SIMULATION MODELING AND MAPPING OF CATASTROPHIC FLOODS IN POORLY STUDIED AREAS FOR EMERGENCY RISK MANAGEMENT

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Abstract

Method presented in the article for modeling parameters of catastrophic floods, such as the water level of the given probability of exceedance and depth of corresponding probability of exceedance, as well as the flooding area for unexplored territories, is based on the use of the digital relief model approach, construction of hydrographic network in the form of oriented graph characterizing the direction of water flow, invoking generalized regime hydrological information in the form of estimated parameters maps of the maximum flow, and the use of virtual gauging stations, as information reference points for calculations.

Keywords: flood, hydrological characteristics probability of exceedance, maximum flow, depth of flooding, virtual gauging station, digital relief model, orgraph.

I. Introduction

The problem of rain floods is typical for various regions of Russia, and the main aspect is the absence or insufficient reliability of the residential areas flooding zones boundaries, determined with disregard for the peculiarities of extreme water flow formation. Among the most dangerous events of the recent years, we can note the flood in Krymsk in 2012, rain floods in the Far East in recent years, and the outstanding flood of 2019 on the Iia River in the Irkutsk Region in June 2019

The flood of 2019 on the Iia River was catastrophic, followed by significant damage and human casualties [1]. Water levels exceeded the design values, not least due to the additional influence of hydraulic engineering structures (bridge crossings, dams) and narrowing of the riverbed [2]. Iia River basin is typical for the region in terms of flood formation conditions, and the region as a whole is quite well studied. Available study materials can be used as well a basis for the development of the methodological framework for assessing rare events required for flood risk management in built-up areas.

In order to reduce flood damage, develop preventive and protective measures for the territories of the Russian Federation constituent entities, it is required to compile the following cartographic materials based on hydrological probabilistic forecasts [3]:

– maps of the river basin marsh territories (boundaries of flood zones at maximum probability of exceedance water levels – 1%, 3%,5%, 10%, 25% and 50%);

– maps of water risks caused by various types of negative water effects (with damage assessment);

– maps of the river basin territory zoning by flood hazard danger.

Methodological procedures of flood forecasting are largely determined by the spatial scale (namely, the degree of locality) of hydrological processes and their extremely large spatial variability. This leads to the fact that almost all main forecasting methods are empirical. Even in cases where theoretical dependencies and model approaches are used, it is necessary to determine their coefficients and parameters for specific water bodies by calibration, based on the results of local observations. This leads to a variety of methods used in practice to predict water regime [4, 5, 6, 7]. All these forecasting methods require large bulk of initial data, instrumental measurements, terrain studies and significant financial costs [8].

To assess the risk of emergencies, caused by floods, it is necessary to determine parameters that are used in flood modeling [9]: maximum rise water level; duration of flooding; zone of possible flooding.

For hydrological estimations having observational data at existing gauge stations, Set of Rules is currently used [10]. It is also advisable to use software package for determining hydrological characteristics for studied and insufficiently studied rivers, which is certified and includes three modules: HydroStatCalc.exe; FreqShrt2009.exe; ComposeFreq.exe [11]. For the river under study, the natural zone in which the river basin is located is established, and according to the available maps, the results of hydrological studies or by other means, the main morphometric characteristics used for calculations and defined in the regulatory documentation are determined [12].

Nowadays, geoinformation systems (GIS) are actively used as applied software for hydrological modeling and forecasting. Free database of hydrological estimation models is available and is constantly being updated; monitoring data, weather, digital terrain models, etc. appear in the public domain [13]. Based on the use of GIS, short-term flood forecasting systems (water levels and flow rates) are being created [14, 15].

It should be noted that in the Russian Federation there is a problem of information availability both on current hydrological characteristics and on archival data of hydrometeorological observations [13], which forms additional restrictions for long-term (strategic) forecasting. Thus, obtaining long–term forecast values of flood parameters (depth of flooding, flooding period duration, flooding zone), forecasts of rare events (floods with probability exceedance of 0.1-1%) is practically based on the use of the simplest correlations and other relationships and dependencies due to hydrological patterns and remains very approximate [6].

With limited data set, models based on geometric principles can also be used for flood modeling [14].

