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The prognosis of influence of the Oder River waters dammed by Malczyce barrage on left bank areas

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Abstract

The finalisation of the construction of the Malczyce barrage is planned for 2015. Damming of the river will cause a change in the water and ground conditions in the adjoining areas. The paper analyses the influence of the water level in the Oder River dammed by the barrage on groundwater table level in the left bank valley.

A model which allows the prediction of groundwater levels depending on the assumed water level in the Oder was constructed. The analysis was conducted for three different variants: for the initial stage before damming the Oder River and for the conditions after damming the water up with and without the drainage devices included in the project.

The calculations were done in several chosen transects across the river valley. The mathematical model of flow in the aquifer based on the Richards equation was applied. The results of calculations were presented as the spatial distribution of piezometric pressures which were used to determine the groundwater table for each of the transects. The calculation results from the vertical models were transposed into a horizontal model. The comparison of appropriate results allowed to positively verify the designed model and to analyse the effectiveness of the realised project solutions.

Key words: *barrage, drainage, groundwater, mathematical model, valley*

INTRODUCTION

The building and operation of the Malczyce barrage, on the 300th km of the Oder River, will change the river's character in a certain area. As of yet, the Oder River below the last barrage in Brzeg Dolny, is a free-flowing river, that exerts a draining effect on adjoining areas. After damming, the adjoining areas above the barrage will fall within the infiltrating influence of the river, hence some areas may become overly moist or vulnerable to flooding [CHALFEN *et al.* 2005; 2008; 2010]. These negative effects will mostly affect the left bank of the river, as the right bank valley is narrow and changes quickly into an adjoining upland. In order to eliminate these phenomena on the left bank, draining devices were designed. Within the Oder embankment just above the barrage, a 1 km long watertight membrane was built, reaching down to the impermeable layers in order to prevent the infiltration of soaking waters into the Rzeczyca village.

Upstream, between Rzeczyca and Zakrzów, the drainage system with a deep ditch equipped with a pumping station in under operation. Above Zakrzów, shallow drainage ditches were designed to channel the waters to the Jeziorka River. These devices aim to collect the infiltrating waters and direct them into the Oder River below the dam. The paper evaluates the influence of these devices on groundwater levels in the left bank valley [BIELECKA 2005].

CHARACTERISTICS OF THE STUDY AREA

The study area is located on the left bank of the Oder River valley between the newly built Malczyce barrage and the barrage in Brzeg Dolny up to the village Głoska. This area is part of the extent Wrocław valley and contains a fragment of the river basin of the middle Oder. In the zone above Głoska the influence of dynamic backflow after damming the Oder waters by Malczyce barrage will be minimal and changes in groundwater table will not considerably affect the moistening of surface soil layers because of the average altitude of approximately 105 m a.s.l. In the river section between Rzeczyca and Głoska (Fig. 1) 13 transects of the valley were selected and analysed. The groundwater levels below and up the dam in Malczyce until the ordinate 101.40 m a.s.l. were analysed too.

The typical transect through aquifer between Odra and Jeziorka River with measurement from 2011 year and forecasted after damming up groundwater level was shown at Figure 2.

