

The development of dangerous exogenous geological processes in the historical part of the Kazan city

Anastasiya Garaeva¹, and Airat Latypov^{1*}, Fedor Bufeev² and Nadezhda Orlova²

¹KAZAN FEDERAL UNIVERSITY, Department of General Geology and Hydrogeology, 420008, 4/5 Kremlyovskaya Street, Kazan, Russia

²SERGEEV INSTITUTE OF ENVIRONMENTAL GEOSCIENCE RAS, Ulanskiy lane 13 bldg 2, Moscow, Russia

Abstract. This article is about studying of dangerous exogenous processes and the assessment of the risk of adverse processes in the historical part of the city of Kazan. As a result of the centuries-old economic development of the urban territory of Kazan, engineering-geological and hydrogeological conditions have significantly changed, which caused the activation of unfavorable geological processes that violate the stability and safety of cultural heritage sites of the city. The authors have developed a methodology based on the analysis of physical, economic, social and environmental risk. This will minimize the losses caused by the manifestation of dangerous geological processes.

1 Introduction

The greatest threat to the central part of the Kazan city is flooding of the territory, karst-suffusion (sinkholes, subsidence) and landslide processes, to a lesser extent - channel and ravine erosion, abrasion (erosion and collapse of the banks). The greatest danger in the activation of these dangerous exogenous geological processes is represented by the territories within which structures with shallow foundations are located. This is mainly the historical part of the city of Kazan. There are 2-4 floors administrative buildings and religious buildings located here. The metro line is located in the immediate vicinity.

Today, the problem of studying the peculiarities of the emergence and activation of dangerous exogenous geological processes in urban areas is most acute, as evidenced by a large number of publications [1, 2].

Assessment and calculation of the risk of hazardous geological and engineering-geological processes is one of the most difficult and urgent tasks in the framework of engineering surveys for various types of construction. Many scientists in Russia and abroad are engaged in these works [3, 4].

Varnes D.J. & Cruden D.M. present a fundamental classification of landslide processes and mechanisms of their formation. The authors emphasize the importance of an integrated approach to the study of EGP [5].

Hungr O., Leroueil S., Picarelli L. expand the classical classification to include new types of mass movements and modern methods of their research [6].

Gariano S.L. & Guzzetti F. analyze global trends in the development of EGP in the context of climate change [7].

* Corresponding author: airatlat@mail.ru

Chen W. & Zhang S. describe the application of machine learning methods to predict EGP [8].

Shroder J.F. & Davies T. present a global analysis of the spread of EGP in various geographical and geological conditions [9].

Reichenbach P., et al. analyze modern statistical methods for assessing the vulnerability of EGP territories [10].

To fully assess the risk of dangerous geological processes, it is necessary to understand the geological conditions of the studied area.

The territory of the historical part of the city is located in the southern part of the Kazaklar shaft. The structure was formed as a result of neotectonic processes inherited from older ones. A system of flat dome-shaped elevations separated by deflections was formed here. For the central part of the city of Kazan, the Kazan anticline structure with a wing drop of up to 0.045 is distinguished along the roof of the Nizhnekazansky sublayer. The Upper Permian (Kazan) deposits in the valley and west of the Volga form a series of elongated blocks elongated along the line Lake Nizhny Kaban – Lake Sredny Kaban – Lake Verkhny Kaban. In most of the area, Quaternary deposits are deposited on the Pliocene. The total capacity of the latter varies from 10 to 60-80 (maximum – 103 m). Geologically, Permian, Neogene and Quaternary deposits are developed on the daytime surface within Kazan and its environs [11].

The territory of the historical part of the city is located on the left bank of the Volga River in the zone of junction of the denudation Pre-Kama upland and the Trans-Volga lowland, the surface of which is covered by alluvial terraces of Quaternary age, attributed to the Neogene deposits of the ancient valley of the Volga River. The following terraces are distinguished in the central part of the city:

The first above-floodplain terrace is almost completely flooded by the waters of the Kuibyshev reservoir (1957), rarely rising above the water surface in the form of separate islands. The terrace surface is located at altitudes 51-55 m.

