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Method of Processing Data to Test for Underground Water Inflow in Layered Strata Using Simulation and Analytical Solutions

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Abstract—This article is concerned with processing of data in testing for groundwater inflow at the Imeretinsky lowland, the area where construction of the Olympic infrastructure for Sochi-2014 is planned. Under the complex hydrogeological conditions of this territory caused by the layered (anisotropic) structure of the stratum and a free-flow filtration regime, interpretation of pumping tests from imperfect wells gives rise to some difficulties related to the ambiguousness of identification of an analytical model. For interpretation, an entire spectrum of methods, including hydrodynamic modeling and analytical calculation, were used.

Key words: Pumping test, modeling, filtration, anisotropy, analytical model, filtration coefficient, vertical heterogeneity.

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In order to develop a reliable drainage system in the territory of the Imeretinsky lowland, where construction of the Olympic infrastructure for Sochi-2014 is planned, it is necessary to develop an adequate hydrodynamic model. For this, first of all, it is necessary to determine reliable calculated parameters.

In geological and hydrogeological contexts, the lowland territory is rather complex, which is associated with the clearly manifested heterogeneity of filtration in plan and geological sections.

The water-saturated stratum is represented by marine sediments, which are widespread in the coastal part of the Black Sea, in the interfluve area between the Mzymta and Psou rivers. The stratum consists of gravel–pebble sediments with sand-filling material, sand interlayers, shell limestones, and inundation clays. The stratum is represented by layers of Nimfeisky ($mQ_{IV}^{3}nf$), New Black Sea ($mQ_{IV}^{3}n\check{c}$), Middle Black Sea ($mQ_{IV}^{2}s\check{c}$), and Old Black Sea (mQ_{IV}^{1} Holocene layers. The thickness of layers in the Imeretinsky lowland reaches 60–75 m. The specific capacity of the wells tapping the underground waters vary within a wide range from 0.1 to 32–80 l/(s m).

In different periods, about 200 pumping tests were conducted in the area of the Imeretinsky lowland, predominantly from individual wells characterized by a great level of imperfection with regard to reservoir penetration degree and by partial penetration. To determine the appropriateness of using all this data, series of cluster pumping tests with aquifer piezometers were performed. Later, the results were considered as etalons, which could make it possible to evaluate the degree of reliability of parameters determined in a well.

Under complex hydrogeological conditions, interpretation of the pumping tests from imperfect wells gives rise to several difficulties connected with the complexity of identification of an analytical model [Borevsky et al., 1983; Mironenko and Shestakov, 1973]. This can be due to the layered (anisotropic) structure of the stratum and free-flow filtration regime, represented by three characteristic time periods of the lowland formation. The time period of the elastic regime is short and it rarely exceeds a few hours. The period of the false stationary regime is characterized by a decrease in the rate of the water level variation or stabilization of the water level. During the period of the gravitational regime, further intensification of the decrease of the underground water level takes place.

During hydrogeological research, the method of analytic calculations for every period was used. However, for justification of these calculations, it is necessary to carry out preliminary analysis of pumping tests. This can be performed, in the best way, only by mathematical simulation [Mironenko and Shestakov, 1973]. For this purpose, the testing cluster must be equipped with a number of proper observation wells to avoid ambiguous interpretation of the results.

Some cluster pumping tests were carried out within two intervals of the section. From the bottom to the top, the lower and upper parts of the section were sampled. At the same time, a decrease of the water level within all intervals was observed, which makes it possible to obtain information about the vertical permeability of the aquifer.

In total, six pumping tests were conducted. For every test, modeling was performed, such that the output in the observation wells during every test at the given parameters corresponded to the actual situation.

A detailed analysis of graphs of time correlation and their primary processing was carried out, which was used later for the modeling.

