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Forecasting groundwater rise in the historic downtown area of Irkutsk city

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Abstract. The purpose of this investigation is to develop an analytical model for predicting the groundwater level rise due to the barrage effect. Processing of a significant volume of production decisions for multiple objects has resulted an analytical model that allows predicting the dynamics of groundwater rise due to the barrage effect when building deep foundation structures. The study has been conducted for the downtown areas of Irkutsk and other cities of Eastern Siberia. Prediction schemes for the groundwater level formation have been made, and an assessment of the study areas by their underflooding conditions has been carried out. Being adequately simple and multi-purpose. The analysis of the research results shows that the hydraulic gradient of the underground water flow and the project structure width have the biggest effect on the groundwater rise. Vertical planning of the territory and the use of pile foundations play a significant role in the formation of the groundwater level. Besides, when evaluating the depth of the underground water formation level and developing the prevention and protection measures, it is necessary to take into account the seasonal rise of the underground waters. The developed model can be applied in the corresponding geological and hydrogeological conditions.

Keywords: groundwater rise, groundwater level, analytical model, prediction, deep foundation

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ГИДРОГЕОЛОГИЯ И ИНЖЕНЕРНАЯ ГЕОЛОГИЯ

Научная статья
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Прогноз подъема уровня грунтовых вод в районе исторических построек города Иркутска

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Резюме. Цель работы заключалась в разработке аналитической модели для прогноза подъема уровня грунтовых вод в условиях барражного эффекта. В результате обработки значительного объема производственных решений разработана аналитическая модель, позволяющая прогнозировать изменение уровня грунтовых вод, которое происходит при строительстве инженерных сооружений с глубоким заложением фундаментов, создающих эффект подпорной стенки (барража). Работа проводилась на участках, расположенных в исторических центрах городов Восточной Сибири, в том числе города Иркутска. Разработаны прогнозные схемы глубин формирования уровня подземных вод первых от поверхности водоносных горизонтов, проведена оценка территорий по условиям подтопления в соответствии с существующими нормативными документами. Анализ результатов исследований показывает, что наибольшее влияние на подъем грунтовых вод оказывают гидравлический уклон потока подземных вод и ширина проектного сооружения. Значительную роль в формировании нового подпорного горизонта в пределах исследуемой территории играют вертикальная планировка застраиваемой территории и использование свайных фундаментов. Кроме того, при разработке профилактических и защитных мероприятий необходимо учитывать многолетние сезонные колебания уровня грунтовых вод. Представленная аналитическая модель достаточно проста, универсальна и может применяться в различных геолого-гидрогеологических условиях.

Ключевые слова: подпор, уровень грунтовых вод, аналитическая модель, прогноз, перезаглубленный фундамент

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Introduction

Underflooding caused by different reasons is observed in many cities all over the world, including the USA, Great Britain, France, Germany, India, Kazakhstan, China, Korea, etc. [1–11]. In Russia, underflooding takes place in many built-up areas of the European part of the country, the Urals, the Far East, and Siberia [12, 13].

The built-up areas in the south of Eastern Siberia are extremely subject to underflooding. The reasons are diverse: disastrous snowmelt floods, leaks from the old underground utilities, failures of the storm sewage systems, and a barrage effect of the deep foundations of civil engineering structures with underground parking lots [11, 14].

In 2002, The State Duma of the Russian Federation passed the law "On the cultural heritage objects of the peoples of Russia" that had an emphasis on the citizens' constitutional obligation to preserve the national historical and cultural heritage. However, in the period 2000–2010, over 2,500 historical and cultural monuments were destroyed in Russia. The state of half of the monuments protected by the government is unsatisfactory, and most of them need urgent protection measures. According to the data from the Ministry of Culture, almost 65 % of the cultural-and-historical heritage objects are either in an emergency or pre-emergency condition[1]. Most of the buildings that are over 100 years old are subject to the negative influence of the ecological factors, including underflooding. The historical cities, especially their downtown areas, require reconstruction projects with an indication of the boundaries of the protected zones. This could make it possible to eliminate a number of the city-planning problems connected with parceling out for new construction in the historic downtown areas. Besides, when building deep foundation structures, it is necessary to take into account the risk of the underflooding of the historical buildings.

Research objective

The research aims to develop an operational forecasting procedure for the changes in the groundwater hydrodynamic regime due to the barrage effect of deep foundation structures to facilitate engineering decision-making on the initial stages of architectural construction projects.

Research methods and procedures

The construction of deep foundation buildings in areas with a small depth of the groundwater level causes a "barrage" effect increasing the risk of the underflooding of the adjacent built-up plots.

