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NUMERICAL MODEL OF SEEPAGE AROUND PLANNED WATER RESERVOIR IN KAMIENIEC ZĄBKOWICKI

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Abstract: With a view to protecting areas lying near the Nysa Kłodzka river and in order to reduce flood wave in Wrocław Waterway System, construction of a water reservoir near Kamieniec Ząbkowicki is being planned. After analysing the hydrology and hydraulics of the river Nysa Kłodzka and the function of reservoirs in Kamieniec Ząbkowicki cascade, a numerical seepage model, based on finite element method (FEM) and taking into account bedrock geology, drainage design and dam sealing, has been proposed. Boussinesq's mathematical model was used to calculate unconfined groundwater table and vector field of seepage velocity. Building a numerical terrain model and visualisation of the water table in GIS tools enabled presenting calculation results in 3-D space.

1. INTRODUCTION

Input data for designing the model were obtained from hydrological documentation *Water reservoir Kamieniec Ząbkowicki on the river Nysa Kłodzka realised within the framework of "Programme for the Odra – 2006"* [3].

The Nysa Kłodzka is a left-bank tributary of the Odra. It is 181.7 km long (70.3 km as far as Bardo section) and its drainage basin has the area of 4566 km^2 (1744 km^2 as far as Bardo section). It flows out from the Śnieżnik Massif, at the height of 975 m, on the slopes of Trójmorski Wierch and joins the Odra below Mikolin in the Opolskie Province at the height of 140 m. Land relief of the Nysa Kłodzka basin above Bardo is very varied, so the surface runoff is high, and the time of flood wave propagation from the tributaries – very short. The main flood wave on the Nysa Kłodzka is intercepted by Otmuchów reservoir, built in 1938, but Topola and Kozielno reservoirs, opened in 2002, with their total flood capacity of 8 mln m^3, also have a small share in controlling the flood wave. Nysa reservoir (built in 1971) intercepts the discharges from Otmuchów and the inflow from the Biała Głuchołaska. These reservoirs are not sufficient though to reduce the flood wave effectively. Therefore, in order to protect the areas lying near the Nysa Kłodzka and achieve the maximum reduction of the flood wave in Wrocław Waterway System, the construction of reservoirs in Kamieniec Ząbkowicki and Racibórz (with flood capacity of 185 mln m^3), whose total storage capacity will enlarge the capacity of all the reservoirs in the Odra basin as far as the mouth of the Nysa Łużycka by 29%. Figure 1 shows the location of the planned water reservoirs.

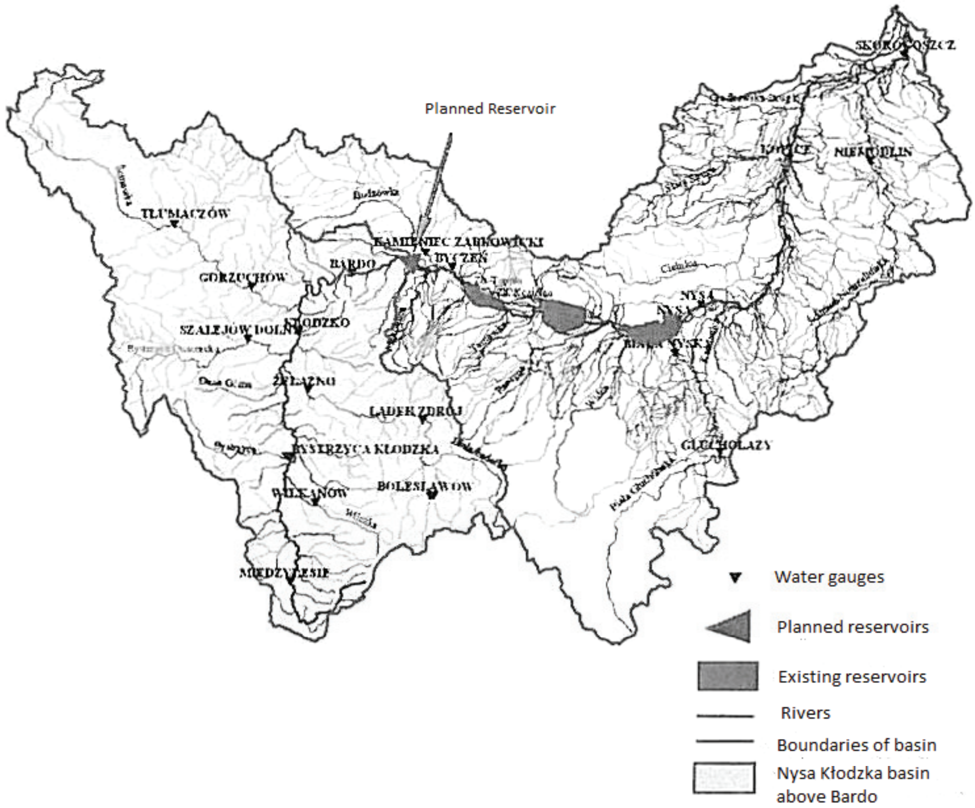

Fig. 1. The location of the planned reservoir and the Nysa Kłodzka basin according to paper [3]

2. HYDROGEOLOGICAL CONDITIONS IN THE AREA OF THE PLANNED RESERVOIR

Around the reservoir, there are three water-bearing horizons: Quaternary, Tertiary, and Palaeozoic-Precambrian. The Quaternary horizon is the most significant one. The Quaternary and the Tertiary horizons are well isolated from each other. The Quaternary horizon reacts poorly to pumping water from the Tertiary horizon.

