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Surface runoff as a complicating factor of engineering geological conditions. design models by the example of Moscow

Abstract

Climate change leads to changes in the volume and distribution of precipitation between seasons. Since water influences the course of most exogenous processes, the task of studying the formation of the connection between surface runoff and the spread of hazardous geological processes becomes relevant. A map of engineering and geological zoning, which is used in Moscow not only for design, but also in the current activities of services responsible for ensuring the safety of the operation of municipal services and environmental protection, was adopted as the initial information. The task is carried out on the Unified Digital Platform of Moscow in ArcGIS. The surface runoff model created on the basis of radar topographic survey is supplemented by methods for determining accumulation and depression zones, which makes it possible to identify areas of excessive soil moisture. Analysis of the intersection of zones of influence of surface runoff with taxa of engineering geological zoning makes it possible to quantify the distribution of connected objects, types of hazardous geological processes in zones of excessive moisture and adjust the assessment of the complexity of engineering geological conditions. As an example, the main regularities of the possible impact of surface runoff on increasing the risk of hazardous geological processes on the territory of cemeteries, cultural heritage sites and specially protected natural areas of Moscow are highlighted. It is proposed to use the methods of formation and analysis of the connection and the designed zones of influence of surface runoff in design, and monitoring systems, and in the current activities of city services.

Keywords: DEM, drain net modeling, flow accumulation, hazardous geological processes, zones of influence of surface runoff

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Introduction

The problem of surface runoff has always occupied a significant place in the management of the urban environment due to the peculiarities of natural and climatic conditions and the land use system[1–3] as well as a set of tasks for collecting, diverting and treating water when discharged into surface waters, the need to comply with construction, sanitary and hygiene standards.[4] Approaches to solving the problem are in many ways consonant with the methods being implemented in international projects related to the creation of safe urban habitats and territorial planning tasks (http://unhabitat.org/). The development of normative legislative support to this problem should be acknowledged at the federal and regional levels in the Russian Federation in recent years (Federal Law of the Russian Federation, 2009, 2011, Interstate standard, 2010, SanPiN, 2011).[5–8] Regulatory activities on tasks associated with designing drainage systems, maintenance of facilities and installations (depending on a groundwater level, water-table uprising, and surface runoff) as well as organizing municipal services,[4] such as cemeteries, forest and parks, historical and cultural heritage sites, and similar objects are being developed.

With the introduction of new information technologies, it became possible to improve computational and analytical methods of surface runoff modeling and drainage system designing, transfer to a unified urban mapping framework was carried out based on which the issues of surface runoff management should be solved when tackling the tasks of territorial and strategic planning and achieving sustainable urban development.[9,10] Solving the problem becomes particularly relevant due to evident climate changes on regional and global scales (Report, 2021),[11–13] especially in urbanized territories, which make the surface runoff studies be focused on developing adaptation measures with the purpose of ensuring a possibility of forecasting adverse effects and preventing the development of exogenic processes - the main risk factor of hazardous geological processes.

Systematic geoecological research for the territory of Moscow is underway in the Institute of Environmental Geoscience RAS (IEG RAS) based on the engineering survey database, engineering geological conditions are studied, the geomorphological structure is analyzed, methods of engineering geological zoning are being improved with consideration of adverse geological processes (Innovative project, 2012).[14] A set of large-scale geological maps of Moscow Mironov[15,16] is widely used for the purposes of new construction design, at that, the integrated map of engineering geological zoning has turned out to be the most demanded.[17]

The surface runoff model was generated in the development of the Moscow project based on the use of remote sensing data (radar surveying).[18] Historical approach to the evaluation of erosion pattern and its transformation for more than 8.5 centuries of Moscow history (over 140 rivers and 400 ponds are located in the city territory) was used to check the surface runoff model adequacy. The evolution of the modeling methods made it possible to introduce a concept of the surface runoff zone of influence.[19,20] It is proposed in this study to use the engineering geological zoning map to assess the surface runoff influence, categories of engineering geological conditions, distribution of hazardous geological processes, data on groundwater depth, and on the basis of a combination of factors, to evaluate the complexity of engineering geological conditions with the purpose of taking adaptive measures. The developed methods assume that the city information resources, such as the engineering geological zoning map, accumulation zones, and zones of the surface runoff influence, shall appear in the city environment management system in the open scientific data mode.

