A SIMPLIFIED APPROACH BASED ON MATHEMATICAL MODELLING FOR THE PRELIMINARY ASSESSMENT OF GROUNDWATER INFLOW TO EXCAVATIONS AT A CONSTRUCTION SITE

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ABSTRACT. A simplified approach is proposed for the preliminary assessment of the possible groundwater inflow to the excavations during underground construction in relatively complex and insufficiently-studied hydrogeological conditions. The approach includes the development of a three-dimensional non-stationary numerical model of the hydrodynamic field in the construction site area, taking into account the excavation geometric characteristics, the effect of in-ground cut-off barriers (slurry walls), and the schedule and mode of operation of the dewatering facilities. The preliminary assessment is obtained after several variants are computed, based on the main model and with different permeability characteristics for the insufficiently-studied low-rank hydrogeological units composing the impacted aquifer. The three-dimensional numerical model and its variations are developed using the Modflow software. The proposed simplified approach is illustrated by the preliminary assessment of the possible groundwater inflow during the construction of station MS9 of the third metro diameter (Line M3) of Sofia Metro.

Keywords: groundwater, hydrogeological numerical models, dewatering excavations at a construction site, Sofia Metro.

ОПРОСТЕН ПОДХОД ЗА ПРЕДВАРИТЕЛНА ОЦЕНКА НА ПОДЗЕМНИЯ ВОДОПРИТОК КЪМ СТРОИТЕЛНИ ИЗКОПИ ПОСРЕДСТВОМ МАТЕМАТИЧЕСКО МОДЕЛИРАНЕ

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РЕЗЮМЕ. Предложен е опростен подход за предварителна оценка на възможния приток на подземни води към строителени изкопи при изграждане на подземни съоръжения в относително сложни и слабопроучени хидрогеоложни условия. Подходът включва разработване на тримерен числен нестационарен модел на филтрационното поле в района на строителния изкоп при отчитане на геометричните характеристики на изкопа, действието на противофилтрационните съоръжения (шлицови стени) и работния график за понижаване на подземните води по време на строителните работи. Предварителната оценка се прави, като на базата на основния модел се проиграват няколко варианта при различна водопропускливост на по-слабо проучените ниско рангови хидрогеоложки единици от състава на засегнатия водоносен комплекс. Тримерният числен модел и неговите варианти са разработени с компютърна програма Modflow. Предложеният опростен подход е илюстриран с направената предварителна оценка на възможния водоприток при строителството на метростанция МС9 от трети метродиаметър на Софийското метро.

Ключови думи: подземни води, хидрогеоложки числени модели, отводняване на строителни изкопи, Софийско метро.

Introduction

Shallow groundwater causes major problems during the construction of tunnels, metro stations, buildings supported on deep foundations, and many other underground facilities (Ivanov and Mihova, 2003; Boukhemacha et al., 2015; Attard et al., 2016; De Caro et al., 2020). In order to solve these, various methods and techniques are applied in engineering practice to limit the groundwater inflow and lower the water level in the excavations during underground construction (Powers et al., 2007; Ivanov, 2013; Liu et al., 2019; Cashman and Preene, 2020).

The choice of the in-ground cut-off barriers and the design of the optimal drainage system for a specific construction site are based on the results of the hydrogeological survey performed in the area. The main task of this study is to achieve a quantitative assessment of the groundwater inflow to the excavations and the possible deformations of the hydrodynamic field caused by the dewatering activities. The unambiguous solution of this problem is not always possible, most often due to the high heterogeneity of the near-surface section and the unclear hydraulic connections between its constituent low-rank hydrogeological units and/or nearby rivers and surface water bodies (Ivanov, 2007). The clarification of these issues in detail is generally expensive and time-consuming and is not always reasonable taking into account the effectiveness of the achieved result.

