The issues of sustainability of historical and cultural areas associated with their periodic underflooding and solutions

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Abstract. The Russian Federation has multiple valuable historical and cultural monuments. Many of these objects are truly unique and belong to the world's cultural treasures. Nearly half of them are objects of federal significance (including more than 20,000 archaeological heritage sites), and the rest are of regional significance, 13 cultural and 8 natural heritage sites are on the list of World Cultural and Natural Heritage formed under the auspices of UNESCO. Observations on the state of objects of historical and cultural heritage in the Russian regions show that such objects are largely susceptible to destruction as a result of adverse natural influences. These impacts adversely affect the preservation of cultural heritage sites, and lead to their destruction and their possible loss. Therefore, it is important to protect the objects of historical and cultural heritage.

1. Introduction

Almost half of the cities of Russia (425) are historical cities (79% in the European part, 11% in the Urals, 10% in Siberia and the Far East), in which there are about 25,000 monuments of federal significance. This is a huge cultural historical heritage that collapses before our eyes when there are no protective measures from dangerous natural processes, environmental disasters and waterlogging of territories [1].

Among the dangerous natural processes that have a long-lasting effect, underflooding stands out, i.e. exceeding the critical values of groundwater levels for sites and territories.[2,3] Underflooding causes the initiation of other hazardous processes, such as landslide, suffusional karst processes, and also leads to waterlogging of the territory and ecological disturbances of built-up historical territories. In addition, a survey of a significant number of objects in the territory of 20 historical cities showed that about 70% of them are deformed, many architectural monuments are in disrepair due to the developing deformations of their underground parts due to the liquefaction of the grounds of the structures, reducing their carrying capacity [3].

Let us give some typical examples of violation of the general condition of historical territories during their underflooding. Rostov the Great is one of the oldest historical and cultural monuments of North-Eastern Rus. It is located on the shore of Lake Nero. [4]The plain lowland position of the city,
as well as backwater from the lake and excessive moisture of the territory, poor drainage of the territory contributed to the violation of ecological balance and waterlogging of the territory, the development of frost heaving of soils and watering of soils, which led to deformation of the walls of old buildings, the formation of cracks in the walls and bright pronounced underflooding of the territory."[5]

Another example is the Novgorod Kremlin. On the territory of the Kremlin, due to leaks from the water-carrying communications and the infiltration of precipitation, a water horizon was formed close to the surface [6]. As a result, the territory was flooded, subsidence phenomena occurred and the bearing capacity of the grounds of the foundations of structures decreased, building deformations happened, and in 1993 a failure of the Kremlin’s divided parts of wall occurred (37 m long section).

On the territory of the Kirillo-Belozersky monastery, the sources of underflooding and environmental discomfort due to waterlogging are Siverskoe Lake, the level of which has increased by 1.9 m due to the construction of the North Dvina hydrotechnical system. The foundations of architectural monuments are being destroyed, and basements of buildings are being flooded [6,7].

In the Kostroma Museum-Reserve, due to the construction of the Gorky Reservoir, the level of groundwater has risen, the territory has been underflooded, vegetation has been degraded, waterlogging has occurred, and the ecological balance has been disturbed. At the same time, the walls and buildings of the Ipatiev Monastery undergo deformations and destruction. There are many such examples [7].

The usual protective and preventive measures against flooding and restoring the ecological balance of the territory are various types of drainage, waterproofing systems, and surface runoff management systems. But there is one significant nuance of applying standard drainage methods in historical territories. All historical territories have one significant feature - the presence of a cultural layer for which water is a preservative. So, for the flooded territory of the Novgorod Kremlin, ordinary water-lowering works turned out to be unacceptable, since there are powerful strata of the cultural layer (the 10th century layer is located at a depth of 6.6 m, the 11th century layer at a depth of 5.9 m, the 15th century - 1.4 m). The cultural layer contains unique archaeological artifacts and it is a valuable archaeological material. By value, the birch bark manuscripts of the Novgorod Kremlin are equated with the Egyptian papyrus. Moist soils ensure their safety [7].

In addition, many buildings in the Russian northern cities have traditionally been located on a wooden base (lumbers - sills, piles – short plates). Humidity of the soil ensures the safety of the wooden base, and its drainage leads to rotting and additional deformations and destruction of buildings [7].

On the other hand, for the exploitation and preservation of buildings, the building itself, the basement and other buried premises must be dry. Therefore, the use of standard drainage measures leads to even greater deformations and losses of the invaluable cultural layer, the destruction of the foundations’ basis of buildings. Thus, drainage can cause a negative drainage effect, suffusion, surface subsidence, overdrying of the soil and further deformation of buildings [7].