According to the Feasibility Study from 2006 [1], the Quaternary aquifer complex lying on the valley floor is 7–13 m thick and the water table lies at the depth of 0.3–4.5 m below terrain level. According to the 1980 documentation, the mean value of hydraulic conductivity for Tertiary formations is 69.9 m/day, in particular k = 36 m/day in dam foreground, and 77 m/day in other sections of the reservoir. The water table is free or slightly perched and it stabilises at the height of 238–239.5 m above mean sea level. The next aquifer complex consists of Tertiary sands and gravels, up to 20 m thick, lying under a layer of poorly permeable soils. According to the 1980 documentation, the mean hydraulic conductivity of the Tertiary layers is 7.2 m/day. The perched water table (pressure of up to 1 bar) occurs at the depth of 1.4–6.0 m below terrain level. In the central part of the valley, hydraulic conductivity values are much higher and they can reach 370 m/day.

In the dam foreground, the thickness of the upper water-bearing layer is 6–8 m. The groundwater table lies at the depth of 2–3 m, and the bottom part of the upper aquifer horizon reveals weakly perched conditions, owing to the fully preserved overburden of fluvial soils. The depth of water occurrence rises towards the upland. Under the aquifer, there is a layer of almost impermeable (k < 0.0086 m/day) at least 1.5 m thick clays, then permeable layers with hydraulic conductivity of ca. 3 m/day. Figure 2 shows a hydrogeological map of the terrain around the planned water reservoir.

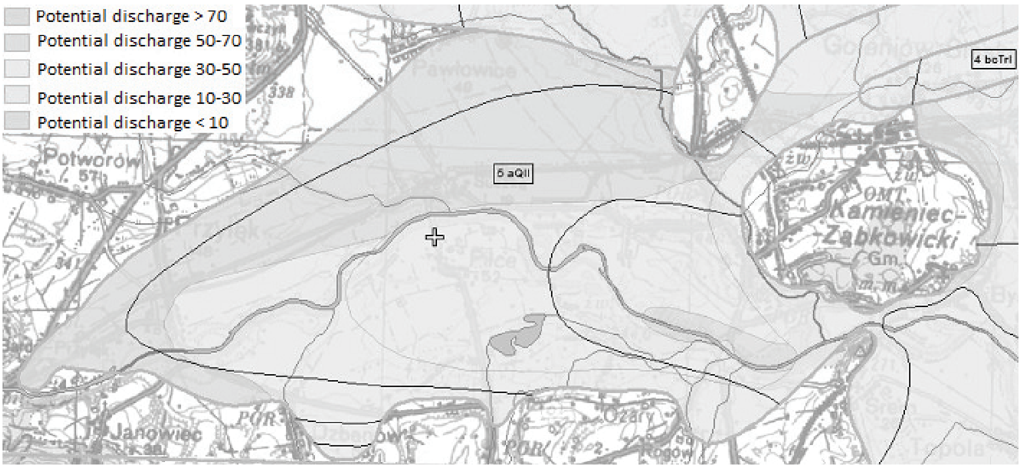

Fig. 2. Hydrogeological map of the terrain around the planned reservoir.
The database of the national hydrogeological service, according to http://epsh.pgi.gov.pl

Near the dam, at the distance of 30–65 m from the river, there is a water collection point for Kamieniec Ząbkowicki. The first group of 7 wells lies to the east of the road Kamieniec Ząbkowicki–Złoty Stok, the water table datum in these wells is 233.0 m. The total discharge of 5 operating wells in this group is 111–129 m^3/h (July 2004), according to the Feasibility Study [1].

3. DESIGN OF RESERVOIR STRUCTURES AND ADOPTED TECHNOLOGICAL SOLUTIONS

The reservoir design was prepared by a team directed by Krzysztof Postoła [1]. The most important structures of the designed reservoir include:

• Front dam: an earthfill dam with a watertight core and bentonite-concrete anti-seepage screen embedded at least 2 m into the poorly permeable layer at the 102.2 kilometre of the river. It will be 2260 m long and will have the maximum height of 18.7 m. The 8 m wide crest will be located at the datum of 258.7 m. The embankments will have a slope of 1:2.5 on the upstream side, which will be enforced with enrockment, and the downstream side, with the slope of 1:2, with a berm at the height of 248.70, will be topsoiled and sown with a grass mix. In the embankment base, pipe drainage will be placed in the inverted filter gravel pack, with inspection chambers and outlets into the drainage ditch. A cross-section through the dam, with the geology of the underlying bedrock, is shown in Fig. 3.