Data sources

The initial data of the research were included:

1. The cartographic materials about the modern and historic data of the river network of Moscow.
2. Digital mapping layer of the City unified mapping platform at a scale of 1:10 000.
3. The engineering geological zoning map from the Moscow project of geological mapping (2010) in scale M 1:10 000.[15,17] The map has a hierarchical structure including, at the first level, the structural and geomorphic blocks: mega-massif A with an uplift trend and mega-massif B with a subsidence trend, at the second level - 6 taxa of macro-massifs with relief forms as glacial-alluvial complexes (taxa I and II), terraces above flood-plain (taxa III, IV and V) and flood plain terrace (taxon VI) of the hydrographic network in the city territory. The map contains the determination of a category of complexity for the engineering geological conditions and distribution of hazardous geological processes including 1 - water-table uprising, 2 - shallow landslides, 3 - potential karst-suffosion process, 4 - karst-suffosion process, 5 - deep landslides, 6 - technogenic soils and 7 - weak soils). The map contains description data for each engineering geological massif with a key which successively includes the codes of mega-massif, macro-massif, and meso-massif (determining the type of geological structure) and a hazardous process code, for example: Б-IV-2в.[18]
4. Mapping data of the Moscow project with a breakdown by the groundwater depth and identification of 4 main levels: up to 1 m, 1-3 m, 3-5 m, and over 5 m
5. The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (SRTM90v.4.1) by the CGIAR-CSI GeoPortal (http://srtm.csi.cgiar.org/). The information obtained from the Shuttle Radar Topography Mission (SRTM) is intended for use in scientific and civil applications. SRTM 90m v.4.1 data were used to generate a terrain model for the Moscow city area. We calculated DEM SRTM for the Moscow city area inside the Moscow ring road (cell 50m) and a surface runoff model including the boundaries of a surface runoff influence zone, design streams with a breakdown by surface runoff accumulation zones, and locally closed boundaries of subsidence or depression.

The research is carried out using software ArcGIS(v. 10.4 upper) Environmental Systems Research Institute, Inc. (ESRI), in Global Mapper Blue Marble Geographics (v. 18.1).

Research methods

The following stages are singled out in the research conducted:

1. An analysis of the normative and regulatory documents governing the types of activities related to the surface runoff (using information law system Consultant) was carried out to set the objectives. A procedure for surveying was defined, and the provision and use of the city information resources were brought under regulation in the urban planning and design systems.

However, an analysis of the normative and regulatory documents governing the activities of the municipal services engaged in maintenance of buildings and facilities (such as local building administrations) and the activities within special territories (such as organizations engaged in the cemetery or forest and parks development and maintenance) showed that the regulations related to the surface runoff do not contain any clear definition of the information source (GOST, 2011),[19] such as information on the groundwater level. It is rational to give information about the complexity of the engineering geological conditions and surface runoff influence zones to specialists of these services to let them perform their duties.[20]

2. The model of surface runoff of urban territory was developed on the base DEM SRTM,[16,20] including filling digital elevation model (DEM_{Fl}) and the closed local lowlands (depressions) by GRID local lowland $GRID_{locll}$ (p.135 Karfidova, 2019).[20] $GRID_{locll}$ with a minimum depth 1m were calculated, the total area of local lowland is a significant value 15 sq. km inside Moscow ring road). GRIDs are successively calculated in computations of the surface runoff model: runoff azimuth direction, accumulation, and length. Linear features - design streams with the parameters of accumulation size at the starting and ending points - are calculated based on the GRID of accumulation zones. The area was calculated in the depression zones while the depth export was performed in the centers of each DEM cell. Based on these data the values of an average depression depth were calculated. It is worth noting that no runoff accumulations are observed in the depression zones contained in the classical model. The calculated surface runoff accumulation zones are linked to the erosional downcutting of riverbeds, the acquisition of data about the history and technogenic transformation of rivers, damming, burying, and management/arrangement of the drainage systems receiving surface waters is underway.
3. The aggregate accumulation zones in the immediate neighborhood area occupying 1 sq. km are calculated. Further, isolines with the value of 10000 cells are calculated based on these values. The isolines represent the boundaries of a surface runoff influence zone where the runoff accumulation exceeds the catchment area of 2.5 sq. km. Based on the calculated surface runoff net in the geographic information system, using means of ArcGIS, on the basis of GRID of the runoff accumulation zones, summations of surface runoff accumulation GRID were calculated using neighborhood operation in a radius of 560м; based on them, isolines of summation of surface runoff accumulation were calculated/ plotted as a map layer. The threshold value of summation of the surface runoff accumulation was taken as SumFlacc >=2,5 km^2, and the chosen isolines were converted into the zones of significant influence of the surface runoff.