The barrage effect is groundwater rise before the dam and its descent after the dam due to the damming of the groundwater filtration flow. Depending on the hydrogeological characteristics of the dammed water-bearing layer and the size of the engineering structure, the level of the groundwater rise varies from a few centimeters to a few meters, causing the ground body deformation, underflooding of the area and nearby structures, and other adverse consequences.

As it was mentioned above, the underflooding due to the barrage effect is common in the modern urban areas. The construction that takes place not only in the urban fringe but also in the historical and cultural zones causes damage to the foundations of the old structures and often leads to the destruction of the historical buildings.

The study focuses on the main causes of the changes in the urban hydrogeological conditions and on the factors determining their hydrodynamic regime [15].

The changes in the hydrogeological conditions of the urban territories located in the Angara River Valley are determined by natural and technogenic factors.

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[1] The 3d parlamentary forum "Historical and cultural heritage of Russia". *The Union of the towns of the Russian Federation*. Available from: http://smgrf.ru/3-parlamentskij-forum-istoriko-kul-turnoe-nasledie-rossii/ [Accessed 09th March 2022]. (In Russ.).

The natural factors are seasonal fluctuations in the atmospheric precipitation. The technogenic factors include the emergency evacuation of water from the Angara cascade reservoirs and the barrage due to the construction and maintenance of deep foundation structures.

The regime-forming factors are divided into regional and local ones.

The regional factors include groundwater rise connected with the filtration of water from the canals, rivers, and other water pools, as well as with the leaks from the underground industrial utilities, large intercepting sewers, etc.

The local factors include the groundwater rise caused by the barrage effect of the underground structures and infiltration of the leaks from the water carrying utilities, as well as the cones of depression due to different types of drainage in the facilities under construction and maintenance.

The present paper focuses on the local technogenic factor associated with the construction of modern buildings with underground shopping centers and parking lots, and other objects with deep foundations that cause groundwater rise due to the barrage effect.

The situation concerning groundwater rise in Irkutsk, Cheremkhovo, Usolje-Sibirskoye, and other cities of Eastern Siberia is complicated. For example, a large part of the downtown area of Irkutsk is represented by the buildings of the late 18^{th} – early 19^{th} centuries, the groundwater level is 1.2–5 m from the earth's surface [12]. A minor part of the unbuilt areas is allotted for the construction of large shopping centers or apartment houses with deep foundations and underground parking lots, which is followed by the reformation of the groundwater filtration flow structure.

The study area is located in a transition zone between the platform flatland and the Baikal mountainous region. The relief of the territory is moderately rugged due to the river valleys and creek valleys of the first and second orders. The main rivers are the Angara River and its tributaries Irkut, Olkha, Ushakovka, etc. The watershed spaces have flat and rounded tops with an absolute elevation 480–520 m and the maximal ruggedness depth 160 m.

In hydrogeological terms, the above areas are associated with the Irkutsk basin, the largest structure of the Angara-Lena artesian basin of the first order.

The major water-bearing sediments are Quarterly (gravel-shingle, sand-clay), Jurassic (sandstone, argillite, and siltstone), and Cambrian sediments (dolomite, saliferous rocks). The sediments have a block structure inherited from the crystalline basement. The position of the rock blocks within the study areas determines the major geomorphological structures. In combination with the joint fissures and erosion network, it has a crucial influence on the engineering-hydrogeological conditions [16–18].

The type section of the central territory of Irkutsk is a two-layer structure: the upper part is represented with loose Quarterly sediments, and the lower one, with Jurassic rock formations. The Quarterly gravel-shingle and sandy-sabulous sediments of the upper part significantly differ by their structure and hydraulic conductivity. The sediments nearest to the surface are sandy-sabulous with the hydraulic conductivity K less than 5–6 m/day. It is the stratum where the groundwater table is formed. The gravel-shingle sediments have much higher hydraulic conductivity, 100–300 m/day. The groundwater level of the Quarterly aquifer is at a depth of 1.2–5 m. The layer’s underlying formation is represented by Jurassic sandstone, siltstone, and carbonaceous shale, the filtration in the disturbed zones being 100 m/day (while the average value is 0.5–1.5 m/day). The aquifer of the Upper Quarterly sediments is shut off by the technogenic ground with an average thickness of 1.5 м [11, 13, 16].

The modeling of such situations for several cities of the Irkutsk region, along with the forecast of the groundwater rise in the adjacent territories has been conducted a few times [11–13, 16]. Based on this, an empirical relationship has been elicited.

The article presents the procedure and methods of the work, using the cases of the sites that were chosen due to their geological structure and hydrogeological conditions typical of the study territory (Fig. 1).