The second above-floodplain terrace lies at altitudes from 51 to 60 m. The width of the terrace is 0.5- 4 km. This terrace is characterized by the presence of sandy and clay, blocked soils with a thickness of up to 30 m and groundwater occurrence close to the daytime surface. In the central part of the city, as well as along the western shore of the near and middle Kaban lakes, the thickness of clay soils ranges from 4-7 to 11 m (Lavrentievskaya, Tukaevskaya, Lebedeva streets). In the area between the middle and far Boar, their capacity reaches 19 m.

As a result of the redevelopment and development of the central part of the city, the terrace area has been significantly changed. In the newly built-up part of the city, as part of the second terrace, in places of terrain irregularities (ravines, swamps, pits, etc.), bulk soils that have accumulated for a long time lie. According to genetic characteristics, bulk soils of Kazan are divided into: construction debris, alluvial soils, industrial waste, household accumulations. They are distributed along Podluzhnaya and Fedoseevskaya streets, along the left bank of the Kazanka River; in Vakhitovsky districts from the Volga floodplain. The capacity of bulk soils is 6-9 m. On the territory of the former circus, in the filled-in karst craters, the embankment reaches 16.5 m, and on Kremlevskaya Street, near the museum - 24.5 m. A significant part of the objects erected on bulk soils have uneven deformations.

The third above-floodplain terrace is located in the western part of the city. The maximum width of the terrace is 5 km. The absolute heights are in the range from 70 to 100 m. The ground layer, with a thickness of up to 80-90 m, is mainly represented by sands.

Below the alluvial terraces of the Quaternary age are the bedrock of the Kazan and Urzhumsky tiers of the Permian system. According to the lithological feature, the Kazan tier is divided into the Lower Kazansky and Upper Kazansky sublayers. The Nizhnekazansky deposits reach the daytime surface only in the area of the Kazan Kremlin, reaching an altitude of 62.38 m, and are represented by a thickness of sedimentary rocks composed of sandstones, limestones, as well as marls and clays. In the rest of the city, the Nizhnekazansky deposits

are overlain by the Verkhnekazansky ones. The Upper Kazanian deposits within the city are exposed near the Kremlin in the cliffs of the second floodplain terrace, on the shore of Lake Sredny Kaban. The rocks lying in the roof of the Upper Kazansky sublayer are usually broken by cracks, leached and quarried in places.

The groundwater of the Quaternary deposits plays an important role in the hydrogeology of Kazan. They affect the basic engineering solutions of new buildings and the technical condition of existing buildings and structures. The depression curve of the groundwater level, smoothly bending, passes from one terrace to another and interacts with the water level in the reservoir.

In clay and sandy soils of Quaternary sediments, groundwater of lenticular occurrence is found according to the type of upper water. In some areas of the city, located on high above-floodplain terraces, where, as a rule, new construction is underway, there is a local increase in the groundwater level. The groundwater level is developed locally here within the III above-floodplain terrace. at a depth of 1.8-4.4 m (altitudes 68.74-78.70 m). It is formed due to leaks from water-carrying communications and infiltration of atmospheric precipitation. A technogenic alluvial horizon is developed within the II above-floodplain terrace at a depth of 3.0-4.5 m (altitudes 58.20-60.63 m). The main Upper Permian aquifer is spread over altitudes of 49.22-53.15 m.

2 Materials and Methods

The physical, economic, social risk and integral risk were calculated on the basis of long-term studies of the engineering and geological conditions of the city of Kazan by the staff of the Department of General Geology and Hydrogeology of Kazan Federal University. Some parameters (of a social and economic nature) were replaced with similar parameters for Moscow. According to the theory of assessment of natural (physical) risks, calculations were performed using the following formulas $\{(6)\}$:

1) Physical risk assessment

$$R_f(H) = P^*(H) * D_f(H) \quad (1)$$

$$D_f(H) = V_f(H) * S_o = (S_H * S_o) / S_t \quad (2)$$

Formula $\{(1)\}$ characterizes the total physical risk of damage to the territory, where $P^*(H)$ is the frequency of occurrence of danger H, numerically equal to its statistical probability (case/year); $V_f(H)$ is the vulnerability of the territory to danger H; $D_f(H)$ is material damage, represented as an area affected by a single occurrence of danger H; S_H – the area affected by danger H; S_o – the area of the object; S_t – the estimated area.