The main task of the modeling was the choice of values of the horizontal and vertical filtration coefficients (k_x and k_z) and the values of storativity and specific yield, wherein the difference between natural (observed during a pumping test) and model values of the water decrease in the wells of a cluster was of a minimal value. The achievement of a high level of consistency between actual and model values of the water level decreases allowed us to assume that the model parameters (the best correlation) are reliable and can be considered as etalons by comparison with the data obtained in individual wells.

For the modeling, we developed three-dimensional models where the section included ten 5 m-thick aquaifers and an upper 2.5 m-thick covering layer.

Because of the radial symmetry of the model, only the sector with an angle of 90° was considered. The grid arrangement was irregular, so the observation wells (test points) were located in the centres of blocks. The central wells in the modeling were drilled in the block with coordinates of 1 : 1 with a Newmann's boundary condition (Q = const). The flow rate (Q) in the modeling was given as equal to 1 : 4 of the actual rate in a pumping test.

Every aquifer was characterized by the transmissivity $T_x = K_x m$ and the leakage coefficient $\beta = m/k_z$ (vertical transmissivity $T_z = 1/\beta$), where m is the thickness of a layer. During the modeling, the values of storativity and specific yield S_s were also selected.

During the modeling, an unsteady-state flow for 12–25 time intervals with a time step from 1–5 minutes at the start of a pumping test to 100 minutes and more at the final intervals was considered.

Figure 1 shows the scheme of clusters and values of k_x and k_z, obtained as the result of modeling.

In all clusters, the data on actual and model decreases of the water level show a high level of correlation; the value of the correlation coefficient is no less than 0.95, which testifies to the high quality of the solutions and their reliability.

As an example, the graphs (Fig. 2) present the variation of actual and model levels in the cluster for the lower and the upper parts of the sampled section.

During the *second stage of research*, the "level" pumping tests were processed using analytical dependences [Sindalovsky, 2006; Shestakov, 1995 and 1955] with the analysis of correspondence between the results obtained and the modeling data. Finally, this made it possible to determine acceptable analytical schemes and dependences for processing the pumping tests made in one interval.

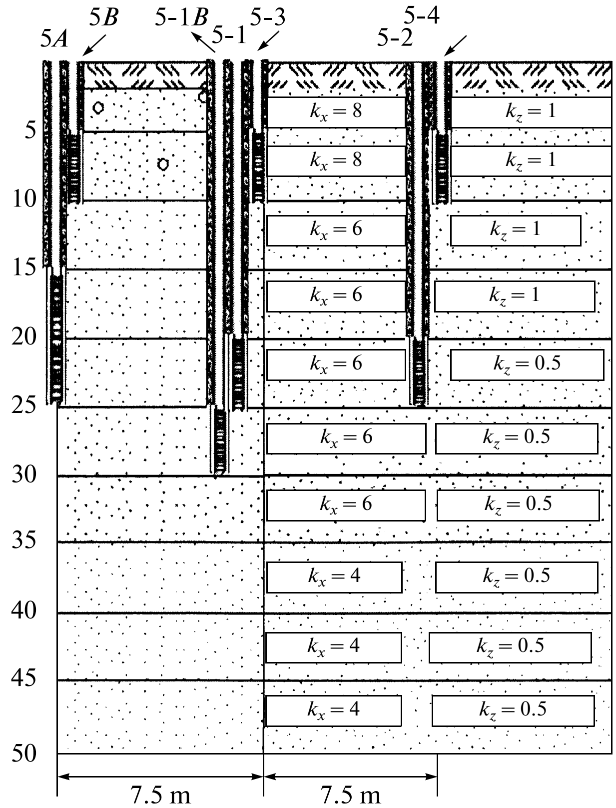

Fig. 1. Values of filtration coefficient (cm/day) of a stratum k_x and k_s calculated based of the results of simulating cluster pumping tests.

First, filtration coefficients were calculated from the results of testing for underground water inflow in the "level" clusters, taking the anisotropy of the medium into account.

