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Optimization of the building process of ground water intakes under the conditions of natural water resources deficits

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Abstract: The article discusses the problems of optimizing and exploiting ground water intakes during times of natural water resource deficits, which are critical sources for the operational resources needed. A deposit of underground water in Rudno in the Lviv region of Ukraine is used for the investigation. To optimize the withdrawal of water for the population in the given district, given the limited natural water resources, and on the bases of a detailed geological, hydrogeological and the hydrological analysis of the area and a review of the literature, a permanent mathematical model for filtration of the chosen deposit was created to evaluate the operational groundwater resources for a long-term period. The model allows for the simulation of water intake exploitation in different operating regimes in order to solve the problems of regulating and optimizing water withdrawal under different conditions of change in the water intakes, expanding productivity depending on the economic needs in the region, and solving problems related to the quality of the drinking water by predicting the possible pollution and depletion of major aquifers during their operation. The model of the Rudno water deposit can be used as a reference when selecting promising sites for new water intakes to reduce material and energy resources during construction.

Keywords: water resources, building water intakes, schematization, mathematic model, numerical modelling, operational resources

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Introduction

As is known, there is an essential deficit in water resources worldwide. Due to global warming and its effects, the problem of water shortage will be even greater (Flörke et al., 2018, Greve et al., 2018, He et al., 2021; Klobucista et al., 2023; Sampathkumar et al., 2021; Tokmajyan, 2022). Therefore, reducing the consumption of exhaustible resources of high-quality water, especially water suitable for drinking, is one of the priorities in order to protect natural resources as is the promotion of pro-environmental activities in line with the principles of sustainable development (Grilli et al., 2021).

Water is the most valuable natural resource, and its absence often leads to even greater problems than the lack of energy. The problem of water deficit increasingly reveals itself in the form of regional or local water supply crisis, due to insufficient hydrotechnical and water sewage infrastructure. Reducing the deficit of water resources can be achieved by increasing the availability of groundwater. Proper identification of intakes, optimization of their exploitation and investment in the construction of hydrotechnical and water-sewage infrastructure are crucial to make water resources available to potential recipients (Qi et al., 2017; Smuszkiewicz et al., 2018; Wu et al., 2022).

Ukraine is among the countries with a deficit of water resources, especially drinking water, in the most of its regions (Khilchevskyi, 2021; Kravchenko, 2021; Yara et al., 2018). This article focuses on the West Ukraine region where the problem of water supply for drinking is particularly critical for the population (Ljuta & Ljutyi, 2016; Shestopalov et al., 2010; Telyma, 2003). The demand for water supply in this region is mainly due to the maintenance of drinking water in Lviv city, the main cultural and industrial centre in West Ukraine.

The Lviv water supply system includes more than 20 water intakes connected in four groups, namely: North, South, East and West. These intakes are situated in the area of the general spreading of ground waters in the water-bearing layers of the Upper Cretaceous, Low Devon and Neogene rocks. The ground waters deposit investigated at the Rudno plot belong to the West water intakes group, where the water resources are formed in the river valleys (Shestopalov et al., 2010; Telyma, 2003).

Studies on underground waters in the above-mentioned rock formations are also focused on finding deposits that can be used for geothermal energy as renewable heat sources in Ukraine (Lis & Savchenko, 2022; Lymarenko, 2021; Redko et al., 2021; Shurchkova, 2019; Yurkevych et al., 2022).

The purpose of our research is to develop a methodology for optimizing the operation of underground water intakes complex natural conditions characterized by limited natural resources, using mathematical modeling methods. First, we created a mathematical filtration model of the main aquifers in the investigated territory of the Rudno deposit. This model is an original development by the authors and has no analogues.

We propose optimal schemes for underground water withdrawal on the deposit based on the results of solving various forecasting tasks, taking into account the potential of natural water resources. The main criterion of the optimization problem is to determine the permissible drawdown on the water intake contour according to projected data, taking into account the optimal volumes of withdrawal from the main aquifers in given region.