2) Economic risk assessment

$$R_e(H) = P_f(H) * d_e * a \quad (3)$$

where $R_f(H)$ - is the physical risk of land loss, case/year; d_e - is the density of national wealth, million units; a - and is the economic vulnerability of the building.

3) Social risk assessment

$$R_s(H) = P_f(H) * d_p \quad (4)$$

where d_p - is the population density, people per hectare.

When assessing hazard H, the average values of the size and frequency of processes, as well as the probability of damage and vulnerability to them of the building and the population, were used. With the simultaneous manifestation of several exogenous processes in a certain area, the integral physical / economic / social risk (damage) will quantitatively and spatially correspond to the largest of the individual physical / economic /social risks. According to the above principle, to calculate the integral risk in the study area, the values of individual risks

were gradually compared with each other, and then the integral risk was equated to the maximum value of an individual risk (Fig. 1).

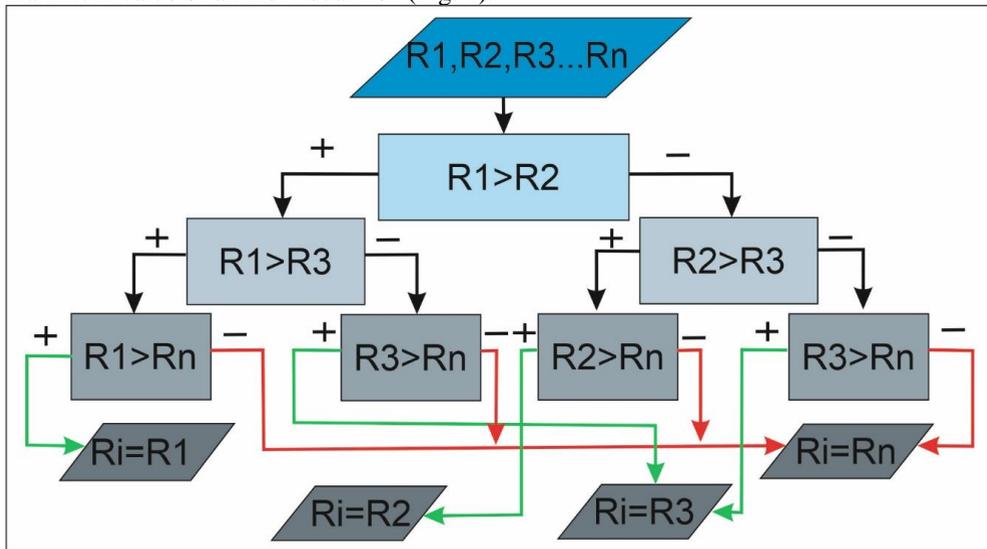


Fig. 1 Risk Assessment Framework

3 Discussion

As a result of the research carried out, it was found that both construction and hydraulic engineering processes leading to flooding are actively manifested in a significant area of the historical part of the city of Kazan. Hydraulic flooding in the studied area is caused by the rise of the groundwater level as a result of the creation of a reservoir. For the territory of Kazan, the construction of the Kuibyshev reservoir in 1957 resulted in the flooding of a vast area and the flooding of a large part of the historical center. Currently, about 20% of the urban area of the city of Kazan can be attributed to the area of hydraulic flooding. However, the creation of a reservoir is not the only reason for the rise of the groundwater level in urban areas. Underground heating mains, water supply and sewerage systems operate within the city, ensuring the operation of not only residential buildings, but also a variety of industrial infrastructure. A significant part of the water circulating through underground urban utilities gets into the ground. In Kazan, the amount of leaks from water-carrying communications (according to the Ministry of Ecology and Natural Resources of the Republic of Tatarstan) is more than 30 million m³/year. Excessive soil moisture is also facilitated by a violation of the evaporation regime of soil moisture caused by the widespread use of asphalt pavement.

