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Numerical Simulation of Groundwater Level Changes: a Case Study of the Strużyna Reservoir

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1. Introduction

Enhancing the dispositional resources of surface waters is one of the more important goals of building water reservoirs (Kałuża et al. 2014). However, reservoirs can fulfil many other specific functions within the river's catchment (Hämmerling et al. 2018, Wiatkowski et. al. 2015, Wicher-Dysarz & Kanclerz 2012). Particular objects often find multilateral applications. According to their purposes, three main categories of reservoirs can be distinguished: farming, recreational, and ecological (Ignatius & Rasmussen 2016, Wiatkowski 2011). Large numbers of reservoirs (15 small retention reservoirs in Great Poland Region) and check dams have been built in central Poland to meet the local residential water demand for flood protection, agriculture irrigation and for soil conservation (Waldon 2012, Zubala, 2009). However, the construction of reservoirs and check dams can lead to changes in local and regional groundwater levels that can cause changes in soil moisture, local flooding and even destruction of buildings (water level in the foundation zone) (Saito et al. 2006, Zhang et al. 2012).

A wide range of solutions can be considered to address problems in groundwater management, which involve both quantity and quality-related issues (Chmist & Hämmerling 2016, Šimůnek & Genuchten 1996). However, the effectiveness of all the solutions and their combinations cannot be verified with field experiments (Šimůnek et al. 2003, Smith et al. 2004, Singh et al. 2006). Moreover, many problems and prospects associated with particular water management options are often not recognized until they are well advanced (Mandare et al. 2008). Simulation models by way of their predictive capability are often the only feasible means of providing input to management decisions (Querner et al. 2012, Poeter 2007). These models can help to forecast the likely impacts of increasing of groundwater level and in a broader context a particular water management strategy. Therefore, the results of simulation studies of existing and proposed dams and water retaining structures for water management may form the basis for the identification of suitable water management plans for the future (Hassan 2004, Gedeon et al. 2007).

Research on the development and application of groundwater flow and transport models has increased significantly over the last decades. One interesting proposal is the Hydrus software (Šimůnek et al. 2003, Šimůnek et al. 2018). These groundwater flow models solve for the spatio-temporal values of filtration hydraulics. The HYDRUS 1D, HYDRUS 2D and HYDRUS 3D programs numerically solve the Richards equation for saturated-unsaturated water flow and the convection-conduction equation for heat transport in one, two and three dimensions, respectively. The program may be used to analyse water in unsaturated, partially saturated, or fully saturated porous media. Examples in which soil thermal parameters have been estimated using HYDRUS include studies by Hopmans et al. (2002), Mortensen et al. (2006) and Saito et al. (2007). The article presents the results of a simulation of groundwater flow in the near vicinity of a small storage reservoir, Strużyna. The aim of this study was to verify the conclusion presented by Kałuża et al. (2017) using the numerical software HYDRUS 2D/3D. The extent of the reservoir's influence on the groundwater in steady flow conditions was determined. The obtained numerical results were compared with field monitoring data.

2. Materials and methods

The Strużyna reservoir is located in Lubuskie state and south of Czerwieńsk City and was built on Strużyna Channel (middle catchment of Odra river). The basic functions of the Strużyna reservoir is water storage, including for agricultural purposes, flattening of the flood wave, creation of the possibility of firefighting water supply of the surrounding forests, recreation and tourism. The reservoir was built in the pre-war period, and after nearly one hundred years of operation the hydraulic structures of the reservoir were in very poor technical condition. After modernization of the spillway and bottom outlet the Strużyna reservoir was filled up again.

According to design project of the modernization, a new hydraulic structure was constructed in the form of a shaft spillway, bottom outlet, fish pass, and earth dam embankment, with an upstream low permeability zone (biomat) on previous foundations (sands). Exact characteristic of geological can found in Chalfen & Czamara (2007). After the reservoir was rebuilt, the normal level of water (NWL) was assumed at the same level as before modernization.