The authors of this article have developed the method for probabilistic forecasting of floods in the absence of data from permanent hydrological observations based on the use of digital relief model, requirements of methodological recommendations for determining hydrological characteristics with insufficient data from hydrometeorological observations [4, 5], as well as spatial regional generalizations of hydrometeorological observations over a long period (regional reference books) [16].

The task of modeling floods of rare recurrence is reduced to the following subtasks:

modeling of the water level rise (determining the flooding depth (waterdepth) at actual gauge stations according to the long-term observations of the highest observed water levels relative to zero of the hydraulic station for each probability of exceedance;

modeling of the water level rise (determining the flooding depth) (waterdepth) at "virtual" hydro posts - arbitrary virtual points on the ground identified by geographical coordinates, not equipped with points of hydrological observation, artificially "placed" in the fairway of the river, depending on the maximum predicted water flow, water flow volume, module and water flow layer, cross-sectional area of the riverbed at the location of the "virtual" gauging station;

possible flooding zone determination.

To determine the rise of the water level (depth of flooding) (waterdepth), logarithmic regression equation is set up on the actual gauge station:

$$waterdepth = b_0 \times \ln(P_{m,\%}) + b_1 \text{ , sm,} \quad (1)$$

where b_0, sm/%, b_1, см – logarithmic regression coefficient.

The empirical curve of the annual probability of exceeding $P_{m,\%}$ is based on the data of long-term observations of the highest observed water levels according to the formula [4]:

$$P_{m,\%} = \frac{m}{n+1} \times 100,\%, \quad (2)$$

where m – index number of the highest observed water levels series term, arranged in descending order, natural number
n – total series term, natural number.

Equation of regression coefficients (1) are determined by the least squares method.

To determine the water level rise of a given probability of exceedance (determining the depth of flooding) (waterdepth) at the "virtual" gauge stations, an original method of probabilistic modeling of the maximum rise of the water level has been developed, based on the construction of a channel network as an oriented graph, using a digital relief model and GIS.

Method of probabilistic forecasting of catastrophic floods parameters has been tested on the pilot Russian Federation entity – the Irkutsk Region.

Total length of the Irkutsk region rivers is 309355 km. According to Roshydromet, as of December 2022, 130 actual gauge stations (hereinafter referred to as AGS) operated in the Irkutsk Region (Fig. 1). Most of them have long observation period (Fig. 2).

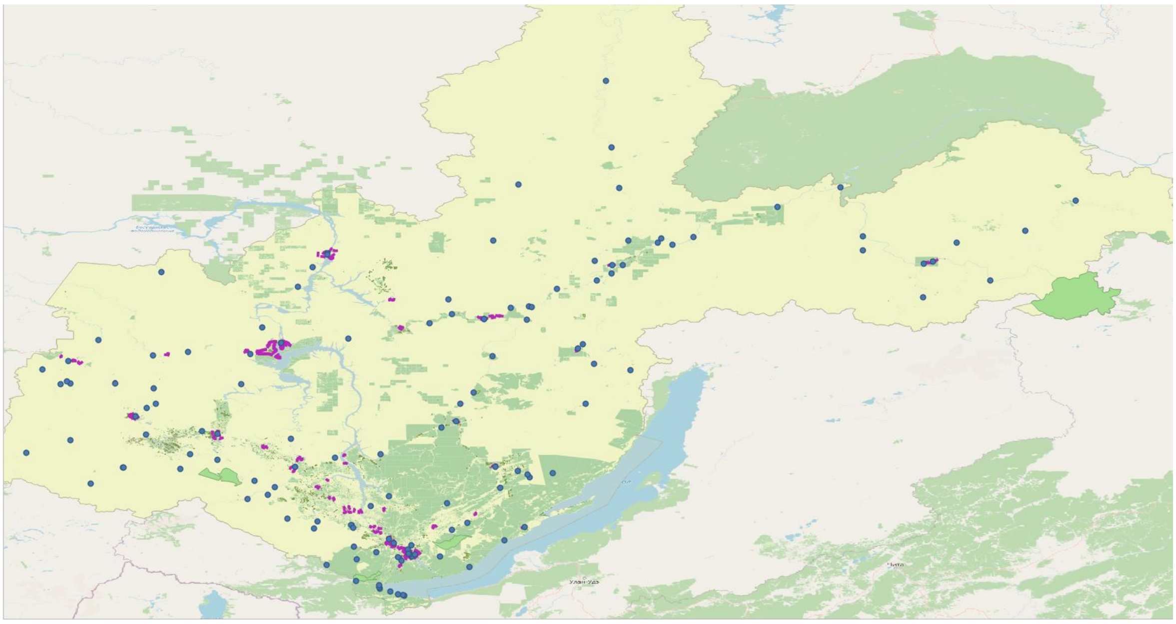


Fig. 1: *Location of the actual gauge stations on the territory of the Irkutsk Region (blue dots) [source: obtained by the authors according to [17]]*