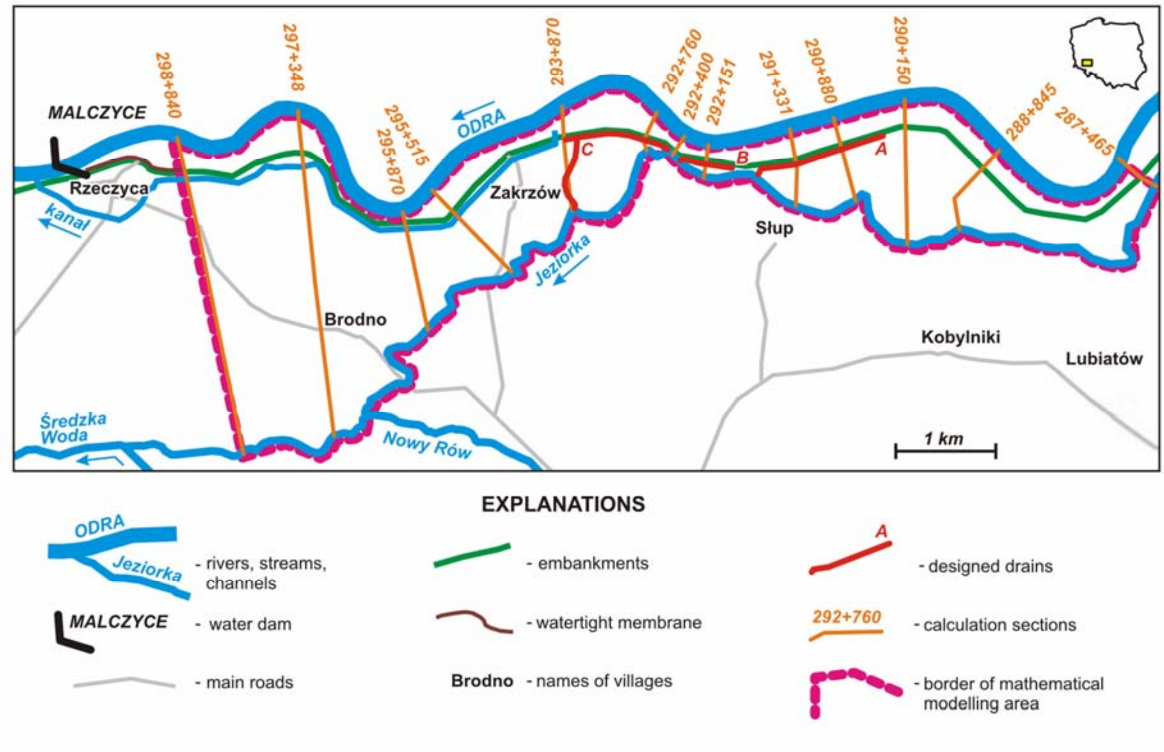

Fig. 1. Study area with selected transects; source: own elaboration

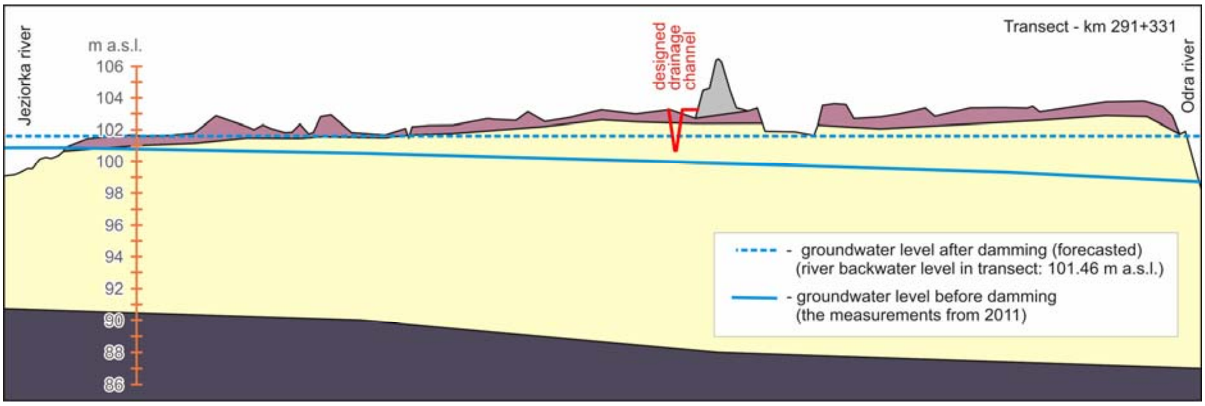

Fig. 2. Example of a transect; source: own elaboration

GEOLOGICAL CHARACTERISTICS OF THE STUDY AREA

Sediments of Tertiary and Quaternary geological layers occur within the study area. The youngest Quaternary formations originate from Holocene. This is sediment from the river accumulations such as alluvial sands, gravels, alluvial soils and organic aggradation mud. Holocene sands and gravels built the main bottom of contemporary Oder together with flood plains. The thickness of Holocene sands and gravels equals 4.5 m on average. Alluvial soils are usually cohesive formations with different contents of loam, mainly silt, heavy clay and loam; less frequent are silts, loamy sand and sands mixed with clay. The thickness of layers of alluvial soils varies between 0.5 and 3 meters. The organic aggradation mud is found usually in local depressions. These are the youngest formations from the Holocene which are still being formed today. Between organic aggradation mud, the insertions of peat can be found. Aeolian sands forming dunes can be found on the floodplain and alluvial terrace. Pleistocene is represented by glacial accumulation formations, glaciofluvial accumulation and river accumulations. Among the Pleistocene formations we can list gravels and sands of accumulation terraces, glaciofluvial sands and gravels, drift clays and gravel with rocks. The river gravels and sands constitute sand and gravel complex lying on uneven surface of Tertiary loams. In the thill rounded pebbles can be found, constituting a non-continuous layer. The thickness of sand and gravel formations can vary considerably: in the central part of the valley it is about 14 meters, in concavities eroded in Pleistocene loams it can be even 30 m. The remaining formations are found on uplands on both right and left banks.

Tertiary sediments are represented by loams and blue and grey silt. In the valley the Pliocene loams constitute an impermeable layer covered by Quaternary formations. The depth of Pliocene loam layer can vary. The biggest height differences occur along the Oder valley due to erosion activity. The surface of loams found under the layer of Quaternary formations is characterised by the appearance of gullies which are parallel and perpendicular to the Oder River. The height differences in Pliocene loams in the Oder River valley can reach approximately 30 m.