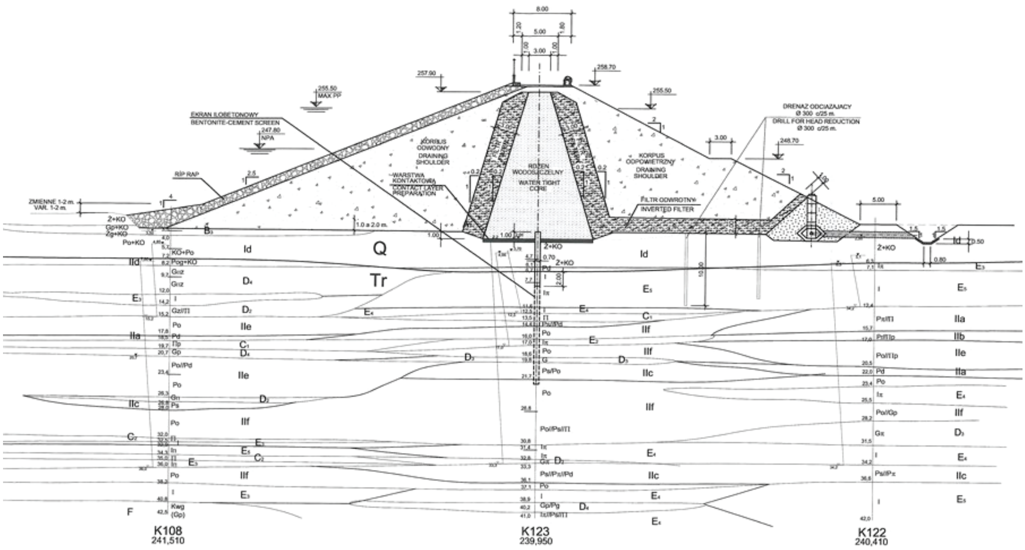

Fig. 3. Cross-section through the front dam with bedrock geology according to [1]

• Outlet structure.

• Fishway.

• Side dam Przyłęk: its function, according to [1], is to protect the village of Przyłęk, roads and the railway line Wrocław–Międzylesie. Dam length is 4900 m, crest datum (5 m wide) is from 257.00 m in the starting section to 257–258.10 m at the end. The planned shape of the lateral dam is shown in Fig. 4.

• Side dam Dzbanów: with crest datum of 257.00 m, embankment slope of 1:10 on the upstream side and 1:3 on the downstream side, built of fluvial soils, topsoiled and grassed, protected with anti-seepage screen with mean depth of 9 m.

• Polders: Dzbanów at Przyłęk.

• Recreational reservoir Ożary: with the area of 10 ha, recharged by the Gruda stream, with water table at the height of 255.50 m, which corresponds to the maximum impoundment level in the main reservoir.

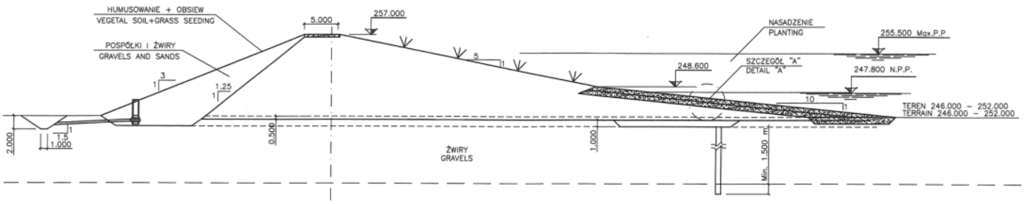

Fig. 4. Lateral dam Przyłęk: cross-section in kms 0+000–3+600 according to [1]

• Recreational reservoir Dzbanów with the area of 34 ha, recharged by the Małucha stream, with water table at 255.50 m above mean sea level.

• Przyłęk reservoir: with the area of 88 ha, after the termination of quarrying. It will be recharged by the waters of the Studew stream. There will be a polder pump station in its area.

4. NUMERICAL TERRAIN MODEL

Numerous resources were used in order to create the NTM of the area under study, including the following maps:

• Reservoir situation plan,

• Topographic map of the area at scale 1:25000,

• maps published on geoportal.gov.pl,

• geological map of the area, obtained in electronic form.

In order to create a spatial numerical map of the area, the authors vectorized topographic maps and the situation plan of the reservoir in the form of a 3D map. The three-dimensional topographic map formed in this way is shown in Fig. 5.

Then, using InRoads software, a numerical model of the terrain was generated.