Based on the calculated surface runoff net in the geographic information system, using means of ArcGIS, on the basis of GRID of the runoff accumulation zones Flacc, summations of surface runoff accumulation GRID SumFlacc were calculated using neighborhood operation in a radius of 560м; based on them, isolines of summation of surface runoff accumulation were plotted. When the threshold value of significant volume of the summarized runoff accumulation SumFlacc >=2,5 km^2, is set, the chosen values of isolines are converted into the zones of significant influence of the surface runoff).

4. The engineering geological zoning map and the surface runoff influence zones (SRIZ) were intersected using spatial analysis tools (Instructions, 2004). The composite map highlights with color the complexity category of engineering geological conditions; the engineering geological massifs with hazardous processes are singled out; the surface runoff influence zones are marked by boundaries and are linked to erosional downcuts, and a zone name is linked to the river names.
5. SRIZ is analyzed using the main components in the engineering geological zoning map including distribution of the SRIZ areas by

mega-massifs, macrotaxons, and hazardous geological processes. The taxonomic formula of geoecological hazard is calculated for the SRIZ. The taxonomic formula for assessment of geological hazard is worked out in the following form:

K1NP1, K2NP2, K3NP3 …,

where: K1> K2 >K3 – percentage of area (integral part) occupied by NP1, NP2, NP3... – negative geological processes in descending order. Codes of the hazardous processes occupying an area of less than 1% are shown in curved brackets. The model for working out the taxonomic formula of geological hazard for the planning city territory is presented in (Karfidova, 2020).

6. In the developed approach, a method of changing GRID- runoff accumulation was adopted wherein in the extreme situations of heavy and long-time precipitations the accumulation values are entered into the GRID cells of a depression zone: in the polygon center - a value proportional to the area of depression (the most cautious option), and at the polygon boundaries - a value of 5 (a minimum value of collection) every 50 m. New design streams are calculated according to the changed accumulation GRID. In this case, new streams are flowing out of the depression zones. The ratio of new accumulation values to the classical model values - K_{add} shows an increase in the runoff volume in extreme situations; with K_{add} values >1.2 in the accumulation zone and further downstream, the erosional downcutting is considered to be a further complicating factor for the complexity of engineering geological conditions.
7. When considering the geoecological situation, the factors were developed for possible scenarios in extreme situations which took into account the complexity of engineering geological conditions, the engineering geological zoning maps, the surface runoff model, the features of hydrogeological conditions within the erosional downcutting zone, taking into account the method.[21]

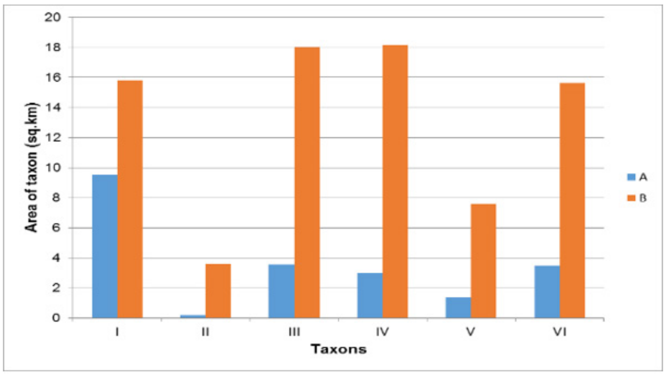

Figure 1 Distribution of areas of the surface runoff influence zones by taxa within the territories of mega-massif A and B.

It is worth noting that the biggest areas are occupied by the third and second terraces above the floodplain, then goes taxon I - glacier complex.

The biggest difference in distribution between the taxa is observed in taxa terraces III, IV, V and VI - floodplain. In mega-massif A - uplift complex - the floodplain area is 4 times smaller than in mega-massif B - subsidence complex.

It is proposed to introduce the three additional complicating factors further to the complexity category of engineering geological conditions (EGC) of the engineering-geological zoning map: 1) K1 - the coefficient for the territories with a low category of EGC complexity for a combination of conditions: at K_{add} > 1,2 and groundwater depth up to 3 m; 2) K2 - the coefficient relating to the territories with an average category of EGC complexity with a combination of conditions: at Kadd > 1,2 and groundwater depth up to 3 m; 3) K3 - the coefficient for the territories with a high category of EGC complexity for a combination of conditions: at Kadd > 1,2 and groundwater depth up to 3 m.

Results

The analysis results of surface runoff influence zones by the occupied area are shown in Figure 1.

