Groundwater movement simulation by the software package PM5 for the Sviyaga river adjoining territory in the Republic of Tatarstan

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Abstract. Data of the ecological-hydrogeological fieldwork at the Predvolzhye region of the Republic of Tatarstan were analyzed. A geofiltration model of the Buinsk region area near the village of Stary Studenets in the territory of the Republic of Tatarstan was constructed by the PM5 software package. The model can be developed to become the basis for estimation of the groundwater reserves of the territory, modeling the operation of water intake wells, designing the location of water intake wells, and evaluation of their operational capabilities, and constructing sanitary protection zones.

1. Introduction
Mathematical modeling of groundwater filtration is used in calculation of operational water resources, estimation of geofiltration parameters, development of the hydrodynamic model of the operational aquifer, in calculation and justification the boundaries of sanitary protection zones, and also in creation of the forecast of the influence of landscapes on groundwater formation and vice versa [1].

PM5 is a software package, designed for modeling the non-stationary spatial geofiltration of groundwater [2]. Its main component is the ModFlow program for constructing hydrodynamic models of various complexity levels, developed in the US Geological Survey. The PM5 software package and its components are used all over the world to model the reserves and movement of groundwater, as well as the migration of contaminants in addressing the depletion of fresh water supplies, the organization of irrigation in agriculture, and the protection of freshwater from pollution [2-9].

The main problem in the modeling of groundwater filtration is the insufficient hydrogeological study of the territories. This problem is observed both in global models and in regional scale models. The lack of data explains the infrequent analysis of geofiltration processes in hydrogeological models [1].

The purpose of this paper is to analyze and process the ecological-hydrogeological fieldwork data of the Buinsk district near the village of Stary Studenets on the territory of the Republic of Tatarstan and to construct a geofiltration model of the selected territory using the PM5 software package.

2. The problem statement
The territory under the study is located between the rivers: the Karla River in the north, the Sviyaga River in the east and the Chilcha River in the south. The western boundary of the territory is the watershed in the relief. The area under the study is approximately 323 km².
Orographically, the selected plot of land is located in the northern part of the Volga Upland. The region has a calm, smooth relief and represents an almost flat lowland (“Buinsky steppes”), dissected by shallow but wide valleys of the left tributaries of the Sviyaga River.

The territory of investigation is located in the zone of a complex geological structure. There is a great variety and variability in the structural-tectonic plan, as well as in the lithologic-facies composition of the water-bearing layers. Underground waters occur in deposits of a wide stratigraphic range. When considering the hydrogeological formation, it is possible to single out a multi-layer system in which alternating permeable and weakly permeable layers are observed. In general, the rock strata in the study area consist of Neogene, Upper Jurassic, Upper Tatar sediments, the Kazan series, Lower Permian (Asselian) sediments. For water supply, the underground waters of the Urzhum and Kazan deposits are mostly often used. The peculiarity of the geological structure of the selected territory is that about half of the area is occupied by the old channel of the Sviyaga River. It is very deep and entirely composed of very good water-conducting rocks. In the rest (western) part of the modeling area, on the contrary, poorly permeable and less abundant rocks with thin (about 1 m thick) aquiferous layers approach the earth's surface.

3. Material and methods
In the selected territory there are 67 engineering-geological and hydro-geological wells and 4 water-intake wells.

The schematization of the hydrogeological conditions of the territory under investigation was carried out mainly on the basis of an analysis of the fund materials for the project "Conducting an ecological-hydrogeological survey of the scale 1:200000 sheets N-38-VI, XII, XVIII, N-39-VII, VIII Predvolzhye, XIII.". Provided by LLC "Scientific and Production Center for Ecological, Geological and Geodetic Research" (Kazan).

To build a numerical geofiltration model, the PM5 software package was implemented. The package is designed to solve stationary and non-stationary problems in conditions of non-pressure, pressure-non-pressure and pressure filtration modes. The software package is represented by the main module and connected to additional tools that can simulate various objects – rivers, wells, drains; boundary conditions of any kind; infiltration recharge and evaporation.

PM5 is a free program created on the basis of ModFlow 2000 [2]. PM5 also includes other components. The model of the geofiltration realized by the ModFlow program in the PM5 structure is based on the equation of the mass balance of the fluid in terms of heads [10, 11]:

$$\frac{\partial}{\partial x} k_x \frac{\partial H}{\partial x} + \frac{\partial}{\partial y} k_y \frac{\partial H}{\partial y} + \frac{\partial}{\partial z} k_z \frac{\partial H}{\partial z} = \eta \frac{\partial H}{\partial t} - \epsilon,$$

where $k_x$, $k_y$, $k_z$ are the hydraulic conductivity coefficients in the directions of the corresponding coordinate axes, $\epsilon$ is the density of external sources; $\eta$ is the specific storage coefficient; $H$ means head.

The PM5 package contains a finite-difference approximation of the differential problem that bases on the equation mentioned above. The calculation is carried out by an iterative method.

To construct the model of the selected area of the Republic of Tatarstan, a rectangular fragment was selected. It is 27.8 km long from west to east, and 24.3 km from north to south. The simulated area was covered with a regular rectangular grid with the cell size of 100 m x 100 m. The calculation domain was identified by setting approximate boundaries of the territory using the topographical base (figure 1). The position of the wells in the calculation area was marked according to their coordinates.
Aquifers and water-resistant horizons were combined into three layers of the aquifer complex. For the entire study area, the markings of the top and the bottom of each computational layer were obtained by interpolation with the assignment of interpolation nodes along the contour isolines and the water level values in the rivers, and as well as according to the register of wells from the fund materials (figures 2-5).

Values of the head were set in the calculation cells in concordance with the water level in the rivers. Head values vary within the following limits: the Sviyaga River – 65.3-70.4 m, the Karla River – 65.3-167 m, the Chilcha River – 70.4-173 m. The water cuts were taken from the topographic base. The values of the water level in each calculation cell were determined between the marks of water cuts by the method of linear interpolation.

The values of the hydraulic conductivity coefficients were determined on the basis of expert estimates, depending on the composition of the aquifer. The porous medium was assumed to be inhomogeneous, isotropic.
4. Results and discussion
To restore the natural regime on the interfluve, a stationary problem was solved. After specifying all the necessary parameters, calculations were made by the conjugate gradient method. The results were obtained as maps of hydroisogypsum and piezoisogypsum (figures 6-8). The head values do not exceed the absolute relief marks at each point of the simulated area, which is the first sign of the correctness of the solution obtained. Higher head values correspond to higher elevation marks.

A geofiltration model of the Buinsk region area near the village of Stary Studenets in the territory of the Republic of Tatarstan was built. The model can be developed to become the basis for estimation of the groundwater reserves of the territory, modeling the operation of water intake wells, designing the location of water intake wells, estimation of their operational capabilities, and constructing sanitary protection zones.

Figure 4. Bottom of the 2nd layer (Top of the 3rd layer).

Figure 5. Bottom of the 3rd layer.

The data on mean total annual precipitation were taken at the Geoportal "River basins of European Russia" [12]. Precipitation is 454 mm/year. Infiltration recharge is 20% of this value for well-permeable rocks: $1.86 \times 10^{-4}$ m/day.

Figure 6. Hydroisogyps map for the first computational layer.

Figure 7. The piezoisogyps map for the second computational layer.
Figure 8. The piezoisogyps map for the third computational layer.

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