Assessment of the possibility of local object to be flooded in megalopolis as a result of a hydraulic system breakage in the area of a transport tunnel

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Abstract. In the article is observed the approach to assessing the safety of the downstream of retaining waterworks in the conditions of the existing urban infrastructure of the metropolis and the transport tunnel built on the border of the water system. Also are described the peculiarities of the methodology for determining the size of probable harm in the event of a hydrological accident of a low-pressure hydroelectric megalopolis complex, the lower pool of which is filled up, the watercourse is taken into the collector. The position of the groundwater level causes flooding of the territory, increasing the hazard indicator due to the activation of included processes (change in soil properties, suffusion, appearance a source of local flooding of an urbanized area, etc.). The results of a numerical experiment to assess changes in the position of the ground water level in the territory in contact with the Mikhalkovsky tunnel in Moscow are presented. It is shown that if the drainage system fails near the tunnel, a significant rise in the ground water level (more than 1 m) may occur, which will cause flooding of the surrounding area and residential buildings. To improve the efficiency of drainage in the lower reaches of the hydroelectric system, it is proposed to create an additional drainage system, including from the collector of the Zhabenka river. Calculation also shows that the emergency situation which may occur due to hydrological crash with implementation of the most difficult and simultaneously the most likely of several possible crash scenario with overtopping of the dam and the formation of the closure channel on the waterworks of Moscow is not likely to occur. The damage in the probable and most severe scenario of a hypothetical hydrological accident is close to zero. Therefore, there will be no damage on most ponds in the megalopolis where the downstream is filled in, planned, fortified, or the diverting section of the watercourse is taken into the collector.

1. Introduction

Suffusion associated with both natural and technogenic factors is currently spread over an area of more than 13% of the territory of the Russian Federation. Natural and technogenic suffusion processes in ground bases affect the majority of urban industrial territories, where technogenic filtration suffusion dominates the natural one. For such large megacities as Moscow, the problem has become relevant in the last decade. It is associated with a number of factors: an increase in the level of ground water that
causes flooding of the territory (in Moscow, more than 40% of the territory is flooded); intensive
construction, which encapsulate pre-existing water bodies and disturbed the prevailing water balance
in the territory (in the last 10 years in "old Moscow" borders were buried about 20 ponds and small
watercourses, was newly constructed only 1 pond-dugout); underground urbanization; changing
climatic indicators territory; leakage from water-bearing communications, slurry tanks and other city
water facilities; development and condition of water supply and Sewerage networks (wear of water
supply and sanitation networks in Russia as a whole is 60...80%, and water losses are 2.5...3 times
higher than the standard permissible level [1]); the service life of water-carrying networks and water
systems, etc. 42 karst-suffusion sinkholes with a funnel diameter of up to 40 m and a depth of up to
5...8 m have been formed in the North-West of Moscow over the past 30 years. This has a negative
impact on traffic on certain main sections of the capital, the condition of vehicles and 3-and 5-floor
buildings.

One of the main reasons that initiates the development of suffusion processes is the high position of
the ground water level (GWL). The development of suffusion manifestations and deformations, along
with the engineering and geological structure of the territory, is influenced by both one-time rises of
the GWL, and the characteristics of fluctuations, their amplitude and frequency. The intensity of
suffusion development in a local area of an urbanized territory is directly related to the production of
earthworks, drilling, and sinking operations, the number of floors in a building, the destruction of
underground water-bearing communications, and so on.

Mikhalkovsky tunnel is section of the North – Western chord in Moscow (Figure 1a) held in
Koptevo district in complex engineering and hydrogeological conditions in the thickness of the
heterogeneous meso-Cenozoic sediments (water-saturated Sands and fluid sandy loam), close to a
drainage system associated with the river Zhabenka collector, which runs almost parallel to the tunnel
and in close proximity to a Large Garden pond. The presence of drainage devices on certain sections
of the route and their condition are not known. Total length of the tunnel section on Bolshaya
Akademicheskaya street is 410 m: the closed part is 110 m, the southern ramp is 161.5 m, and the
Northern ramp is 138.5 m. The tunnel width along the outer contour is 29.86 m. During construction,
there were concerns that the construction of an underground tunnel in the immediate vicinity could
dramatically affect the ecological environment of the reservoir and surrounding areas, and construction
work near the border of the Petrovskoe-razumovsky estate Park would lead to waterlogging of the
Park and the death of valuable trees. The reservoir in which the Zhabenka river is enclosed is in a
satisfactory condition (Figure 1b). The underground channel of a fairly deep river has a small
historical section made of large stones, but the main part of it is from reinforced concrete. The average
height of the collector is 3.2 m, and the width is 2.7 m.