The left tributaries of the Moskva River are located in mega-massif B; on the whole, the area of their influence zones is 4 times bigger than in mega-massif A.

The analysis results of surface runoff influence zones by the distribution of hazardous processes are shown in Figure 2. It is worth noting that the water-table uprising process dominates amongst the hazardous processes.

The distribution between the mega-massifs differs sharply: the absence of processes in mega-massif A is two times higher as compared to mega-massif B while the water-table uprising process in mega-massif B is 1.5 times higher as compared to mega-massif A.

The set of geoecological indicators within the surface runoff influence zones is shown in Table 1. In accordance with the proposed methods, the engineering geological zoning maps in which a hazardous process is present belong to the average complexity category of engineering geological conditions; in cases when a combination of processes takes place, for example, the most common combination of water-table uprising and karst-suffosion processes, then such zones belong to the high complexity category of engineering geological conditions. The codes of the processes that are less than 1% of the total area are shown in the taxonomic formula in { }.

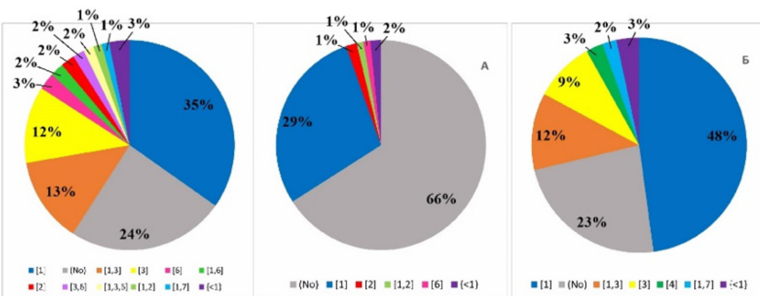

Figure 2 Distribution of the hazardous processes by the share of areas in the surface runoff influence zones (left-to-right): in the territory of Moscow inside the Moscow ring road, in the territory of mega-massif A, in the territory of mega-massif B.

Table 1 Geoecological indicators of the surface runoff influence zones in the territory of Moscow within the Moscow ring road

I. The zones of influence of runoff megamassive A

№	River name	Area (sq. km)	Max. acc. (GRID cells)	Proportion of the occup. territory by taxones (%)						Taxonomic formula of hazard of the zone of influence
				AI	AII	AIII	AIV	AV	AVI	* in descending order by processes, No - no processes
1	Gorodnya	18,05	36334	53	0	8	17	3	20	63 (No) 35 [1] 1 [2] 1 {[6] [1,2]}
2	Setun	12,53	26544	27	0	25	21	11	16	49 [1] 37 (No) 3 [1,6] 3 [1,2] 2 [1,3] 2 [6] 2 [2] 1 [1,3,6] 1 {[2,6] [3] [3,6] [2,5]}
3	Chertanovka	11,88	12665	86	-	2	5	1	7	73 (No) 24 [1] 2 [1,2] 2 {[2] [6]}
4	Khvilka	8,95	5171	69	4	6	19	-	1	72 (No) 28 [1] 1 {[1,6]}
5	Ochakovka	8,71	6539	95	-	-	-	0	5	77 (No) 17 [1] 4 [2] 1 [1,6] 1 {[1,2] [6]}
6	Kotlovka	8,12	7399	76	-	7	9	1	7	85 (No) 9 [1] 3 [6] 1 [1,2] 1 {[1,6]}
7	Ramenka	6,99	17135	82	-	5	2	3	8	68 (No) 24 [1] 5 [2] 3 {[2,6] [6] [1,6] [1,2]}