According to the calculation of the anisotropy coefficient based on data of cluster interval pumping tests $\chi = \sqrt{k_z/k_x}$ it is supposed that the decrease in observation well 1, located at a distance of r_1 from the central well, with a filter at the same depth as in the central well, is described by the formula (1):

$$S_1 = \frac{Q}{2\pi K_x l_c} 2\operatorname{arcsinh}\frac{0.5l_c}{r_1\chi}. \quad (1)$$

The decrease in the observation well 1, located at a distance from the central well, with a filter in the lower part of the section (Fig. 3) is described by formula (2):

$$S_1' = \frac{Q}{4\pi K_x l_c}\left[\operatorname{arcsinh}\frac{0.5l_c - z}{r_1\chi} + \operatorname{arcsin}\frac{0.5l_c + z}{r_1\chi}\right]. \quad (2)$$

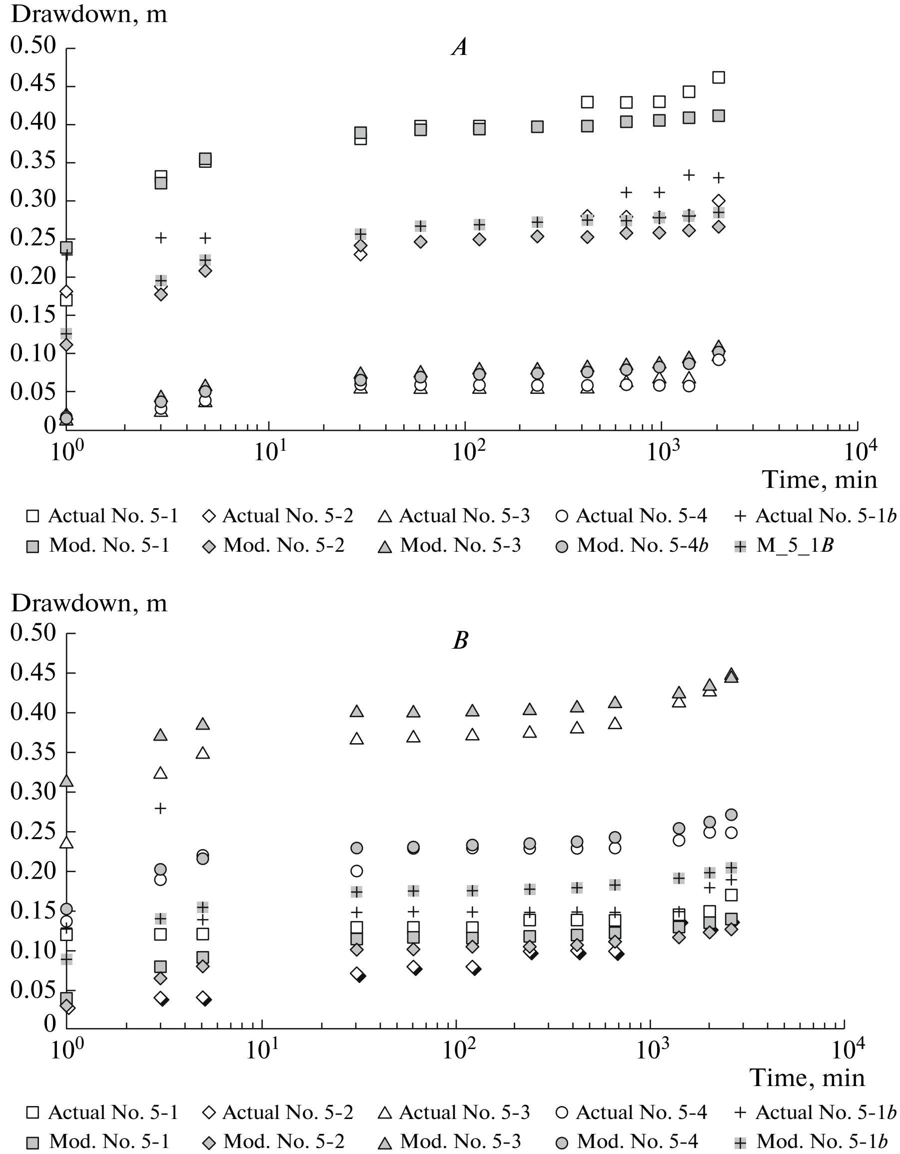

Fig. 2. Comparison between model and actual decreases in wells of the cluster 5M (*A*, from well 5A with a discharge of 172.8l/c; *B*, from well 5B with a discharge of 198.8l/c).