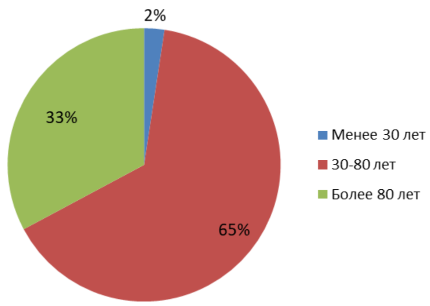


Fig. 2: *Duration of observations at gauge stations of the Irkutsk Region [source: obtained by the authors according to [17]*

At the same time, about 2,100 settlements are located near rivers in the Irkutsk Region, and most settlements do not have points of regular instrumental hydrological measurements (gauge stations), i.e. they are considered as unexplored.

Territory of the Irkutsk Region belongs to three basin districts – Angara-Baikal, Yenisei, Lena (Fig. 3).

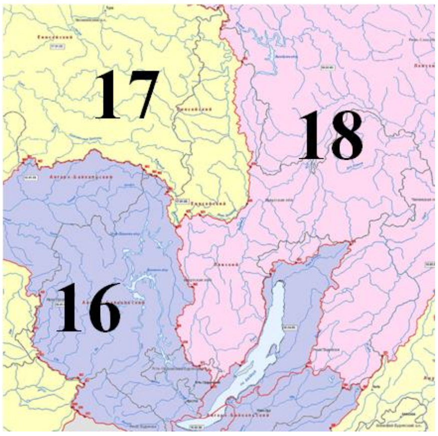


Fig. 3: *Basin districts [18]. The numbers on the map are indicated by:*
16 – Angara-Baikal Basin District; 17 – Yenisei Basin District; 18 – Lena Basin District

The region under consideration is characterized by increased flood danger, in recent decades there have been severe rain floods, led to enormous damage [2].

II. Methods

The method of probabilistic modeling of the catastrophic floods parameters is applicable for virtual gauging stations (hereinafter referred to as VGS) - arbitrary virtual points on the ground identified by geographical coordinates, not equipped with points of hydrological observation, artificially "placed" in the fairway of the river, relative to which the calculation of flood zones is carried out [12].

Virtual gauging station placement is an important stage in the modeling and forecasting of catastrophic flood parameters is [12, 19, 20]. VGS disposal was performed "manually" in the geographic information system QGIS – a free cross-platform open geographic information system for all watercourses of all river sections:

every 10 km starting from the mouth of each river on the main channel. It is recommended to place VGS on the relatively straight riverbed;

at a distance of 2-3 km downstream from the confluence of the river with another river;

additional VGS are installed in the middle between the gauge stations (AGS and/or VGS) in case of the settlements boundaries location at a distance of less than 2.5 km to the river.

Theoretical foundation of the method used is based on estimated dependencies that allow calculating hydrographic characteristics on the basis of digital relief model, determining hydrological parameters of floods of the given probability of exceedance: water level rise, duration of flooding, zone of possible flooding.

The main hydrological characteristic determining the water rise level is the maximum flow rate, determined in the absence of analogous rivers by the reduction formula [10]:

$$Qpmax = q_{200}\left(\frac{200}{S\_basin}\right)^{n} \times_{p} \times \delta_1 \times \delta_2 \times S\_basin, \quad (3)$$

where q_{200} – the module of the maximum instantaneous annual water discharge of the probability of exceeding 1%, reduced to the catchment area of 200 km2; n - indicator of the maximum flow module reduction degree, determined by the map of the USSR rivers maximum rain runoff modules; S_basin - catchment area at the point of hydrological observation; λ_p - transition coefficient from the probability of exceeding 1% to the probability of p.