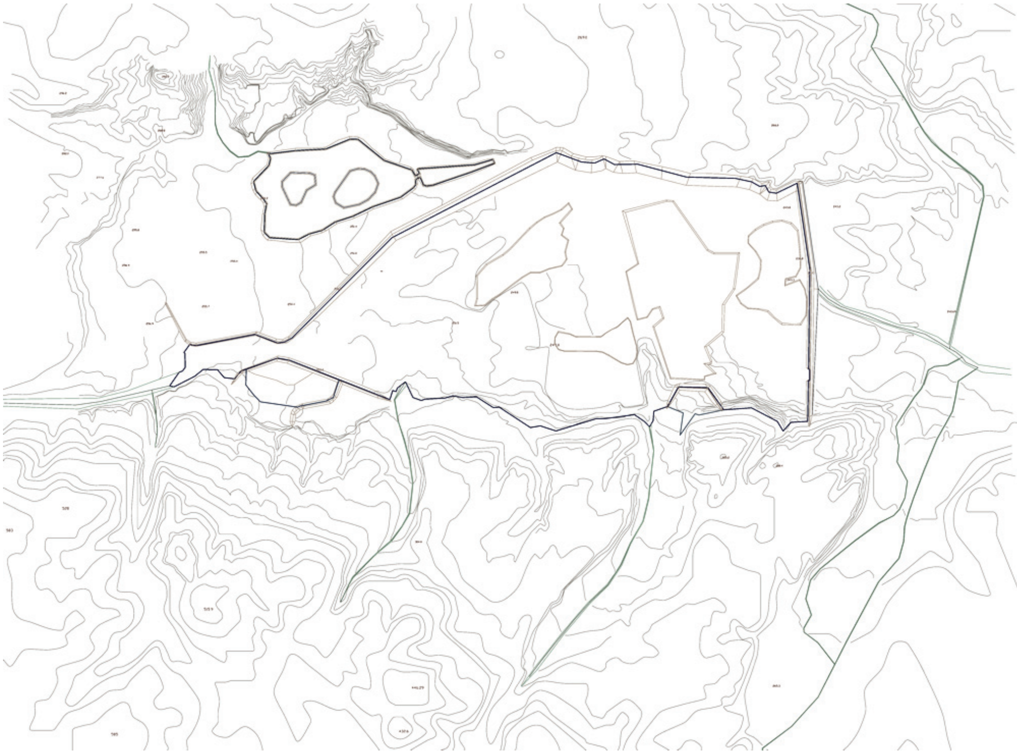

Fig. 5. Top view of a three-dimensional topographic map of the area in MicroStation [5]

5. NUMERICAL MODEL OF SEEPAGE FLOW

Based on geological maps, an area was designated for calculations, and seepage area was divided into regions varying in hydraulic conductivity. Additionally, the authors plotted the outlines of water reservoirs and the lines along which drainage pipes and drainage ditches run. Figure 6 shows the division of the numerical model of seepage flow into regions for the area discussed.

5.1. MATHEMATICAL DESCRIPTION OF WATER FLOW IN THE GROUND

Adopting the most general three-dimensional model is difficult in the case of free-surface problems, as the geometry of unconfined water table is not known beforehand. This is an unknown boundary problem. Unknown boundary problems of this kind can be solved by using finite element method, but owing to the complexity of the model, it is difficult to validate the computational procedure. Therefore, prior to building a complex three-dimensional model, one should calculate the unconfined water table in 2-D space.

Fig. 6. Division of seepage flow area into regions

To do this, the Boussinesq equation will be used for calculations. According to [2], Boussinesq equation for unsteady flow assumes the form

$$k\left[\frac{\partial}{\partial x}\left((H-Hs)\frac{\partial(H-Hs)}{\partial x}\right)+\frac{\partial}{\partial y}\left((H-Hs)\frac{\partial(H-Hs)}{\partial y}\right)\right]+\varepsilon=0 \qquad (1)$$

where:

H – hydraulic head relative to the adopted reference level,

Hs – position of the floor of the impermeable layer,

k – value of the averaged hydraulic conductivity,

ε – infiltration intensity.

The above non-linear Boussinesq equation (1) is the mathematical model adopted for calculations of the unconfined seepage water table in the area discussed.

A vector field of superficial flow velocity is determined from Darcy's law

$$v_x = -k\frac{\partial H}{\partial x},$$
$$v_y = -k\frac{\partial H}{\partial y}. \tag{2}$$

In order to calibrate the model, the results of water level measurements conducted in boreholes and wells in the area studied were used.

The components of velocity vectors can be expressed by means of stream function Ψ in formulas

$$v_x = \frac{\partial \psi}{\partial y}, \qquad v_y = -\frac{\partial \psi}{\partial x} \tag{3}$$

where Ψ is the stream function, constant along streamlines. The pattern of streamlines described by the function Ψ = const, and equipotential surfaces (along which the hydraulic gradient is constant) is referred to as hydrodynamic flow mesh.

5.2. BOUNDARY CONDITIONS OF THE PROBLEM

In Flex PDE v.6 software [4], Dirichlet-type conditions are written as "value", Neumann-type as "natural", and "load" is the third type. For example, in a place with hydraulic head value H0, the condition is "value(H)=H0", at the boundary between permeable and impermeable soils, where no flow occurs – "Natural(H)=0", and at the boundary between two permeable layers – compatibility condition "Load(H)=0". Figure 7 presents boundary conditions for border lines of particular regions.