The relationship between the decreases in these wells is described by formula (3):

$$\frac{S_1}{S_1'} = \frac{2\operatorname{arcsinh}\dfrac{0.5l_c}{r_1\chi}}{\operatorname{arcsinh}\dfrac{0.5l_c - z}{r_1\chi} + \operatorname{arcsinh}\dfrac{0.5l_c + z}{r_1\chi}}, \qquad (3)$$

For the anisotropy coefficient $\chi = \sqrt{k_z/k_x}$, one can choose values such that the calculated relationship S_1/S_1' is equal to the actual ratio of the decreases.

For calculations, the decreases were determined for the period of the pseudo-state flow. The results of calculation of the anisotropy coefficient in the clusters for different pairs of wells showed that x values vary within a wide range from 0.2 to 0.9, which testifies to the strong heterogeneity of the water-bearing stratum. The results of x calculation were found to be similar to the results of the modeling. In Table 1, the results of calculations in three clusters are presented.

As was mentioned above, in the territory of the investigations more than 200 pumping tests were conducted, including cluster tests. As a rule, the cluster pumping tests were performed according to the scheme where the filters of the central and observation wells were located in the same interval of the section. Accordingly, for purposeful use of these data for the parameterization of a model it is important to determine how they correlate with values of the horizontal filtration coefficient obtained during processing the data of level pumping tests.

Thus, the *following step of the second stage* (the stage of analytical calculations) was to show the possibility of using the data obtained from calculation of the filtration coefficient in a horizontal direction (k_x) with analytical solutions. In addition, in a complex layered stratum it is always unclear which boundary conditions should be taken into account during the processing of the pumping test results, especially from the pumping tests conducted in a free-flow aquifer. So, different schemes with different boundary conditions were used in calculations and then the results were compared.

For the period of pseudo-steady-state flow, the calculations were performed according to equations presented in Table 2. The symbols in the formulas are as follows:

Q—discharge of well;

t—time from the start of a pumping test;

S_i—drawdown in i well;

r—distance from an observation well;

r_c—the radius of a filter in the central well;

l_c—length of a filter in the central well;

m—thickness of an aquifer;

l_0—penetration of the upper part of the filter in the central well relative to the top of the aquifer or free surface;

l_z—distance from the lower part of the filter in the central well to the base of the aquifer;

z—distance between centers of the observation and central wells (along the vertical);

k—filtration coefficient calculated in the central well;

k_i—filtration coefficient calculated in the observation well;

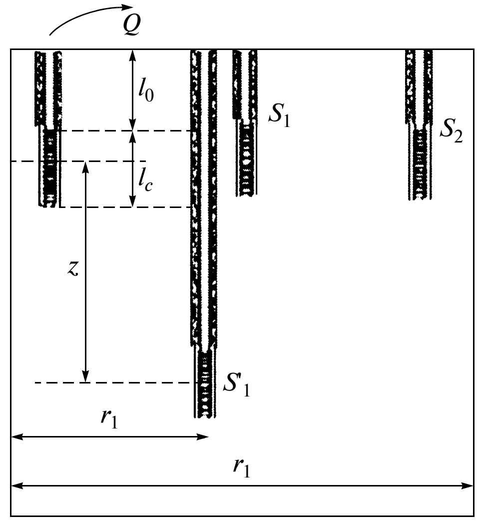

Fig. 3. Scheme for calculation of anisotropy coefficient $x = \sqrt{\frac{k_z}{k_x}}$.

