Complex approach to evaluating the underground hydrosphere stability for the urbanized areas in the Angara river basin (East Siberia, Russia)

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Abstract. The development of East Siberia is accompanied by the urban population and infrastructure growth, which in turn, leads to an increase in the intensity of the technogenic impact on the geological environment (GE). One of the most unstable GE components is the underground hydrosphere. In hydrogeological terms, the research area is located within the Angara-Lena artesian basin. The sedimentary cover of the area has a block structure, which, along with the erosion network, predetermines the formation of the current hydrogeological conditions. The article considers the key factors for evaluating the complex index of the hydrosphere stability. There are three groups distinguished: natural factors forming the stability margin, technogenic factors causing the underground hydrosphere evolution, and natural-technogenic factors reflecting the ongoing evolution. The article focuses on the first group concerning evaluation of the drainage degree and the model filtration cross-sections stability. Ecological-hydrogeological zoning of the areas under research based on the complex hydrosphere stability index allows us to mark out the sites where environmental measures are required to prohibit the urbanization negative impact.

1. Introduction
Urbanization is a process of formation and development of urban settlements including large agglomerations with multimillion population and complex urban infrastructure. The urban growth is characteristic of all the continents and is likely to continue on an even more intensive scale in the third millennium.

East Siberia is not an exception. In spite of a general decrease in the population growth observed in the last 26 years, there has been a permanent growth of the large cities population, including the capital city. The region area is 775,000 square kilometers; the population is 2,404,000, 78.8% of which live in 22 cities. The biggest cities are Irkutsk (624,000), Angarsk (226,000), Bratsk (231,000), Ust-Ilimsk (82,500), Usolje-Sibirskoje (77,900), Cheremkhovo (51,000) and Shelekhov (47,600). Most of the cities are situated near large transport lines, namely the Trans-Siberian railroad and the Baikal-Amur railway. There are 15 zones within which most of the ecologically dangerous stationary objects are located. Six of the industrial cities in the central part of the region are on the list of the most polluted cities of the Russian Federation. 957 enterprises of the cities exhaust industrial wastes in the atmosphere or surface water, the total volume of the atmospheric pollutants being 1,200,000 – 1,300,000 tons, including dust, sulfur, nitrogen, carbon, chlorine oxides, etc. [1].

The soils of the industrial cities are polluted with lead, mercury, zinc and tin, while the surface waters, with mercury, iron and copper. The ground water (GW) pollution and the phreatic decline are
also the case due to the industrial wastes, polluting agents leakage and the uncontrolled water intake accompanied by violation of the technical and sanitary requirements. The ongoing rise in the ground water level in the biggest cities (Irkutsk, Angarsk, Usolje-Sibirskoje) impacts the physical-mechanical soil properties and the bearing capacity, which often causes the facilities destruction. Many of the polluting enterprises do not take measures to reduce the hazardous effect on the environment. As a result, natural-technogenic processes are intensified, the ecological situation in the cities and industrial zones is aggravated, that is, the “man-environment’ conflict is worsened [2].

The above problems are quite diverse, but most of them are directly or indirectly connected with the underground hydrosphere (UH) state. This is why one of the urgent tasks at the moment is to create a complex evaluation system to forecast the UH evolution and develop recommendations on the technogenic impact control. For this purpose, a complex index of the underground hydrosphere stability (UHSI) has been devised that includes characteristics of the region’s nature conditions (geostructural, geomorphological, hydrogeological and engineering-geological), as well as integral estimates of the technogenic load indices, the set of the latter being selected depending on the scale and function character of the research territory [2].

The research done includes numerical modeling of the UH change retrospective conditions based on the monitoring observations and historical-geological analysis (epignose modeling), reconstruction of the UH current state (current-state modeling), and forecast of the UH state with the account of the current technogenic loads (predictive modeling). As a result, the key factors forming the UH state have been defined according to the object taxonomy level, and three factor groups have been distinguished: natural stability, technogenic load and natural-technogenic. A set of the factors has been taken as a basis for the UHSI definition and further zoning of the areas by this index.

The article presents the methodology for the complex index development and the UH stability natural factors estimation for the urban areas.

2. Research procedure
A systems’ approach is applied in the research: the research objects are considered as natural-technogenic systems functioning by certain laws [3] and having a distinct taxonomic hierarchy (Figure1) that allows us to consider the significance of each factor and the character of their interrelation. The research procedure is of a universal character and has the following algorithm: collecting and systematizing the data on the geological and hydrogeological conditions of the area under research, as well as the data on the factors of the technogenic impact and on the results of the impact (pollution dynamic and/or natural-technogenic processes intensification); creating a database using a specific form; numerical modeling (epignose, current-state and predictive), analysis of the results obtained and defining the key natural and technogenic factors; defining typical UH models with the account of the natural-technogenic conditions complexity; ecological-hydrogeological zoning based on the complex index; developing environmental measures.