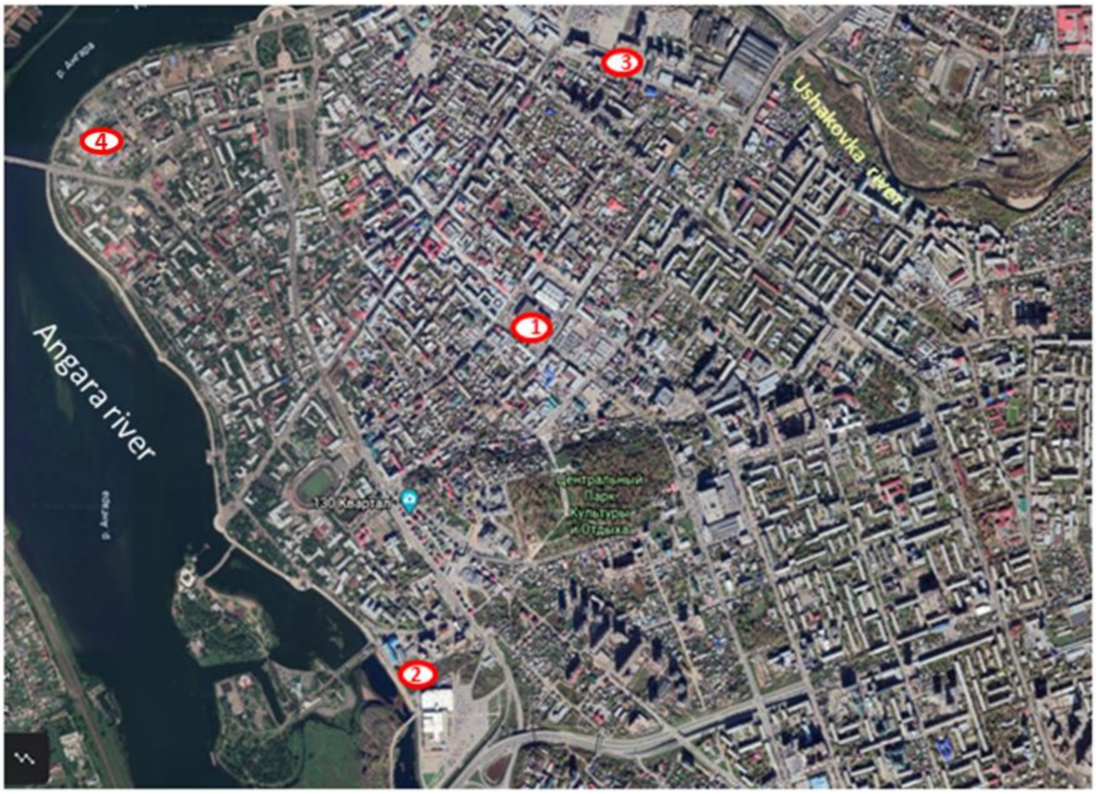

Fig. 1. Location of key (standard) sites no. 1, 2, 3, 4 in Irkutsk
Рис. 1. Расположение ключевых (типовых) участков № 1, 2, 3, 4, г. Иркутск

Site 1 is situated in the central zone of the historic housing estate area of Irkutsk. It was planned for the construction of a 5–10-storeyed building with a three-level underground parking lot and a foundation depth of 8–12 m. Based on the initial data analysis [10–13, 16, 17, 19], a database that included 13 attribute characteristics by 96 points, was created.

As a result of the natural conditions schematization that was conducted following the existing Russian standards[2] and the appendix recommendations[3], a hydrogeological model was developed.

The vertical structure of the watered stratum of the terrace alluvial sediments is assumed two-layered. The upper part of the section consists of dense loam and clay sand with thin sand interbeds with a total average thickness of 2.45 m and *K* = 1–5 m/day. The middle and lower parts of the section consist of Upper Quarterly gravel-shingle sediments 2 to 5.1 m thick, which are the main collectors of the groundwater and have a homogenous isotropic structure with *K* = 84.5 m/day. The re-formation of the groundwater level takes place in the loam and clay sand sediments of the upper part of the section.

The gravel-shingle sediments almost all over the territory have much less penetrable underlying eluvial Jurassic sediments with *K* being 0.5–1.5 m/day.

The hydraulic regime of the alluvial aquifer ground water is unconfined. The insignificant groundwater pressure (0.05–0.4 m) in certain wells drilled on the site in the period 1966–2008 is most probably connected with the influence of the pressure water of the Jurassic aquifer and the local waterproof rock lenses in the Upper Quarterly sediments.

The hydrodynamic model of the territory is represented in Fig. 2.

[2] Building codes 104.13330.2016. Engineering protection of territories from flooding and underflooding. Updated edition of the Building codes and regulations 2.06.15-85. *Consortium code.* Available from: http://docs.cntd.ru/document/456054204 [Accessed 09th March 2022]. (In Russ.).