2.1. Impact of reservoir on groundwater level

Kałuża et al. (2017) estimated that modernization of the Strużyna reservoir should not cause significant changes in the level of the groundwater table. Unfortunately, soon after filling the reservoir (March 15. 2012), a building on the left bank of the Strużyna channel was flooded. The cellar of the warehouse building was flooded, with an area of about 80 m^2 being flooded with 5 cm of water. After the intervention of the owner of the building, the level of normal damming was lowered by several centimeters. However, due to the dampness of the walls and floor as well as the storage properties of the goods, the building has not been used.

Kałuża et al. (2017) carried out analyses based on the technical documentation of the reservoir and piezometric measurements (groundwater table).

The calculations of water flow in porous media were conducted using HYDRUS 2D/3D software. The authors also pointed out that some planned solutions have never been applied, such as a piezometer network. That is why a piezometer network around the flooded building was installed, as presented schematically in Figure 1. The measurements have been collected once a week since October 2014, during near half an year. At the same time, measurement of the water level upstream and downstream of the Strużyna reservoir was performed.

Fig. 1. Scheme of analyzed area with installed piezometer network

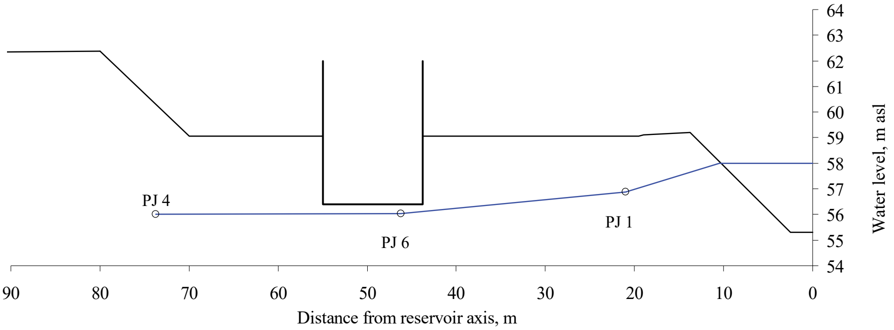

Fig. 2. Cross section (A-A) of groundwater table perpendicular to the left bank of the reservoir

In Figure 1 the line shows a cross-sectional A-A perpendicular to the left bank for which the groundwater table is presented in Figure 2. The building bottom level is 56.10 m asl and and foundation is lower about 0.5 m.

The research conducted during six months (Fig. 3) excluded the influence of rainfall on groundwater level.

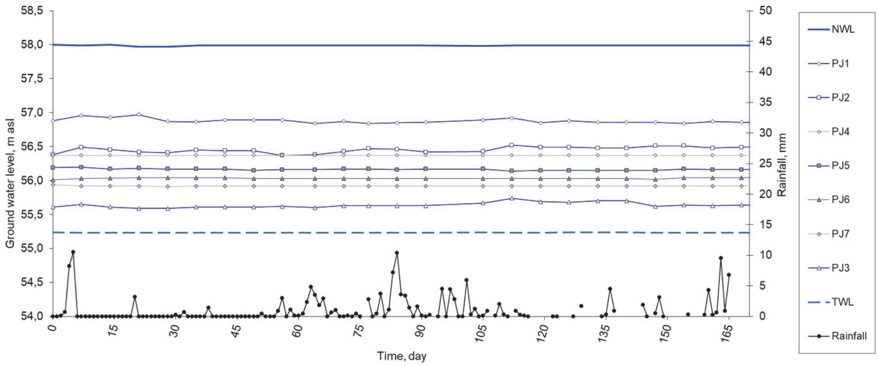

Fig. 3. Variations of water level in piezometers and normal (NWL) and tail (TWL) water level in the Strużyna reservoir in comparison with the precipitation level (Zielona Góra meteorological station)

The results of analyzed groundwater table expressed as piezometric pressure in time can be presented as a spatial direction of groundwater flows. Groundwater flows and levels taking into account the old abutment wall are presented in Figure 4.