![Figure 1](image1.png)

**Figure 1.** General view: (a) - Mikhalkovsky tunnel; (b) - underground collector of r. Zhabenka
As long ago as in the 50s and 60s of the twentieth century, the entire Koptev plain was marked by increased GWL and wetlands. Therefore, a special horizontal drainage network was designed. Then the construction of 5-and 9-floor residential buildings began. In the 90s, the street was built up with multi-storey modern buildings. However, drainage is not laid everywhere, so to this day there is flooding of basements of individual residential buildings, sinkholes due to seeps and springs beating from underground. The area is full of utilities; historically, it has a complex water system that has been repeatedly reconstructed, but despite this, the area in the lower reaches of the hydroelectric complex, which was filled in last century, is now very swampy. Knowing that the neighborhood is located on water-saturated ground, any movement can lead to unpredictable consequences.

2. Materials and methods

Many works are devoted to identifying the causes of accidents and assessing the risk of accidents in urbanized areas. In particular, Dar/VODGEO has developed an integrated risk assessment method based on the analysis of factors and types of harmful effects of natural and man-made filtration suffusion on the infrastructure of the urban industrial territory and its degree of susceptibility to dangerous impacts and possible consequences. The assessment of the risk of flooding and damage, both for the entire territory as a whole and for local objects, is based on the calculation of the doses of harmful effects D caused by it.[1,2]

\[ D = \lambda_{\text{op}} \cdot \nu_{\text{уязв}}, \]  

where \( \lambda_{\text{op}}, \nu_{\text{уязв}} \) – coefficients correspond to the risk of flooding and vulnerability of the territory. For urban-industrial territories, taking into account the features of development, their values are determined for each indicator of the risk of flooding according to the corresponding tables [1, 2]. For local objects, the calculation mechanism is integral.

\[ \lambda_{\text{op}} = \sum_{i=1}^{4} \delta_i a_i \lambda_{\text{op}}, \quad \nu_{\text{уязв}} = \sum_{i=1}^{4} \phi_i b_i \nu_{\text{о}}, \]  

where: \( \delta_i \) and \( \phi_i \) - significance coefficients of the \( i \)-th hazard and vulnerability indicator; \( a_i, b_i \) – the value of the score for the \( i \)-th hazard and vulnerability indicator; \( \lambda_{\text{op}}, \nu_{\text{о}} \) - normalizing multipliers.

The algorithm for determining the values of all coefficients is described in detail in [1,2]. With a known dose of harmful effects \( D \), the method called "probit analysis" in risk theory is used to find the annual risk from flooding, taking into account the cost of the object before the damage, i.e. without taking into account the flooding of the territory. To get correct results, you need to know some constants that characterize the specifics of harmful effects on this object. As a first approximation for the calculation to estimate the annual damage from flooding \( R \) object value \( C_e \) can be taken dependence (3), recommended in [2] for any value of the dose \( D \), which should further take into consideration the nonstationary nature of flooding and the design features of the object under construction and the surrounding area

\[ R = 6.5 \cdot 10^{-3} \operatorname{erfc}[\frac{-2.36 lnD - 3}{C_e}]. \]  

If there is no harmful effect of flooding \( D \to 0 \). In accordance with (3) and \( R \to 0 \), i.e. there is no risk (damage) from flooding.

One of the main factors in the list of risk factors from flooding, when calculating the doses of harmful effects on individual local objects, is the depth of groundwater, which is included in the first hazard indicator, the degree of which (large, medium or small) is characterized by the capacity of the flooding zone and the coefficient of flooding of the object. In this regard, to assess the degree of danger for the first hazard indicator, it is necessary to make a forecast of flooding on the territory of the object being designed, built or operated. In this area of the capital, flooding of the territory can cause activation of landslide processes with an average degree of danger. The neighborhood is characterized by relatively high position of the GWL. The first horizon from the surface lies at a depth of 0.5 to 5 m, with an oscillation amplitude in the range of 1...1.5 m.