The proposed simplified approach for the assessment of groundwater inflow to the excavations uses three-dimensional numerical models and is applicable for construction sites characterised by relatively complex and insufficiently-studied hydrogeological conditions. It uses general data on the spatial boundaries of the low-rank units and on the possible range of their hydrogeological parameters, as well as calculation schemes with variation of these parameters. Data on the excavations geometric characteristics, the design of in-ground cut-off barriers, and the schedule of construction activities are also used. The obtained results for the expected groundwater inflow, though derived after applying a probabilistic analysis, can be utilised in order to assess the effectiveness of in-ground cut-off barriers and to design an optimal drainage system. They give an idea on the local redistribution of the hydraulic heads, gradients, and velocities near the excavations, as well as on the size of the regional piezometric depression in the affected aquifers.

This simplified approach is the result of more than twenty years of experience of ours in solving various problems related to the dewatering of natural terrains and excavations at construction and mining sites in a variety of hydrogeological and technological conditions (Stoyanov, 2006, 2011, 2014a, 2014b, 2019; Stoyanov and Lakov, 2009; Stoyanov et al., 2016a; Stoyanov et al., 2016b; Stoyanov and Dimovski, 2020). In recent years, it has been used as a tool for assessment and prognostication in different stages of the construction of Sofia Metro (Stoyanov, 2011, 2019; Stoyanov et al., 2016a; Stoyanov and Dimovski, 2020). In this article, the proposed simplified approach is illustrated by the performed preliminary assessment of the possible groundwater inflow during the construction of station MS9 of the third metro diameter (Line M3) of Sofia Metro (Figure 1).

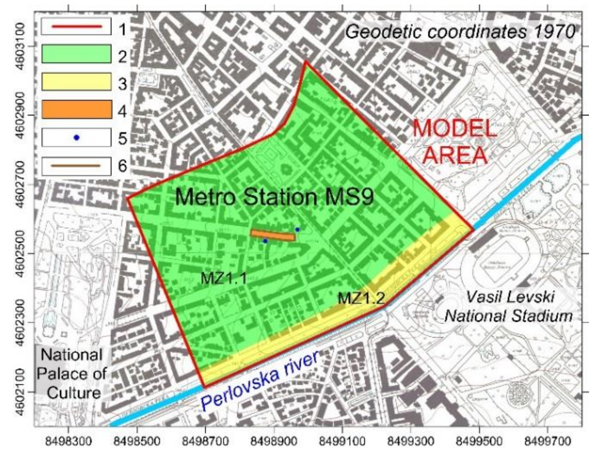

Fig. 1. Location of the studied construction site.
1 – Boundaries of the model area; 2 – Model zone MZ1.1; 3 – Model zone MZ1.2; 4 – Excavation; 5 – Hydrogeological well (Monitoring point); 6 – Slurry wall.

Conceptual model

When developing the 3D numerical model for estimating the groundwater inflow to the excavations during the construction of metro station MS9, the following general concept for the hydrogeological technological conditions is accepted:

(i) The major hydrogeological unit in the construction site area is the Neogene-Quaternary aquifer. Quaternary alluvial and diluvial deposits comprise its upper part. The alluvial deposits compose layers of clayey sand and gravel, widely represented in the terrace of the Perlovska river that has a thickness of about 10-15 m. The diluvium is represented by alternating layers of clay, dusty clay, sandy clay and clay with occasional gravel inclusions with a total thickness of 3-4 m. The Neogene sediments of the Lozenets Formation build the lower part of the complex. They are represented by alternating layers of clay, sandy clay and sand with a total thickness of over 100 m.

(ii) Four low-rank hydrogeological units (HGU) are differentiated into the Neogene-Quaternary aquifer:

- Upper low-permeability horizon (HGU1). It consists of alluvial and Neogene clay and sandy clay layers established to a depth of 17-18 m below ground surface (down to elevation of 528.5 m).
- *Upper high-permeability horizon (HGU2)*. It is composed of well-washed alluvial gravel and sand having a thickness of about 15 m. It covers a narrow strip in the terrace of the Perlovska river with a width of 50-60 m.
- *Middle high-permeability horizon (HGU3)*. It includes several well-established layers of sand, having a total thickness of 10-12 m, interbedded with thin layers of clay and sandy clay. It is present in the interval from 18 down to 30 m below ground surface, respectively between elevations 528.5 and 516.5 m.
- *Lower low-permeability horizon (HGU4)*. It is represented by Neogene clay, dust clay, sandy clay and clayey sand. It builds the lower part of the studied hydrogeological section and covers the interval from 30 to 45 m below the ground (between elevations 516.5 and 500.0 m).