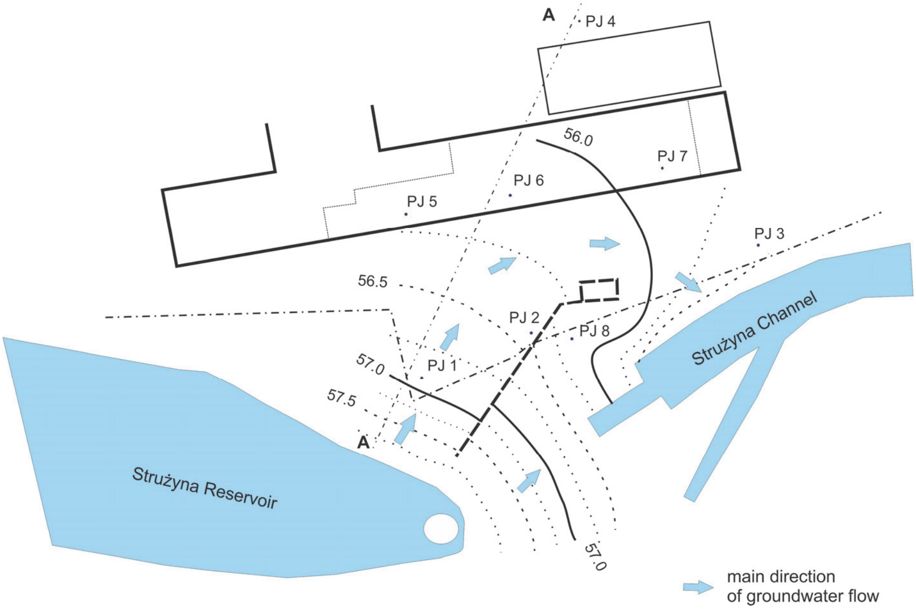

Fig. 4. Directions of groundwater flow taking into account the influence of the abutment wall and buildings

2.2. Numerical model

The Hydrus 3D software is commonly used to simulate water flow, mass and heat in three dimensions in variably saturated media (Błażejewski et al. 2018) and also used to simulate seepage within and under an embankment dam (Šimůnek et al. 2011, Nieć et al. 2017, Nieć et al. 2016a). Flow under unsaturated conditions in soil with laminar flow was calculated in the presented model using the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \tag{1}$$

where:
θ – volumetric water content [-],
h – pressure head [m],
K – unsaturated hydraulic conductivity [m/d],
K_{ij}^{A} – components of a dimensionless anisotropy tensor KA
(which reduces to the unit matrix when the medium is isotropic),
S – general sink term [1/d],

t – time [d],
x_i, x_j – spatial coordinate [m].

The unsaturated soil hydraulic properties, $\theta(h)$ and $K(h)$, in (1) are in general highly nonlinear functions of the pressure head (Šimůnek et al. 2011). The HYDRUS software also implements the soil-hydraulic functions of van Genuchten (Šimůnek, 1999) and the statistical pore-size distribution model of Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{3}$$

where:

$$m – 1 - 1/n,\ n > 1 \tag{4}$$

θ_s – saturated water content [-;],
θ_r – residual water content of sand [-],
α, m, n, l – empirical parameters [1/m,- ,-,-],
h – pressure head [m],
S_e – effective water content [-],
K_S – saturated hydraulic conductivity [m/d],
$K(h)$ – unsaturated hydraulic conductivity [m/d].

Initially the two-dimensional numerical model was created in HYDRUS 3D software according to cross section A-A (Fig. 1) due to identify the properties of the ground and biomat. Based on above assumptions and field measurements the soil parameters were appointed and the three-dimensional model was constructed. To obtain numerical solutions it is necessary to set appropriate initial and boundary conditions. The boundary condition II of the second kind $q_n = 0$ (no flow marked by 1) was assumed on the bottom and surface of the cross section. Two kinds of the boundary condition of type I (marked by red nos. 2 and 4) were defined as the constant water level in the reservoir equal to 2.7 m at the bottom of the reservoir and on the left and right side filtration area as the equilibrium from the lowest located nodal point (Fig. 5). The initial condition, defined for the entire seepage area, was established similarly as the second boundary condition with the pressure head as the equilibrium from the lowest located nodal point (groundwater level mapping). The part of the numerical model mesh and the boundary conditions are presented in Figure 5. On the bottom and reservoir banks were implemented 0.2 m thickness layer as a blanket.