2.1. Geological-hydrogeological conditions of the area under research
The procedure test is done on the urban areas in the Angara river basin. The research region belongs to the Irkutsk basin, one of the Angara-Lena artesian basin’s largest structures of the 1st order. The water-bearing deposits are: sandy cobble (Quaternary formation); sand-rocks, siltstone and clay stone (Jurassic formation); dolomites and haloid rocks (Cambrian formation). The sedimentary rock mass has a block structure inherited from the crystalline basement. The tectonic fault systems with the corresponding erosion network pattern define the geomorphological picture and, to a large extent, the current hydrogeological and engineering-geological conditions of the region. The first and the second above the flood-plain terraces confined to the lowered earth crust blocks are at a significant distance from the Angara river, the main drain. They are quite heavily built-up, with a correspondingly developed infrastructure, and with the level of the ground water in the most loaded zones being 0-1 m from the earth surface, while the flood-plains situated at the water’s edge and formed by the blocks
raised relative to the other basement blocks, with the same technogenic conditions have a much lower ground water level, 6-7 m [3].

Figure 1. Taxon hierarchy.

2.2. Technogenic conditions and natural-technogenic processes

Analysis of the geological environment current state and the character of its change under the technogenic influence helps to define both the main kinds of the technogenic loads and the results of their impact such as pollution of the ground water, waterlogging, change in the physical-mechanical properties of the soil, as well as underwashing and ground subsidence processes.

Diversified pollution of the ground water (chemical, thermal, biological) is caused by different reasons. One of the main reasons is dumping the sewage water in the Angara river that is the main water way and drinking water source of the region. The sewage water volume is up to 3 km$^3$/year, 75% of which dumped in Angara, and 50%, without water treatment. The ground waters of the aquifers nearest to the surface normally have a close hydraulic connection to the river; therefore, the chemical industry liquid waste dump significantly impacts the geochemical conditions.

Significant pollution of the ground water is observed in the Irkutsk urban area. The pollution reasons are connected with the municipal sewage tanks in the suburban districts and the petroleum product lenses formed on the ground water table as a result of the activity of the Zhilkin department of Irkutskefteproduct, a joint-stock oil company. Novo-Irkutsk thermal electric station, a department of Irkutskenergo, an electric power engineering joint-stock company, has detected ground water pollution with boron, fluorides (with the concentration three times exceeding the allowed limit (AL), iron and manganese (up to 35 times), aluminum (4 times) and petroleum products (up to 13.6 times) on the ash dump site. In some parts of the treatment utilities of Irkutsk, ammonium concentration is 67.3 times higher than AL [1]. In 2014, the ground water mineralization at the slimes tank site of Usoljekhimprom, Ltd. was 14.5 g/dm$^3$, which was most probably connected with the polluted atmospheric precipitation having penetrated the water through the waste filter.
Another important reason of the original conditions change is the state of the facilities causing diverse pollution: chemical (high content of nitrates, ammonium nitrates and phosphorus in the ground water); thermal (heat lines leakage increasing the ground water temperature up to 10-12°C, with the zone temperature of 3-4°C, and in the center of Irkutsk, up to the abnormal 45°C [5].

The underground utilities leakage often causes an increase in the ground water level followed by waterlogging and ground flooding. About half of the urban areas of the region are being waterlogged, so this is one of the most intensive natural-technogenic processes. Waterlogging is a complex process happening due to a set of factors. There are two groups of factors distinguished. The first group defines natural conditions for the filtration flows formation: the geostuctural position of the region, the peculiarities of the fault-block tectonic, the lithological composition of the water containing sediments, the set of the hydrogeological parameters of the water bearing segments (hydraulic connection with the surface waters, depth of the ground water, filtration parameters of the water bearing sediments). The second group defines the technogenic impact: underground facilities leakage leading to the formation of dome structures with the ground water depth of 0 to 1-2 m from the surface; water discharges of the Irkutsk hydroelectric station causing the Angara river water level fluctuation of 2-3 m/year [5]; by-pass filtration from the water-storage reservoir; over deepened building footings and underground structures causing a barrage effect; change in the physical-mechanical and water properties of the construction sites grounds as a result of the ditches and trenches backfill; change in the natural drain conditions resulting from the area planning, construction and development of the road network and often leading to waterlogging.

Another widely observed process in the urbanized areas is underwashing and ground subsidence. It is caused by three factors: the underwashing process itself, loessial and loess-type soils collapse, and subsidence of the undersealed fill-up soil often registered on the engineering facilities construction sites. Underwashing and ground subsidence mostly take place at the footings of the structures, there are also dip craters in the asphalt cover of the motorways and footways.

The change in the physical-mechanical properties of the ground has a significant impact on the engineering-geological conditions of the urban areas. It aggravates the load-carrying capacity of the structures footings and increases the seismic risk [6]. For example, monitoring of the soil humidity in Irkutsk shows an average change from 18.7 to 20.6% leading to a decrease in the inner friction angle and modulus of deformation [2].