In addition to flooding due to leaks of water-carrying communications, suffusion processes are developing in the territory of the Vakhitovsky district. From 2013-2024, local subsidence with a diameter of several meters and a depth of up to 1 m was recorded in the central part of the city on Gogol, Nuzhin, Bauman, Dzerzhinsky, Astronomical and Trade Union streets, Tatarstan from Levo-Bulachnaya Street, Kavi-Najmi Street, near the northern part of the Kremlin Hill near Baturin Streets.

The territory of the Kremlin Hill is located within the complex of high terraces from Baturin Street to St. The university has long been famous for karst sinkholes, described in detail in numerous scientific and public publications. The surface has the appearance of a flat-rounded hill covered with bulk soils and surrounded from the north, west and east by the first over-floodplain terrace. The slope height is 13-19 m, the steepness is 10°-45°, the absolute marks of the sole are 60-65 m, the edges are 78-85 m, the slope is covered with grassy, sometimes shrubby vegetation. Engineering-geological section to a depth of 30 m. It is represented by heterogeneous bulk soils: loams and clays, sand and sandy loams of

Quaternary age; sands, clays and loams of the Pliocene; carbonate-clay flour, gravel and crushed carbonate eluvial rocks of Permian age, and Permian bedrock. The most frequently considered series of failures in the area of Alexandrovsky Passage, which occurred in the 70s of the XX century. There are 11 funnels, with a diameter of 3-4 m to 5-7 m, and a depth of about 3-6 m. The field of funnels stretches from northwest to southeast, parallel to the southern slope of the Chernoozersk depression.

Karst sinkholes have also been recorded in the inter-lake space of the Upper and Middle Boar. In 1925, a 7.5 m deep sinkhole occurred on Diaghternaya Street, and in 1949, a 23 m deep sinkhole occurred on Ostrovsky Street. To the south of the above-described territory, in the south-western direction from Lake Sredny Kaban, there is a section of sinkholes known as the "Devil's Corner". Over the last century, there have been two sinkholes with a depth of 15 m.

Landslides in the central part of the city of Kazan occur annually, which is manifested in the appearance of cracks in the walls of various buildings. This is typical, as a rule, for buildings with a shallow foundation, located in close proximity to the edge of the slope, composed of "weak" sandy loam-loamy soils. The appearance of such deformations indicates the stressed state of the soil mass, the underestimation of which can lead to a decrease in the operational reliability of structures. In 2024, landslide processes were observed in the sloping part of the wall of the Kazan Kremlin, in the retaining walls along Trade Union Street on the territory of the KFU, Dzerzhinsky Street in the walls of the Ivanovo Monastery, along Podluzhnaya from the side of the slope of the Millennium Bridge, on a terraced slope along Malaya Krasnaya Street. Landslide processes are predominantly delapsive and sequential in terms of the mechanism of displacement of rocks — landslides are viscoelastic, according to the depth of rock capture by landslide deformations, they are shallow. In the slopes and sides of the ravine, dispersed soils are opened in unstable dynamic equilibrium (at a height of > 7 m and a steepness of > 40 degrees).

The main factors in the formation of landslides in the historical part of the city of Kazan are:

- the steepness of the slopes, as a rule, is more than 30°, due to both natural and man-made factors;
- the predominance of sandy loam-loamy soils in the section, which provide weak resistance to tangential stresses in the massif;
- temporary or permanent increase in soil moisture as a result of active snowmelt, prolonged rains, as well as leaks from water-carrying communications;
- loading of the slope with structures for various purposes, contributing to an increase in stresses in the soil mass;
- dynamic loads from moving ground and underground transport, pile driving and so on.

The peculiarities of the geological and geomorphological structure of the territory of Kazan also led to the development of gully processes. During the period of the city's development, ravines began to be of interest as objects of territorial reserve [6], for example, as highways, which helps to reduce the load on the existing transport network of the city. Examples of such objects are Pushkin Street, Butlerova Street, Tolstoy Street, Zhukovsky Street, Vishnevsky Street (bottom of Gorkinsky ravine), etc.

One of the optimal solutions for the development of the ravine network is the construction of facilities at several different levels (Pushkin St., Zhukovsky St., Zaslونov, etc.).

Ravines are also used as conservation areas for the distribution of rare plant species and animal habitats. In Kazan, such places include "Russian-German Switzerland", which has the status of a natural monument of regional importance. Sometimes gully systems can be used as parks (Gorky Park).