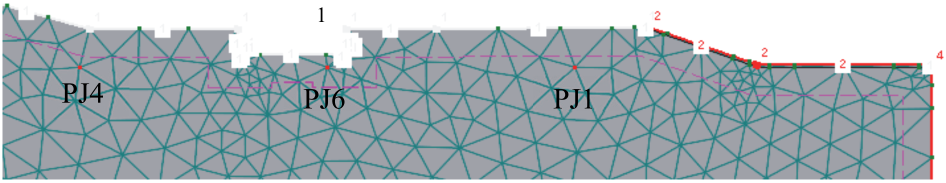

Fig. 5. Part of the numerical mesh with boundary conditions and observation points (PJ1, PJ6 and PJ4)

Soil parameters are presented in Table 1. Subsoil parameters were estimated during field measurements. In practice, it is important to estimate the hydraulic conductivity (HC) and using field test methods appropriate for different soils, as reported by Nieć & Spychała (2014). Using inappropriate methods for estimation of HC can give a different value, even by about one order of magnitude. The parameters of others materials called blanket were estimated in subsequent calculations. Additionally, parameters of the clogging layer – biomat (Finch et al. 2008) – which probably was created on the bottom of the reservoir during one hundred years of operations, were used.

Table 1. Physical parameters of analyzed soils

Soil		θ_r -	θ_s -	α 1/m	n -	K_s m/d	l -
Sand	Subsoil	0.045	0.43	14.5	2.68	7.1280	0.5
Sand (without blanket)	Blanket	0.045	0.43	14.5	2.68	7.1280	0.5
Sandy Loam		0.065	0.41	7.5	1.89	1.0610	0.5
Sandy Clay Loam		0.100	0.39	5.9	1.48	0.3144	0.5
Sandy Clay		0.100	0.38	2.7	1.23	0.0288	0.5
Silty Clay		0.070	0.36	0.5	1.09	0.0048	0.5
Biomat[1]		0.050	0.32	3.0	2.22	0.0140	0.5

[1] parameters presented by Finch et al. (2008)

3. Results and discussion

The calculations were conducted for cross section A-A according to the line in Fig. 1 where three observations points were set at the same place where piezometers PJ1, PJ6 and PJ4 were installed. For the analyzed blanket composite of sandy, sandy loam or sandy clay loam groundwater levels are very high, which is why the building floor is wet. The results of numerical calculations for sandy soil (without blanket) are convergent with the observed groundwater level and condition of the building (Fig. 6).

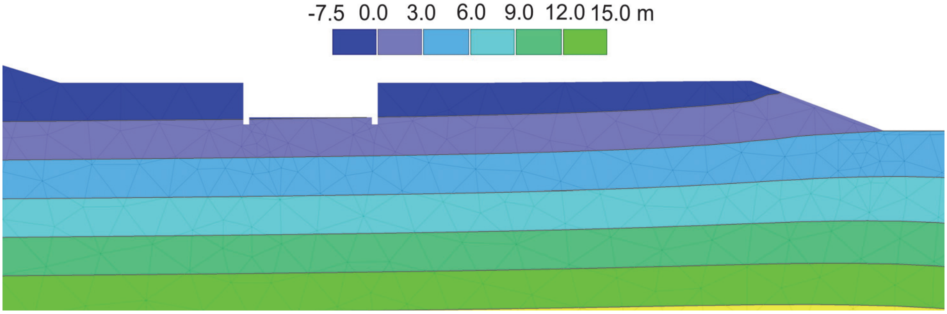

Fig. 6. Piezometric pressure level without blanket (only permeable sandy soils)

Using the blanket with lower permeability material -biomat causes the groundwater level to be distant from building elements. In that case the building floor will be dry (Fig. 7).