[3] Underflooding prediction and drainage systems calculation for developed or built-over territories. Reference book for the Building codes and regulations 2.06.15-85. *Codes and standards library.* Available from: https://files.stroyinf.ru/Data1/2/2697/ [Accessed 09th March 2022]. (In Russ.).

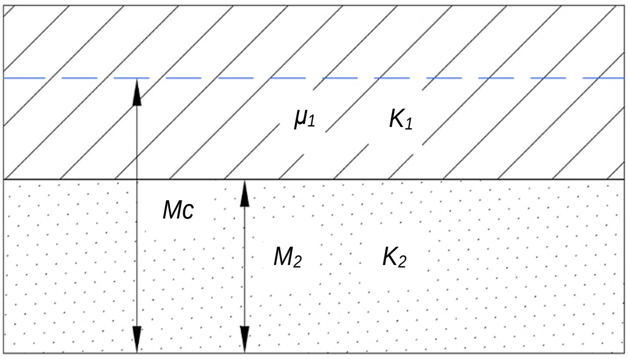

Fig. 2. Hydrodynamical model of a site:
Mc – groundwater flow rate (average value is 5.02 m); μ_1 – water yield of the upper layer (0.92); K_1 – hydraulic conductivity of the upper layer (1–5 m/day); K_2 – hydraulic conductivity of the lower layer (84.5 m/day); M_2 – average flow rate of the lower layer (4.07 m)
The generalized hydrodynamical model uses averaged parameter values

Рис. 2. Гидродинамическая модель участка исследований:
Мс – мощность потока грунтовых вод (среднее значение – 5,02 м); μ_1 – коэффициент водонасыщения верхнего слоя (0,92); K_1 – коэффициент фильтрации верхнего слоя (1–5 м/сут.); K_2 – коэффициент фильтрации нижнего слоя (84,5 м/сут.); M_2 – средняя мощность нижнего слоя (4,07 м)
В обобщенной гидродинамической модели использованы осредненные значения параметров

The groundwater table incline varies depending on the position of the main drain (in this case, the Angara River) and a few dome-shaped structures formed in the area due to the underground facilities leakage. The direction of the main flow is southeast to northwest, the flow incline increasing from 0.016 to 0.027.

The bed is modeled as an unlimited calculation scheme. The infiltration is assumed homogeneous all over the area, and its effect on the groundwater level change Δh is not taken into account on this stage of modeling as it does not influence the character of the groundwater stationary rise in the homogenous strata [20, 21]. In this case, the problem is considered stationary and determinate, i.e. within the defined stages of the groundwater rise formation, the main elements of the groundwater flow stay constant. The prediction of the stationary process consists of plotting the depression curves on the concluding stage of the time interval meeting the boundary conditions[4] [22].

The distribution of the levels in the one-dimensional homogenous isotropic stratum when solving the stationary problem not taking into account the infiltration feed is described with the Laplace's equation modification [20, 21]:

$$\frac{\partial^2(\Delta h^2/2)}{\partial x^2} = 0. \qquad (1)$$

Here, Δh is groundwater rise in section x.

In the first stage, a 'nowcast' model is built, i.e. a model for the existing conditions; on the second stage, a 'forecast' model is built, i.e. a model for the conditions caused by groundwater rise [13, 23].

The analysis of the nowcast model with the use of the software complex Surfer 10 has made it possible to represent a general picture of the existing hydrodynamic conditions, specify the direction of the flow, and define the hydraulic incline of the underground water table on different sites, as well as the average depth of the groundwater level (which in this case is 2.5 m).

The predictive modeling has shown that the maximal rise of the groundwater level on the study site is 0.5 m, and the minimum depth of the groundwater level after the construction has been completed is 1.7 m (Fig. 3). Thus, by the existing Russian standard-setting documents (Building Codes 104.13330.2016), the territory is, in the main, classified as moderately underflooded. The general direction of the underground water flow movement has not changed, and the local re-formation of the groundwater level has taken place around the project structure (which is connected with the formation of the groundwater rise) and has covered a significant part of the historic area (Fig. 4).

[4] Gavich I. K. *Hydrogeodynamics.* Moscow: Nedra; 1988. 349 p. (In Russ.).