II. The zones of influence of runoff megamassive B

№	River name	Area (sq. km)	Max. acc. (GRID cells)	BI	BII	BIII	BIV	BV	BVI	Taxonomic formula of hazard of the zone of influence
1	Nischenka	16,38	14049	6	-	34	30	4	27	36 [1,3] 25 [3] 23 [1] 8 (No) 6 [3,6] 2 [1,3,6] 1 {[6] [1,3,7]}
2	Likhoborka	14,79	20867	58	12	3	21	3	3	42 [1] 32 (No) 22 [1,3] 4 [3] 1 {[6] [1,6]}
3	Tarakanovka	13,82	9243	49	-	42	2	-	7	32 [1] 26 (No) 22 [4] 13 [3] 2 [4,6] 2 [1,4,6] 1 [1,3] 1 {[1,4] [1,3,6] [6] [3,7]}
4	Sosenka	11,59	10025	52	1	20	26	-	-	78 [1] 11 (No) 4 [3] 4 [1,3] 3 [1,7] 2 {[1,6] [1,3,7] [1,6,7] [7]}
5	Budayka	9,42	5451	67	1	12	18	-	2	90 [1] 9 (No) 1 [1,6] 1 {[1,3]}
6	Serebryanka	9,24	11386	16	-	27	47	2	8	50 [1] 23 (No) 12 [1,3] 11 [1,7] 4 [3] 1 {[1,3,7] [1,6]}
7	Kopytovka	9,09	6933	79	-	3	9	2	7	64 [1] 30 (No) 2 [1,3] 2 [1,6] 1 [6] 1 {[3]}
8	Churilikha	7,39	5168	51	-	42	5	-	2	67 [1] 18 (No) 15 [1,7]
9	Skhodnya	7,22	1837	39	1	4	21	10	25	52 (No) 32 [1] 6 [1,3] 4 [3] 2 [1,6] 1 [1,2] 1 [5] 1 [2] 1 {[1,5] [3,6]}
10	Neglinnaya	6,24	4336	46	1	16	8	1	28	64 [1] 13 (No) 11 [1,3] 6 [3] 2 [1,6] 1 [1,3,6] 1 [3,6] 1 {[6] [2,6]}

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The set of taxonomic formulas for the surface runoff influence zones demonstrates that distribution of the high complexity category dominates in mega-massif B within the influence zones while the distribution of the average complexity category of engineering geological conditions dominates in mega-massif A. As a result of the proposed scenario for calculation of the additional runoff volumes coming from the depression zones, evaluations of the geoecological situation were obtained in which it is necessary to use the magnification coefficients for the complexity categories of engineering geological conditions Figure 3.

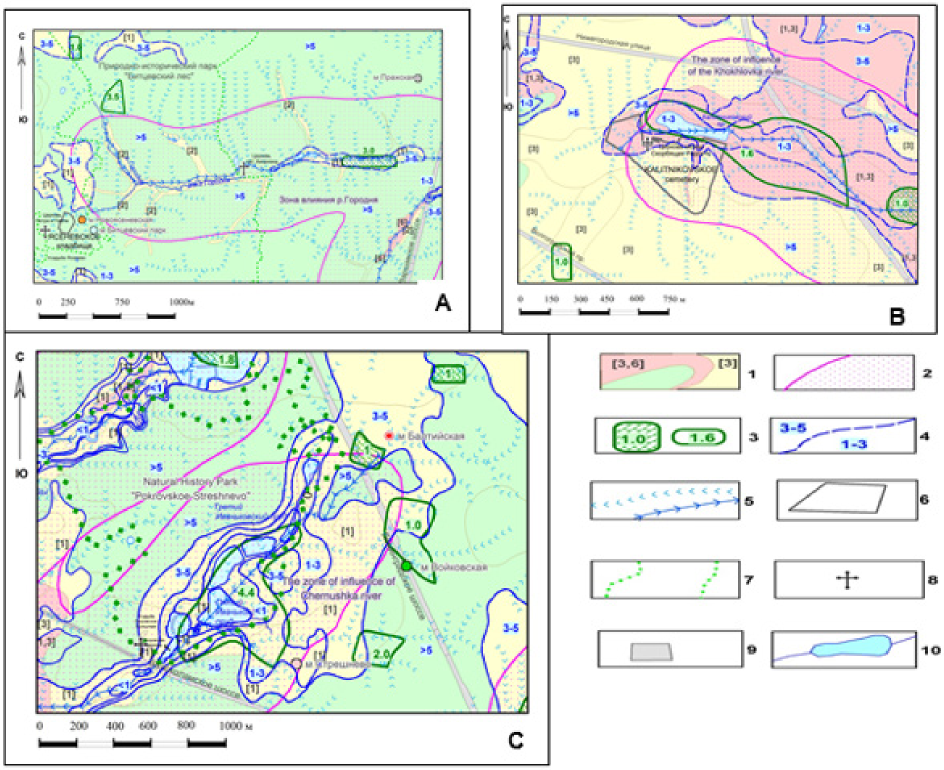

Figure 3 Examples of schematic maps with geoecological situations within the surface runoff influence zones: A - low category of complexity, B - average category of complexity with complicating coefficient K2, C - high category of complexity with complicating coefficient K3.

