of infiltration and evapotranspiration for a given model class were obtained during model calibration. The applied calibration method (trial-and-error) compared the work (reaction) of the model with the work of the existing system. When identifying models, the minimal value of the function of the object that was considered the indicator of a correct simulation stage, was determined as the difference between the measured and calculated value of hydraulic head. In the calibration stage, model sensitivity was tested based on the presented methods of error calculation; influence of rates in infiltration, evapotranspiration and transmissivity of bottom sediments. These values were statistically evaluated and stand deviation values were obtained. The obtained results: ME = -0.0047, MAE = 0.494 m, and RMS = 0.590 m allowed accepting the optimal values of particular parameters in further calculations and modeling.

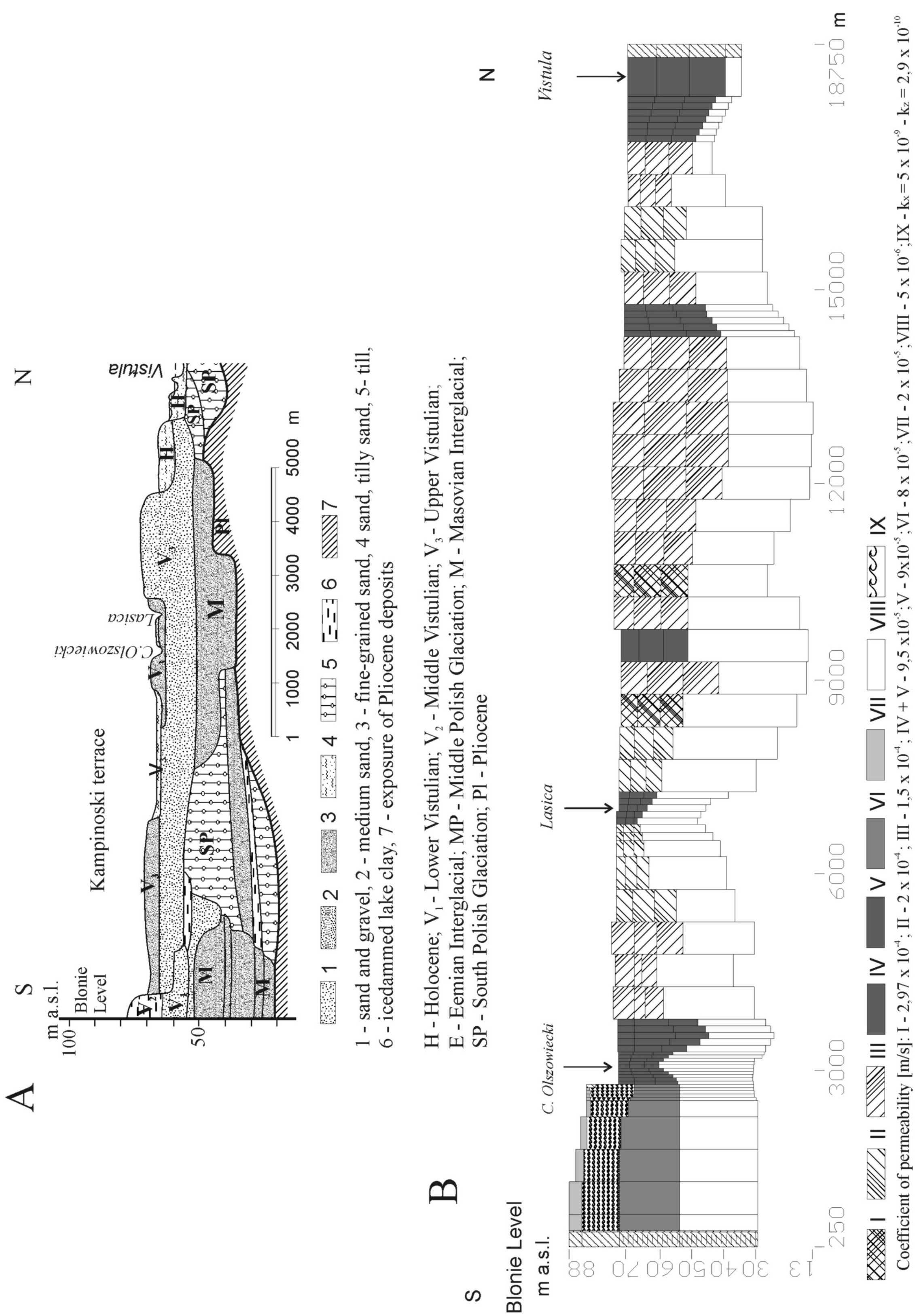
The lowest value of infiltration was noted within the swamp belts, where it ranged from 10.5 mm/year to 33.2 mm/year (a mean of 28.6 mm/year) (Table 7).