HYDROGEOLOGICAL CONDITIONS

Within the analysed area, the aquifers are built of the Tertiary and Quaternary layer. In the Quaternary stratum the water-bearing layer is built of sands, sandy gravels and Holocene and Pleistocene gravel that fill the river valley. The aquifer is continuous. Groundwater table is free or confined depending on the level of water in the river and the depth of hardly permeable formations. The riverbed between Brzeg Dolny and Malczyce is of a draining character. Infiltration of river waters into water-bearing layer in the narrow belt near the river banks is observed only during periods of high water levels [AR Wroc. 1970–2011].

FILTER PROPERTIES OF WATER-BEARING LAYERS

The paper uses the results of a field study [Documentation 1968]. The results show that sandy soils in the Oder River valley are characterised by a high water filtration coefficient. For fine sands it can range between $3.3 \cdot 10^{-3}$ and $1.1 \cdot 10^{-2}$ $\mathrm{cm \cdot s^{-1}}$, for medium sands which constitute the biggest part of soils it was between $1.1 \cdot 10^{-3}$ and $4.7 \cdot 10^{-2}$ $\mathrm{cm \cdot s^{-1}}$. The filtration coefficients for coarse sands was between $2.4 \cdot 10^{-3}$ and $2.8 \cdot 10^{-2}$ $\mathrm{cm \cdot s^{-1}}$, for loamy sand-gravel mix between $2.8 \cdot 10^{-3}$ and $9.6 \cdot 10^{-2}$ $\mathrm{cm \cdot s^{-1}}$, and for gravels – between $4.0 \cdot 10^{-3}$ and $1.6 \cdot 10^{-1}$ $\mathrm{cm \cdot s^{-1}}$.

METEOROLOGICAL CONDITIONS

The study area is located in region I – the Oder River basin according to [SCHMUCK 1965]. The annual mean temperature is 8.7°C, annual mean rainfall about 600 mm, and relative humidity about 75% [WRN 1959]. The yearly amplitude of temperature is the lowest and the time of non-winter is over 300 days. The warmest month is July, which is also the time of the biggest sum of monthly rainfall. The coldest month is January and February is the month of the lowest monthly rainfall. According to Bac, the region is located within the agroclimatic region B-2, which is moderately humid, warm and moderately sunny [BAC *et al.* 1993].

HYDROGRAPHY OF THE REGION

The Oder River valley within the study area is asymmetric. The width of the left bank part varies between 4 and 5 km. The elongated slope of the valley varies between 0.1 and 0.5‰. The cross-falls are between 4 and 15‰. The drainage basin of the Jeziorka River, a tributary to the Średzka Woda River (which in turn flows into the Oder in Malczyce), is situated directly within the Oder valley. The course of the Jeziorka is practically parallel to the Oder and the distance between the two rivers varies between 0.2 and 2 km. The upper course of the Jeziorka is affected by the dam in Brzeg Dolny, whereas the lower course is still under the draining influence of the Oder [PŁYWACZYK 1988; 1997].

The draining canal Rzeczyca–Zakrzów was dug in 2011 as part of the "Malczyce Barrage" project. It is mostly parallel to the Oder embankment, apart from its lower course which goes further away from the embankment and encircles Rzeczyca from the south. The upper course of the canal will be connected with the Oder riverbed and periodically fed with water for ecological reasons. Water from the canal will be discharged into the Oder River near the lower part of the barrage. At higher water levels the water will be pumped mechanically by the pumping station in Rzeczyca. Along the draining canal, the drainage system is constructed which connects with the Rzeczyca – Zakrzów canal. Additional draining canals above Zakrzów which would discharge into the Jeziorka River are also planned.

SIMULATORY CALCULATIONS

AREA OF MODELLING STUDY

The analysis of the influence of dammed Oder River waters on groundwater table in adjoining areas was performed from section km 287+465 to section km 300+400. The upper section lines up with the estimated extent of the influence of dynamic backflow on the Oder River water level, the lower section was selected 400 m below the barrage. From the north, the study area is limited by the Oder River, from the south by the Jeziorka and Średzka Woda rivers. The dimensions of the study area are: WE – 11.45 km, NS – 3.71 km, the surface area is 18.04 km^2. Fig. 1 presents the map with the borders of the study area and transects selected for calculations.