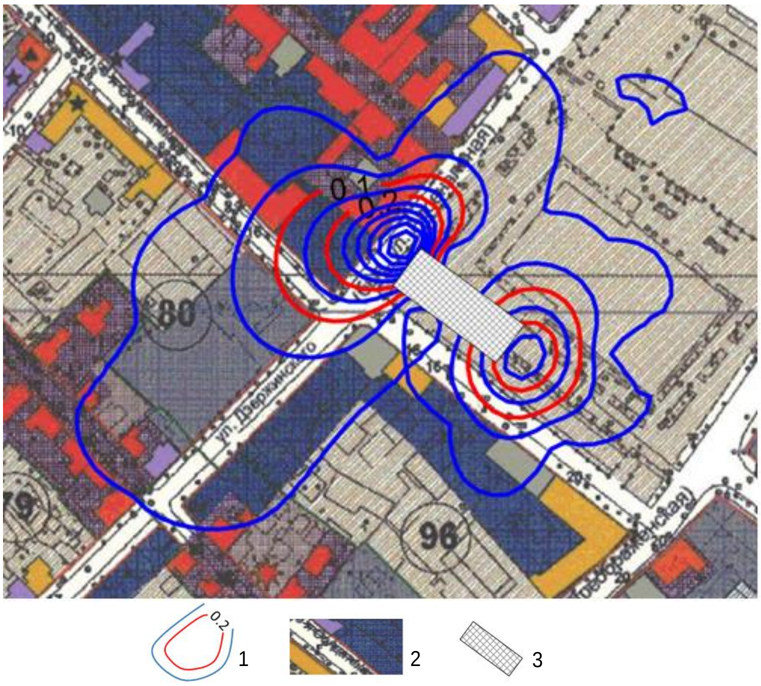

Fig. 3. Isolines of the groundwater level rise ∆h [24]:
1 – isolines of the groundwater level rise due to the groundwater logging (iteration is 0.05 m);
2 – underlay with the location diagram of historical and cultural heritage sites; 3 – designed structure
Рис. 3. Изолинии величины подъема уровня грунтовых вод ∆h [24]:
1 – изолинии величины подъема уровня грунтовых вод в результате подпора (шаг – 0,05 м); 2 – подложка со схемой расположения объектов историко-культурного наследия; 3 – проектируемое сооружение

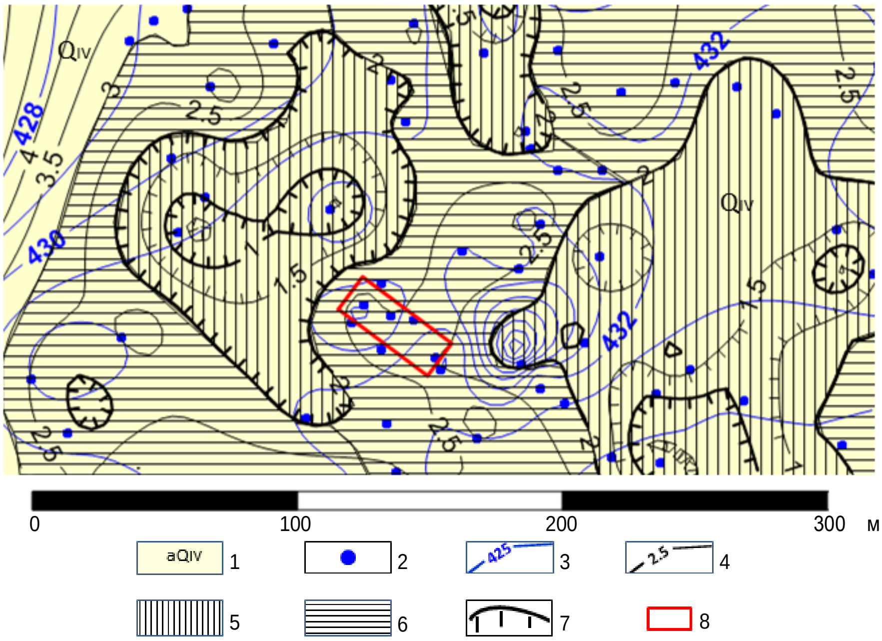

Fig. 4. Zoning diagram of the site no. 1 by the underflooding degree [24]:
1 – quarternary alluvial sediments; 2 – mine workings (wells, manholes, pits); 3 – elevation mark of the underground water level after the groundwater rise (construction), m; 4 – formation depth of the underground water level after the groundwater rise (construction), m; 5 – moderately underflooded territory; 6 – weakly underflooded territory; 7 – boundary of the moderately underflooded territory; 8 – project structure
Рис. 4. Схема районирования территории участка № 1 по степени подтопления [24]:
1 – аллювиальные отложения четвертичного возраста; 2 – горные выработки (скважины, колодцы, подвалы); 3 – абсолютная отметка уровня подземных вод после подпора (строительства сооружения), м; 4 – глубина формирования уровня подземных вод после подпора (строительства сооружения), м; 5 – умеренно подтопленная территория; 6 – слабо подтопленная территория; 7 – граница умеренно подтопленной территории; 8 – проектное сооружение

The described algorithm was applied for other similar study sites classified as underflooded with different percentages of strongly, moderately, and weakly underflooded subzones.

