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Evaluation of hydrogeological conditions based on modelling: a case study in the Kampinos National Park region, central Poland

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Hydrogeological modelling of the Kampinos National Park (KNP) region has been carried out. The KNP comprises a hydrogeological unit of valley relatively simple structure, and has been investigated empirically and theoretically since the 1970's. Results of numerical modelling given here provide a quantitative evaluation of hydrogeological parameters, recharging infiltration, river drainage and evapotranspiration processes (groundwater evaporation), water balance and the role of hydrodynamic zones in the recharge and drainage contribution in the water balance of the Vistula valley unit.

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INTRODUCTION

The Kampinos Forest (KNP — Kampinos National Park) and the surrounding forest (protection zone) cover an area of about 750 km^2. The park is located in the Vistula valley, northwest of Warsaw. The area of KNP comprises an easily distinguishable hydrological and hydrogeological unit, bordered by the Vistula River to the north and east, by the Bzura River to the west and by the edge of the Błonie Upland (Błonie Level) to the south (Fig. 1).

Evaluation of the KNP region hydrogeology given in many publications and based on extensive archive material mainly concerns interpretation of point data (borehole profiles, Fig. 2A). The hydrogeological model described below has enabled preparation of the valley unit water balance, identification of hydrogeological parameter values and forecasts of groundwater level. The results of this research together with the geospatial database (boreholes, geophysical research, and measurements in the KNP monitoring network) enabled determination and analysis of the hydrogeological conditions, aimed at protecting the environment at the Park, and has provided an initial concept for changes of groundwater level in the KNP region.

SCOPE AND RESULTS OF MODELLING RESEARCH FOR THE KNP REGION

Survey of the hydrogeological conditions, preparation of diagrams and other research involved in evaluating of the groundwater status and dynamics in the KNP area was carried out mainly in the Groundwater Hydrology Department of Warsaw University, Institute of Hydrogeology and Engineering Geology (Krogulec, 2000; Table 1).

The following team made the general model of the KNP region: Kazimierski, Pilichowska-Kazimierska, Sikorska-Maykowska, Michalak and Krogulec (Kazimierski and Sikorska-Maykowska, 1996; Kazimierski *et al.*, unpubl.). This model imaged one aquifer occurring within the Kampinos terrace and Vistula and Bzura rivers flood plain, which is recharged by infiltration of precipitation. This model only partially includes the northern part of the Błonie Level (south part of the KNP protection zone) where the hydrogeological conditions are more complicated. The result of the calculations was: water balance over an area of 910 m^2 (exceeding the area of the KNP), which includes river drainage of ground and surface water (239106 m^3/d), lateral flow from the Błonie Level aquifer (1512 m^3/d), recharging infiltration (248 m^3/d) and the effective infiltration coefficient (average value of 0.17).