2. Methods
An important solution for soft regulation is the use of a criterion for the threshold of hydrogeological hazard, the critical level of groundwater, which is determined for each object and the plot of built-up area [8]. To determine the critical and limiting groundwater levels for various buildings, a typology of objects was developed depending on the properties of the foundations [9]. In the historical territories, 4 main classes of objects were identified according to the requirements for draining: these are objects that allow and do not allow the humidified state of the ruined structures and basements, and among these groups there are objects located on a stone or wooden base (Figure 1).
Figure 1. Schematic image of different types of foundations of buildings in historical areas. Scheme 1 - the object allows humidification, but not the flooding of the basement, the foundation is located on a stone base; Scheme 2 - the object allows humidification, but not flooding of the basement, located on a wooden base; Scheme 3 - the object does not allow humidification, the foundation is located on a stone base; Scheme 4 - the object does not allow humidification, is located on a wooden base.

(Where: \(H_n\) - limit groundwater level (GWL) for objects (upper boundary), \(H_{br}\) - limit GWL for the wooden base of the building; \(H_0\) is the initial level; \(Z_n\) is the distance to the foundation from the water column; \(H_c\) - capillary border; \(H_{n}\) - the permissible range of fluctuations of the level for an object, \(H_{n}\pm(-)\) excess (decrease) over the average annual level).

3. Results

The typology of objects performed by the properties of the foundations made it possible to determine the critical and limiting levels of groundwater and drainage rates, taking into account the depth and material of the basis of the foundations of objects, the presence of basements, the effective zone of capillary border, seasonal excess levels [10]. It is important that fluctuations in the groundwater level relative to the critical level do not exceed the effective height of the capillary rise, within which the soil is saturated with water and ensures the safety of the cultural layer and the wooden base [10,11]. The flexibility of regulation provides the condition for the location of the groundwater level within the capillary border zone.

For solutions of flexible regulation of the groundwater regime, mathematical modeling was performed, the software and computing complex was developed [12]. At the heart of the software and computing complex is a method for solving extreme problems of determining parameters for regulating the regime of groundwater, which make it possible to maintain the level of groundwater in an acceptable safe range [12,13]. Computing of the calculated groundwater level with regulation parameters (drainage, pumping, specified as boundary conditions and source functions with the opposite sign) is performed using the Boussinesq equations (this is a parabolic partial differential equation, on the basis of which geofiltration is modeled, with appropriate boundary and initial conditions). The optimality criterion is the volume of the dried prism of the cultural layer and the dried area of the ruined premises [14]. Optimization criteria are formulated as functionals. The minimization of the functional determines the degree of closeness of the calculated lower values of the groundwater level by means of control actions to the specified value. The optimal solution that provides a minimum
of the optimization goal functionality is the desired optimal control parameter, which physically corresponds to the selected position of the drain or the pumped-out volume of water [14,15].

4. Conclusions
To develop optimal solutions by regulating the regime of groundwater, an appropriate method has been developed. The technique includes a sequence of actions: the introduction of initial information about the object of protection, the setting of the boundaries of the area, the initial and boundary conditions; the fulfillment of the predicted position of the groundwater level (solution of the direct geofiltration problem) and the calculation of optimization criteria; determination of the optimal position of the groundwater level; determination of the optimal position of drains, their mode of operation and calculation of optimization criteria for the foundation of the building and the adjacent soil (cultural layer); the choice of a compromise option (in the case of two opposite criteria - the Paretian solution); implementation of the visualization of the result, comparison of various options for the solutions obtained (Figure 2) [16,17].

![Figure 2. a) Fragment of the depth-to-water map of the Novgorod Kremlin territory; b) A variant of the calculation of drainage systems for the object of the Novgorod Kremlin.](image)

In case of opposite requirements for draining, the compromise position of the depth of the drain is determined by the intersection of the curves (functional) of optimization criteria for the object and the cultural layer [18]. Figure 3 shows a graphical solution for determining the optimum position of the drain that provides the optimal values for the optimization criteria.

The developed methods and algorithms were used to justify the development of design solutions for the prevention of emergencies on the territory of the Novgorod Kremlin. The technique supports the development of management decisions also in the presence of conflicting requirements for drainage rates and water drainage regimes. The results of its application can serve as a basis for making decisions on preventing emergencies, improving environmental safety during underflooding for various objects of the technosphere, including objects of high cultural and material value, potentially dangerous and critical objects [19,20].
Figure 3. The definition of a rational solution - the optimal position of the drain, ensuring minimal drainage of the cultural layer and the foundation of the building.

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