(iii) The implemented hydraulic conductivity values for each HGU are presented in Table 1. The hydraulic conductivity values for HGU1 and HGU3 are determined by pumping and slug tests, for HGU4 – according to data from grain size analysis (as a weighted average for the lithological varieties found in the section), and for HGU2 – according to reference data (Fetter, 1994; Spitz and Moreno, 1996).

Table 1. *Hydrological and model units. Implemented values for the hydraulic conductivity k.*

Hydrological unit	Model units		k, m/d
	Layer	Zone	
HGU1	ML1	MZ1.1	0.1
HGU2		MZ1.2	7.0
HGU3	ML2		4.5
HGU4	ML3		0.1

(iv) The aquifer in the area of the construction site is confined. The piezometric surface levels are established at a depth between 4.7 and 7.6 m below ground surface.

(v) The hydrogeological units differentiated into the aquifer complex are hydraulically connected. The groundwater flow is in southeast (SE) direction targeted towards the Perlovska river. The average hydraulic gradient is about 0.005.

(vi) The recharge of groundwater is accomplished by precipitation and by groundwater flow coming along the northwest (NW) border of the region. The recharge rate is determined as a function of the average permeability in the near-surface section, the average annual air temperature, and the average annual precipitation (Bredenkamp, 1990). The achieved value is 5E-5 m/d.

(vii) The depth of the excavation at the construction site reaches elevation 525.0 m. During construction, for a period of 18-24 months, the water table in the excavation area has to be lowered and maintained below the elevation of 524.0 m.

(viii) The lateral groundwater inflow to the excavation is limited by a slurry wall that is 28 m deep and 0.8 m wide. It closes the outer contour of the construction site and steps into the clay layers that compose the Lower low-permeability horizon (HGU4). According to the technological characteristics, the hydraulic conductivity value for this facility is not higher than 1E-8 cm/s.

(ix) The assessment of the expected inflow is made for steady-state groundwater flow assuming that the water table in the excavation is below the elevation of 524.0 m.

Methodology

Using the Modflow program (McDonald and Harbaugh, 1988; Anderson et al., 2015; Stoyanov, 2019), a three-dimensional flow model is compiled. It covers part of the Neogene-Quaternary aquifer, having an area of about 0.5 km^2, down to a depth of 45 m. The model is a 3D computer simulation of the specific hydrogeological conditions taking into account the effect of the in-ground cut-off barrier (slurry wall) and the lowered water table in the excavation area that is maintained below the elevation of 524.0 m during the construction of metro station MS9 (Figure 1). The 3D grid frame of this basic model includes 3 layers (ML) and 2 zones (MZ), simulating the spatial boundaries of the low-rank hydrogeological units differentiated into the Neogene-Quaternary aquifer complex and the heterogeneity of the hydrodynamic medium (Table 1). The appropriate software packages are used in order to set different boundary conditions – General Head Boundary, River, Recharge, Horizontal Flow Barrier, and Specified Head.

The regional flow is modelled by simulating the recharge along the northwest (NW) boundary of the model using the General Head Boundary scheme. The Perlovska river is set as a three-dimensional object with the appropriate geometry and hydraulic characteristics of the river flow with the boundary condition River. Values are accepted for the hydraulic heads along the NW border and the river at which the average hydraulic gradient in the model area is 0.005. The recharge from precipitation is set as a constant value in the first model layer using the boundary condition Recharge. The slurry wall is modelled with the boundary condition Horizontal Flow Barrier. The excavation at the construction site is simulated as a surface drainage using boundary condition Specified Head at elevation 524.0 m.

The model is calibrated, taking into account the groundwater levels at two monitoring points and the surface water levels in the Perlovska river, varying the values of the hydraulic conductivity, the recharge from precipitation, and the regional groundwater flow.