MATHEMATICAL MODEL

After analysing the existing hydro- and geological data it was decided to use flat models in vertical X–Z cross-sections through the water-bearing layer for the simulation. Such models allow to precisely describe the uncompleted, existing and designed draining canals, ditches, drainages and potential vertical drought proofing. For the numerical analysis, thirteen characteristic cross-sections from the Oder riverbed to Jeziorka and Średzka Woda were selected. For each of the sections, filtration was calculated using models based on the two-dimensional stationary Richard equation (2). The calculations were done for the state before damming (using the measurements from 2011) and after damming in two variants: first – without the draining devices, and second, with draining devices that are already built or planned to be built. The calculated levels of groundwater table were marked on the sections on the horizontal map, and for the remaining points of the area the values of groundwater table were interpolated. The calculated groundwater table ordinates together with land ordinates became the basis for drawing isobaths and comparative analysis of the effectiveness of the designed draining devices within the discussed area.

VERTICAL MODEL

The phenomenon of untraced filtration with free or pressure flow regime in a flat cross-section through the water-bearing layer was described by the Richards equation [REINHARD 1992; RICHARDS 1931]:

$$(C+\beta S_S)\frac{\partial h}{\partial t}=(K(p)h_x)_x+(K(p)h_z)_z+S \qquad (1)$$

where:
x, z – spatial variables, L;
t – time, T;
h – piezometric height, L;
p – pressure value, L;
$K(p)$ – hydraulic conductivity, L^2·T^{-1};
C – specific moisture capacity;
S_S – resilient capacity;
β – coefficient;
S – source function, L·T^{-1};
h $= z + p$.

The above equation describes in dynamic terms the water flow within cross-sections in both saturation and aeration zones. The function of hydraulic conductivity $K(p)$ was assumed to be as that proposed by van Keulen and Wolf [REINHARD 1992].

Because the paper analyses only the flow in steady motion conditions, it was assumed that the partial time derivative of piezometric height $\frac{\partial h}{\partial t}=0$ and hence the equation (1) was simplified to stationary form:

$$(K(p)h_x)_x+(K(p)h_z)_z+S=0 \qquad (2)$$

EXTERNAL BOUNDARY CONDITIONS AND INFILTRATION SUPPLY

The equation (2) was supplemented with Dirichlet and Neuman's boundary conditions. On the left bank, that is in the Jeziorka and Średzka Woda riverbeds, and on the right bank, that is in the Oder riverbed, the first-type Dirichlet condition was assumed with piezometric height equal to water level in the riverbed. For the thill of permeable layer, the second-type Neumann's condition was assumed for the flow equal to $q = 0$ m^3·d^{-1}·m^{-1} and describing the impermeable bank. For the land surface it was assumed that there is constant infiltrating supply estimated on the basis of field study and modelling research conducted in the study area [CHALFEN *et al.* 2012; GŁUCHOWSKA *et al.* 2008]. It was assumed that 20% of mean annual rainfall (500–600 mm·year^{-1}), that is about 100–120 mm·year^{-1} of rainfall water, infiltrates through the aeration zone to groundwater table. Hence, the infiltration was estimated at w = 0.0003 m·d^{-1}.

FINITE ELEMENTS METHOD FEM

Thus created differential equation (2), together with the boundary conditions, was solved with the finite element method [WOSIEWICZ *et al.* 2005; ZIENKIEWICZ *et al.* 2005] by dividing the filtration area into triangular elements and applying linear base functions. The size of the triangular mesh varied between 0.5 to 5.0 m. The author's program FIZ was used to calculate filtration in two-dimensional flat models for vertical or horizontal planes. Figure 3 and Table 1 show the examples of calculation results for section in km 291+331.

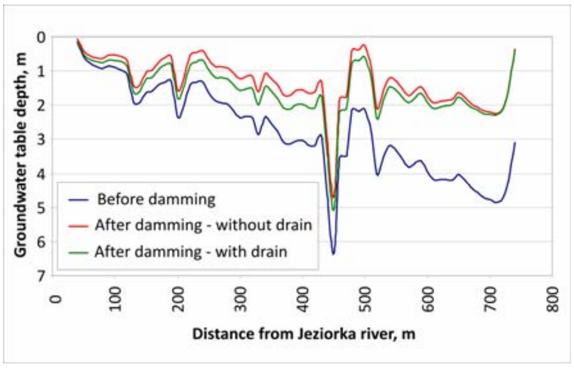

Fig. 3. Groundwater table depth – km 291+331; source: own elaboration

Table 1. Water flow balance q ($\mathrm{m^3 \cdot d^{-1} \cdot m^{-1}}$) in cross section in km 291+331

Variant of calculation	Water flow q, $\mathrm{m^3 \cdot d^{-1} \cdot m^{-1}}$			
	Jeziorka	Oder	aeration zone	canal
Before damming	+0.13	–0.44	+0.23	–
After damming (without draining devices)	–0.34	+0.06	+0.23	–
After damming (with draining devices)	–0.17	+0.13	+0.23	–0.20

Source: own study.

After damming the direction of groundwater flow has changed. The Oder has become the feeding river, the Jeziorka – the draining river. Water coming from the Oder River flows into Canal A.