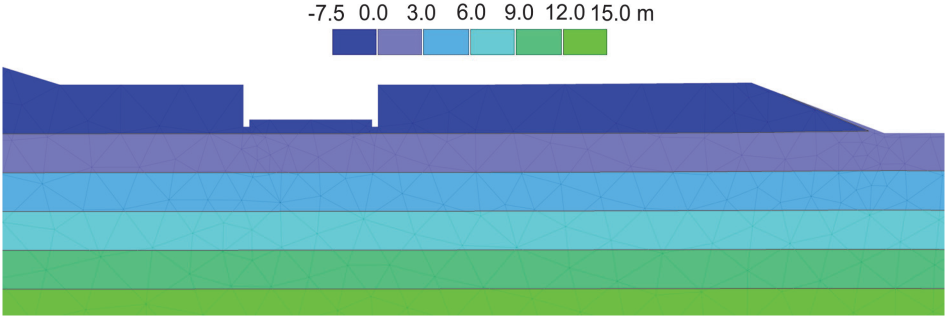

Fig. 7. Influence of low-permeability blanket (biomat) on changes of hydrostatic pressure

The influence of kind of soils or material used as the blanket on groundwater level was particularly important for observation point PJ6 located under the building. Only in the case of using low-permeability materials with hydraulic conductivity lower than Ks < 0.03 m/d is the groundwater level drop significant and with a distance greater than 1 m. The building fundaments and floor will be out of reach of capillary rise. The results of changes of groundwater level under the building – level zero (for PJ6) – are presented in Figure 8.

The results of calculations confirmed the influence of blanket permeability on groundwater level. The measured groundwater level at PJ6 and PJ1 was about 2.5 cm and 15 cm higher in comparison to numerical solutions. The result of calculations using the two-dimensional numerical model gave the best convergence with field measurements in the case where the bottom blanket consists of material with hydraulic conductivity of approximately 1 m/d. Based on the above, a simplified three-dimensional model was constructed to simulate seepage from the reservoir to Strużyna Channel. These calculations take into account the existing (designated for demolition) abutment wall, which directed groundwater flow to the warehouse building. The abutment wall was modelled as 1.0 m width no permeability structure. The result of HYDRUS 3D simulation are similar to field measurements. The steady state conditions were achieved after 5 days. The changes of seepage pressure during 4 days are presented in Figure 9.

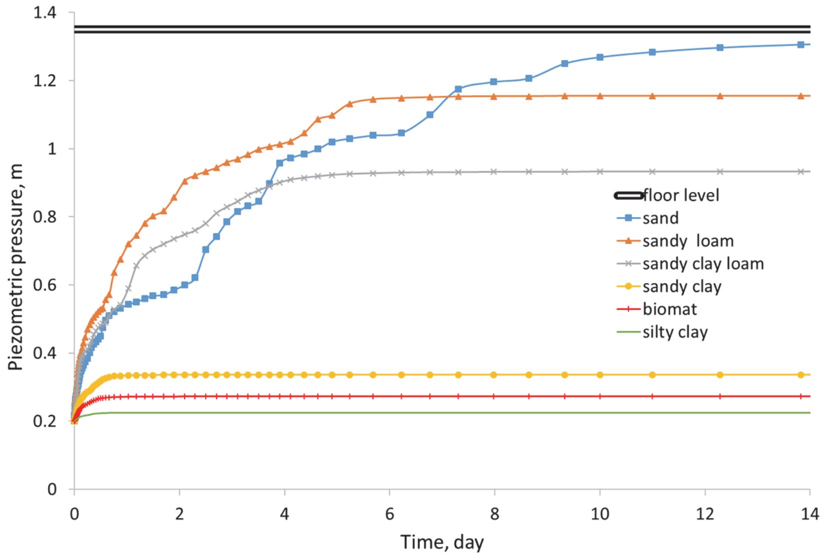

Fig. 8. Changes of groundwater level at observation point PJ6 for different kinds of upstream impervious zone.