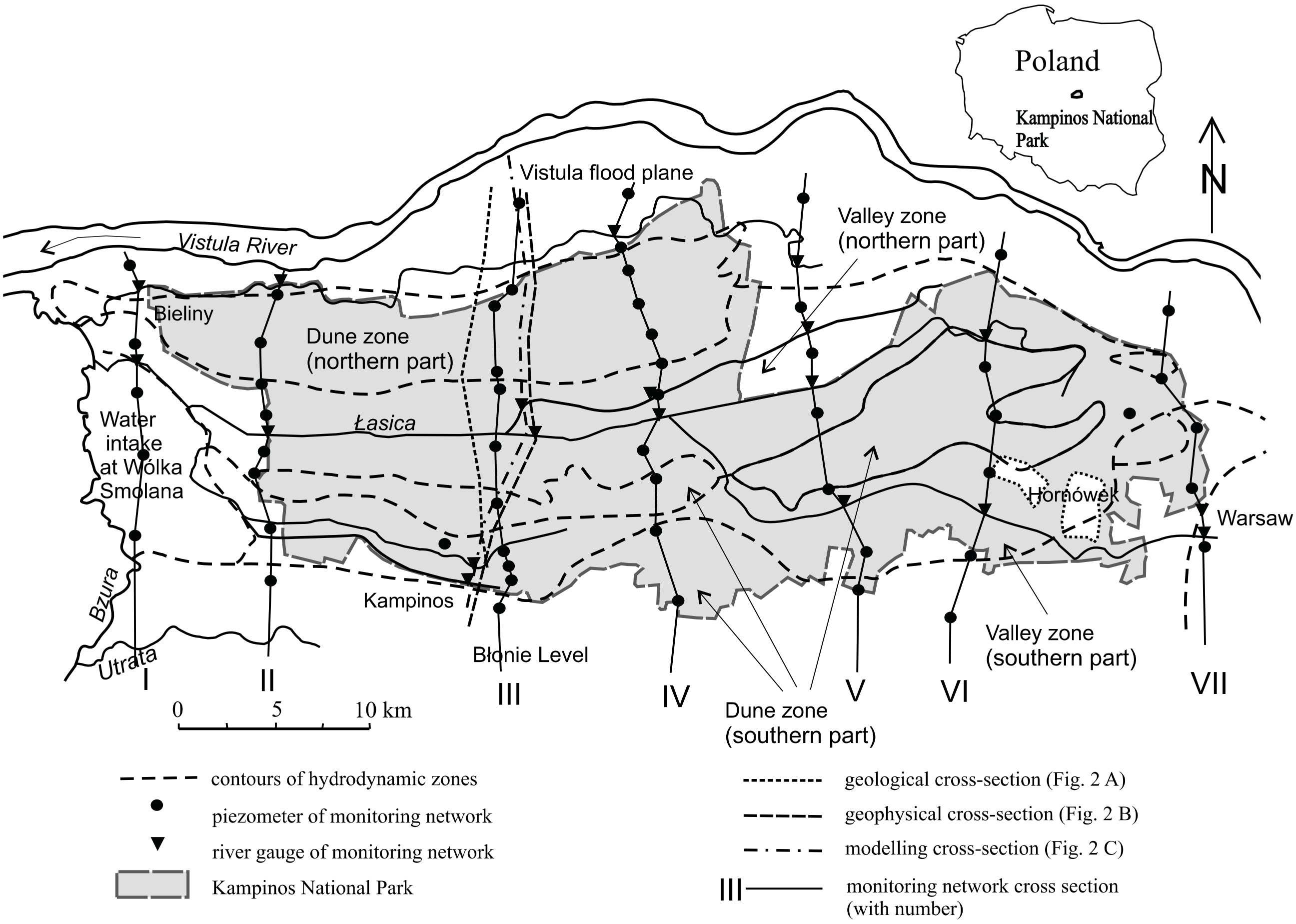

Fig. 1. Location of geological, geophysical and modelling cross-sections in the Kampinos National Park region

The evaluation of the role of the Błonie Level aquifer in recharging the southern part of the KNP and the identification of hydrogeological parameters in this region was made on three mutually supplementing digital models, with diversified range and digitised space (Krogulec, 1994, 1996, 1997*a*, *b*, 2001*b*). The identified values of filtration parameters for the aquifers have become the basis for the quantitative evaluation of lateral recharge to the aquifer on the Kampinos terrace from the side of the Błonie Level and the volume of water infiltrating through the varved clays of the Błonie Level (Table 2).

The target of performed model calculation in the Wólka Smolana region (south-west part of the KNP protection zone) was a complex documentation of changes in groundwater level as well as the volume and range of depression of groundwater due to exploitation of water intake (Kazimierski and Pilichowska-Kazimierska, unpubl.). The result of the model calculations shows that during exploitation of the groundwater intake at the approved exploitation resource level (about 900 m^3/d) from the Bzura River and Olszowiecki Canal there are significant amounts of water inflowing to the aquifer with simultaneous drainage reduction of these watercourses. Due to the exploitation drainage the lateral recharge from the aquifer of Błonie terrace has been intensified.