GROUNDWATER TABLE INTERPOLATION

The ordinates of groundwater table calculated for 13 vertical cross sections were marked on the map of the area and for the remaining points of the area the groundwater table was interpolated by the method of reversed distances with division into 4 sectors. The *X–Y* plane around each interpolated point P_0 was divided into 4 quarters (Fig. 4) and for each of the quarters the closest point to P_0 with data calculated in cross sections was found. Those points were marked as P_1, P_2, P_3 and P_4. The groundwater table in the interpolated point P_0 was calculated as a weighted average of groundwater table levels in calculated points P_1, P_2, P_3 and P_4 according to the formula:

$$ZWG(P_0) = \sum_{i=1}^{4} w_i ZWG(P_i) \tag{3}$$

where the weights w_i were defined as the reversed distance of point $\mathrm{P_i}$ from the interpolated point $\mathrm{P_0}$.

$$w_i = \frac{w_i'}{\sum_{j=1}^{4} w_j'}, \quad w_i' = \frac{1}{d(P_0, P_i)} \tag{4}$$

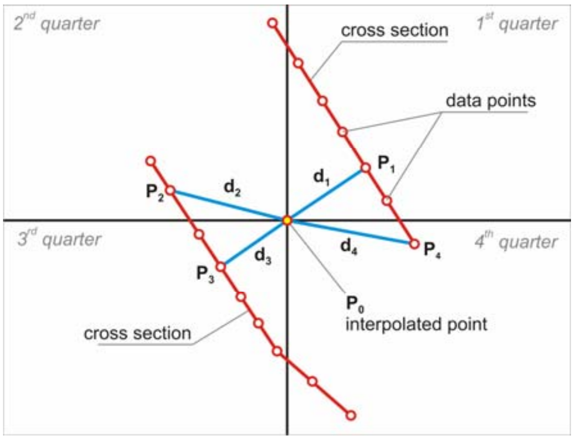

Fig. 4. Reversed distances method with the division into 4 quarters; source: own elaboration

Next, it was divided by the sum of all weights, thanks to which the weights are positive and sum up to 1. The interpolation of groundwater table level in the whole modelled area allowed us to draw the maps of ground water contours and isobaths.

GROUNDWATER CONTOUR MAPS

The groundwater table levels calculated for cross sections and interpolated in other points of the area before and after damming (with the draining devices) are shown in Fig. 5 and 6.

The map of groundwater table ordinates calculated by the model for 2011 (Fig. 5) was compared with the ground water contour map drawn on the basis of piezometric observations from 2011 (Fig. 7) and satisfactory compatibility of measured and calculated values was achieved.

Fig. 8 shows the rise of groundwater table levels after damming compared with the state before damming. The areas for which the rise of groundwater table level after damming is bigger than 0.5 m are marked. In the area parallel to the Oder's riverbed, especially in between the embankments, the rise can vary from 1.0 to almost 5.0 m, while in the central and south parts of the valley it is smaller than 1,0 m.

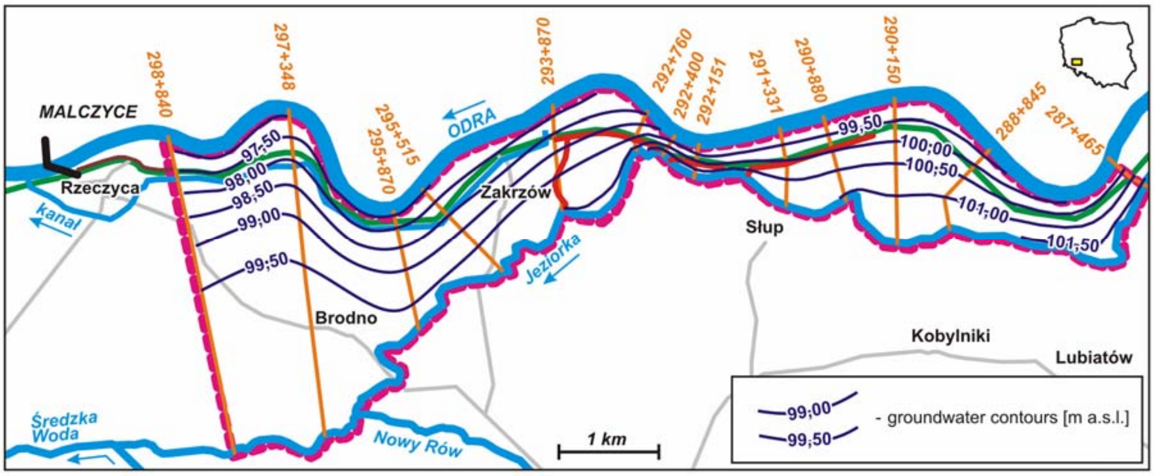

Fig. 5. Calculated groundwater table levels before damming; source: own elaboration