1. Methodology

The geological and hydrogeological conditions of the region under consideration have been the subject of many scientific and practical studies. In our opinion, the fundamental work on this topic comes from the Tectonic map of Ukraine, which includes a section on considered region (Gurskiy & Kruglov, 2007). The work by Zajats (2013) presents data on the geological structure of the Carpathian region based on seismic investigations, which provided additional information on the hydrogeological properties of Mesozoic rocks. Information on the hydrogeological characteristics of water resources formed in natural and artificial conditions, which was interpreted and used in the creation of the conceptual model of the given deposit, are presented in the work (Shestopalov et al., 2010). The study by Ljuta and Ljutyi (2016) analyzes changes in the chemical properties of underground waters at the operation intakes of the Lviv region in modern conditions. The authors recommend improving the sanitary control of water supply from existing water intakes, among other things.

The research methodology involves a detailed analysis of the geological and hydrogeological conditions of the existing and projected water intakes in the considered region. To achieve this, materials from geological, hydrogeological, and hydrological surveys were used and analyzed, which enabled the creation of a permanent filtration model of the deposit. The developed model is original and was created for the considered water intakes for the first time. The computer programs were developed specifically for the investigated object and are also original. The finite-difference method was used during the numerical implementation of the model.

2. Results and discussions

Our own research carried out at the sites of the West group water intakes revealed a direct hydraulic connection between the aquifer deposits of the Lower Baden and the Upper Cretaceous aquifer. The recharge of these aquifers is ensured by the infiltration of atmospheric precipitation in areas where the Middle and Lower Baden deposits lie directly under the weakly water-permeable Quaternary deposits, while discharge takes place in the form of numerous springs in the river and stream valleys.

Based on the analysis of the geological and hydrogeological conditions of this territory, it was concluded that the Lower Baden – Upper Cretaceous aquifer is the main aquifer for water supply in this region. The aquifier is conditionally well protected and consists of fissure-type collectors with varying thickness and different filtration properties.

The filtration model created for the deposit covers an area of 120 km^2 (12 km × 10 km) and is divided into irregular blocks of a finite-difference mesh. The maximum step size of the mesh is 1140 m and the minimum is 285 m. The model consists of 1152 (36×32) nodes. The filtration of ground waters was simulated in two aquifers within the Quaternary and Lower Baden-Upper Cretaceous sediments that are hydraulically connected through a weak permeable layer. To implement the created model, a special original computer program was used, which is based on the finite--difference representation of the mathematic filtration model in multilayer water--bearing thickness.

Based on the analysis of hydrogeological data of the given deposit, the flow domain was schematized in both plan view and cross-section. In the cross-section, the aquifers in the Quaternary and Baden-Cretaceous sediments were represented as a two-layer water-bearing thickness with a separate layer in between. The feeding of the Quaternary aquifer in the plan view was considered to from atmospheric precipitation while the leakage from the underlying strata was assumed to be zero.

The outer boundaries of the model in the plan view were chosen based on the conditions of the aquifer's lateral spread, filtration heterogeneity, and stability, as well as the possible influence of the Maltytsa intake. To define these boundaries, the second type of boundary conditions (zero lateral inflow contours) were used.

The internal boundaries of the model were the Verschytsa and Stara rivers and their tributaries, which represented the concentrated feeding contours. The river network was specified by the boundary condition of the third type, while the existing Maltytsa intake and the projected Rudno intake were specified by the boundary condition of the second type, with constant withdrawal.

Based on the chosen schematization, the transient flow in the two-layer interaction water-bearing thickness can be described by the following system of differential equations with partial derivatives (Telyma, 2003; 2021):

$$\mu_1(x,y)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left[T_1(x,y)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[T_1(x,y)\frac{\partial h}{\partial y}\right]-\frac{k_0}{m_0}(h-H)+W(x,y), \quad (1)$$

$$\mu_2(x,y)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left[T_2(x,y)\frac{\partial H}{\partial x}\right]+\frac{\partial}{\partial y}\left[T_2(x,y)\frac{\partial H}{\partial y}\right]+\frac{k_0}{m_0}(h-H)-\sum_{l=1}^{N}Q_l, \quad (2)$$