Modelling research on the Kampinos terrace by Sikorska-Maykowska (unpubl.) was performed to evaluate the volume of recharging infiltration for practical use, particularly in the digital models. Identifying values and choosing an appropriate observation period in conditions of transient filtration determined the value of the effective infiltration coefficient. The specific research results were assignation of each lithological type and statistic analysis of model calculation results. The obtained supply values (ranging from 0.119 for mud and peat to 0.303 for dune sands) have limited regional and time application ranges over the area of the Kampinos terrace.

The evaluation of hydraulic relations between ground and surface water was performed on a hydrogeological model in the Wyszogród area (north-west part of the KNP protection zone). Another target of these researches was finding a way to include additional resistance occurring in the contact zone of groundwater and the river in the hydrogeological calculations, and the form of mathematical record in modelling (Kazimierski, unpubl.). The following parameters characterising the hydraulic relation between groundwater and the river have been employed: bed seepage resistance equivalent value — ΔL, hydraulic resistance — F and coefficient of permeability of the sediment in the zone under the riverbed — k. The modelling showed that the ΔL and F parameters are characteristic for conditions of existing hydraulic connection between groundwater and the river. The value of these parameters for this area is included in the range: (ΔL — from 6.6–70.7 m; k — from 5.8–134 m/d; F — from 7.3x10^{-3}–40.0x10^{-3} d/m^2.

Table 1

Hydrogeological models of the Kampinos National Park region

Modelling area	Tasks and results obtained from modelling	The authors' team
	Analogue models	
Groundwater intake in Wólka Smolana	Evaluation of groundwater resources with forecast for intake extension	Macioszczyk, Kazimierski and Sikorska (unpubl.)
Flood plain of Vistula River and Kampinos terrace	Analysis of Vistula River levels influence on hydrogeological conditions of adjacent areas, evaluation of influence speed and range	Michalak and Sikorska (1977)
Area of Kampinos terrace	An attempt to reconstruct palaeohydrogeologic conditions	Kazimierski (1977)
Edge zone of the Błonie Level in the Kampinos region	An attempt to evaluate the contact of ground-water from the Kampinos terrace and Błonie Level	Kazimierski *et al*. (unpubl.)
	Digital models	
Kampinos terrace, region of Bieliny	Evaluation of the influence of atmospheric factors on dynamics of ground waters	Michalak (unpubl.)
Region of Wyszogród	Model evaluation of parameters characterising relations of ground waters and river waters, proposal of expressing riverbed resistance forces in the form of mathematical record	Kazimierski (1993, unpubl.)
Bzura and Łasica rivers junction	Evaluation of effective infiltration coefficient value	Sikorska-Maykowska (unpubl.)
General model of Kampinos National Park and protection zone region	General water balance, identification of hydrogeological parameter values in the Kampinos terrace aquifer and flood plain	Kazimierski *et al*. (unpubl.)

Apart from the models given, which are characterised by innovative calculation techniques, in the application of new procedures and the resolution of many methodological problems, several typically "useful" models have been made (Table 1).

MODELLING RESEARCH IN THE CENTRAL PART OF THE KNP REGION

The construction of the model in 2001 was preceded by detailed analysis of the geological structure and hydrogeologic conditions. The extensive research included electrical logging of the cross-section (Krogulec and Pomianowski, 2001), measurements of ground and surface water levels and analysis of data from archive boreholes.

The model was constructed on the 16 km cross-section (width 1 m) in the central part of the KNP and its protection zone. The cross-section line, running north-south, starts from the Utrata River drainage basin watershed and ends at on the Vistula River (Figs. 1and 2 C).