The results of the analytical calculations at the modeling without taking the anisotropy into account and for the 5M cluster are given in Table 3.

Analysis of the calculation results shows that the filtration coefficient values calculated in the central well do not depend substantially on the type of the boundary conditions and the type of source (imperfectness of the well regarding penetration into the aquifer). The calculation based on formulas (4), (6), (8), (10), (12), and (14) (the formulas for the central wells) gives the same values of k_x.

It is noteworthy that k_x values calculated in the central and observation wells of the same cluster are, as a rule, slightly different. This testifies to the rather good quality of the central wells and a weak skin-effect (low

Table 1. Results of calculations of the filtration coefficient k_x with account for vertical anisotropy

Index of cluster	9M				8M				5M			
Index of central well	9-A		9-B		8A		8B		5A		5B	
Index of observation wells	9-1	9-2	9-3	9-4	8-1	8-2	8-3	8-4	5-1	5-2	5-3	5-4
Q (discharge of pumping test, m^3/day)	976		216		778		130		173		199	
S_{cent} (drawdown in the central well)	6.1	6.1	5.0	5.0	5.5	5.5	4.12	4.12	4.37	4.37	5.7	5.7
S_{obs} (drawdown in observation wells)	0.53	0.29	0.2	0.15	0.75	0.53	0.23	0.2	0.45	0.28	0.4	0.27
r_j (distance from the central well)	5	10	5	10	2	4	2	4	7.5	15	7.5	15.1
l_c (length of the filter in the central well)	3.5				3.5		3		11		3.7	
l_0 (penetration of the upper part of the filter in the central well, with regard to the top)	26.5		4.9		26.5		6		16.3		5.8	
χ	0.65				0.4				0.2			
$k_x = \frac{Q}{2\pi(S_1-S_2)l_c}\left[\operatorname{arcsinh}\frac{0.5l_c}{r_1\chi} - \operatorname{arcsinh}\frac{0.5l_c}{r_2\chi}\right]$	21		22		27		34		1		2	
Model values	30		24		24		12		6		8	

Table 2. Formulas for calculating the filtration coefficient based on the results of pumping tests

Type of boundary conditions		Formula	Index of formula
Non-limited medium	Point source	$k_i = \frac{Q}{2\pi S_{\text{cent}} l_c} \ln \frac{0.7 l_c}{r_c}$	4
		$k_i = \frac{Q}{4\pi S_i \sqrt{r_i^2 + z^2}}$	5
Filter in the central well under no-flow boundary		$k = \frac{Q}{4\pi S_{\text{cent}} l_c}\left(2\ln\frac{0.7 l_c}{r_c} + \frac{l_c}{2l_0 + l_c}\right)$	6
		$k = \frac{Q}{4\pi S_{\text{obs}}}\left(\frac{1}{\sqrt{r_i^2 + z^2}} + \frac{1}{\sqrt{r_i^2 + (2l_0 \pm z)^2}}\right)$	7
Filter in the central well under specified-head boundary		$k_i = \frac{Q}{4\pi S_{\text{cent}} l_c}\left(2\ln\frac{0.7 l_c}{r_c} - \frac{l_c}{2l_0 + l_c}\right)$	8
		$k_i = \frac{Q}{4\pi S_{\text{obs}}}\left(\frac{1}{\sqrt{r_i^2 + z^2}} - \frac{1}{\sqrt{r_i^2 + (2l_0 \pm z)^2}}\right)$	9
Non-limited medium	Linear source	$k_i = \frac{Q}{2\pi S_{\text{cent}} l_c} \ln \frac{0.7 l_c}{r_c}$	10
		$k_i = \frac{Q}{4\pi S_{\text{obs}} l_c}\left[\text{arcsinh}\frac{0.5 l_c - z}{r_i} + \text{arcsinh}\frac{0.5 l_c + z}{r_i}\right]$	11
Filter in the central well under no-flow boundary		$k = \frac{Q}{4\pi S_{\text{cent}} l_c}\left(2\ln\frac{0.7 L_c}{r_c} + \frac{l_c}{2l_0 + l_c}\right)$	12
		$k_i = \frac{Q}{4\pi S_{\text{obs}} l_c}\left[\text{arcsinh}\frac{0.5 l_c - z}{r_i} + \text{arcsinh}\frac{0.5 l_c + z}{r_i} - \text{arcsinh}\frac{2l_0 + 0.5 l_c - z}{r_i} + \text{arcsinh}\frac{2l_0 + 1.5 l_c - z}{r_i}\right]$	13
Filter in the central well under specified-head boundary		$k = \frac{Q}{4\pi S_{\text{cent}} l_c}\left(2\ln\frac{0.7 L_c}{r_c} - \frac{l_c}{2l_0 + l_c}\right)$	14
		$k_i = \frac{Q}{4\pi S_{\text{obs}} l_c}\left[\text{arcsinh}\frac{0.5 l_c - z}{r_i} + \text{arcsinh}\frac{0.5 l_c + z}{r_i} + \text{arcsinh}\frac{2l_0 + 0.5 l_c - z}{r_i} - \text{arcsinh}\frac{2l_0 + 1.5 l_c - z}{r_i}\right]$	15

