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 km². 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 m² (exceeding the area of the KNP), which includes river drainage of ground and surface water (239106 m³/d), lateral flow from the Błonie Level aquifer (1512 m³/d), recharging infiltration (248 m³/d) and the effective infiltration coefficient (average value of 0.17).
The evaluation of the role of the Blondie 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, 1997a, b, 2001b). 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 Blondie Level and the volume of water infiltrating through the varved clays of the Blondie 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 m³/d) from the Bzura River and Olszowiecki Canal there are significant amounts of water inflowing to the aquifer on the Kampinos terrace from the side of the Blondie Level and the volume of water infiltrating through the varved clays of the Blondie Level (Table 2).

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 — $\Delta L$, hydraulic resistance — $F$ and coefficient of permeability of the sediment in the zone under the riverbed — $k$. The modelling showed that the $\Delta L$ 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: $(\Delta L)$ from 6.6–70.7 m; $k$ — from 5.8–134 m/d; $F$ — from $7.3 \times 10^{-3}$–$40.0 \times 10^{-3}$ d/m².

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Fig. 1. Location of geological, geophysical and modelling cross-sections in the Kampinos National Park region
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, its protection zone. The cross-section line, running north-south, starts from the Utrata River drainage basin watershed and ends at the Vistula River (Figs. 1 and 2 C).

### Table 1

Hydrogeological models of the Kampinos National Park region

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

### Table 2

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

<table>
<thead>
<tr>
<th>Parameter/Volume</th>
<th>General model</th>
<th>Detailed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal coefficient of permeability — Blonie Level varved clays</td>
<td>$7.99 \times 10^{-9}$ m/s</td>
<td>$1.39 \times 10^{-9}$ m/s</td>
</tr>
<tr>
<td>Horizontal coefficient of permeability — Blonie Level varved clays</td>
<td>$0.89 \times 10^{-9}$ m/s</td>
<td>$0.18 \times 10^{-9}$ m/s</td>
</tr>
<tr>
<td>Subterranean horizontal coefficient of permeability of the Blonie Level aquifer</td>
<td>$7.52 \times 10^{-6}$ m/s</td>
<td>$1.01 \times 10^{-5}$ m/s</td>
</tr>
<tr>
<td>Infiltration intensity through the varved clays of the Blonie Level</td>
<td>$1.42 \times 10^{-3}$ m$^3$/d</td>
<td>$0.48 \times 10^{-3}$ m$^3$/d</td>
</tr>
<tr>
<td>Drainage of the Olszowiecki Canal</td>
<td>0.250 m$^3$/d</td>
<td>–</td>
</tr>
<tr>
<td>Recharge of the southern part of the Kampinos terrace aquifer from deeper aquifer of the Blonie Level</td>
<td>0.248 m$^3$/d</td>
<td>–</td>
</tr>
</tbody>
</table>
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 B³onie Level edge zone. These models (Krogulec, 1997a) enabled detailed evaluation of the supply routes for the southern part of the Kampinos terrace (Krogulec and Rossa, in press). The standard error of “calculated” and “measured” groundwater levels is smaller than 10 cm and is a satisfactory compatibility test (Krogulec, 2001a; 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 m³/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 m³/d, Lasica River — 0.34 m³/d, Kromnowski Canal — 0.12 m³/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 m³/d (over an area of 2500 m²), in the southern valley zone it is 0.16 m³/d (over 1000 m²) and in the Vistula River region it is 0.48 m³/d (over 5000 m², 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, the remaining subzones take 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).

<table>
<thead>
<tr>
<th>Balance “subzones” (compatible with the run of the hydrodynamic zones)</th>
<th>Blonie Level</th>
<th>Kampinos terrace</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of model in [m] (cross-section width 1 m)</td>
<td>0</td>
<td>2500</td>
</tr>
</tbody>
</table>

Table 3

| Model balance — inflow: 2.2376 – outflow: 2.2465 = balance difference: – 0.0089 |
General characteristics of hydrogeological conditions in the Kampinos National Park region

<table>
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<tbody>
<tr>
<td>Dune zone</td>
<td>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)</td>
<td>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</td>
<td>Recharging infiltration — 0.9 m³/d</td>
</tr>
<tr>
<td>northern part</td>
<td>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</td>
<td>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</td>
<td>Recharging infiltration — 0.51 m³/d</td>
</tr>
<tr>
<td>southern part</td>
<td>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</td>
<td>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</td>
<td>Evapotranspiration value is 0.31 m³/d (2500 km²)</td>
</tr>
</tbody>
</table>

Valley zone

| northern part           | 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 m³/d, evapotranspiration value is 0.48 m³/d (5000 km²) |
| 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 | |

Vistula flood plain

| 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 m³/d (2500 km²) |

Blonie Level

| 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 m³/d, evapotranspiration value is 0.48 m³/d (5000 km²) |
| 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 Blonie Level in the researched area (Kampinos terrace) is 0.22 m³/d for each metre of slope |

0.51 m³/d (14.76 l/s over the entire area of 2500 m²), northern dune zone, 0.9 m³/d (41.7 l/s over the entire area of 4000 m²) and in the Vistula River floodplain, 0.61 m³/d (24.7 l/s over the entire area of 2500 m²; 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 Blonie Level. The lateral recharge value in the researched area is 0.22 m³/d per metre of slope width, which is nearly 10% of the recharging infiltration in the area modelled (18 500 m²).

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 Blonie 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;
— determination of water recharging infiltration volume through the complex succession of poorly permeable sediments in the B³onie Level;
— evaluation of the role of B³onie Level aquifer in the re-
charge 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 cen-
tral part of KNP was preceded by a detailed analysis of the geo-
ological 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 rechange determine
groundwater resources of the KNP region. The modelling re-
search confirmed the prevailing role of the Vistula River in de-
termining the hydrodynamic regime in the valley unit analysed
(groundwater drainage, 0.55 m³/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 m³/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

Fig. 2. A — geological cross-section, B — geophysical cross-section with geological interpretation, C — modelling cross-section
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 m³/d (area modelled 18 500 m²). The Kampinos terrace is also recharged by lateral flow of groundwater from the deeper aquifer of the Blonie Level (0.22 m³/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.

REFERENCES