The cross-section line extends significantly beyond the KNP protection zone, but this is justified by the model edge conditions. North-south direction was generally drawn along

Table 2

Results of the model in northern edge zone of Błonie Level (southern part of KNP region)

Parameter/Volume	General model	Detailed model
Horizontal coefficient of permeability — Błonie Level varved clays	7.99×10^{-9} m/s	1.39×10^{-9} m/s
Horizontal coefficient of permeability — Błonie Level varved clays	0.89×10^{-9} m/s	0.18×10^{-9} m/s
Subterranean horizontal coefficient of permeability of the Błonie Level aquifer	7.52×10^{-6} m/s	1.01×10^{-5} m/s
Infiltration intensity through the varved clays of the Błonie Level	1.42×10^{-3} m^3/d	0.48×10^{-3} 1.42×10^{-3} m^3/d
Drainage of the Olszowiecki Canal	0.250 m^3/d	–
Recharge of the southern part of the Kampinos terrace aquifer from deeper aquifer of the Błonie Level	0.248 m^3/d	–

Table 3

Water balance — results of modelling research in central part of Kampinos National Park region

Balance "subzones" (compatible with the run of the hydro-dynamic zones)	Błonie Level	Kampinos terrace						
		Southern part of the valley zone	Southern part of the dune zone	Northern part of the valley zone	Northern part of the dune zone	Zone of Kromnowski Canal	Wilków re-gion	Vistula flood plain
Length of model in [m] (cross-section width 1 m)	0 2500	3500	6000	9500	13 500	15 000	16 000	18 500
Elements of balance [m/dm^3]								
Effective in-filtration	↓ + 0.0205 ↓	↓ + 0.00 ↓	↓ + 0.5067 ↓	↓ + 0.00 ↓	↓ + 0.9008 ↓	↓ + 0.00	↓ + 0.2252 ↓	↓ + 0.3844 ↓
Evapotranspir ation	↑ – 0.00 ↑	↑ – 0.1595 ↑	↑ – 0.00 ↑	↑ – 0.3119 ↑	↑ – 0.00 ↑	↑ – 0.3984 ↑	↑ – 0.00 ↑	↑ – 0.0836 ↑
River and ca-nals drainage		Olszowiecki Canal		Łasica River		Kromnowski Canal		Vistula River
		↑ – 0.2862 ↑		↑ – 0.3396 ↑		↑ – 0.1176 ↑		↑ – 0.5497 ↑
Flow in aqui-fer between balance subzones	⇒ Lateral flow + 0.2 ⇒	⇒ 0.2227 ⇒	⇐ 0.2170 ⇐	⇒ 0.2904 ⇒	⇐ 0.3607 ⇐	⇒ 0.5402 ⇒	⇒ 0.0242 ⇒	⇒ 0.2494 ⇒
Model balance — inflow: 2.2376 – outflow: 2.2465 = balance difference: – 0.0089								

the III-rd cross-section of the surface and groundwater observation monitoring network in the KNP (Fig. 1). Analysis of hydrogeological conditions with particular allowance for the hydraulic contour line shows that the determined cross-section (model) may be recognised as compatible with the direction of groundwater filtration.

The choice of modelling method was motivated not only by the possibility of performing additional hydrogeological surveys but also by experience from earlier modelling of the cross-section, applied only for the Błonie Level edge zone. These models (Krogulec, 1997*a*, *b*) enabled detailed evaluation of the supply routes for the southern part of the Kampinos terrace (Krogulec, 2000) which was a starting point for modelling of the cross-section running across the whole width of the Kampinos terrace.

Model calculations were performed using *VisualMODFLOW 2.20* software, which adapts the method of finite differences. Model simulations have been made using the Strongly Implicit Procedure Package (SIP) (McDonald and Harbaugh, 1988) digital method. The modelling was carried out for an unconfined aquifer; modelling using the basic *MODFLOW* set can lead to errors (McDonald and Harbaugh, 1988). In order to avoid this, an additional *Block Centered Flow* (BCF2) (McDonald *et al.*, 1988) calculation procedure was applied.