In three dimensional simulations the observations points were located according to the installed piezometer network. Differences between measured and calculated groundwater levels are presented in Table 2.

Table 2. Results of comparisons obtained using field monitoring data and numerical solutions

Observation points	Piezometers	calculated m asl	Groundwater levels measured m asl	difference m
1	PJ8	56.10	56.30 ± 0.02	-0.20
2	PJ1	57.00	56.88 ± 0.03	0.12
3	PJ2	56.60	56.50 ± 0.05	0.10
4	PJ3	55.20	55.66 ± 0.02	-0.46
5	PJ5	56.20	56.19 ± 0.02	0.01
6	PJ6	56.10	56.04 ± 0.01	0.06

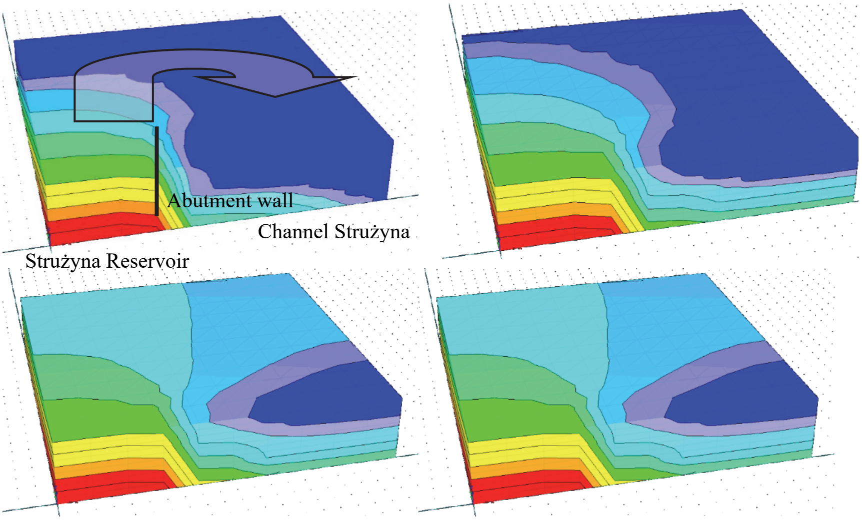

Fig. 9. Visualization of groundwater inflow from Strużyna Reservoir to Strużyna Channel around the abutment wall without biomat

Three dimensional simulations allow one to find the difference between PJ2 and PJ8, which are located close to each other but on two sides of the abutment wall. The influence on the results obtained in PJ3 has appointed boundary conditions due to location of PJ3 on the border of the modelled area. The presented simulations confirmed groundwater flow observed in field measurements.

The Strużyna reservoir is located in the forest, and small organic and mineral particles sediment on the bottom. As a result, a natural low-permeability layer on the bottom of the reservoir was created after many years of operations and the soil bottom became clogged (Nieć et al. 2016b). Spychała & Błażejewski (2004) confirmed that in sand the clogging process can be produced during one year (depending inter alia on hydraulic loading and temperature). Use of HYDRUS software in the analysis of the clogging process was presented in a previous study (Wang et al. 2017).The authors showed the effects of streambed clogging on changes in hydraulic properties. An iteratively increasing total hydraulic resistance during the slug test was considered to correct the estimation of streambed hydraulic conductivity. The mentioned paper suggested the possibility of using one-dimensional coupled water modelling with HYDRUS to quantify the effects of seasonal changes in stream and streambed temperature on streamflow losses. The modelling results for the Strużyna reservoir confirmed the influence of the natural clogging process on water outflow from the reservoir and effects of destruction of the low-permeability layer. In the case of reservoirs, the long-term clogging process occurring at the bottom is very important for water management (including water losses, water quality, supply of aquifers) and the impact on the areas bordering the reservoir (Xanke et al. 2016, Sojka et al. 2019).