Coefficients values used in the reduction formula (3) are given in regional reference books and regulatory documents. Such a regional reference book is, for example, a multi-volume publication [16], the data in which has not been updated for the last 50 years. Since the Irkutsk Region does not belong to the regions with increased climatic risks [22], the long-term stationarity of the coefficients used in the formula (3) was assumed in the work.

Raster maps are used for carrying up hydrological estimations. GIS layers were created based on the raster maps of the USSR rivers maximum modules of the rain runoff, with a probability of exceeding p=1% (parameter q_{200}, $м^3$/с×км2) (Fig. 4) [21, Appendix 5], indicator of the maximum flow module reduction degree n [21, Appendix 6].

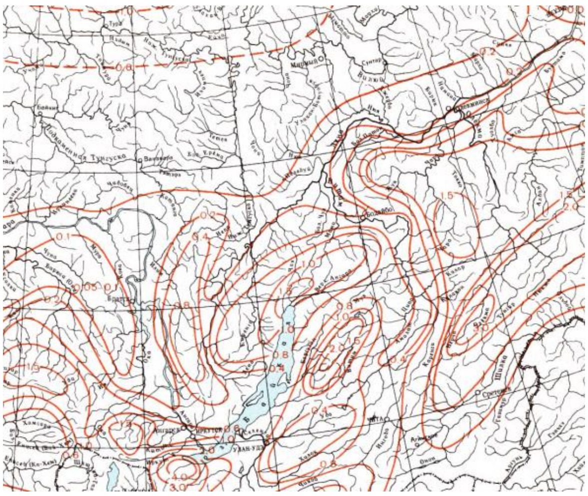


Fig. 4: *Part of the map reflecting maximum modules of the USSR rivers rain runoff, with a probability of exceeding p= 1%, for a part of the Irkutsk Region [21, Appendix 5]*

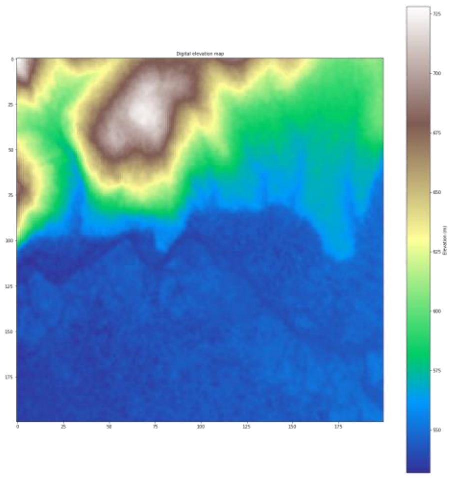
Algorithm for determining the hydrological parameters listed above and used in formula (3) by interpolation using GIS has been developed and presented in [19].

The area of *S_basin* catchment in the absence of data can be determined using digital terrain models (hereinafter referred to as DTM) [14] using the Deterministic Eight Neighbor algorithm [23].

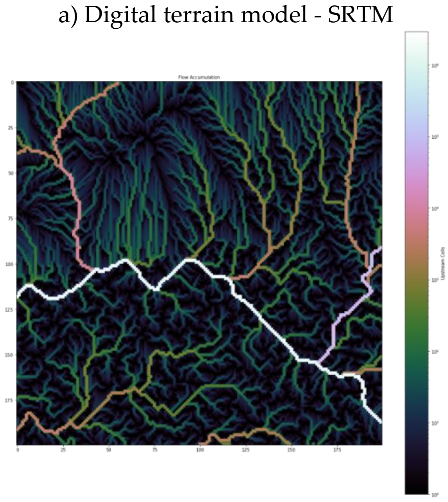
In the works [12, 19, 20], method for determining the catchment area using DTM was applied and an approach to constructing hydrographic network using orgraph G = (V, E) with information about the flow, where each node in the node set V={ v_1, v_2, …, v_n } is also shown and applied contains the coordinates of the cell (lon_x, lat_y) in the DTM, the height of the cell (height) of the

DTM above sea level, the number of cells that "flow" into this cell (acc_flow), and each edge $v_i \rightarrow v_j \cap E$ shows that node vi is the parent node for the descendant node v_j (water "flows out" from node v_i and "accepted" by node v_j) [19, 24].

