Application of HEC-RAS software in modelling of urban flooding by surface rainwater runoff and assessment of emergency conditions in case of precipitation of different availability

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Abstract. The presented paper investigates the application of HEC-RAS software for modelling of urban area waterlogging by surface rainfall runoff on the Black Sea coast of Russia. The authors assess the risk of emergencies caused by rainfall of different intensities. Using a digital elevation model and an orthophotoplane obtained by airborne laser scanning and aerial photography, the territory and surface types are analyzed. The results of the study identify sensitive areas and consider the feasibility of constructing barrier structures to manage surface runoff. Data on the capacity of the existing pipe and its effect on runoff accumulation are analyzed. The study is of practical relevance for risk assessment and emergency prevention measures related to surface runoff in urban environments on the Black Sea coast.

1 Introduction

In case of insufficient engineering protection of the territory, surface runoff can be a source of risk of emergency situations (ES) and cause damage not only to infrastructure, but also to human life and health. At the same time, it is inexpedient to erect overly powerful structures of engineering protection of the territory, as it leads to the increase in the cost of their construction. In this regard, it is important to give a correct assessment of the risk of an emergency, as well as to estimate its scale. A properly developed surface runoff model can help solve these tasks.

The Black Sea coast of Russia is characterized by an increased risk of natural hazards caused by heavy rainfall, the most significant among them were the events of 2002, 2010, 2012-2015 [1].

The study area is located in the drainage basin of the Aderba River (North-Eastern Black Sea coast, Gelendzhik area), and is conditionally divided into two parts: the Southern Industrial Zone and a part of the southern slope of the Markhotsky Ridge. From the mountain slope melt and rain water passes through a 1000 mm diameter pipe to the territory of the industrial zone. Further on the slope of relief the surface runoff moves by gravity and

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enters the floodplain of the Aderba River, the main source of feeding which is atmospheric precipitation and groundwater, because of which the passage of rain floods cause a sharp alternation of pronounced rises and falls of water during the year, the number of which, for individual rivers, up to 25 [2].

Fig. 1. Study area

This study considers the feasibility of constructing barrier structures to intercept and divert surface runoff from the mountainous area adjacent to the Southern Industrial Zone of Gelendzhik. The purpose of the study is to assess the risk of emergencies caused by surface runoff in the current conditions and in the conditions after the construction of barrier structures.

2 Materials and Research Methods

In this study, a digital elevation model with an image cell size of 13 x 13 cm and an orthophotomap obtained from aerial laser terrain scanning and aerial photography were used.

Using the manual digitization method, a layer in ".shp" format was created containing information about surface types. Surfaces are categorized into the following types: "roofs", "asphalt", "lawn", "mountainous part", and "soil". The surface type "lawn" includes land areas that are covered with vegetation, the surface type "ground" includes land areas that are not covered with vegetation but do not have a hard surface, the surface type "buildings" includes the roof contour of all city structures, the surface type "asphalt" includes all hard surfaces of the city, and the surface type "mountainous part" includes the investigated part of the Markotkhsky Ridge. Each type of surface has its own Manning roughness coefficient value: for "roofs" the coefficient has a value of 0.012, "asphalt" - 0.015, "ground" - 0.03 [3], "mountain part" - 0,1 [4]. In addition, the roughness of the culvert was taken into account - 0.012 [5].

Pluviograms of precipitation have been developed Calculated pluviograms of rainfall with probability of 1%, 2%, 5% (Table 1. According to Roshydromet data).

Table 1. Calculated precipitation parameters with a rainfall limit of 20 minutes and precipitation pluviograms of precipitation taking into account infiltration.

Estimated rainfall including infiltration, mm			
Time, min	**With a 1% endowment**	**At 2% security**	**At a 5% endowment**
1	0.180	0.147	0.120
2	0.581	0.474	0.387
3	0.982	0.802	0.654
4	1.383	1.129	0.921
5	1.784	1.457	1.188
6	2.708	2.211	1.803
7	3.651	2.982	2.431
8	4.122	3.367	2.745
9	3.651	2.982	2.431
10	3.179	2.597	2.117
11	2.708	2.211	1.803
12	2.236	1.826	1.489
13	1.784	1.457	1.188
14	1.583	1.293	1.054
15	1.383	1.129	0.921
16	1.182	0.966	0.787
17	0.982	0.802	0.654
18	0.781	0.638	0.520
19	0.581	0.474	0.387
20	0.380	0.311	0.253
21	0.180	0.147	0.120
Amount, mm	36	29.402	24

Modelling is performed in HEC-RAS software (Hydrologic Engineering Center - River Analysis System); this software is widely used for flow modelling in rivers, streams, and other watercourses. The program allows modelling of various flow scenarios including steady-state and non-steady-state flow. The shallow water equation solved by the Eulerian-Lagrangian method (SWE ELM) was chosen as the calculation equation [6].