with the initial conditions:

$$t=0,\ h(x,y)=h_0(x,y),\ H(x,y)=H_0(x,y),\ (x,y)\in D_k+G_k,\ k=1,2 \quad (3)$$

and boundary conditions:

$$t>0,\ \beta T_1(x,y)\frac{\partial h}{\partial n}+\alpha h=0,\ (x,y)\in G_1, \quad (4)$$

$$\beta T_2(x,y)\frac{\partial H}{\partial n}+\alpha H=0,\ (x,y)\in G_2, \tag{5}$$

where h, H are the ground waters levels and heads in the Quaternary and in the Lower Baden-Upper Cretaceous aquifers, respectively; $\mu_1(x,y)$, $\mu_2(x,y)$, $T_1(x,y)$, $T_2(x,y)$ are the storage and transmissivity coefficients of the aquifers; k_0, m_0 are the filtration coefficient and thickness of the separate low permeability layer, respectively; $W(x,y)$ is the infiltration feeding from atmospheric precipitation; $Q_l(x,y)$ is the debit of the separate well exploited in the main aquifer in the Lower Baden-Upper Cretaceous sediments; G_k is the boundaries of the filtration domain of the upper and lower aquifers which coincide with each other; α, β are the coefficients in the boundary condition in the general form, at $\alpha = 0$, $\beta = 1$ – boundary condition of the second type with the zero inflow on the contour of G_k, at $\alpha = \beta = 1$ – boundary condition of the first type; h_0, H_0 are the initial spreading of the levels and heads in the first and second aquifer, respectively.

During the modeling of the feeding-outflow conditions from the river network on its contours, constant levels of the water were given that coincide with the marks of the water front in the rivers and in these case k_0 and m_0 – are the coefficients of the filtration and the thickness of the under river sediments, respectively, where m_0 is determined as $m_0 = m_1 + H_r$. Here m_1 and H_r – are the thickness of under river sediments and the river depth, respectively.

In terms of the infiltration feeding of the Quaternary aquifer, it was taken into account as the difference between the average precipitation value over the model and the evaporation rate, and was given as 0.00042 m/day.

To obtain a more reliable forecast, the model calibration was performed, which involved the precise determination of the main filtration parameters.

In the first stage of the model calibration, the group pumping from the two exploratory wells was simulated. The parameters obtained from interpreting the pumping data using analytical methods (i.e. transmissivity and storage coefficients) were used. The model drawdowns obtained were 2.4 and 3.4 m, respectively. The comparison of the model and test pumping data for the observed wells, which were situated 10 m from the central withdrawal well (with drawdowns of 3.36 and 3.37 m, respectively) showed an error of 22% on average, decreasing with the distance from the central well. This level of error is permissible for the evaluation of the operation resources (Shestopalov et al., 2010).

Reproducing group pumping tests on the model allowed the values of the filtration parameters on the Rudno deposit to be identified and improved calculative model.

In the next stage of model calibration, the distribution of the aquifer head in undisturbed conditions was modeled. The base map for solving this inverse problem was created during the analysis of the data about the heads on the considered plot using the results of the preliminary hydrogeological research. The creation of the schematic map of the heads in undisturbed conditions allowed for the model map of the transmissivity to be created over the entire model domain. The distinctiveness of the considered problem solution consists in the use of the data about the aquifer heads in the same points of the model network as additional information when determining the transmissivity coefficients in those points. An effective interpolation method called kriging was used for the automatic creation of this map, similar to the method used for creating the map of the heads in undisturbed conditions (Yeh et al., 2018; Zatserkovnyi et al., 2017).

The advantage of this method is that it improves the validity of given input data and determines the probable values of filtration parameters even at points of the region where there are no observational data. Additionally, the method is an exact interpolator at given points of observation, and an autocorrelation structure of input data is used in creating cartographic materials. However, the disadvantage of the method is that it only provides one theoretical solution, whereas in practice, alternative engineering solutions for the considered problems may arise, and in such cases, new model solutions must be provided. The number of the solution variants may be restricted based on the analysis and comparison of the computed and input field data in separate points of the considered domain.