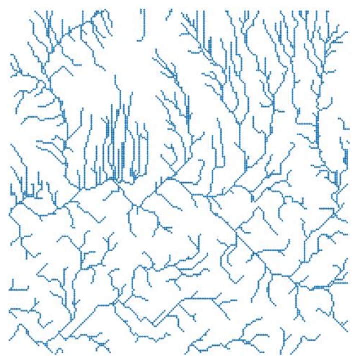
Construction of a channel network diagram in the form of the orgraph was performed using the NetworkX library, created in Python and designed to work with graphs and other network structures [25] (Fig.5).



a) Digital terrain model - SRTM



b) Flow accumulation raster



c) Orgraph of flow directions (watercourse model)

$G = (V, E)$; $V=\{v_1, v_2, \ldots, v_n\}$; $v_i \rightarrow v_j \cap E$

Fig. 5: *Procedure for constructing watercourse model using DTM and orgraph*

The predicted depth of flooding at the location of the virtual gauge station is determined on the basis of the maximum water flow calculated according to the formula (1) of the given probability of exceedance and the water area (cross-section). The cross section of the riverbed and valley at the location of the virtual gauge station is constructed using digital relief model by constructing virtual plane perpendicular to the riverbed and finding the coordinates of the intersection of the virtual plane with DTM [20].

The depth of flooding (waterdepth) for each Q_{pmaxi} of the given probability of exceedance (frequency) and each cross-section of the riverbed and valley is determined by the iteration method according to the graph of the flow curve of a given probability of exceedance (Fig.6), illustrating the relationship between flow rates and water levels for the type watercourse section, given in general form by the formula:

$$h=f(Q), \quad (4)$$

where Q – flow, м^3/с;

h – waterdepth, м.

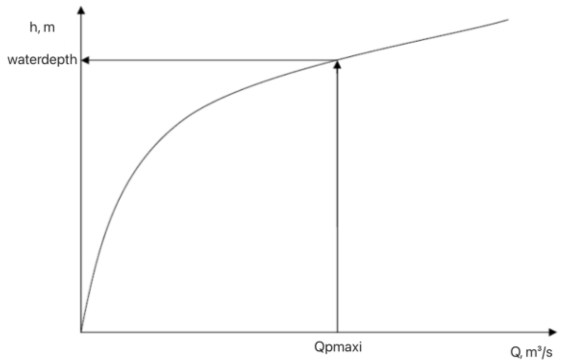


Fig. 6: *Function graph h=f(Q) [20]*

Construction of the probable flooding zone using watercourse model presented in the form of oriented graph G = (V, E) (Fig.5c) was carried out using digital relief model by the excess method [19], for which the open library pysheds [20] was used.

III. Results

To simulate catastrophic floods parameters, the VGS was arranged for all watercourses of the Irkutsk Region (Table 1, Fig. 7).

Table 1: Number of gauging stations used for modeling

Basin District	AGS number	VGS number
Angaro-Baikal	78	1162
Yenisei	7	110
Lensky	45	626
Total	130	1898