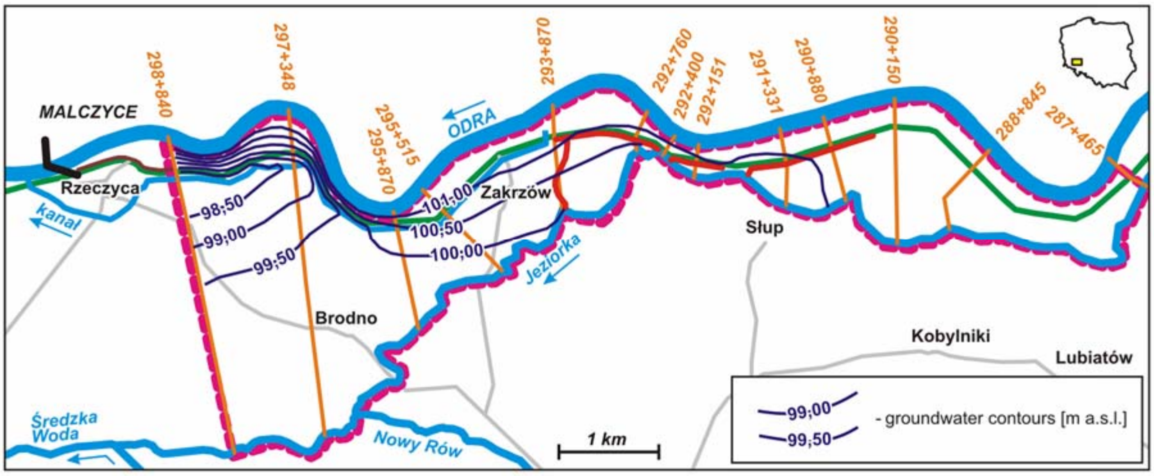

Fig. 6. Calculated groundwater table levels after damming; source: own elaboration

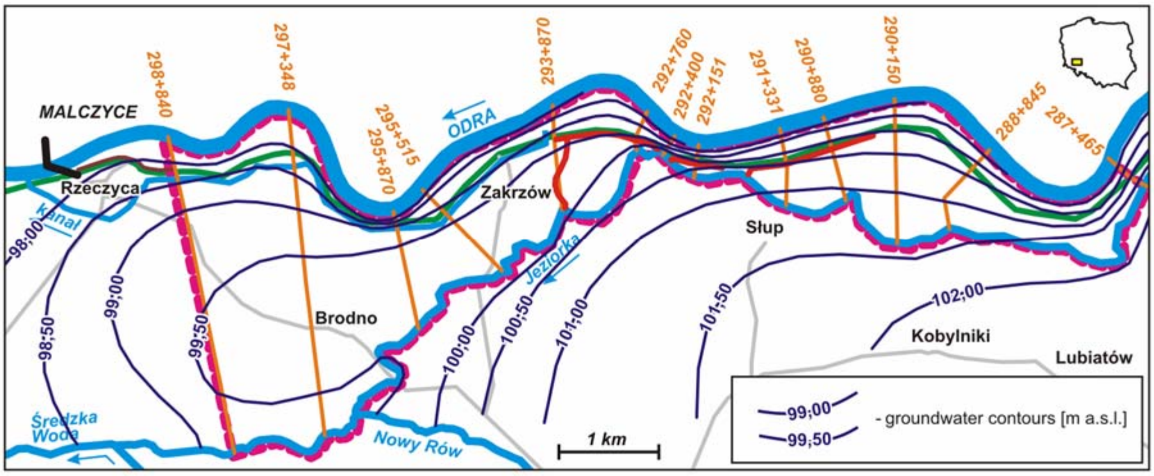

Fig. 7. Ordinates drawn on the basis of measurements from 2011; source: own elaboration