colmatation of the near-well zone of the central wells). Thus, we have reliable information from the observation wells and from the central wells.

The relatively high reproducibility of the calculation results allows us to state that the most reliable values of the horizontal filtration coefficient were found in the observation wells located close to the central ones. These observation wells are equipped with filters at the same interval as in the central well. The boundary conditions are as follows: the boundary with permanent pressure or the no-flow boundary (at the top or bottom) do not significantly influence the calculated values of the filtration coefficient.

The calculation of the filtration coefficient in the central wells of the clusters, as a rule, gives generally low values, which may be caused by the skin effect

Table 3. Comparison between model and calculated filtration coefficients in the cluster of wells

Index of central well		5A						5B					
Index of observation well		5-B	5-1	5-2	5-3	5-4	5-1b	5-A	5-1	5-2	5-3	5-4	5-1b
r_i		2.0	7.5	15.0	7.8	15.1	7.8	2.0	7.8	15.0	7.5	15.1	8.5
l_c		11.0						3.7					
z		15.0	0.0	0.0	15.0	15.0	20.0	15.0	15.0	15.0	0.0	0.0	20.0
l_0		16.3						5.8					
K_{FC} value													
Model		8.0						6.0					
Analytical													
Index of formula	4, 6, 8, 10, 12, 14	3						6					
	5	8	4	3	7	7	5	6	6	4	5	4	4
	7	10	8	7	15	15	7	9	10	7	8	7	6
	9	5	12	2	5	5	3	2	2	1	2	1	1
	11	8	4	3	8	8	5	6	6	4	5	4	4
	13	12	4	4	12	12	8	23	20	9	8	7	12
	15	4	3	2	3	3	2						

(presence of colmatation in the near-well area), as well as by the vertical anisotropy of a layer.

The vertical anisotropy significantly influences the values of the calculated filtration coefficient, which is manifested in its decrease. The calculated filtration coefficient based on a pair of observation wells with anisotropy considered is 1.5 times less then without considering the anisotropy. Accordingly, this fact should be weighed during the choice of the calculated parameter k_x.

Thus, when choosing the calculated parameters to develop the model it is necessary, first, to use the results of modeling the pumping test clusters, and second, to use the results of analytical calculations based on a pair of nearly observation wells that are equipped in the same interval as the central well. The results, based on individual pumping tests can be used only in wells of perfect quality, which, under the given conditions, are established based on of the discharge value. The discharge in these wells must be 5 l/s at a minimum. It follows that in a layered stratum the sum conductivity can be evaluated individual pumping tests.

From the data set a frequency curve of the filtration coefficient was constructed for all testing of underground water inflow (Fig. 4).