Model simulations were performed for steady flow conditions, giving an average value of river water and groundwater levels taken from more than 2 years monitoring observations performed in the model cross-section region (observations along the III-rd cross section of the KNP surface and groundwater monitoring network, Fig. 1). The hydrodynamic analysis has been performed based on data from the period 30.11.98–14.12.00 (Table 4). A two-year observation period provides a good basis for hydrodynamic analysis and enables comparison with previously published values and sensible conclusions concerning ground and surface water table locations (Krogulec, in press). The standard error of "calculated" and "measured" groundwater levels is smaller than 10 cm and is a satisfactory compatibility test (Krogulec, 2001*a*; Krogulec, in press; Krogulec and Rossa, in press).

The modelling has confirmed the prevailing role of the Vistula River in governing the hydrodynamic regime in the valley unit analysed. The river is a regional drainage base, recharged by a groundwater volume of 0.55 m^3/d for each metre of river length. The remaining rivers and canals drain the aquifer with the following volumes: Olszowiecki Canals A and B — 0.29 m^3/d, Łasica River — 0.34 m^3/d, Kromnowski Canal — 0.12 m^3/d for each metre of river length. The groundwater drainage in the research area is also related to evapotranspiration (groundwater evaporation) which is significant only in valley zone and along the Vistula River flood plain, where the groundwater table is less than 1.5 m b.t.l. (below surface level). Evapotranspiration in the northern valley zone is 0.31 m^3/d (over an area of 2500 m^2), in the southern valley zone it is 0.16 m^3/d (over 1000 m^2) and in the Vistula River region it is 0.48 m^3/d (over 5000 m^2, flood plain, Kromnowski Canal zone and Wilków region; Table 3).

The aquifer is recharged by infiltration. The values of recharging infiltration in the balance subzones corresponding with the hydrodynamic zones are: southern dune zone,

Table 4

General characteristics of hydrogeological conditions in the Kampinos National Park region

Hydrodynamic zone		Hydrogeological conditions on the base of boreholes, geophysical research (Krogulec and Pomianowski, 2001)	Groundwater monitoring network data from the period 30.11.1998–21.12.2000	Results of modelling research — numerical model in central part of KNP region
Dune zone	northern part	Thickness of the aquifer in some places exceeds 60 m, dividing into two parts: higher with thickness about 30 m (medium and variable grained sands) and lower with thickness to 30 m (fine grained sands, silty)	Depth of the ground water table is from 1.3–4.49 m. b.t.l. (below surface level), ordinates 68.04–73.44 m. a.s.l. (above sea level), there is range of changes max. to 1.76 m	Recharging infiltration — 0.9 m^3/d
	southern part	Thickness of the aquifer is smaller not exceeding 45 m, it also has similar duality as in the northern zone with thickness respectively 25 and 20 m	Depth of the water table is smaller and is from 1.27–4.38 m (ordinates 68.60–77.88 m. a.s.l.) with range of changes max. to 1.18 m	Recharging infiltration — 0.51 m^3/d
Valley zone	northern part	Thickness of the aquifer is significant and even reaches 50 m; the horizon vertical profile splits into three parts: the highest part with thickness of 4–5 m consists of coarse grained sands with gravel, lower with thickness to 10 m consists of variable grain sands, and it is underlain by a horizon of fine grained sands with thickness about 35 m	The location of ground water table is small and in average from 0.74–1.5 m. b.t.l. (ordinate from 68.19–81.81 m. a.s.l.); the registered level change is small on average from 0.64–1.67 m	Evapotranspiration value is 0.31 m^3/d (2500 km^2)
	southern part	There is a typical split of the aquifer for the whole area of KNP; lower 10 m thick and higher to 15 m		Evapotranspiration value is 0.16 m^3/d (1000 km^2)
Vistula flood plain		Thickness of the aquifer is above 45 m, there is a clear split, the higher part consists of medium and coarse grained sands with thickness about 30 m, lower part consists of fine grained sands and silty sands, with thickness about 15 m	The location of the ground water table on average at the depth from 0.83–4.33 m. b.t.l. which corresponds to ordinates from 65.76–75.7 m. a.s.l., with the variation range on average from 0.58–1.93 m	The values of recharging infiltration is 0.61 m^3/d, evapotranspiration value is 0.48 m^3/d (5000 km^2)
Błonie Level		There are 2–4 aquifers, mostly 2 aquifers: lower directly recharging the Kampinos terrace aquifer with thickness to 40 m and upper with small thickness and insignificant commercial meaning	In the subsurface aquifer the average depth of ground water table is from 1.89–3.23 m (from 82.97–91.83 m. a.s.l.) with range of changes to 2.0 m	The recharge from deeper aquifer of the Błonie Level in the researched area (Kampinos terrace) is 0.22 m^3/d for each metre of slope