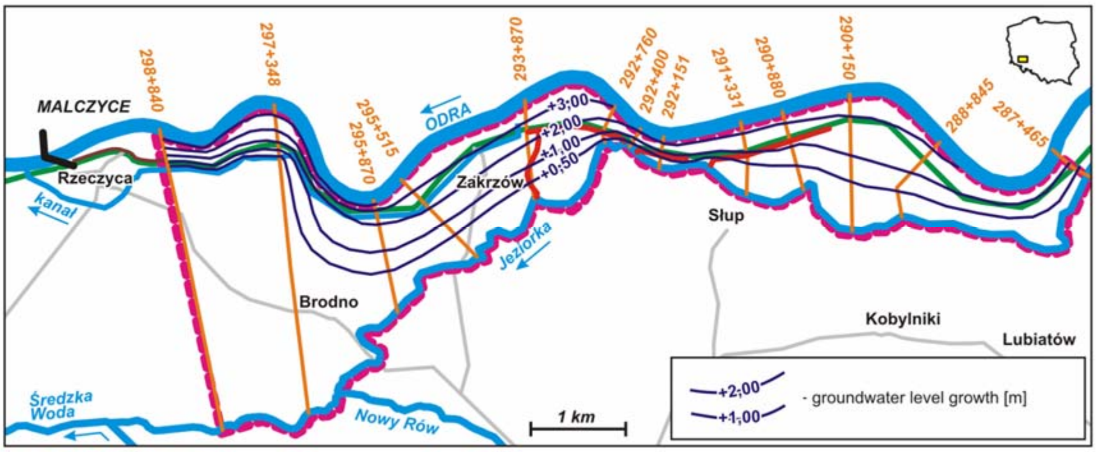

Fig. 8. The rise in groundwater table levels after damming; source: own elaboration

ISOBATH MAPS

The comparison of area ordinates and groundwater table ordinates calculated for the three variants allowed us to draw isobath maps for each of the variants separately. The area ordinates were introduced into the model on the basis of topographical maps drawn in 1:10 000 scale with contours drawn every 1.25 m. Between isolines the area ordinates were interpolated linearly, so we can assume that they were drawn to an accuracy within 0.30–0.50 m and hence we need to assume that the maps of isobaths are drawn with the same accuracy. Fig. 9 shows the isobaths before damming, Fig. 10 after damming and including the draining devices.

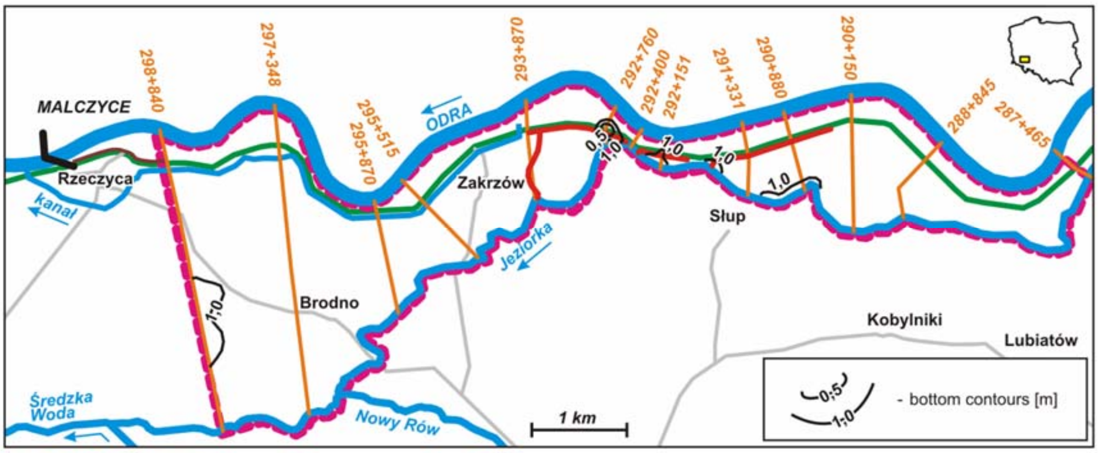

Fig. 9. Isobaths before damming; source: own elaboration

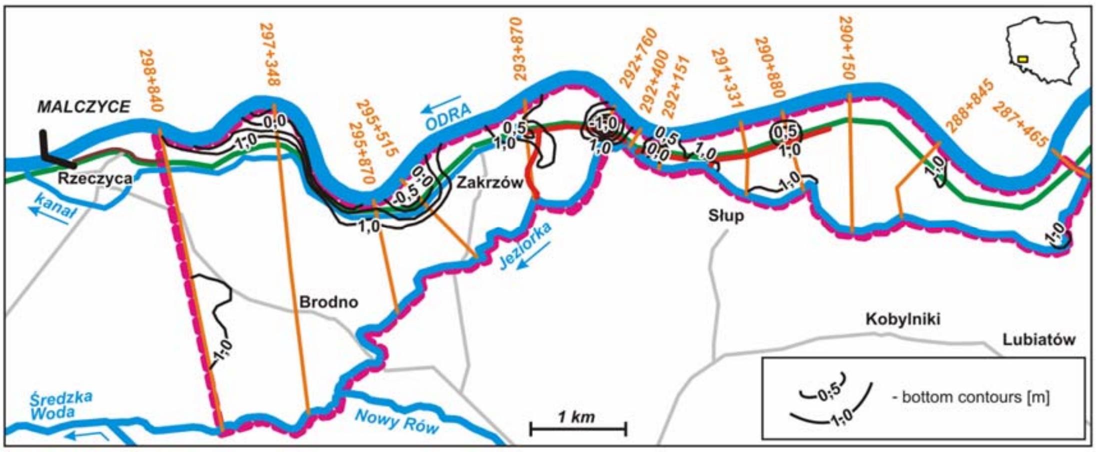

Fig. 10. Isobaths after damming; source: own elaboration

Isolines of values smaller than or equal zero show the areas where groundwater can surface and cause flooding. Such areas are located within two regions between the embankments:

- in section km 292–293: because the bottom ordinates were estimated too high, the designed ditches B and C are not sufficient to drain the region. If the area ordinates and necessary slope of the canal bottom allow it, the canal should be deepened.
- in section km 295–300: because of high backwater just above the barrage in Malczyce, the existing canal Rzeczyca–Zakrzów is not sufficient to lower the groundwater table ordinates between the embankments.