The management of groundwater resources directly impacts stream flows through stream-aquifer interactions. A previously presented (Dogrul et al. 2016) example of application to California's Central Valley showed that surrogate models may be insufficient. These approaches may introduce restrictive, sometimes inaccurate, representation of the groundwater flow dynamics and additional modelling steps. Other authors (Fienen et al. 2016, Li et al. 2017) similarly as in our case, have presented the advantages of a non-linear, three-dimensional, finite element groundwater model.

In the filtration studies through the earth dam, as in our work, the effect of the piezometers' location on the analysis of groundwater levels was verified. The exact dependence of water levels in the reservoir on groundwater levels in the work is confirmed by the process of interaction between the reservoir and areas adjacent to the reservoir observed in the article (Shawet al. 2013). This also affects the quality of groundwater and water in the reservoir (Kidmose et al. 2013).

4. Conclusions

During modernization of the overflow structure the natural low-permeability layer was removed. Probably that was the reason for flooding of neighbouring buildings. Using numerical solutions it was easy to predict groundwater level according to many different blankets (differing in permeability) installed on the reservoir bottom.

The conducted research allows us to draw the following conclusions:

1. HYDRUS 3D software can be used to calculate engineering seepage for both design and assessment of reasons. A mathematical model can be used to easily predict water seepage, pressure and velocity in different accepted variants of dam construction.
2. The artificial impervious blanket built during modernization probably has two orders higher permeability (hydraulic conductivity) compared to a natural clogging layer. The authors expect in future reduction of seepage water flow due to the phenomenon of clogging.
3. The cause of the high water level under the building was identified as improper executed of the low-permeability layer in the reservoir.
4. The conducted numerical simulations confirmed correct built low-permeability layer prevents fundament flooding.

An additional reason for increased risk of flooding in the vicinity could be the abutment wall, which has never been destroyed and can direct groundwater to the building.

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Abstract

The article presents the results of a simulation of groundwater flow in the near vicinity of a small storage reservoir, Strużyna. The calculations of water flow in the porous area were conducted using HYDRUS 2D/3D software. The extent of the reservoir's influence on the groundwaters in steady flow conditions was determined. The results were compared with field monitoring data. The field measurements confirmed the negligible impact of precipitation on groundwater level. It was found that the permeability of bottom reservoir has a significant impact on the extent of the reservoir influence. Increasing the groundwater level with simultaneously removal of low permeable soil created a flood risk to buildings near the reservoir. As a result the probable cause of fundament inundation in the near vicinity was indicated.

Keywords:
HYDRUS 2D/3D, seepage velocity, low-permeability blanket

Symulacje numeryczne zmian wód gruntowych na przykładzie zbiornika Strużyna

Streszczenie

W artykule przedstawiono wyniki symulacji przepływu wód gruntowych w pobliżu niewielkiego zbiornika retencyjnego Strużyna. Obliczenia przepływu wody w obszarze porowatym przeprowadzono za pomocą oprogramowania HYDRUS 2D/3D. Określono zasięg oddziaływania zbiornika na wody gruntowe w warunkach stałego przepływu. Wyniki zostały porównane z pomiarami terenowymi, wskazały m.in. pomijalny wpływ deszczu na poziom wód gruntowych. Stwierdzono, że poziom uszczelnienia dna zbiornika ma istotny wpływ na wody gruntowe w jego otoczeniu. Zwiększenie poziomu piętrzenia przy jednoczesnym usunięciu z dna i ścian bocznych zbiornika gruntów o niskiej przenikalności stworzyło zagrożenie podtopieniem dla budynków zlokalizowanych w pobliżu zbiornika. W rezultacie wskazano prawdopodobną przyczynę zalania fundamentów w najbliższym otoczeniu.

Słowa kluczowe:
HYDRUS 2D/3D, prędkość filtracji, warstwa uszczelniająca