Lateral flow conditions

Lateral baseflow discharge from the glacifluvial deposits of the ice-dammed plain and from the plateau deposits of the entire valley unit in the KNP area, determined on the basis of balance model calculations, exceeds 21552 m^3/24h over a length of 59 km (Table 8). In the eastern part of the KNP, the value of lateral baseflow discharge reaches 6160 m^3/24h; in the central part it is

Model - central part of KPN		
Hydrozone	Infiltration [mm/year]	Evapotranspiration [mm/year]
Vistula flood plains	56.12	12.21
Swamp areas – south part	33.20	58.22
Swamp areas – north part	10.47	32.53
Dunes areas - south part	74.00	0
Dunes areas - north part	82.20	0
Blonie Level	28.90	0
Mean value	47.48	34.32
Model - east part of KPN		
Hydrozone	Infiltration	Evapotranspiration
Vistula flood plains	94.54	92.48
Swamp areas – south part	43.87	61.77
Dunes areas - south part	160.92	0
Hill plateau	83.36	0
Mean value	95.67	77.12

Table 7. Value of infiltration [mm/year] and evapotranspiration – modelling results



Text-fig. 2. A – geological cross-section through the Vistula River valley in the Kampinoski National Park and B – line of numerical model (central part of KPN)

Base information	Eastern region	Central region	Western region
Length [km]	20	29	10
lateral baseflow discharge [m^3/24 h on 1 m]	0.308	0.248	0.82
lateral baseflow discharge [m^3/24h]	6160	7192	8200
Share in recharge	6%	4%	Water utilized by large local water intake

Table 8. Values of lateral baseflow discharge from the margin of the glacifluvial deposits of the ice-dammed plain and the post-glacial plateau to the Vistula River valley (results of model calculations)

7192 m^3/24h (Table 8). In the western part, in the neighbourhood of the glacio-fluvial plain deposits is located a large intake of drinking water, and hence calculations were not made for this area.

Analysis of the results of lateral baseflow discharge obtained from modelling indicates the low significance of lateral components from the surrounding areas (glacifluvial plain deposits and glacial plateau) in the groundwater flow system of the wide Vistula River valley, reaching from 4 to 6% of total infiltration in areas where groundwater intakes do not occur (Table 8).

DISCUSSION AND SUMMARY

The infiltration results obtained differ, depending on the two computation methods as well as on the time and spatial scale of the evaluation (Table 9).

Variable values of infiltration computed with the application of different methods are linked to different input data, applied simplifications, and calculation method. The different values for the periods 1951–2000 and 1998–2002 are due to the dynamics of the hydrological process in time and space and depend mainly on meteorological factors. The results presented are an argument for a very careful (particularly in the case of methodological basics) and cautious selection of the method of evaluation recharge and for a correct interpretation of all factors included in the calculations and final results of the computation.

The results show that for a mean depth of groundwater level in the Vistula River valley of 1.69 m below the ground surface, infiltration reaches according to modelling values from 8 to 16% of the amount of precipitation and varies from 8 to over 26% in different hydrozones. When indicating the recommended value for

Hydrozone	Mean depth 1998-2002 (fluctuation) [m]	Method of estimation	Infiltration 1951-2000 [mm/year]	Infiltration 1998-2002 [mm/year]
Vistula flood plains	1,9 (0,99 – 2,16)	Empirical method	133-166	118-147
		WTF	-	73
		Numerical method	-	56-95
Swamp areas	1,30 (0,35 – 2,27)	Empirical method	133	118
		WTF	-	73-100
		Numerical method	-	10-44
Dunes areas	2,88 (2,18 – 3,34)	Empirical method	192	177
		WTF	-	131-207
		Numerical method	-	74-161
Blonie Level	2,43 (1,99 – 3,99)	Empirical method	33	29
KNP area	2,04 (0,35-3,99)	Meteorological method	121	107
		Empirical method	161	143
		WTF		143
		BFI	81	50-102
		Numerical method		48-94

Table 9. Value of infiltration – summary of different calculation method

further calculations, e.g. in evaluation of the groundwater vulnerability for contamination, results of modelling of the rates of recharge should be used.

Modelling results which include all factors that influence the recharge rate, enable calculations for selected areas and regions within larger units. Analysis of the value of lateral baseflow discharge obtained in model studies indicates the low significance of lateral discharge from the surrounding areas (glacifluvial deposits of the ice-dammed plain and the post-glacial plateau) in the water circulations system of Vistula valley, where groundwater intakes do not occur.

Remarks of adopted methods:

- water table fluctuation method characterizes the recharge in zones beyond the impact of anthropogenic factors,
- hydrograph separation, based on automated calculation of baseflow characteristics in accordance with a modified **B**ase **F**low **I**ndex (BFI) algorithm, covers only a part of KNP (Lasica River catchment),
- the empirical methods offers a quick assessment of infiltration as a proportion of precipitation, land use, terrain and geology, and are useful in regional surveys, e.g., assessment of the groundwater vulnerability to contamination,
- the most representative infiltration rates in a river valley on the regional groundwater level, have been adjusted and supplemented with results obtained from other methods such as modelling. Simulation studies have enabled water balance calculations on models and in specific hydrozones areas.

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REFERENCES

Anderson, M. and Woessner, W. 1992. Applied Groundwater Modeling, 381 pp. Academic Press Inc.; London.

Centre Naturopa, 1998. The paneuropean ecological network. *Questions and answers,* **4**, 43 pp.