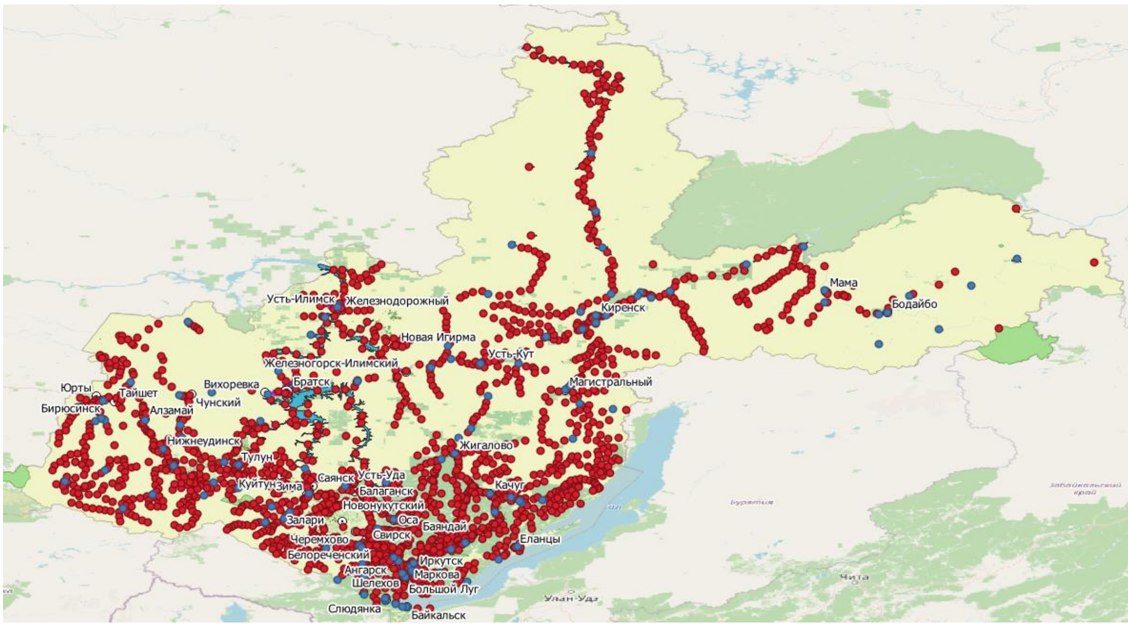


Fig. 7: *Location of AGS and VGS on the Irkutsk Region territory*
The map shows: AGS – blue dots; VGS – red dots [source: obtained by the authors]

Below are the results of modeling and mapping the parameters of catastrophic floods in some areas of the Irkutsk Region (Uslon municipality and the city of Zima), which were flooded in July 2019 as a result of an emergency, the source of which was a dangerous hydrometeorological phenomenon.

The municipalities under consideration are not equipped with stationary hydrological observation points. The nearest gauging station is located at a distance of 12 km from the village of Samara (FHP 8207 Ukhtui).

Water levels diagram in the period from 01.06.2019 to 30.08.2019 at FHP 8207 Ukhtui is shown in Fig.8.

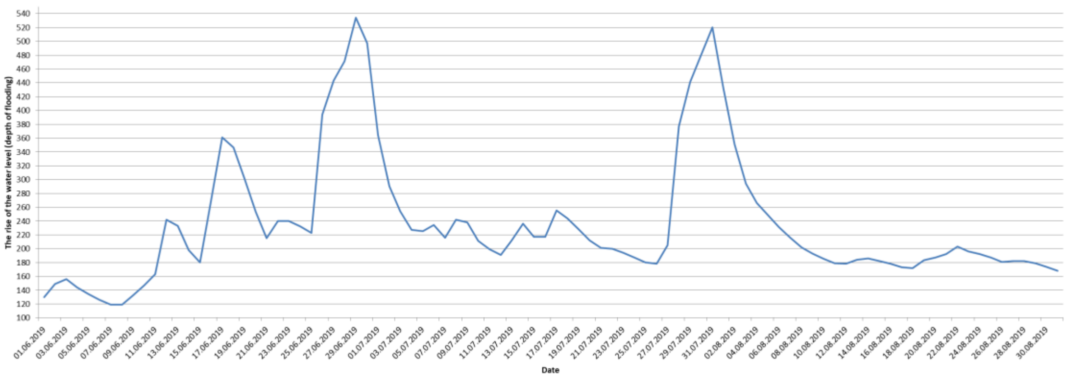


Fig. 8: *Water levels diagram at FGP 8207 Ukhtui*

Simulated values of catastrophic floods parameters for AGS and VGS in the city of Zima area and Uslonsky municipality (Samara village, Nizhny Khazan village, Zaimka Polkovnikova), which were flooded [26], are given in Table. 2 and in Fig. 9.