As follows from these data, more than 20% of the wells have relatively high values of their discharge and filtration coefficients. These data can be used for determination of the total conductivity of strata. At the same time, we consider conditionally that the low values from this data set are characteristic of layers with clay filling material.

In order to consider a layered strata as an anisotropic one, let us consider a section with thickness M_{sum} consisting of n different alternating layers with a uniform thickness m ($m_{sum} = nm$) and the "isotropic" filtration coefficient k_i. According to well-known dependences, the total conductivity of this layer is calculated from the formula:

$$T = m\sum_{i=1}^{n} k_i. \quad (4)$$

Accordingly, vertical conductivity A_0 is calculated from the following formula:

$$A_0 = \frac{1}{m\sum_{i=1}^{n}\frac{1}{k_i}}. \quad (5)$$

The average anisotropy coefficient is calculated from the combination of formulas (4) and (5) sup-

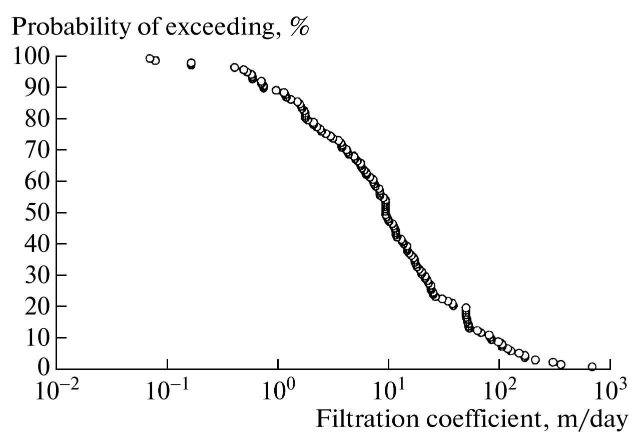

Fig. 4. Frequency curve of filtration coefficients for the dataset on individual pumping tests.

Table 4. Results of determination of weight-average filtration coefficients in Holocene marine sediments

Geological index	$mQ_{IV}nf$	$mQ_{IV}nc$	$mQ_{IV}sc$ and $mQ_{IV}dc$
Number of determinations	31	17	39
k_x, m/day	30	15	25
χ	0.2	0.4	0.4
k_z, m/day	1.2	1.4	4

posing that an equally probable combination of every layer in the cross-section is possible.

$$\chi = m_{\text{sum}}\sqrt{\frac{A_0}{T}} = n\sqrt{\frac{1}{\sum_{i=1}^{n} k_i \sum_{i=1}^{n} \frac{1}{k_i}}}. \quad (6)$$

Since, as a rule, the length of the well filters where the samples were collected is rarely more then 5 m at a total thickness of 80–100m, one can suppose that the horizontal filtration coefficient was determined at every sampling for a single layer. Accordingly, with such an approach, the number of layers may equal the number of determinations of the filtration coefficient values.

Thus, during the choice of the calculated parameters for the development of the model, one can accept the average values calculated for the whole dataset, including the data from pumping test clusters. The results of the determination of parameters are listed in Table 4.

CONCLUSIONS

1. The water-bearing stratum is characterized by a high level of filtration heterogeneity in plan view and section, which may be caused by a variable lithological composition of the rocks and filling material.

2. For calculation of reliable values of the filtration parameters of the medium, it would be more reasonable to use the mathematical simulation of the "level" pumping tests with arrangement of filters in the observation wells at all intervals of the stratum studied. It seems possible to calculate filtration coefficients from the results of cluster tests of underground water inflow using the analytical dependences. For this purpose, careful testing of the analytical scheme will be necessary.

3. For justification of the calculated parameters chosen for the modeling, one can use the results from the whole dataset of filtration coefficients. In this case, the total conductivity can be determined in individual wells with high discharge.

4. It is possible that the values of filtration coefficients given in this work and based on the results of modeling and the analytical solutions are approximate. This fact needs to be analyzed thoroughly during the data choice for parameterization of regional models.

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