Figure 1 shows the schematic map of transmissivity of the main aquifer created using computing methods based on the interpretation of the field data on the Rudno deposit. The map is original and created for the first time.

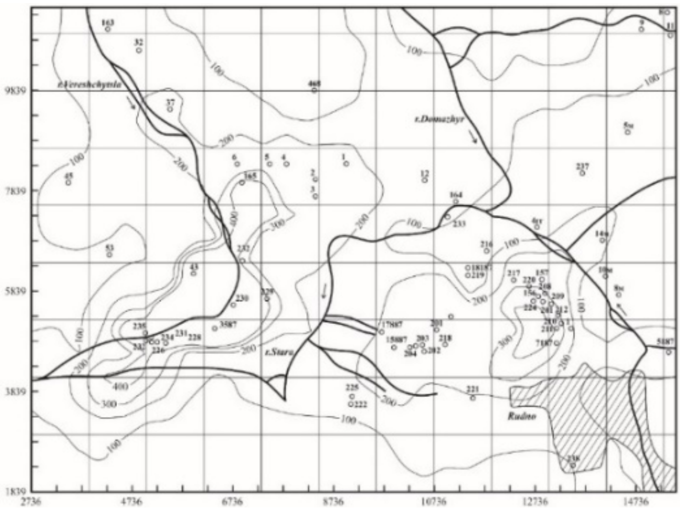

Fig. 1. A schematic map of the transmissivity of the main aquifer created using the kriging method according to the results of research and surveys works on the Rudno deposit (*own research*). Scale: 1:50 000

The map shows the general pattern of the transmissivity in the investigated deposit, with values ranging from 100 to 400 m^2/day. The kriging interpolation method was used to create the computer version of the transmissivity map using separate points from pumping tests input data.

To determine the permeability of under river sediments in the valleys of the Vereschytsa and Stara rivers and their tributaries, as well as the permeability of the separate layer in the Quaternary rocks, the inverse transient problem was solved. The transient regime was reproduced on the model using the Malchytsa water intake operation, which consisted of 7 exploited wells with a total debit of 21 000 m^3/day. The model drawdown in the centre of the intake over a 25 years period was 14.63 m, while the observed data for the regime was 14.2 m. As a result of solving the inverse transient problem, the permeability values of the above mentioned sediments were obtained at 0.00004 and 0.00063 day^{-1}, respectively.

Overall, solving the series of inverse problems substantially improved the reliability of the forecast for the Rudno deposit. The forecast tasks were solved using the finite-differences method, and the obtained results were graphically presented using the kriging method. Figures 2 and 3 show schematic maps of drawdowns of the heads in the main aquifer in both plan view and space. These maps are original and reflect the spreading of the drawdowns over the entire filtration domain. As evident from the maps, the depression cone joins the projected Rudno deposit and the Malchytsa water intake area, with a general minimal drawdown of 2 m.

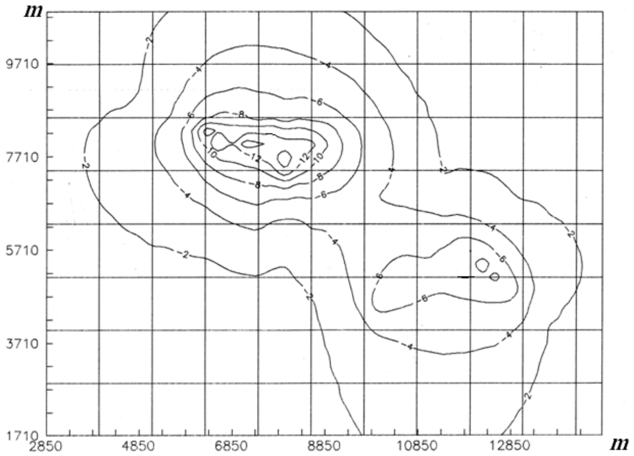

Fig. 2. Schematic map of underground water head drawdowns on the Rudno deposit created based on the results of simulation of the forecast problem using of the kriging method. The upper part of the figure shows the depression cone of heads at the Malchytsia water intake, and in the lower part of the figure, the cone of drawdowns at the projected water intake near the town Rudno (*own research*)

As a result of the simulation, the maximum drawdown in the centre of the depression cone of the designed water intake was 8.59 m, and in the center of the Malchytsa water intake it was 15.04 m, with a permissible drawdown of the heads in the centre of the Rudno water intake area of 15 m. This means that the designed withdrawal within the defined area is secured at the accepted value of the projected drawdowns of the groundwater heads.