0.51 m^3/d (14.76 l/s over the entire area of 2500 m^2), northern dune zone, 0.9 m^3/d (41.7 l/s over the entire area of 4000 m^2) and in the Vistula River flood plain, 0.61 m^3/d (24.7 l/s over the entire area of 2500 m^2; Table 3).

Analysis of the balance elements shows that the southern part of the Kampinos terrace is recharged (lateral flow) by groundwater from the deeper aquifer of the Błonie Level. The lateral recharge value in the researched area is 0.22 m^3/d per metre of slope width, which is nearly 10% of the recharging infiltration in the area modelled (18 500 m^2).

The choice of balance "subzones" compatible with the hydrodynamic zones (Krogulec, 2000; Krogulec and Rossa, in press) enabled a more detailed evaluation of recharge and drainage, which is a function of these zones in hydrodynamic regime of the valley unit.

Elements of the water balance, resulting from the simulated calculations are an effect of determining schemes of the hydrogeological conditions for purposes of modelling (hydrogeological schematisation), spatial digitisation and the calculation procedure itself. When analysing each of the balanced elements it should be remembered that some values, e.g. recharging infiltration or evapotranspiration, are mean values (resultants) for the block area and thus cannot be directly interpreted.

CONCLUSIONS

Results of the model researches of the KNP region are as follows:

— identification of: hydrogeological parameter values for the Kampinos terrace; the value of the coefficient of permeability for the Błonie Level varved clays; and the value of the effective infiltration coefficient for various lithological units in the subsurface formations;

— preparation of a general water balance for the Kampinos National Park;