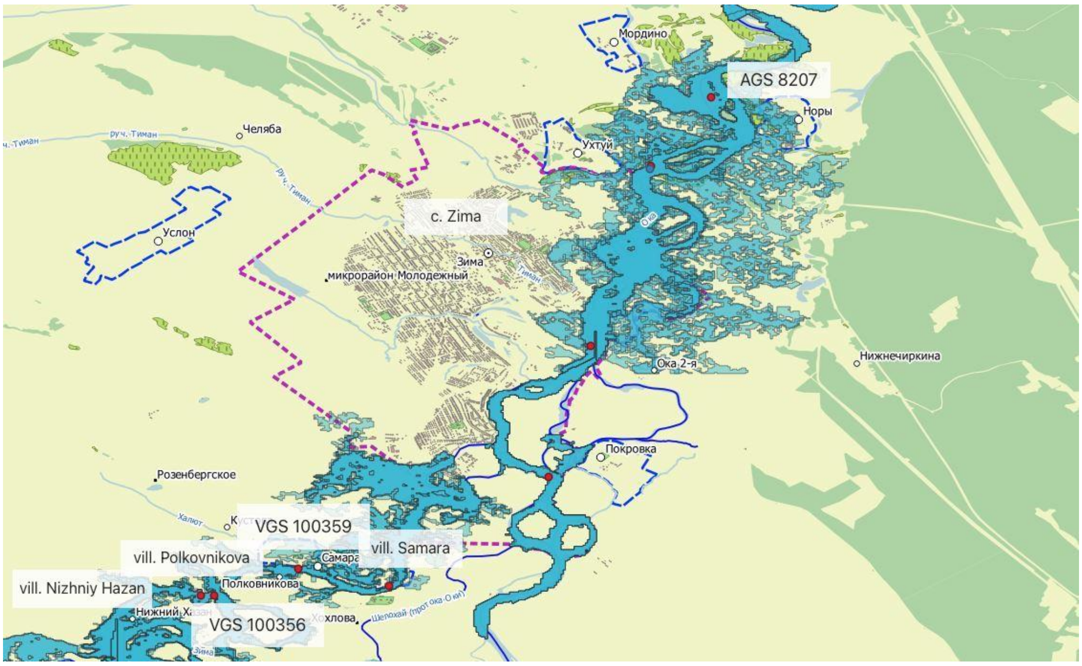


Fig. 9: *Flooding zones for virtual and actual gauging stations shown in Table 2*

Based on the simulation results, spatial data sets were formed in the shape file format, including information about gauging stations (actual and virtual) and flood zones, with the estimated parameters of flooding depth and duration for each probability of exceedance (so-called synthetic flood catalogs).

Table 2: *Estimated results of catastrophic floods parameters for actual and virtual gauging stations in the area of the city of Zima and the Uslonsky municipality (Samara village, Nizhny Khazan village, Polkovnikova zaimka) (Fig.9)*

GS number	GS type	Latitude, degrees.	Longitude degrees.	River	S_basin	q_{200}	Probability of exceedance, %	Q_{pmaxi} (formula (3))	Flooding depth, waterdepth, м
100356	VGS	53,843135	101,981208	Zima	4531,31	0,1	0,5	190,03	2,79*
							1,0	152,02	2,60*
							5,0	106,42	2,33*
							10,0	85,13	2,18*
							20,0	68,41	2,05*
100359	VGS	53,8498110	102,005462	Zima	4564,37	0,1	0,5	190,93	2,29*
							1,0	152,74	2,12*
							5,0	106,92	1,87*
							10,0	85,54	1,74*
							20,0	68,73	1,62*
8207	AGS	53,949550	102,092926	Oka	27000	0,1	0,5	N/A	7,00**
							1,0	N/A	6,53**
							5,0	N/A	5,45**
							10,0	N/A	4,94**
							20,0	N/A	4,42**

Notes:

* – flooding depth estimated according to the formula (3)

** – flooding depth estimated according to the formula (1)

IV. Discussion

Original method of catastrophic floods modeling and mapping in the areas poorly studied in hydrological terms is presented, based on the digital relief model use, hydrographic network construction in the form of orgraph characterizing water flow direction, engagement of generalized regime hydrological information in the form of maps, as well as the results of its application for the pilot entity — the Irkutsk Region.

It is found that with the same catchment areas, maximum water consumption is affected by the value of the maximum urgent annual water consumption module of the probability exceeding 1%, which depends on the geographical location of virtual gauging stations.

Developed original method can be used in predicting emergencies consequences, caused by floods, in planning protective measures, determining the boundaries of the population emergency notification about the threat of occurrence or the occurrence of emergency situations. Obtained flood zones allow determining the index of the territory's susceptibility to floods [27, 28] within the framework of remote risk assessment technology [29].

Original method can also be used in the development of unified documents for the territorial planning and urban zoning of a settlement, an urban district, which should include information about territories at risk of natural and man-made emergencies.

In general, the wide application of the presented original method in the activities of local self—government bodies, executive authorities of the Russian Federation entities, design, insurance and scientific organizations will reduce the risk of emergency situations, move from the practice of responding to emergency to its prevention, ensure the achievement of Sustainable Development Goal 11 - Ensuring openness, security, resilience and environmental sustainability of cities and settlements.

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