Using the calibrated basic model, the following models estimating the water budget and revealing the structure of the flow field have been developed:

(i) Model of the structure of the normal hydrodynamic field – FM1;

(ii) Model for estimating the possible groundwater inflow – FM2;

(iii) Variant models for estimating the probable range of possible groundwater inflow as a function of the hydraulic conductivity in model layer ML3 – FM2v1-6.

The main assumptions accepted in the different models are presented in Table 2. In the first two models (FM1 and FM2), it is presumed that the Lower low-permeability horizon (model layer ML3), into which the slurry wall steps, is homogeneous and characterised by very low permeability having hydraulic conductivity k_{ML3} = 0.1 m/d. In fact, it is highly heterogeneous and has hydraulic conductivity ranging from 0.01 up to 1.0 m/d. Therefore, with variant models FM2v1-6, the prognostication for the possible groundwater inflow is made under the condition that the slurry wall steps into a homogeneous layer with hydraulic conductivity k_{ML3}, which in each variant assumes a different value, respectively 0.01, 0.05, 0.2, 0.3, 0.5 and 1.0 m/d.

Table 2. *Models estimating the water budget and revealing the structure of the flow field*

Model	Main assumptions		
	Slurry wall	Excavation dewatering	k_{ML3}, m/d
FM1	No	No	0.1
FM2	Yes	Yes	0.1
FM2v1-6	Yes	Yes	0.01 – 1.0

Note: k_{ML3} – hydraulic conductivity in model layer ML3

Results and discussion

The structure of the normal hydrodynamic field in the Neogene-Quaternary aquifer complex determined by the FM1 model is illustrated in Figure 2. The prognostications made with the FM2 model for the changes in the structure of the hydrodynamic field, the redistribution of the hydraulic heads around the excavation, and the extent of the regional piezometric depression caused by the dewatering activities are presented in Figure 3, Figure 4, Figure 5, and Figure 6.

The water budget obtained with the FM1 model in normal conditions is given in Table. 3. The changes in the budget elements predicted with the FM2 model and caused by the drainage activities, as well as the value of the possible groundwater inflow determined under these conditions are presented in Table. 4. The functional relationship between the possible groundwater inflow and the hydraulic conductivity of the Lower low-permeability horizon HGU4 (model layer ML3), into which the slurry wall steps, and is illustrated in Figure 7.

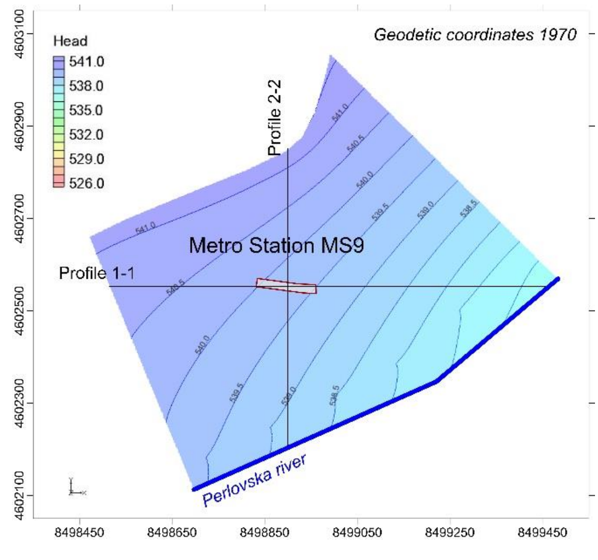

Fig. 2. Model FM1. Structure of the normal hydrodynamic field in the Neogene-Quaternary aquifer complex

Table 3. *Model FM1. Water budget in normal conditions*

Income elements, Q_I^{IN}, L/s	
Recharge along the NW boundary of the model	3.58
Recharge from precipitation	0.47
Total	4.05
Outcome elements, Q_I^{OUT}, L/s	
Drainage across the SE boundary of the model	1.23
Drainage in Perlovska river	2.81
Total	4.04
Budget error 0.02 % (difference)	

The presented results of the performed model studies give reason to make the following summaries and conclusions:

(i) Within the scope of the model area, the natural resources of the Neogene-Quaternary aquifer complex are approximately 4 L/s.