Civita, M.V. 1993. Ground Water Vulnerability Maps: A Review. Proc. IX Symp. Pesticide Chemistry "Mobility and Degradation of Xenobiotics", Piacenza, 587–631.

Cygański, K. and Woźniak, E. 1997. Mapa hydrogeologiczna Polski w skali 1:50 000, arkusz Błonie. [Hydrogeological Map of Poland in scale 1:50,000, Sheet Blonie]. Państwowy Instytut Geologiczny; Warszawa.

Healy, R.W. and Cook, P.G. 2002. Using ground water levels to estimate recharge. *Hydrogeology Journal*, **10**, 91–109.

Harbaugh, A.W., Banta, E.R., Hill, M.C. and McDonald, M.G. 2000. MODFLOW-2000. The U.S. Geological Survey Modular Ground-Water Model - User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 pp.

Krogulec, E. 1997. Numeryczna analiza struktury strumienia filtracji w strefie krawędziowej poziomu błońskiego. Wydawnictwa Uniwersytetu Warszawskiego, Warszawa. [Numerical analysis of filtration stream in the margin zone of blonski level], 97 pp.

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

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

Krogulec, E. 2004. Ocena podatności wód podziemnych na zanieczyszczenia w dolinie rzecznej na podstawie przesłanek hydrodynamicznych. Wydawnictwa Uniwersytetu Warszawskiego; Warszawa [Assessment of groundwater vulnerability to contamination in the River valley on the basis of hydrodynamical indications], 116 pp.

Krogulec, E. and Andrzejewska, A. 2005. Zastosowanie automatycznych pomiarów stanów wód podziemnych w lokalnym systemie monitoringowym. [Electronic groundwater level observation in local monitoring system]. *Współczesne problemy hydrogeologii*, **12**, 397–405.

Learner, D.N. 1997. Groundwater recharge. In: Geochemical processes, weathering and groundwater recharge in catchments, pp. 109–150. AA Balkema; Rotterdam.

Learner, D.N. Issar, A.S. and Simmers, I. 1998. Groundwater. A Guide to Understanding and Estimating Natural Recharge, Volume 8, 345 pp. Verlag Heinz Heise.

Liro, A. (Ed.). 1998. Koncepcja krajowej sieci ekologicznej ECONET – Polska. Fundacja ICUN Poland; Warszawa. 1–205 pp. [The concept of ecological net-work EECONET]

Magnuszewski, A. 1990. Zautomatyzowany sposób obliczania charakterystyk niżówkowych [Automatized way of low water characteristics estimation]. *Przegląd Geofizyczny*, **1-2**, 79–83.

Małecki, J. 1998. Rola strefy aeracji w kształtowaniu składu chemicznego płytkich wód podziemnych wybranych środowisk hydrogeologicznych. *Biuletyn Państwowego Instytutu Geologicznego*, **381**. [Role of aeration zone in forming of chemical composition of shallow groundwater of chosen hydrogeological environments], 1–156 pp.

McDonald, M.G. and Harbaugh, A.W. 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6, Chapter A1, 586 pp.

Paczyński, B. (Ed.). 1995. Atlas hydrogeologiczny Polski, skala 1:500 000, część II. [Polish Hydrogeological atlas, scale 1:500 000, part II], Państwowy Instytut Geologiczny; Warszawa.

Pazdro, Z. 1983. Hydrogeologia ogólna. [General hydrogeology], 506 pp. Wydawnictwa Geologiczne; Warszawa.

Rudzińska-Zapaśnik, T. 2000. Mapa hydrogeologiczna Polski w skali 1:50 000, arkusz Sochaczew. [Hydrogeological Map of Poland in scale 1:50,000, Sheet Sochaczew]. Państwowy Instytut Geologiczny, Warszawa.

Scanlon, B.R. Healy, R.W. and Cook, P.G. 2002. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, **10**, 18–39.

Simmers, I. 1990. Aridity, groundwater recharge and water resources management. In: A guide to understanding and estimating natural recharge. IAH, **9**, 1–20. Verlag Heinz Heise.

Soczyńska, U. Gutry-Korycka, M. Pokojska, P. and Mikos, D. 2003. Water balance as base for proper water management in the Lasica catchment (Kampinoski National Park). *Ecohydrology and Hydrobiology*, **3**, 291–309.

Somorowska, U. 2003. Risk assessment of the occurrence of extreme groundwater levels, discharge and soil moisture stages. *Ecohydrology and Hydrobiology*, **3**, 311–321.

Stephens, D.B. 1996. Estimation of infiltration and recharge for environmental site assessment. API Publ 4643. 143 pp. Health and Environmental Science Department, Albuquerque; New Mexico.

Tomaszewski, E. 1998. Zastosowanie zmodyfikowanego algorytmu FRIEND do oceny wielkości podziemnego zasilania rzek. In: Magnuszewski, A. and Soczyńska, U. (Eds), Hydrologia u progu XXI wieku. Komisja Hydrologiczna PTG, Wydawnictwa Uniwersytetu Warszawskiego; Warszawa. [Applying of modified FIEND formula for supply of baseflow evaluation], 285–293.

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