The spatial distribution of the main geological processes in the territory of the historical part of the city of Kazan is shown in Figure 2.

As a result of the combined action of unfavorable geological processes, deviations from the vertical of walls, destruction of brickwork, cracks, subsidence of soil, traces of wall soaking, destruction of the finishing layer of many historical buildings were recorded in certain territories. Examples are the Suyumbike Tower, buildings and structures of the architectural ensemble of the Kazan Kremlin, the ruins of the Pentagonal Tower, the Peter and Paul Cathedral, the Ivanovo Monastery, etc.

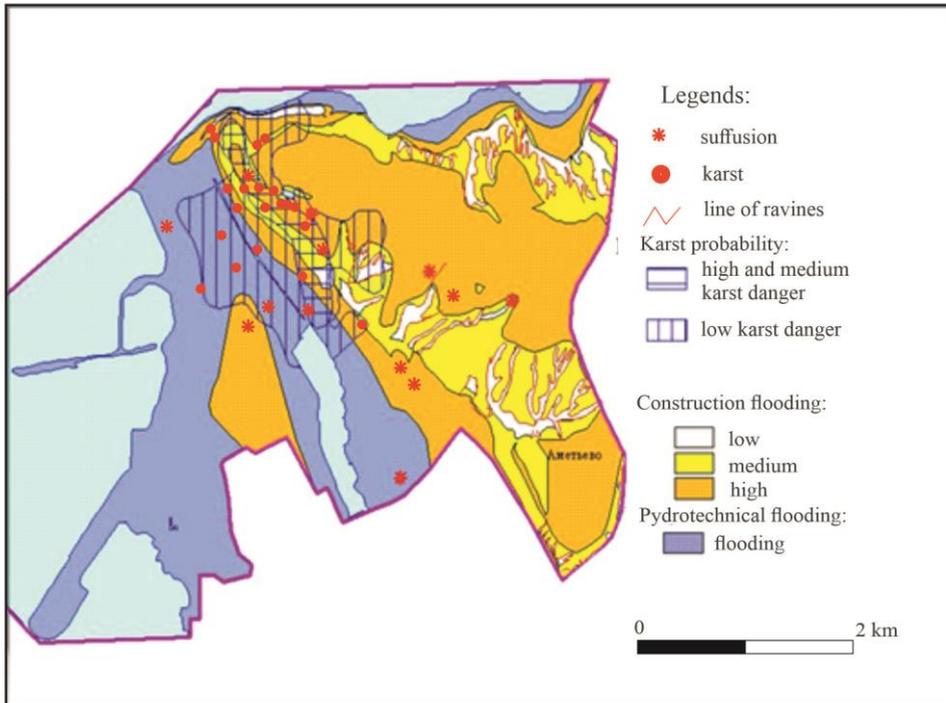


Fig. 2. Geological processes on the territory of the historical part of the Kazan city

4 Results

The conducted studies show that the northwestern part of the studied territory is characterized by increased risk values due to karst danger. The maximum probability of risk is 1 case in 10 years, economic damage is 22.5 million units, and social risk is 4 people in 100 years. The lowest probability in this area is 3 cases per 1000 years, possible economic damage is 100-150 thousand units, and social risk is 1 person per 1000 years. The probability of hydraulic flooding is very low here. The territory occupied by low terraces is characterized by the risk caused by karst danger and hydraulic flooding. The probability of karst here is 1 case. over 1000 years, economic damage – 50-100 thousand units, social risk – 1 per 1000 years. The probable increase in the groundwater level is 0.5 m, economic damage is 500-700 thousand cu. The remaining areas are characterized by widespread development of hydraulic flooding and a low probability of karst. The probable increase in the groundwater level is from 0.5 to 1 m., possible economic damage is 500-1000 million units. The probability of karst is 1-2 cases. over 1000 years, possible economic damage – 50-500 thousand units, probable social risk – 1 person per 1000 liters.