(ii) The groundwater lowering by 16 m in the excavation area is the reason for a very strong deformation in the structure of the hydrodynamic field (Figure 3, Figure 4, Figure 5 and Figure 6). The most pronounced distortions are at the peripheral area of the construction site in a zone having a span of about 60-70 m. The Lower low-permeability horizon (HGU4) at the base of the slurry wall and below the bottom of the excavation is predominantly affected. There, the hydraulic gradients and velocities will be relatively high.

(iii) The results of the composed water budget (Table 4) show that, during the construction activities, when the water table in the area is lowered and maintained below the elevation of 524.0 m (1 m below the excavation's bottom), the expected total groundwater inflow to the excavation is 3.73 L/s. This value is not high and is commensurate with the identified natural resource.

(iv) The solutions obtained with variant models FM2v1-6 show that the range of the possible groundwater inflow is wide – from 0.5 up to 21 L/s (Figure 7). This is logical given the assumption that in the limit variants, the in-ground cut-off barrier (slurry wall) steps either into dense clay or into sand, whose hydraulic conductivity values are 0.01 and 1.0 m/d respectively.

(v) It can be expected that the groundwater inflow will be below 7 L/s, in case the slurry wall steps into a low-permeable base (clay and sandy clay) with hydraulic conductivity not higher than 0.2 m/d (Figure 7). By the way, the available data show similar hydrodynamic characteristics for the Lower low-permeability horizon. If more permeable layers of sand and clayey sand dominate at the bottom of the slurry wall and underneath it (0.2 < k < 1 m/d), the expected groundwater inflow will be much higher – around and above 10-15 L/s, and it is even possible to reach 21 L/s (Figure 7).

(vi) The high groundwater inflow values (above 10 L/s) are associated with the widening of the general piezometric depression, as well as with bigger (up to several times) decreases of the hydraulic heads, gradients, and velocities, especially at the base of the slurry wall and underneath the bottom of the excavation. These changes significantly increase the risk of uneven subsidence and suffosion.

(vii) The calculations made, using the developed 3D non-stationary numerical model of the hydrodynamic field, show that in the initial moments, during the dewatering of the construction site, the abstracted water quantities will be the largest and the hydraulic gradients and velocities will be many times higher.

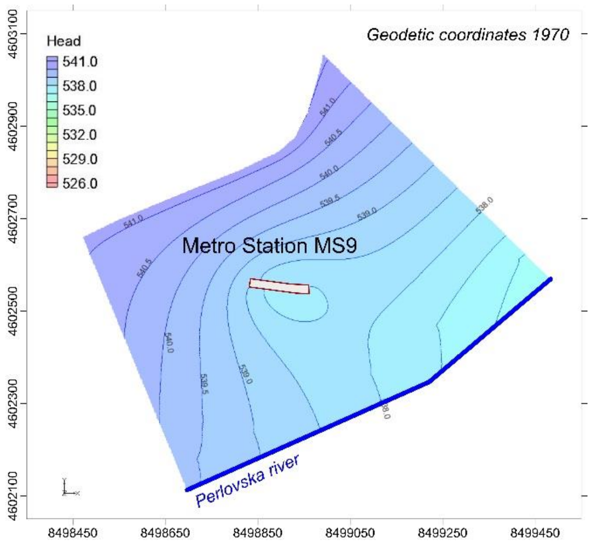

Fig. 3. Model FM2. Structure of the disturbed hydrodynamic field in HGU1 and HGU2 (model layer ML1)