In spite of the natural inheritance aspects, it is the technogenic factors that influence the development of the natural-technogenic processes including underwashing, ground subsidence and flooding.

2.3. Data base and modeling the conditions for the underground hydrosphere state formation

The next stage of the research is designing the structure and creating a database with further numerical modelling. The database consists of 19 attributive positions.

Modelling is done for three time periods. The first one is based on the data from the regular observations aimed at defining the conditions of the initial natural state of the hydrogeological systems (for some objects, the period being over 30 years).

On the second stage, the current state of the natural-technogenic system and underground hydrosphere is modeled. The stage is based on a system approach using the multifactor analysis of the initial data and the main component method [8].

The third period includes predictive modeling that allows evaluation of the UHSI natural components change as a result of the technogenic impact. For example, under the condition that the level of the technogenic influence in the central part of Irkutsk remains as it is now, the ground water level is going to rise at a speed of 0.5-3 mm/year, with 5-7% aggravation of the load-carrying capacity of the structures footings grounds (inner friction angle, modulus of deformation).

The modeling results have allowed us to specify the set of the natural and technogenic factors that are part of UHSI and form the current state of the UH different taxonomy levels (Figure1).
Of most practical value is the taxon including the urban areas (Figure 1 – T III). Figure 2 shows the set of the factors used to evaluate the UH stability for the urban areas.

2.4. Defining sample UH models and ecological-hydrogeological zoning
At present, two directions in UH stability evaluation are developed: a hydrogeochemical one aimed at evaluating the UH protection in relation to the diverse pollution, and a hydrodynamic one defining the ability of the UH to keep the natural structure of the filtration flows [7, 8]. The article focuses on the principles of evaluating and mapping of the UH hydrodynamic stability [7, 9].

To optimize the evaluation procedure, Quantum GIS, an advanced open geoinformation system (GIS) is used, based on which Atlas of the Geological, Hydrogeological and Technogenic Conditions of the Irkutsk Urban Area” has been compiled [10]. The Atlas presents every item of the geological environment, every factor of the technogenic load and the result of the technogenic impact as an independent raster or vector layer.

Then, an integral index of the UH stability is defined and ecological-hydrogeological zoning of the area is done.

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**Figure 2. Structure of the hydrosphere complex index for the urban areas.**
Ecological-hydrogeological mapping is based on an expert numerical score review relating to the drainage degree conditions, filtration properties of the model hydrogeological cross-sections, and the depth of the ground water level. The second groups of the factors are technogenic loads and their expert evaluation described in the previous works [9, 10]. And the last component concerns the results of the technogenic impacts manifested in the engineering-geological processes [10, 11].

3. Results
The researchers suggest different approaches to the drainage degree evaluation [9, 10], in particular, elevation of the observation point above the base drains, and introducing a parameter of the natural drainage within elementary drainage areas of the erosion network [11], as well as the surface slope angle [2]. Thus, drainage in the context of the present work indicates the capacity of the area to discharge the ground water resources formed by the atmospheric precipitation, infiltration from the surface drains and flow from the adjacent water bearing structures and technogenic sources. The index has a significant influence on the formation of the engineering-geological conditions under which construction and maintenance of the urban infrastructure is done. The drainage conditions of the Irkutsk urban area are presented in Figure 3.

![Figure 3. Integral drainage scheme: 3-4 – underdrained, 5-7 – moderately drained, 8-10 – well-drained, 11 - 12 – high-drained/](image1)

![Figure 4. Scheme of zoning by the stability of the model filtration sections: 1 – stable, 2 – middle stability, 3 – poor stability, 4 – unstable.](image2)

The next important natural factor indicates the capacity of the rock mass to filter the ground water and is determined by the peculiarities of a geological section, including the presence of the poor permeable rocks, filtration capacity of the country rock and their thickness. Based on the results of the above characteristics, a zoning map is charted by the type of a filtration cross-section. For example, there have been 6 sample cross-sections distinguished that form different geomorphological elements and have a similar geological structure (Figure 4).

The result of the integral evaluation of the selected parameters in the form of the ecological-hydrogeological drainage scheme and the stability map of the model filtration cross-sections in the Irkutsk urban area is presented in Figure 3 and 4.

4. Conclusions
Based on the results of the research done for the big cities of East Siberia, three groups of factors have been defined that determine the underground hydrosphere stability in the urbanized areas: the first one includes the natural characteristics, the second one, types of the main technogenic loads, the third one, the results of the loads in the form of the natural-technogenic processes.
The second and third group of factors are described and evaluated in the earlier works [9, 10, 11]. The present work focuses on the first group of factors distinguished as the main factors influencing the UH stability: morphometric relief indices that indicate the drainage degree of the areas under research, and the filtration capacity of the rock mass expressed as model filtration cross-sections.

The quantitative evaluation of the above indices using an expert review method allows us to finalize the definition of the structure of the hydrosphere stability complex index (UHSI) and revise the methodological principles of ecological-hydrogeological mapping for the urban areas of East Siberia, including the ones in the Angara river basin.

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