Landslide processes are developing along the left bank of the Kazanka River and on the ledges of the terraces. The probability of landslide deformations is 1-2 cases per 1000 years, the possible maximum economic damage is 600 thousand units, the probable social risk is 1 person per 1000 years. The final possible damage to the assessed buildings from the karst-suffusion process is 30%, from landslide formation – 13%, from hydraulic flooding – 42%.

The conducted studies have shown a very high dependence of the socio-economic sphere of the central part of the city of Kazan on exogeodynamic conditions. The maximum values of physical, economic and social risk are characterized by the north-west of the district – Kremlevsky Hill and the vicinity of Kremlevskaya Street. The main reason for such a high geological risk is the widespread development of karst–suffusion processes, high population density, dense buildings. The rest of the studied area is usually characterized by not so high values of geological risk, which is due to less complex engineering and geological conditions and a lower population density. Sustainable and safe development of the central part of the city of Kazan must necessarily be based on reducing geological risk, which, in turn, should be based on constant monitoring of the activity of geological processes (monitoring) and on a set of carefully planned measures for the engineering protection of structures. The recommended measures will significantly reduce the economic and social risk from exogenous geological processes within the central part of the city of Kazan.

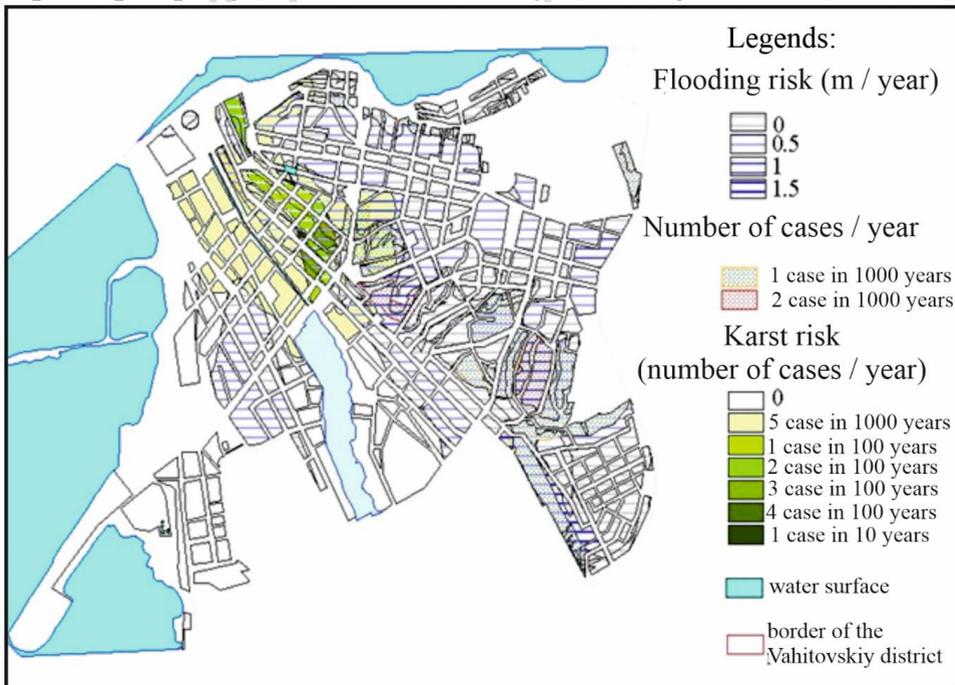


Fig.3. Integral physical risk from dangerous natural and anthropogenic processes in the territory of the historical part of the city of Kazan in the Vakhitovsky district

5 Conclusion

1. The proposed methodology for assessing physical, economic, social and environmental risks is aimed at minimizing damage from the impact of hazardous geological processes on the safety of buildings in the central part of the city of Kazan.
2. Today, there are significant deformations and destruction of historical architectural monuments of Kazan (including the objects of the Kazan Kremlin, temple buildings and monastery complexes).
3. The most dangerous zone of development of exogenous geological processes is the northwestern part of the territory, where karst processes, landslides and flooding are actively developing.
4. In order to ensure the sustainable and safe development of the central part of Kazan, it is necessary to reduce geological risk by organizing constant monitoring of geological processes and implementing comprehensive measures of engineering protection of

structures, which will minimize economic and social risks from the effects of exogenous geological processes.

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