5.3. PARAMETERS OF NUMERICAL SEEPAGE MODEL

The boundary of seepage area was determined with the use of geological maps. While doing this, areas varying in hydraulic conductivity were delineated. The values of hydraulic conductivity were adopted from project documentation and [1]. The

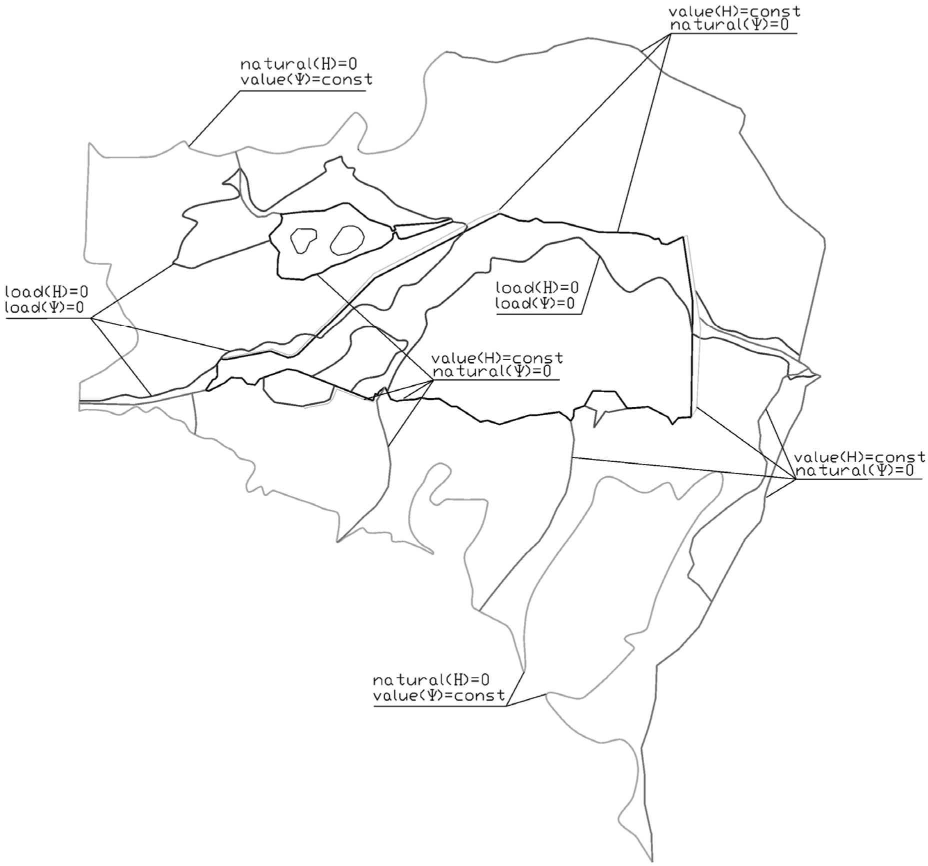

Fig. 7. Boundary conditions of the numerical seepage model

model was divided into 31 regions, whose borders were: the seepage area boundary, the boundaries of areas varying in hydraulic conductivity, rivers, reservoir banks, and drainageways. The discharges of working wells in the model area were averaged: for 5 operating wells with the total discharge of 120 m^3/h, the discharge of a single well was adopted at 24 m^3/h. Drainage was allowed for by creating regions where drainage ditches or pipes lie.

The finite element mesh generated by the system is shown in Fig. 8.

5.4. RESULTS OF NUMERICAL CALCULATIONS

Calculation results are shown in the form of graphs presenting hydraulic head and the vector field of velocity. The water table isohypse map obtained from a numerical model is shown in Fig. 9.