3. Results and Discussion

The extraordinary nature of the situation has led to the need for numerical modeling to assess the impact of the tunnel on the groundwater of the adjacent territory, one part of which belongs to the
protected areas, and the other to the microdistrict of dense residential development. Materials from surveys conducted by MOSINZHPROEKT and MOSGEOTREST were used as the basis for modeling, and the position and diameter of drains were taken from the geo-base. The paper presents surveys conducted by MOSINZHPROEKT and MOSGEOTREST were used as the basis for where protected areas, and the other to the microdistrict of dense residential development. Materials from surveys conducted by MOSINZHPROEKT and MOSGEOTREST were used as the basis for the degree of danger according to the first indicator of the risk of flooding of territories adjacent to the highway Mikhailovskaya tunnel on Bolshaya Akademicheskaya street in the northwestern administrative area of Moscow [3]. The aquifer complex has a single level surface, which is characterized by the hydroisohyposes map (Figure 2a). The site is composed of upper Jurassic sand, sandy loam and layered loam. The underground water level of the complex lies at a depth of 0.5...5 m. In unfavorable years, levels may rise by 1...1.5 m. Oxford clays serve as a water barrier for the aquifer complex at the site of the tunnel passage. The assessment of the impact of the Mikhailov tunnel on groundwater was based on a comparison of the results of modeling the position of the GWL before and after its commissioning.

Calculations of changes in GWL on the site territory, including adjacent territories, to assess the degree of danger for the first hazard indicator were performed using mathematical modeling on a three-dimensional model [3, 4]. Since the tunnel does not completely cover the nadirskiy aquifer complex, the US Geological survey MODFLOW program and a preprocessor for preparing PMWIN data were used to solve the problem [4, 5]. Vertically, for numerical calculations, the filtration area is divided into blocks-parallelepipeds of different sizes: near water intake wells, the filtration rates, which are calculated for the indoor units according to the formulas:

$$V_{x_{i+1/2}} = k_{x_{i+1/2}} \frac{2(H_{i} - H_{i+1})}{(\Delta x_{i+1} + \Delta x_{i})},$$

$$V_{y_{i+1/2}} = \frac{2(H_{i} - H_{i+1})}{(\Delta y_{i+1} + \Delta y_{i})},$$

$$V_{z_{i+1/2}} = \frac{2(H_{i} - H_{i+1})}{(\Delta z_{i+1} + \Delta z_{i})},$$

where $H_{i}$, $H_{i+1}$ - pressures in the centers of gravity of the blocks $i$, $j$, $k$; $i$, $j$, $k$; $i+1$, $j$, $k$ respectively; $\Delta x_{i-1}$, $\Delta x_{i}$, $\Delta x_{i+1}$ - size of blocks $i-1$, $j$, $k$; $i$, $j$, $k$; $i+1$, $j$, $k$ along axis $x$; $k_{x_{i+1/2}}$ - average...
filtration coefficient along the x axis between blocks \(i-1, j, k\) and \(i, j, k\); \(k_{x_{i+1}}\) - average filtration coefficient along the x axis between blocks \(i, j, k\) and \(i+1, j, k\).

Speeds are calculated similarly for indoor blocks \(V_{x_{i+1}}\); \(V_{x_{i-1}}\) and \(V_{x_{i}}\).

Integration (5) performed for each block of the model allowed us to obtain a system of algebraic equations of the next type:

\[
A_{i,j,k}H_{i-1,j,k} + B_{i,j,k}H_{i,j,k} + C_{i,j,k}H_{i-1,j,k-1} + P_{i,j,k}H_{i,j,k} + E_{i,j,k}H_{i,j,k+1} + F_{i,j,k}H_{i,j+1,k} + G_{i,j,k}H_{i,j,k+1} = I_{i,j,k},
\]

where \(H\) - unknown pressures or levels in the centers of gravity of the model blocks;

\(A_{i,j,k}\) and etc. — coefficients determined based on filtration parameters and the geometry of the aquifer;

\(I_{i,j,k}\) - the free term of equation (8), which mainly includes the source-stock components.

The total number of equations and unknowns is equal to the number of parallelepiped blocks \(N_x \times N_y \times N_z\).