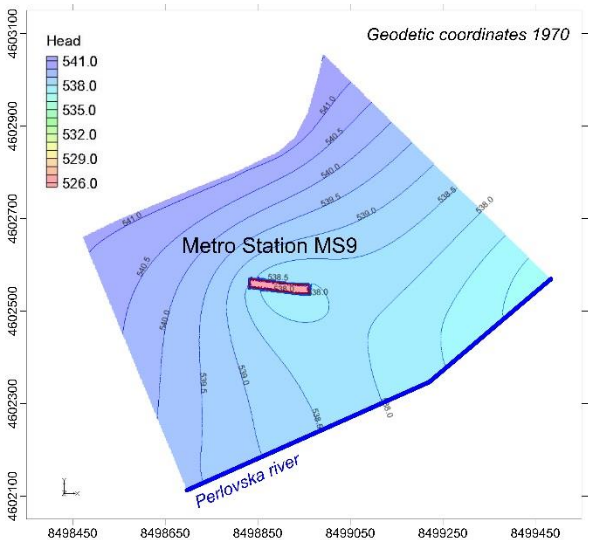

Fig. 4. Model FM2. Structure of the disturbed during the dewatering activities hydrodynamic field in HGU3 (layer ML2)

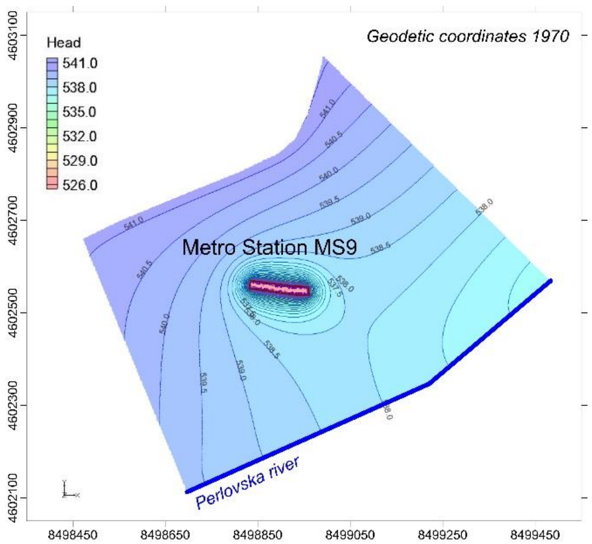

Fig. 5. Model FM2. Structure of the disturbed during the dewatering activities hydrodynamic field in HGU4 (layer ML3)