CONCLUSIONS

1. The exact recognition of ground and water conditions in the left bank of the Oder valley, as well as the landform within the study area, influence the final results of modelling research on evaluation of groundwater table levels after damming the Oder and the effectiveness of the designed draining devices.

2. The mathematical model of water filtration in the left bank of the Oder valley, connecting detailed models of flow in several cross-sections with a general flat plane model, turned out to be a useful tool in analysing the influence of existing and designed draining devices in the areas adjoining the Oder River.

3. The results from the models indicate that after damming the biggest rise in groundwater level (from 1.0 to almost 5.0 m) will appear within the 400 m wide belt from the Oder riverbed between Rzeczyca and Zakrzów and further east up to Głoska.

4. The Oder, from km 201 downstream, after damming with the Malczyce barrage until ordinate 101.40 m a.s.l. will become the river feeding water-bearing layers. in the whole south bank area the Jeziorka River, after damming the Oder, will become the draining river. The average flow to the Jeziorka is estimated at about 0.5 $m^3 \cdot d^{-1} \cdot m^{-1}$.

5. Between km 290+500 and km 291+700, draining canal A lowers the groundwater levels between the Oder's embankment and the Jeziorka by about 0.40 m. The groundwater table depth will be about 1.5–2.0 m.

6. The designed canals, marked as B and C, do not lower the groundwater table level in 292–293 km. Therefore, designing different parameters of those ditches (broader and deeper) or mechanical draining devices between the embankments are worth considering.

7. The existing Rzeczyca–Zakrzów canal can protect the valley in the area stretching from the Jeziorka up to the flood embankment from the increased flow of infiltrating waters from the Oder riverbed. The existing draining system parallel to the canal from the Oder's riverbed side is on the level (or above) of calculated free groundwater table and does not operate; in parts it is below this table. After damming the Oder it will work periodically, during infiltration of rainfall water and high water level in the Oder.

8. After damming the Oder it is advised to still conduct piezometric observations and measurements of water conditions within the valley and to measure the filling rate of the canals in order to verify the calculations and evaluate the functioning of the draining system.

9. The analysis can be used in order to establish the necessary additional works aimed at keeping the groundwater at appropriate levels and securing the Oder valley from the negative impact of damming.

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Prognoza wpływu piętrzenia wód Odry stopniem wodnym Malczyce na tereny lewobrzeżne

STRESZCZENIE

Słowa kluczowe: *dolina, drenaż, model matematyczny, wody gruntowe, zapora*

Zakończenie budowy stopnia wodnego Malczyce jest planowane na rok 2015. Spiętrzenie rzeki wpłynie na zmianę dotychchczasowych warunków gruntowo-wodnych na terenie przyległym. Przedmiotem pracy jest analiza wpływu poziomu wód Odry spiętrzonych tym stopniem na poziomy wód gruntowych na terenie lewobrzeżnej doliny. Opracowany został model matematyczny, który umożliwia symulację poziomów wody gruntowej w lewobrzeżnej dolinie w zależności od przyjętego poziomu wody w Odrze. Analiza została przeprowadzona w trzech różnych wariantach: stan przed piętrzeniem wody w Odrze oraz po spiętrzeniu z uwzględnieniem i bez uwzględnienia urządzeń odwadniających przewidzianych w projekcie. Obliczenia symulacyjne przeprowadzono w kilkunastu wytypowanych przekrojach pionowych przez dolinę. Zastosowano model matematyczny przepływu bazujący na równaniu Richardsa. Jako wyniki obliczeń uzyskano przestrzenny rozkład ciśnień piezometrycznych, które posłużyły do wyznaczenia w każdym przekroju pionowym linii zwierciadła wód gruntowych. Uzyskane wyniki obliczeń z modeli pionowych na drodze interpolacji zostały przetransponowane na model horyzontalny. Porównanie wyników obliczeń w wariancie przed piętrzeniem z mapami hydroizohips wykreślonymi na podstawie obserwacji terenowych dało podstawę do pozytywnej weryfikacji opracowanego modelu. Wykonane obliczenia umożliwiły przeanalizowanie skuteczności przyjętych do realizacji rozwiązań projektowych.