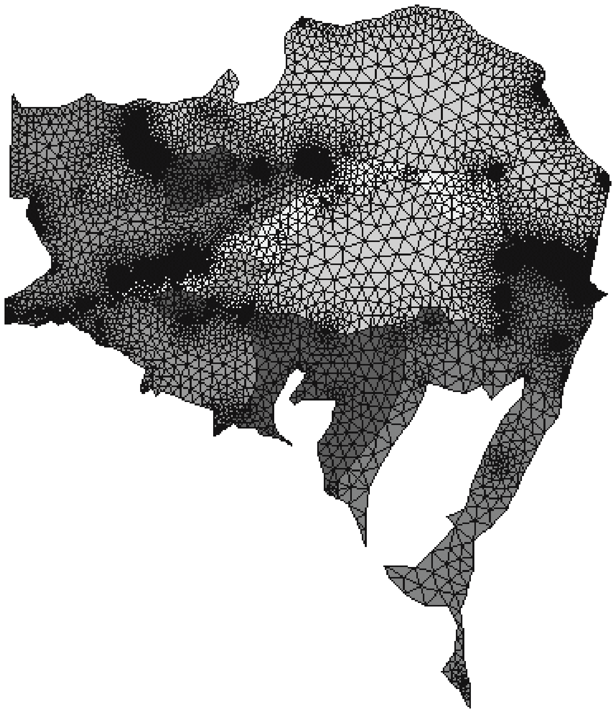

Fig. 8. Finite element mesh for the terrain model

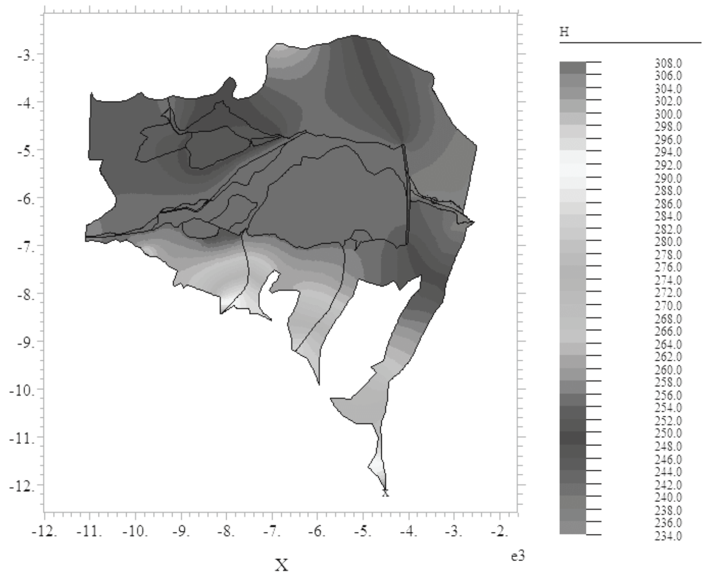

Fig. 9. Water table isohypse map

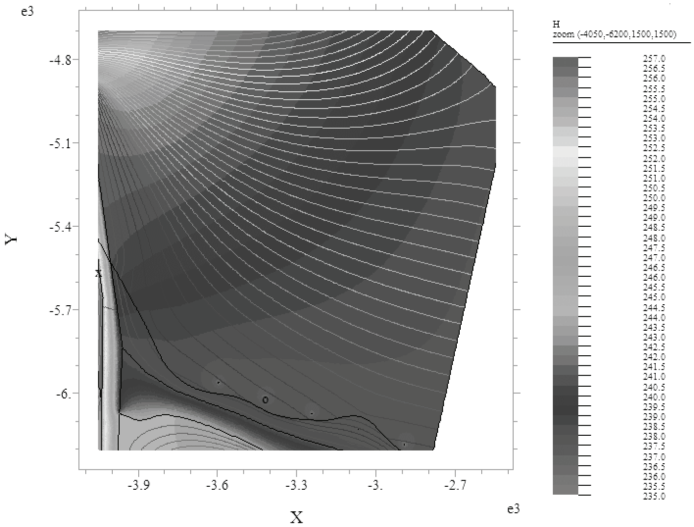

Fig. 10. Map of hydraulic head and streamlines
– the area between the main dam and the eastern boundary of seepage zone

On the obtained water table map for the whole area, one can identify areas where groundwater table lies at the highest (Ożarski Potok), and the lowest datums (water collection point for Kamieniec Ząbkowicki). The calculated water level in wells (235 m) is comparable to the level reported by the Feasibility Study for Kamieniec Ząbkowicki Reservoir (233 m above mean sea level). Figure 10 shows a section of the hydrodynamic flow mesh for the area lying close to the main dam.

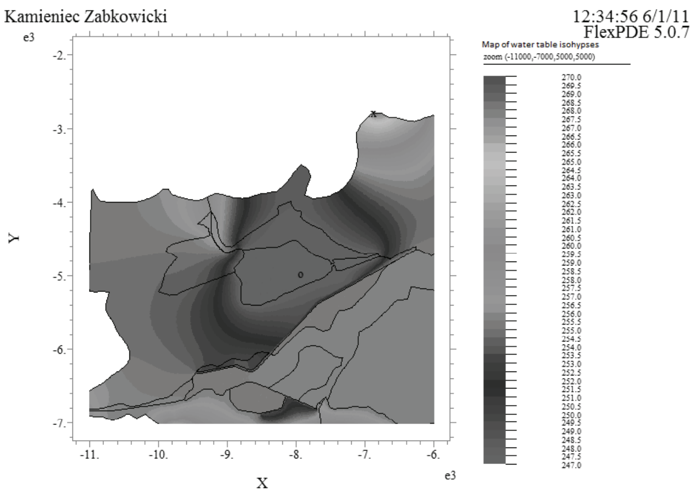

Fig. 11. Map of water table isohypses around Przyłęk Polder

A considerable groundwater table drawdown is observed in the north-western part of the model (Przyłęk polder), which is shown in Fig. 11.

Places with much lowered groundwater table relative to the surrounding area also occur in the neighbourhood of the water collection point for Kamieniec Ząbkowicki and the area behind the dam of Ożary reservoir. The calculated water level in the wells is comparable to that reported by the Feasibility Study for Kamieniec Ząbkowicki Reservoir (233 m). The spatial shape of the unconfined water table in this area is shown in Fig. 12.