Site 2 is located in the central part of Irkutsk, in the Angara riverbed area. It is intended for the construction of a residential complex with a foundation depth of over 6 m. The underground part of the structure is going to be used as a parking lot. The pile foundation partially blocks the groundwater stream both by area and in section. The project specifies vertical planning of the territory with landfilling of over two meters thick. The use of pile foundations together with vertical planning makes it possible to avoid aerial underflooding of the territory despite the groundwater rise to 0.3 m (Fig. 5).

Site 3 is also located in the center of Irkutsk, in the Ushakovka riverbed part. The depth of the strip foundation of the planned administrative and business center is 4.5 m, with no vertical planning included. Thus, with the underground water rise to 0.2.m only, a big part of the territory is going to be underflooded (Fig. 6).

Site 4 is located on the right bank of the Angara River. The depth of the foundation of the planned administrative building is 2.5 m without taking into account the vertical layout. After the predicted groundwater rise by 0.8 m, part of the territory will be flooded (Fig. 7). The obtained results show that the territory planned with technogenic ground landfilling and a pile foundation has minimal underflooding risk.

Research results and analysis

As a result of the study aiming to forecast the change of the hydrogeological conditions, the main causes of the process of change and regime-forming factors have been distinguished.

The present paper gives a detailed consideration of the prediction of the local technogenic factor connected with the construction of structures with deep foundations causing the groundwater rise due to the barrage effect.

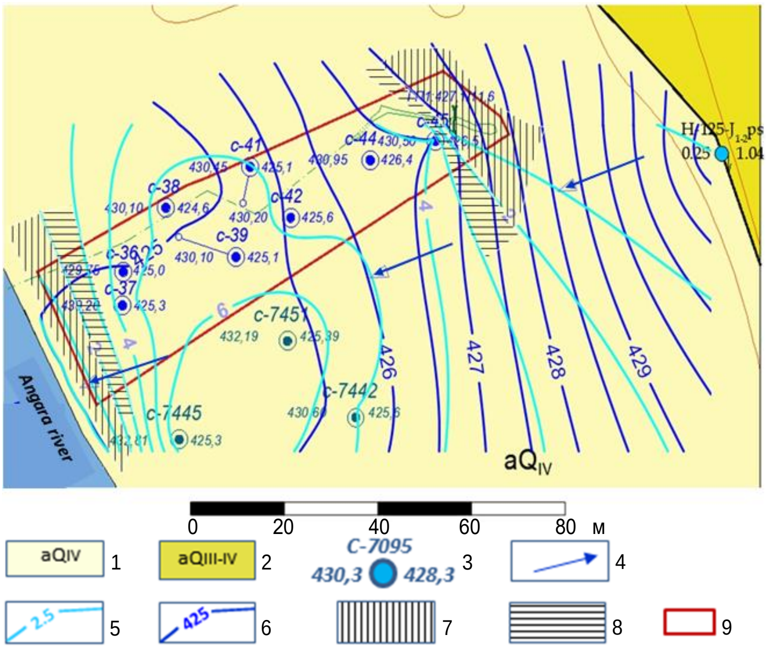

Fig. 5. Zoning diagram of the site no. 2 by the underflooding degree [24]:
1, 2 – quarternary alluvial sediments; 3 – well: at the top – number, on the left – elevation mark of the earth surface, m, on the right – elevation mark of the underground water level, m; 4 – underground water flow direction; 5 – formation depth of the underground water level after the groundwater rise (construction), m; 6 – elevation mark of the underground water level after the groundwater rise (construction), m; 7 – moderately underflooded territory; 8 – weakly underflooded territory; 9 – project structure

Рис. 5. Схема районирования территории участка № 2 по степени подтопления [24]:
1, 2 – аллювиальные отложения четвертичного возраста; 3 – скважина: вверху – номер, слева – абсолютная отметка поверхности земли, м, справа – абсолютная отметка уровня подземных вод, м; 4 – направление движения потока подземных вод; 5 – глубина формирования уровня подземных вод после подпора (строительства сооружения), м; 6 – абсолютная отметка уровня подземных вод после подпора (строительства сооружения), м; 7 – умеренно подтопленная территория; 8 – слабо подтопленная территория; 9 – проектное сооружение