Before starting the modelling, the buildings, as well as the culvert under alignment, were mapped onto the DEM using internal tools in the HEC-RAS software.

Several modelling scenarios were developed to meet the modelling objectives:

1. The calculation model includes the industrial territory as well as the mountainous part, modelling is carried out for rainfall probability of 1%, 2%, 5% (Fig. 2).

Characteristics of the electronic model created under Scenario 1:
- Design geometry area: 156.679 Ha
- The size and shape of the cells of the design geometry: a square with a side of 4 meters.
- The size and shape of the cells of the computational geometry in the refinement area: a square with a side of 1 meter.
- The size and shape of the cells of the design geometry in the flow tube: a square with a side of 0.5 meters.
- Number of cells: 522266
- The calculation step is 1 second.

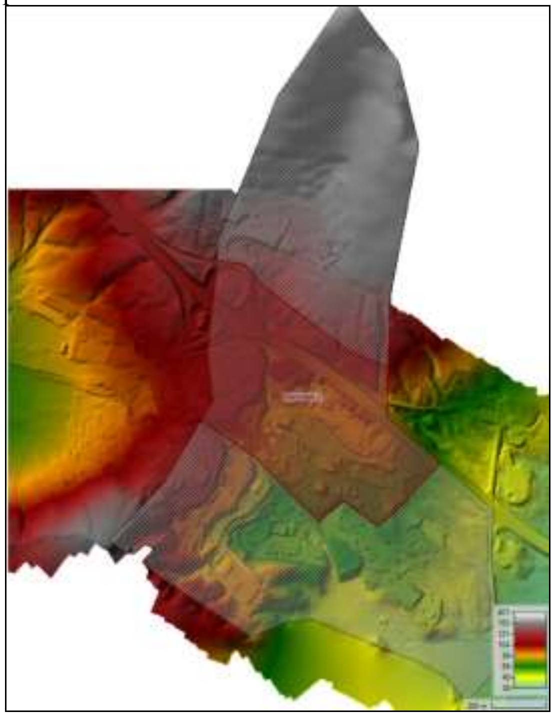

Fig. 2. Modelling boundary created within the first modelling scenario

2. The calculation model includes the industrial area, but does not include most of the mountainous area, modelling is carried out for rainfall probability of 1%, 2%, 5%. Thus, surface runoff in the urban area is modelled under the condition that an "ideal" blocking structure has been built in the mountainous part, which completely diverts all stormwater runoff entering the urban area from the mountainous part (Fig.3).

Characteristics of the electronic model created under scenario 2:
- Design geometry area: 112.964 Ha
- The size and shape of the cells of the design geometry: a square with a side of 2 meters;
- The size and shape of the cells of the design geometry in the flow tube: a square with a side of 0.5 meters;
- Number of cells: 282280
- The calculation step is 1 second.

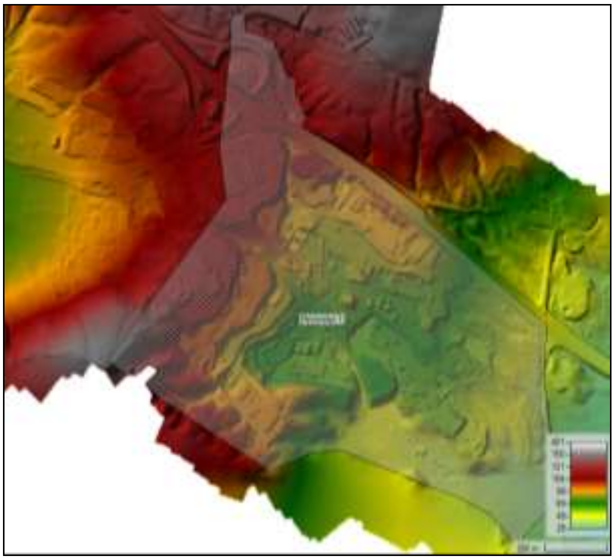

Fig. 3. Modelling boundary created under the second modelling scenario.

3 Results of the study and their discussion

The calculations allowed one to obtain the computational spatial model presented in Figure 4. Furthermore, a comparative analysis of the parameters: maximum height of the formed water level, maximum flow velocity (Tables 2 and 3) was carried out for the control points.