As a result of verification of the model and solving the inverse problem, a design map of hydroisohypses was obtained (Figure 2b), which characterizes the position of levels even before construction, which was then used for comparison with forecasts based on the results of modeling (before and after construction) and obtaining maps of changes in GWL depending on the location and operation of drainage (Figure 3a). When calculating changes in the distribution of GWL after the construction of the Mikhalkovsky tunnel, it was assumed that the tunnel overlaps underground water.

![Figure 2. Map of isohypses GWL: (a) according to the survey; (b) the results of solving the inverse problem](image-url)

The forecast of changes in the GWL is a result of tunnel construction (Figure 3b) showed that the rise of GWL in the entire territory where the object is being built, including the adjacent territories on both sides of the tunnel, cannot be assumed to be the same, including the area of the object. However, the change in the position of the GWL caused only by the tunnel was predicted to be very small, the first centimeters. This value is comparable to the accuracy of the measurement of GWL and can be practically ignored. This slight rise can be explained by two reasons: the tunnel does not completely block the flow of underground water (the nadyursky aquifer complex) and the smooth operation of existing drains that stabilize the GWL. Therefore, calculations were made to analyze changes in the position of the GWL under the combined action of two factors: the impact of the tunnel and the destruction of drains near it. The results of the forecast of changes in the GWL for this option showed that the rise of GWL when drains fail can exceed 1 m, which, taking into account the amplitude of fluctuations and the unsteadiness of the flooding process, can cause dangerous flooding of the territory.
and residential buildings located on it, and in particular the house No. 57 on Bolshaya Akademicheskaya street, whose residents constantly and previously complained about flooding of basements. To prevent the situation of cessation of operation of the drainage recommended to develop additional measures to preserve existing drainage and/or create a new one, i.e. the creation of additional support drainage system to ensure a stable position of the groundwater table at the existing marks and at least two observation wells to a depth of 10...15 m, to upgrade stormwater and urban sewer, water and heating in the district. Analysis of the map obtained for this case of changes in the position of the GWL caused by the impact of the tunnel, partial failure of the existing drainage and the construction of additional drainage showed that changes in the GWL in this case are insignificant.

For a more complete assessment of the integral degree of danger $\lambda_{oc}$ of flooding of the tunnel adjacent territory and local objects on it, in addition to the depth of groundwater occurrence, it is necessary to more correctly determine the degree of danger for each indicator separately: corrosion aggressiveness of groundwater, changes in the strength and deformation properties of soils during flooding and drainage, activation of dangerous processes. To estimate the dose of the harmful impact of flooding on an object using (1), using the dependencies (2) and (3), it is also necessary to collect additional data and find all four indicators of vulnerability: urban, geotechnical, environmental and operational. Only then will it be possible to fully assess the maximum annual damage from possible flooding of the object.

However it should be noted that in modern conditions for the water system of the Big Garden pond and the territory, adjacent to tunnel, also assessment of emergence and development of number of possible scenarios of hydrological breakage is relevant. Such scenarios are connected with changes in work of the collector of the Zhabenki River and the system of drainage, its interaction its developed, but partially destroyed with the tunnel, and also with impossibility of the admission water throughput constructions of the water-engineering system of high-water flows and the water flow rate which is specially arriving from Golovinsky ponds for watering of the Yauza River a natural channel of the Likhoborki River. This analysis was carried out under an agreement with Mosvodostok [6] and showed that when the maximum calculated flow rate of the rare supply of the Zhabenka river (approximately 1 m$^3$/s) and water discharge from Golovinsky ponds are in transit, it will take more than 1.4 days to create a normal oxygen balance in the Yauza river (the water supply flow rate is 5 m$^3$/s) even with the spillway culverts are not working (assumption) to raise the water level in the