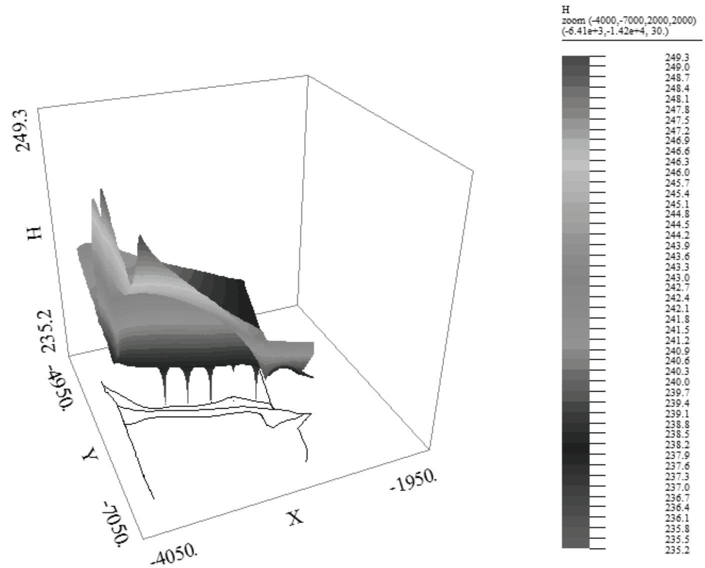

Fig. 12. Spatial map of water table height in the area of water collection point for Kamieniec Ząbkowicki, generated for the water level in the reservoir of 255.50 m

Based on the presentation of velocity vector field, one can observe places where increased water flow will occur. Such a subarea comprises regions located in the immediate neighbourhood of the recreational reservoir Przyłęk, which is shown in Fig. 13.

The results of hydraulic head calculations were exported to InRoads software and a numerical model of unconfined water table was generated. The previously obtained numerical terrain model and the numerical model of unconfined water table obtained from these calculations were both generated in MicroStation software, which in effect produced mutual penetration of both surfaces, which is shown in Fig. 14.

The obtained result correctly projects the predicted shape of water reservoirs.

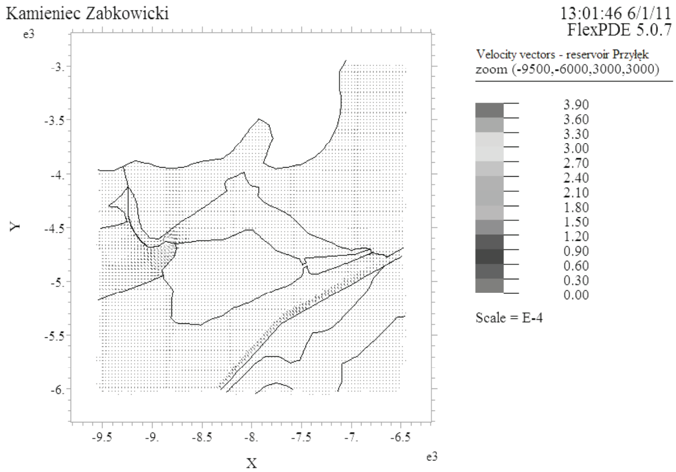

Fig. 13. Velocity vectors in the area of recreational reservoir Przyłęk

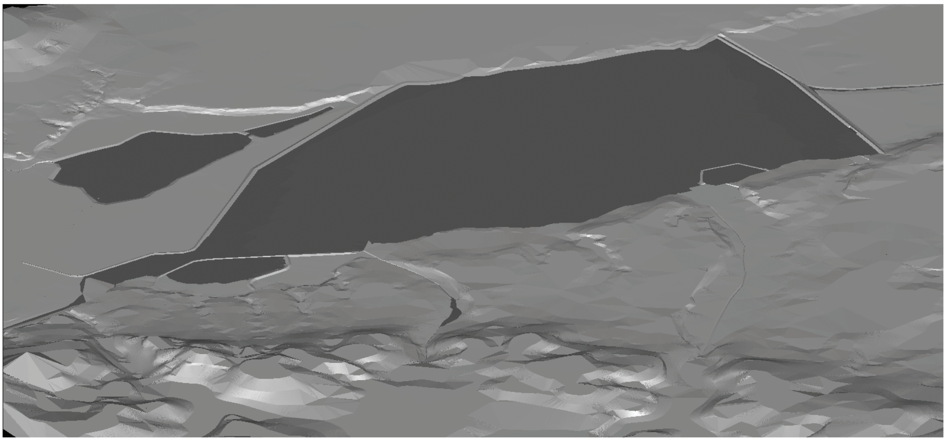

Fig. 14. Mutual penetration of numerical terrain model
and numerical unconfined water table model

Then cross-sections through both surfaces were produced, which allowed defining how water table runs both below and above the terrain surface. The cross-sections were generated for the reservoir water table levels of 255.50 m and 247.80 m, including Przyłęk reservoir. The ratio of the vertical and horizontal scale in the cross sections is 10:1. On the horizontal axis, distances in hectometres were plotted, and on the vertical one – elevation in metres. Figure 15 shows the pattern of all cross-section lines for which the mutual position of terrain surface and the unconfined water table in the Quaternary layer was analysed, as well as two examples of horizontal cross-sections 1-1 and A-A.