Explanations to Figure: 1 - Engineering geological zoning map with marked complexity category of engineering geological conditions: engineering geological complexity (EGC): Green – low degree, yellow – average degree, purple – high degree. 2 - surface runoff influence zone by an aggregate accumulation of catchment area exceeding 10 000 cells or 2.5 sq. km, the influence zone name is connected with the river which the surface runoffs flow into or with the canalized river. 3 - depression zones, depressions with fill - sealed, without fill - open territories with green spaces, digits in the center - average depth of subsidence. 4 - boundaries of distribution of groundwaters with different occurrence depths: <1, 1-3, 3-5, >5 (m). 5 - lines of design streams with directions of movement with allocation: insignificant < 300-400 cells, > 400 cells - significant streams or over 1 sq. km. 6 - cemetery borders. 7 - borders of historic-cultural parks. 8 - historic-cultural sites (churches, estates). 9- roads. 10 - hydrography.

Schematic map A shows a geoecological situation with a low category of EGC complexity without distribution of hazardous processes in the surface runoff influence zone of Gorodnya river within the territory of mega-massif A with the uplift trend. The western part of this zone belongs to one of the largest natural-historic parks (Bitsevski natural park) in the territory of Moscow. In the eastern part of this Zone, on the exit of runoff from the depression (with an average depth of 3m), the design runoff magnification coefficient in a possible extreme situation is Kextr > 1.2, however, the coefficient is not applied as the groundwater depth in the river's erosional downcutting is 3-5 m.

Schematic map B shows a geoecological situation with an average category of EGC complexity with the distribution of the water-process in the surface runoff influence zone of Chernushka river in the territory of mega-massif B with subsidence trend. The western part of this belonges to Pokrovskoe-Streshnevo natural-historic park (similar to approach Paule-Mercado, 2017).[23] Historical and cultural heritage sites are located within the park territory. The situation features a cascade of ponds - historical river dams. The calculated coefficient of a runoff increase from the depressions located in the northeast part of the zone in a possible extreme situation Kextr > 1.34. This is why it is necessary to introduce coefficient K2 - a complication of the average category of complexity given that the groundwater depth is 1-3 m. The highest pressure pertains to the drainage system in the southwest part of the river's erosional downcutting.[24] It is necessary to introduce more frequent examinations of Pokrovskaya church or the country estate located nearby, or better, geotechnical monitoring.

Schematic map C shows a geoecological situation with a high category of EGC complexity with the distribution of water-table uprising processes and a combination of the water-table uprising process with the karst-suffosion process within the surface runoff influence zone of Khokhlovka river in the territory of mega-massif B with a subsidence trend. Historical Kalitnikovskoe cemetery is located within the influence zone territory. Kalitnikovskyi pond is located to the north of the cemetery; it is surrounded by a depression zone which is large in terms of the area occupied and has an average depth of 1.6 m. The groundwater depth at the depth of the river's

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erosional downcutting is 1-3 m, which makes it necessary to introduce K3 - complicating the high category of EGC complexity. Frequent examinations and readiness to arrange water drainage works are necessary at the cemetery territory during long-time precipitations. Special attention should be paid to the church foundation condition (a historical and cultural heritage site).

Conclusion

The proposed methods make it possible to determine the surface runoff influence zones within the city territory. The chosen method of establishing a link between the engineering geological zoning map and the expanded surface runoff model makes it possible to understand the distribution peculiarities of hazardous processes in relation to the endogenous factors - affiliation to the uplift mega-massif and subsidence mega-massif.

The chosen method of calculating the additional accumulation zones makes it possible to evaluate the least possible projected increase in design streams. The combined express approach makes it possible to consider not only the complexity of engineering geological conditions, groundwater depth, and a possible increase in design stream but also the need to introduce the complicating coefficients.

The effectiveness of the proposed methods is based on reducing the cost of eliminating the cumulative damage from dangerous geological processes and climate change in the city management system. Examples of the schematic geoecological situation assessment maps that were considered in terms of surface runoff influence make it possible to understand and provide the required priority adaptation measures related to climate change. The use of the proposed methods is fully consistent with the goals of sustainable development (11- Make cities and human settlements inclusive, safe, resilient and sustainable and 13 -Take urgent action to combat climate change and its impacts) (https://sdgs.un.org/goals).Transition to the open spatial data to be employed as city information resources,[25–27] together with an increased emphasis on motivating specialists to use them, is a prerequisite for further development of the method.[28,29] In the future, such a specialist can grow into a spatial data designer to take care of the surface runoff problem within the catchment area in the development of methods such as Borris.[11]

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None.

Conflicts of intertest

The author declares there is no conflict of interest.

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