![Figure 3](image_url). Maps: (a) - placement of drains and water bodies in the area of construction of the Mikhalkovsky tunnel; (b) - isolines of changes in the GWL during operation of the Mikhalkovsky tunnel in case of failure of drains.
Bolshoy Sadovoye pond with its current dimensions to the dam crest mark. If hypothetically such filling occurs, and the operation service cannot eliminate the emergency situation during this time, then the prerequisites for the operation of the hydroelectric power plant will be created in 5 possible scenarios [7]. However, a preliminary assessment shows [6, 7] that in the most severe scenario, the probability of a hole forming in the dam body is unlikely, since the lower slope of the dam is filled in, planned, reinforced, and partially paved. It is more likely that a dam crest of limited width will overflow than that a significant mass of water will flow through the resulting gap in the form of a breakout wave. In this case, the height of the overflow layer when the culverts are not working (assumption) it will not exceed 6 cm when spilling over the crest of the dam on a section equal to the length of the dam along the crest (about 310 m). The water level in the pond towards the edge of the shore from the Timiryazevsky Park will rise slightly, the flooding will be unnoticed, and environment of the coastal Park area at the end of the pond and the left shore, where is the stadium "Science" with number of areas (ex: dealership, body shop, OOO Elkom-yuna, etc.) and Bolshaya Akademicheskaya street. Only the beach and boat dock can be briefly under a layer of water from 1.5 to 0.1 m deep and the width of the coastal strip is less than 3 m.

Pass of the verification flow, occurring in this scenario, will cause the breakdown through the manifold R. Zhabenki laid along Bolshaya Akademicheskaya St., will happen in free-flow mode at the maximum depth of 0.85 m at the height of the cross section of the reservoir is 3.2 m. Thus, flooding of areas downstream of Large Garden pond with the big share of probability will not be. At the same time, it should be noted that in any of the other considered accident scenarios, is affected the territory of the RGAU Park Timiryazev (Forest experimental dacha, arboretum garden named after R. I. Schroeder, Botanical garden of the Moscow agricultural Academy named after S. I. Rostovtseva and estate Petrovsko-Razumovskaya adjacent to the waters of the pond and having the status of nature reserve protected areas), and the area Bolshaya Academic, a distance of from 40 to 250 m from the water practically will not be flooded above the corresponding regular operation of the main spillway of the pond when you pass the waterworks flow calibration repeatability 1 time in 1000 years. Thus, the area of hypothetical flooding does not include settlements, industrial facilities, valuable land, forests, flooding of which may cause damage to third parties, therefore, there will be no damage to all components of the damage as a result of the accident. The damage from the consequences of all accident scenarios is approximately equal to zero. An emergency situation due to a hydrodynamic breakdown will not occur if the most severe and at the same time the most probable accident scenario is realized.

4 Conclusions

Analyzing the materials obtained, we can conclude that the problem of improvement, correct assessment of the position of the GWL and stabilization of its position after the construction of any transport tunnel in the metropolis should be solved comprehensively. The formation of a groundwater table in the area of the tunnel with fixation of its provisions should be adapted to scientific requirements for the preservation of ecological security and state waters adjacent thereto of a water body, in the case of water systems of district and historical monument of the estate "Petrovsky-Razumovsky" with a Large Garden pond. Calculations have shown that the creation of additional drainage will allow maintaining the GWL at existing levels and, if necessary, improve the situation. Special attention should be paid to the organization of operation of existing drainage systems and structures that are on the balance of various organizations. Since one of the reasons for the rise of GWL may be a violation of water-bearing communications (water supply, Sewerage, etc.), it is necessary to take measures to preserve them. It is quite possible that the results of monitoring will require the reconstruction of the existing old drainage system of the entire microdistrict, including the main collector of the Zhabenka river and household sewer collectors.

In addition to performing the recommended actions is necessary operational evaluation of the quantitative and qualitative condition of groundwater at the ebb side of a dam of waterworks facility, which, coupled with the assessment of the harmful effects of groundwater flooding at the site will
allow you to obtain the correct value of the likely damage resulting from hydrological accident, hydraulic and transport facilities in urban areas. The analysis of the probability of occurrence of hydrological hypothetical accident on a water body adjacent to Mihalkovskiy tunnel, and location of residential and economic facilities downstream of the dam showed that the emergency situation as a result of hydrodynamic accidents during the implementation of the most difficult and simultaneously the most likely scenario accident will arise. A potential accident of the pond structures cannot create a direct threat to the surrounding area. The probable damage for the most severe and at the same time the most probable accident scenario turned out to be the same and equal to zero. There will be no damage to third parties for which liability arises when the Bolshoy Sadoviy pond dam breaks, as well as for most small ponds in the territories of most administrative districts of the megalopolis, the diverting channel of watercourses in the lower reaches of which is taken into the collector.

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