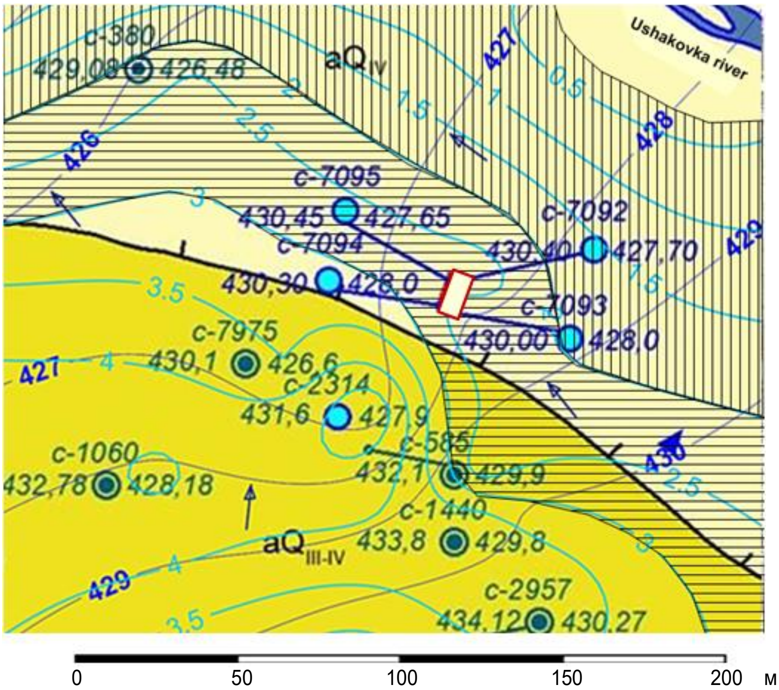

Fig. 6. Zoning diagram of the site no. 3 by the underflooding degree [24]

See the legend of Fig. 5

Рис. 6. Схема районирования территории участка № 3 по степени подтопления [24]

Условные обозначения см. на рис. 5

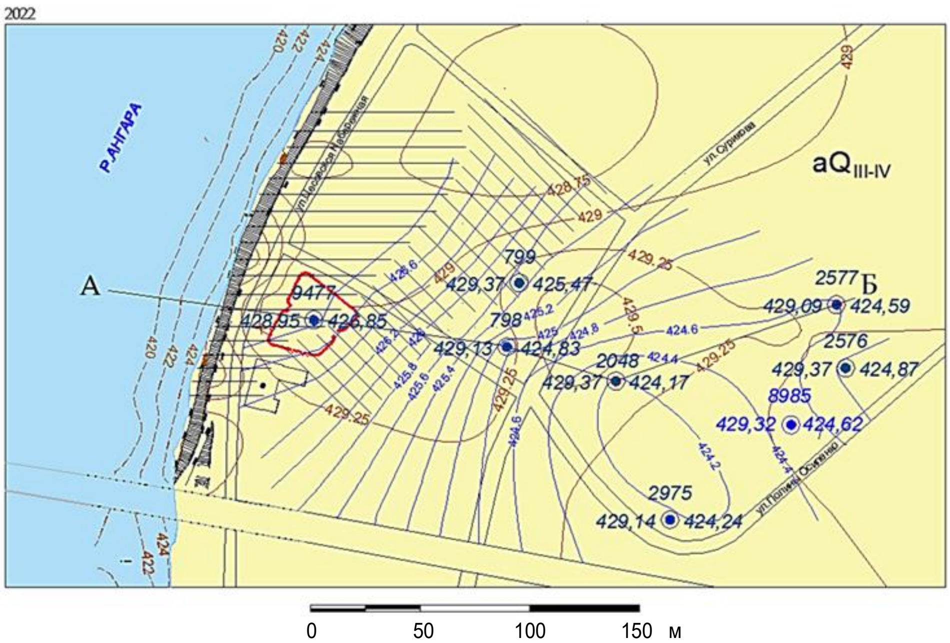

Fig. 7. Zoning diagram of the site no. 4 by the underflooding degree

See the legend of Fig. 5

Рис. 7. Схема районирования территории участка № 4 по степени подтопления

Условные обозначения см. на рис. 5

The modeling of the groundwater rise formation for several sites of Irkutsk and other cities of the Irkutsk region, as well as the results of the analytical solution of the Laplace' equation for the taken calculation scheme (Fig. 2), including the solution of the equation system in partial derivatives of a parabolic type with the given initial and boundary conditions, have shown that the hydraulic decline of the flow and the width of the project structure has the biggest effect on the groundwater rise. The conclusions allow setting up and using the following analytical solution to evaluate the upsurge of the groundwater level Δh [24]:

$$\Delta h = \frac{I \cdot B}{1{,}78}. \qquad (2)$$

Here, I is the underground water table incline; B is the width of the retaining wall (barrage), m; 1.78 is the coefficient obtained analytically.

The gradient values taken for the calculations correspond to the real values existing in the ground flow of the upper aquifer in the study territories. The calculated values of the structure width are 15, 25, 50, 80, 110, 170, and 200 m (Fig. 8), which well corresponds to the size of the currently designed buildings with the foundation depth up to 8 m.