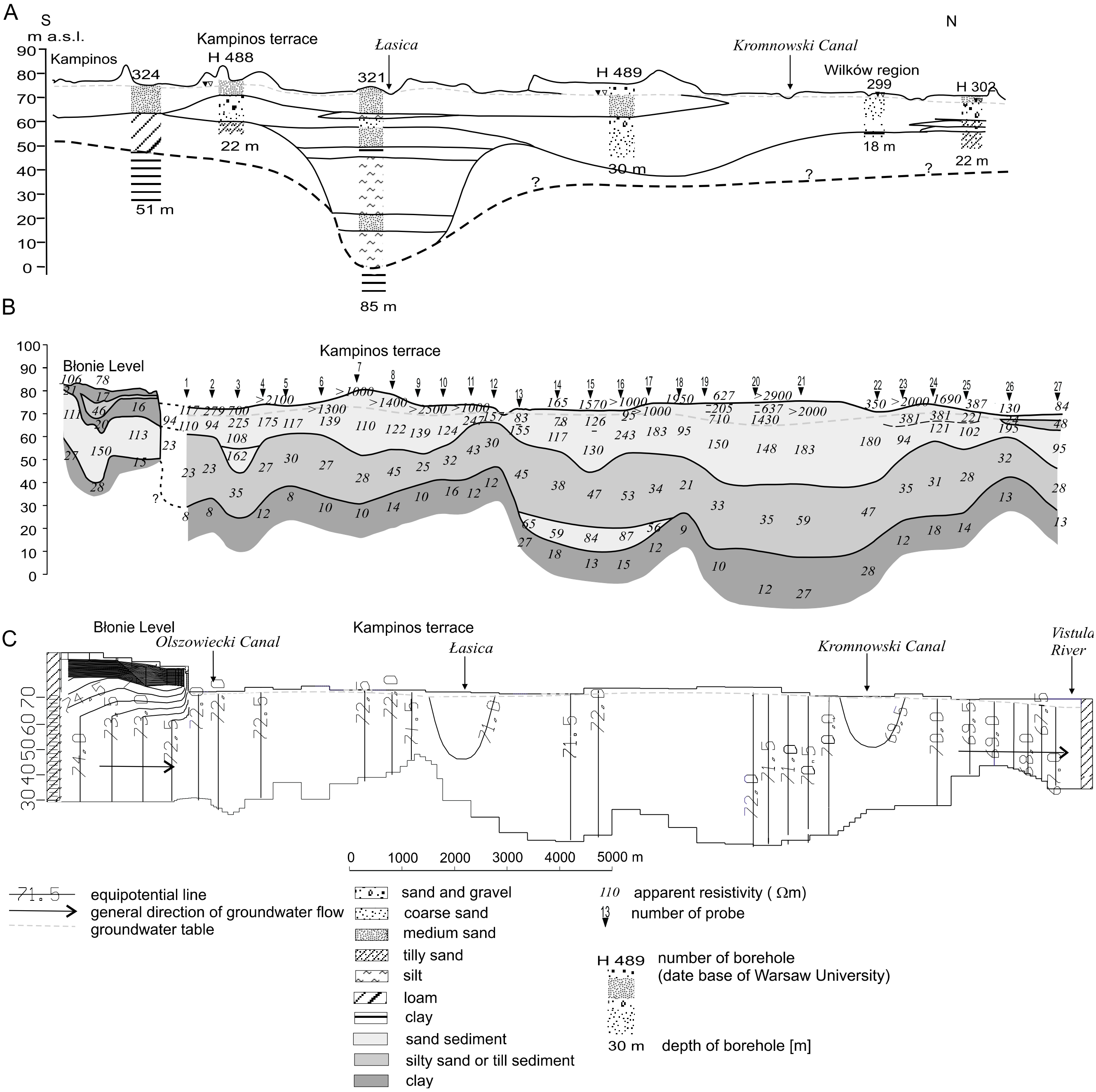

Fig. 2. A — geological cross-section, B — geophysical cross-section with geological interpretation, C — modelling cross-section

— determination of water recharging infiltration volume through the complex succession of poorly permeable sediments in the Błonie Level;

— evaluation of the role of Błonie Level aquifer in the recharge of the Kampinos National Park aquifer (southern part of the KNP region);

— a methodical approach to the evaluation of riverbed zone transmissivity in modelling research.

The construction of the hydrogeological model in the central part of KNP was preceded by a detailed analysis of the geological structure and hydrogeological conditions and followed analysis of other numerical research in this region. The volume of recharging infiltration, evapotranspiration, type of relations with surface water and volume of lateral recharge determine groundwater resources of the KNP region. The modelling research confirmed the prevailing role of the Vistula River in determining the hydrodynamic regime in the valley unit analysed (groundwater drainage, 0.55 m^3/d for each metre of river length). The local groundwater drainage is limited by small rivers (canals), which drain the aquifer with a volume 0.74 m^3/d (for each metre width of cross-section). The groundwater drainage in the research area is also related to the evapotranspiration process which is significant only in the area of valley zone and where the groundwater table is less than

1.5 m b.t.l. The aquifer is recharged by infiltration from precipitation, which is particularly intensive within the dune zone. The recharging infiltration was modelled assuming 2.02 m^3/d (area modelled 18 500 m^2). The Kampinos terrace is also recharged by lateral flow of groundwater from the deeper aquifer of the Błonie Level (0.22 m^3/d for each metre of slope).

The hydrogeological numerical model in the central part of the KNP region, should serve a base for the 3D model, to determine the structure of the filtration stream in the entire hydrogeological unit. This model was based on detailed survey of the hydrogeological conditions in the area modelled, and indeed the research results clarify the development of hydrogeological conditions in this region (Fig. 2A–C and Table 4), particularly taking into consideration quantitative evaluations of the recharge and drainage contribution of each zone and thus their share in the water balance of the valley.

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