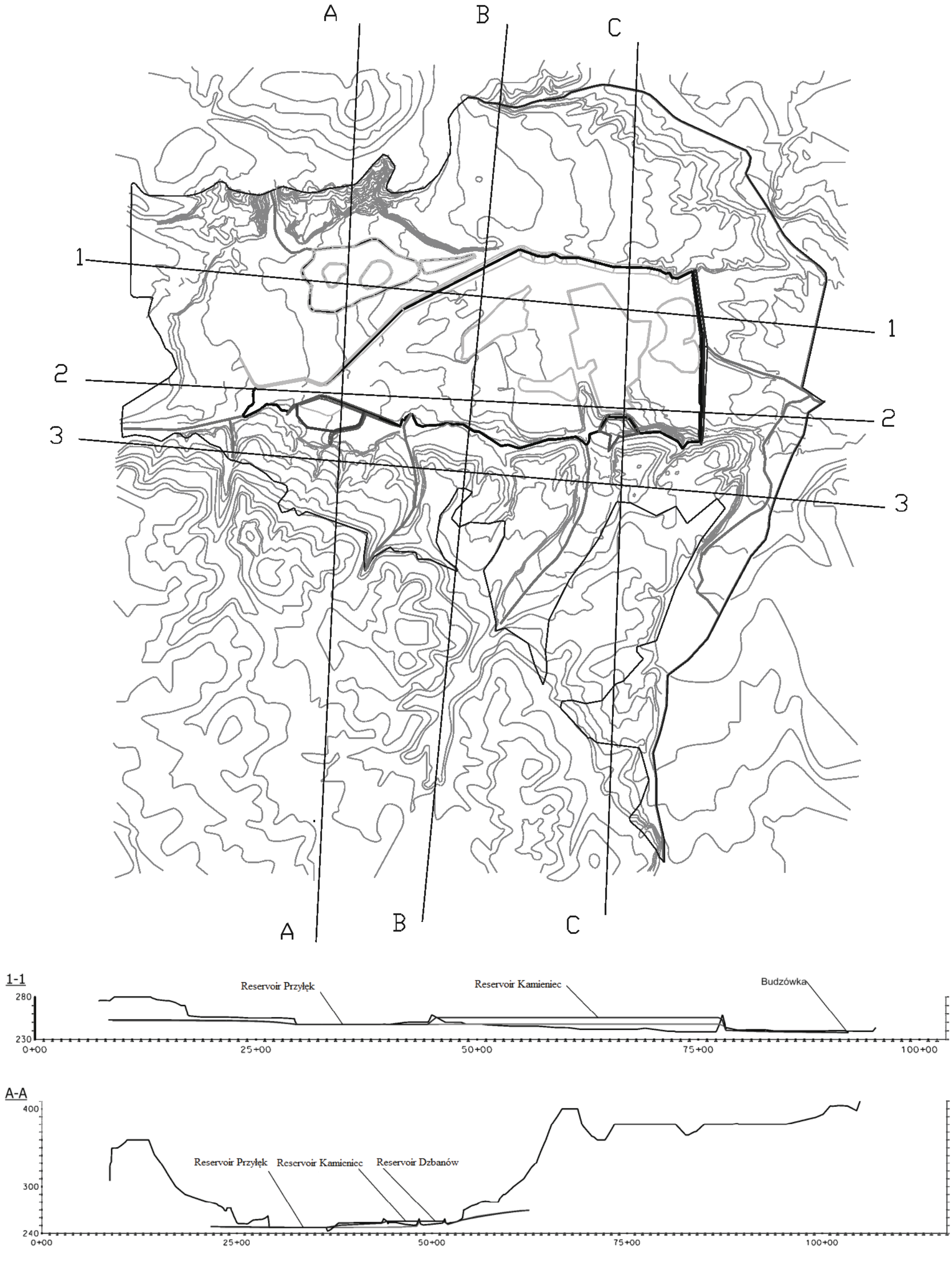

Fig. 15. Examples of cross-sections through the area around the reservoir

5. SUMMARY

The numerical calculations performed with finite element method demonstrate that the adopted method of groundwater flow modelling is the most appropriate for solving problems related to seepage flows in the area of water reservoirs, since:

• The finite element mesh generated automatically by software enables extending calculations to include all drainage installations (pipe drainage, drainage ditches), rivers, their tributaries and wells, despite the fact that the model describes the flow process for a big area.

• Employing software FlexPDE v.6 for FEM calculations enables obtaining high precision of calculations through defining the size of maximum iteration error,

• The numerical model produced projects well the geological and hydrological conditions of the area where groundwater flow is calculated.

The calculations performed with finite element method (FEM) demonstrate that numerical seepage modelling allowing for the complex geological conditions of the bedrock produces solutions consistent with engineering intuition.

The results of numerical calculations do not reveal any places where groundwater water table will rise as much so as to cause terrain flooding. For levels MaxPP and NPP, results differ significantly only in the reservoir bowl, while they are very similar on model boundaries, which can be seen both on water table isohypse maps and in cross-sections. Therefeore, it can be said that the area to be covered by calculations was correctly defined. The largest differences in the water table datum occur within Przyłęk floodplain when calculations are performed for the maximum level of the water table in the main reservoir.

Based on calculations of seepage flow through the dam, it can be said that the designed horizontal drainage fulfils its function. Water flow does not cause a loss of seepage stability of the dam.

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