The depression cone is mainly distributed in the center of the model area, which confirms the availability of water supply for the projected water withdrawal, thanks to the feeding from the river network and leakage through a low-permeable separate layer from above. According to the simulated data, the main source of operational resources at this site is the natural resources, with a volume of 50 400 cubic meters/day, including the amount of water recharge at the expense of the river network and due to the leakage through a separate layer from above, which accounts for 31 600 m^3/day. Therefore, the operational resources of the ground waters on the projected water intake are fully provided by the natural resources.

The reliability of the data concerning the quantities and aspects of groundwater resources is ensured due to the validated calculation scheme and modeling, using the trustworthy values of the main hydrogeological parameters, which were improved by solving a series of inverse identification problems.

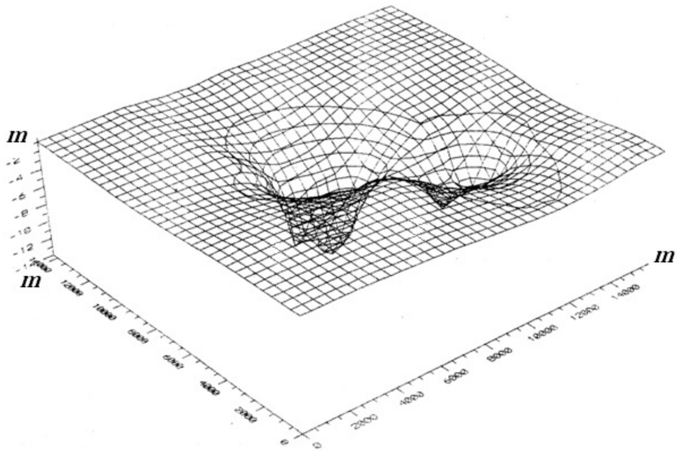

Fig. 3. Schematic three-dimensional block-diagram of groundwater head drawdowns created from the results of simulation of the forecast problem on the Rudno water intake deposit. 1 – Malchytsa water intake; 2 – Rudno water intake (*own research*)

Conclusions

Addressing water deficits requires reliable knowledge and appropriate technologies. Proper protection of water resources and well-thought-out water management are important. Groundwater, which needs to be pumped out, requires appropriate infrastructure. The method of groundwater protection and its sustainable exploitation depend on various natural and technical criteria, such as the boundaries of supply areas, geological structure of the substrate, hydrological and hydrogeological conditions, as well as the type of intake and its technical condition. Therefore, it is necessary to assess the groundwater resources correctly in a given region, optimize the operation of the groundwater intake in complex natural conditions, especially those with limited natural resources, and create optimal water intake schemes for a given deposit and intake, taking into account the natural potential of water resources.

A permanent mathematical model has been created for assessing groundwater resources based on a comprehensive analysis of geological features and hydrogeological conditions on the territory of the projected water intake. The model allows consideration of various options for water intake operational regimes, depending on technical and economic conditions and the possible increases in water supply needs, taking into account environmental measures and the impact of the water intake on the environment.

The optimization problem solution criteria were based on the permissible value of the drawdowns on the contour of the projected intake. As a result of the simulated research, the groundwater resources in the Rudno water intake area were defined, and consequently, the water availability increased for the population of this territory for a long-term period, reducing the load on existing water intakes, thereby regulating the ground waters resources of the given region without damaging the natural resources conditions.

The obtained results can be used as an example of an optimization problem solution in the optimization operation and research hydrogeological works during the reassessment of underground water reserves, the organization of environmental protection measures and other studies where the analysis and interpretation of a significant amount of primary data with a low degree of probability is required.

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