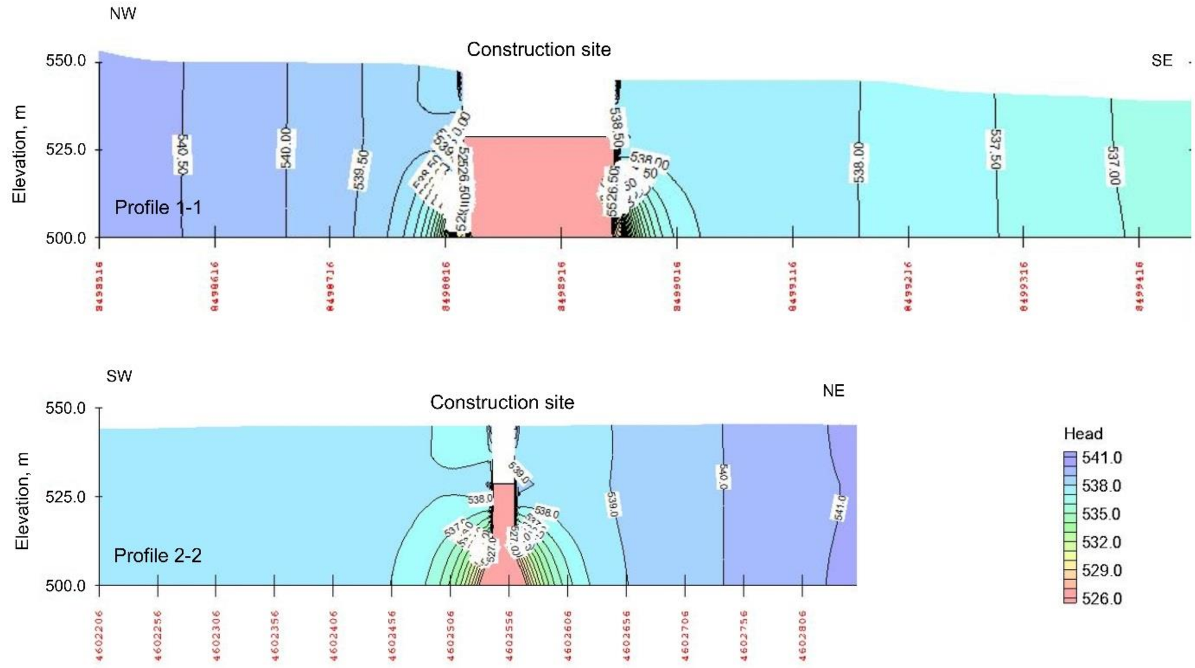

Fig. 6. Model FM2. Structure of the disturbed hydrodynamic field in the Neogene-Quaternary aquifer complex during the dewatering activities. Hydrodynamic sections along Profile 1-1 and Profile 2-2. The location of the profiles is illustrated in Figure. 2.

Table 4. *Model FM2. Water budget during the dewatering activities*

Income elements, Q_I^{IN}, L/s	
Recharge along the NW boundary of the model	5.54
Recharge from precipitation	0.47
Total	6.01
Outcome elements, Q_I^{OUT}, L/s	
Drainage across the SE boundary of the model	0.32
Drainage in Perlovska river	1.95
Groundwater inflow to the excavation	3.73
Total	6.00
Budget error 0.33 % (difference)	

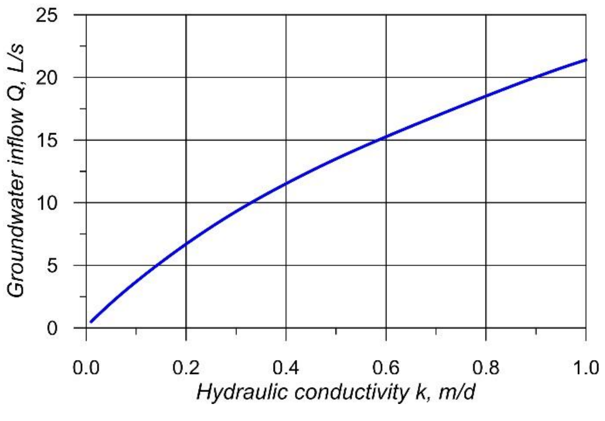

Fig. 7. Model FM2v1-6. Groundwater inflow to the excavation as a function of the hydraulic conductivity in model layer ML3

Conclusions

The accomplished preliminary assessments show that the range of the possible groundwater inflow is wide – from 0.5 up to 21 L/s, depending on the hydrodynamic characteristics of the layer at the base of the slurry wall and below the bottom of the excavation. If this layer is composed of clay and sandy clay and has hydraulic conductivity not higher than 0.2 m/d, then the expected groundwater inflow will be below 7 L/s. The available data show that the near-surface section in the region has similar hydrodynamic characteristics. If more permeable layers of sand and clayey sand, having hydraulic conductivity up to 1.0 m/d, dominate below the bottom of the excavation and underneath the slurry wall, then the expected groundwater inflow will be much higher – around and above 10-15 L/s.

The performed model studies show that the dewatering activities during the construction of station MS9 of the third metro diameter of Sofia Metro will be the reason for rapid and long-lasting changes in the hydrodynamic field in the Neogene-Quaternary aquifer complex. The deformations will be very dynamic and of high intensity, especially near the drained areas, where the amplitudes of fluctuation of the piezometric levels in particular sectors and for a short time will reach 16 m. The most intensive distortions will be at the peripheral area of the construction site in a zone having a span of about 60-70 m. Predominantly affected will be the sector at the base of the slurry wall and below the bottom of the excavation.

The obtained results demonstrate the efficiency of non-stationary flow models as a tool for assessment and prognostication of the potential negative impacts caused by dewatering as part of construction activities. The proposed approach can be successfully applied in regions with similar hydrogeological problems.

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blvd. - Centre - Zhitnitsa str." (from km 4 + 320 to km 11 + 966.34); Subproject: Metro station MS 9.

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