Fig. 4. Scheme of flooding of the territory, main waterlogged zones at high intensity of 1% precipitation without the designed collector.

Table 2. Values of depths and velocities at control points calculated under modelling scenario 1.

	1% and water overflows through the flow pipe		**2% and water overflows through the throughput pipe**		**5% and water overflows through the throughput pipe**	
Time, min	**Maximum depth, m**	**Maximum speed, m/s**	**Maximum depth, m**	**Maximum speed, m/s**	**Maximum depth, m**	**Maximum speed, m/s**
Reference point 1 bottom point of the pit in front of the culvert under the federal highway	3.67	0.53	3.03	0.6	2.46	0.49
Control point 2. Lowered area near the territory of the Khoreka-South enterprise (ditch north of cadastral plot 23:40:0411006:22)	2.54	0.47	2.4	0.42	2.15	0.46
Control point 3 lower area near the laboratory building (territory of cadastral plot 23:40:0411006:227)	1.49	0.31	1.28	0.29	1.08	0.26
Control point 4 Lowered area near bitumen warehouse-electric shop (territory of cadastral plot 23:40:0411006:226)	0.53	0.3	0.46	0.27	0.4	0.24

Table 3. Values of depths and velocities at control points calculated under modelling Scenario 2.

	1% and water overflows through the flow pipe		**2% and water overflows through the throughput pipe**		**5% and water overflows through the throughput pipe**	
Time, min	**Maximum depth, m**	**Maximum speed, m/s**	**Maximum depth, m**	**Maximum speed, m/s**	**Maximum depth, m**	**Maximum speed, m/s**
Reference point 1 bottom point of the pit in front of the culvert under the federal highway	1.19	0.59	1.03	0.57	0.92	0.58
Control point 2. Lowered area	2.45	0.23	2.22	0.28	2.09	0.26

near the territory of the Khoreka-South enterprise (ditch north of cadastral plot 23:40:0411006: 22)						
Control point 3 lower area near the laboratory building (territory of cadastral plot 23:40:0411006: 227)	1.6	0.35	1.34	0.27	1.15	0.23
Control point 4 Lowered area near bitumen warehouse-electric shop (territory of cadastral plot 23:40:0411006: 226)	0.5	0.51	0.42	0.39	0.37	0.34

The analysis of the obtained scheme has clearly shown that:

- The existing working culvert has inadequate capacity during intense precipitation events, creates water back-up, contributes to runoff accumulation upstream of the federal highway, and acts as a regulator of uniform runoff delivery to the urban area topography;

- At a precipitation of 5,2,1% of security in the urban area (communal and storage area), there is a moment of accumulation of precipitation up to 5 meters high in the low part near the federal road;

- At 5.2.1% precipitation of security in the urban area (municipal and warehouse zone), there is a moment of accumulation of precipitation up to 1.5-2 meters high in the lowered part of the ditch (ravine) near the territory of production enterprises;

- At precipitation of 5.2.1% of security in the urban area (communal and warehouse zone) there is a moment of accumulation of precipitation of up to 5-10 cm in the average relief and 25-30 cm in the formed streams.

Taking into account these circumstances, and when comparing the results obtained with the parameters and criteria specified in the procedure for establishing the fact of violation of living conditions in an accident at a hazardous facility, including the criteria by which the fact is established (Order of 30.12.2011, N 795), as well as the methodology for assessing damage from emergencies (Order of the Ministry of Emergency Situations of Russia from 1.09.2020, No 631) in the area under consideration does not arise violation of living conditions and impossibility of human habitation due to the destruction or severe damage to other territories, and there is no probability of the a violation of sanitary and epidemiological conditions in the area under consideration. Based on the results of the modelling, we also see that in the area under consideration there is no threat to transport communication between the residential area and other areas and there is no probability of violation of sanitary and epidemiological well-being of the population.

At the same time, it should be taken into account that a situation can develop in which damage to aquatic biological resources may be caused by the washing of loose construction materials from the territory of production enterprises into the Aderba River by surface runoff (under the condition of improper storage).

4 Conclusions

The results of calculations, modelling and spatial analysis showed that:
- the steady-state overflow regime from the adjacent mountainous area has an insignificant effect on the resulting flooding conditions in the production area;
- it is acceptable not to develop additional engineering protection structures for the territory of the Southern industrial zone of Gelendzhik from surface runoff. Gelendzhik from surface runoff.

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