It is necessary to mention the constraints on the use of the given formula:

– Provisionally homogenous water-bearing layer;

– Perpendicularity of the building and flow;

– Complete ‘cut-in’ of the foundation (when the underground part of the foundation completely blocks the underground water flow);

– Constancy or absence of the infiltration.

The calculation of the groundwater rise due to the incomplete cut-in of the project structures can be realized by recalculating the empirical coefficient 1.78 in Eq (2) as a percentage of the foundation cut-in depth as it was done for the objects 2, 3 and 4.

Discussion

The groundwater level surface is a highly dynamic index. For example, in the period 1984–1997, the average annual level by the data from several observation wells in the central part of Irkutsk changed by 0.8–1 m. Thus, when developing technological schemes, it is necessary to take into account that the predicted level of underground water can reach 0.9–1.4 m from the earth's surface. In this case, the major part of the territory is classified as moderately underflooded [12]. The prediction is especially important for the downtown areas because the underflooding affects not only the modern buildings but also the architectural monuments most of which, being the national endow objects, are in an emergency condition because of the fast-developing deformations of the underground elements. Hydro isolation daub that is currently used to protect the foundations of historical buildings from the destructive effect of the underground water is not effective. The more appropriate prevention measures include engineering preparation of the territories and the use of protection drainage systems that are common in construction and maintenance processes. The above also includes vertical planning, i.e. artificial increase of the planned elevation marks of the developed territory, hydraulicking, wall drainage, etc. [23, 25, 26].

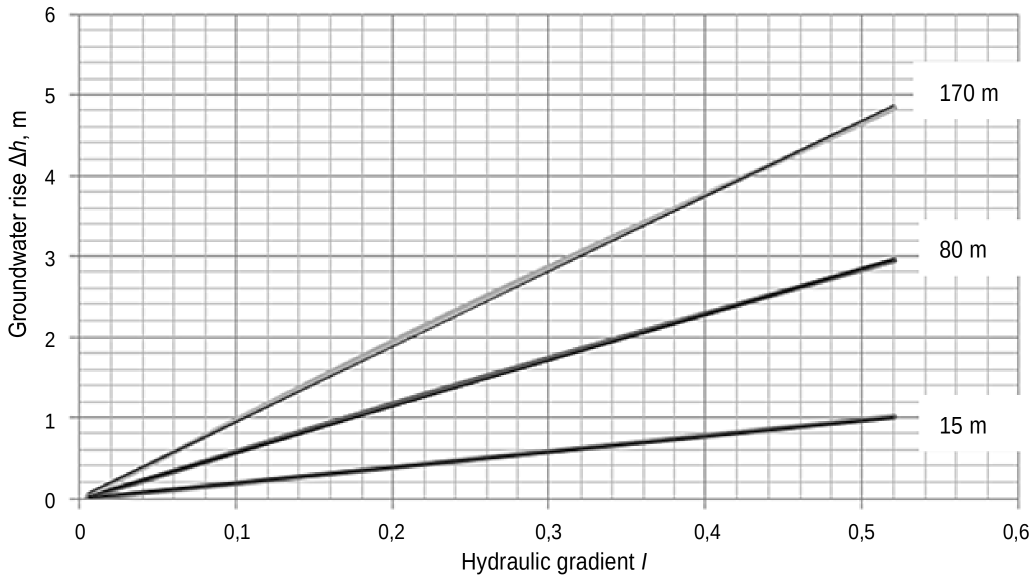

Fig. 8. Groundwater rise value Δh for the different values of the groundwater table incline I (hydraulic gradient) and the building width B
Рис. 8. Величина подпора подземных вод Δh при различных значениях гидравлического уклона I и ширине здания B

The above aspects predetermine the necessity of timely and correct prediction of the groundwater level change for the construction and further engineering preparation of the city territory, as well as for the development of effective protection measures. The realization of this extremely urgent and important task is necessary for the preservation of the historical and cultural heritage of the old Siberian cities.

Conclusion

The analysis of the research results shows that the hydraulic gradient *I* of the underground water flow and the project structure width *B* have the biggest effect on the groundwater rise. The equation solutions for multiple objects have made it possible to develop an analytical model for the prediction of the groundwater rise. The model is quite multi-purpose and can be used for the groundwater rise forecasts in many historical urban areas with similar geological and hydrogeological conditions.

Vertical planning of the territory and the use of pile foundations play a significant role in the formation of the groundwater level. Besides, when evaluating the depth of the underground water formation level and developing the prevention and protection measures, it is necessary to take into account the seasonal rise of the underground waters.

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