IOP Publishing
2388 (2022) 012134 doi:10.1088/1742-6596/2388/1/012134

Geoinformation support for studies of the boundaries of flood zones in urban areas

F N Lisetskii, A O Poletaev[*] and Zh A Buryak

Federal and Regional Centre for Aerospace and Ground Monitoring of Objects and
Natural Resources, Belgorod State National Research University, 85 Pobedy Street,
Belgorod, 308015, Russia

[*] E-mail: poletaev@bsu.edu.ru

Abstract. The article presents the results of the use of geoinformation modelling of the processes of urbanised territories' flooding by river waters. Physical, geographical, and climatic parameters of the key river basin (Vezelka River within the boundaries of the city of Belgorod) have been determined. A list of input data and methods that were used to create geoinformation models is presented. The peculiarities of the technique of aerial photography and the creation of a digital terrain model on its basis are disclosed. The formulas for the calculation of the level of water rise and calculation of the flooding model corrected by the terrain are disclosed. The results of determining high levels of river water by calculated sites are shown, longitudinal and transverse profiles with estimated water levels during flooding with different levels of the expected probability of occurrence have been created. The final map of the boundaries of flood zones in the urban area, which are calculated using geoinformation modelling, is demonstrated. We propose that the results of geoinformation modelling of flooding scenarios for large rivers be included in the regional GIS portal.

1. Introduction

The flooding of areas is a negative natural process that causes material damage to buildings, structures, and communications, endangers the lives of the population living in the flood zones, poses a threat of the loss of material values, loss of crops, washing away of fertile soils, and changes in the landscape. Therefore, it is important to forecast the flow of rivers, since this makes it possible to manage flood risks to reduce damage and determine priority sources of sediment inflow into the river system [1, 2]. Multiscale forecasts are developed for the short term (several hours or days), for the medium term (several weeks), or for the long term (up to nine months) [3]. Reliable flow forecasts can be an important basis for effective real-time flood management, including flood monitoring, management, and prevention [4]. At the same time, the integration of data management with forecast modelling tools is currently ensured by the use of remote sensing data and GIS technologies [5, 6]; artificial neural networks have become of particular importance in forecasting [7]. Due to this, various flood scenarios can be modelled, which will make it possible to analyse the dynamics of river floods and assess their possible consequences in the near future [4]. Ultimately, all this will make it possible to determine flood zones with high accuracy and implement effective flood control measures. Studies of flooding of river floodplains and adjacent territories in the Belgorod region were carried out earlier [8, 9], but without the use of advanced technologies. In this study, an assessment of the possibilities of

GIS technologies was carried out for determining the boundaries of flood zones on the example of the Vezelka River within the boundaries of the city of Belgorod.

2. Study area and dataset

2.1. Study area

The study region (the forest steppe of the Central Russian Upland) is distinguished by both a high soil erosion intensity [10] and a significant accumulation of alluvium on river floodplains. Thus, in talweg the catchment areas (transect-catena in the bottom of the ditch) over 3.5 centuries there was an accumulation of pedosediments with the thickness of 950 mm at an average speed of 2.58 mm yr^{-1} [11]. On average, the estimated intensity of alluvium accumulation in river floodplains of the Central Russian Upland over the last millennium is up to 1 mm yr^{-1} [12]. As a result, the length of the regional river system decreased by 38% over 200 years [13]. Siltation of riverbeds during 200 years of agrarian development of watersheds has led to a change in the water regime on floodplains and often leads to flooding of settlements.

The typical water catchment area (figure 1) is located in the temperate continental climate, characterised by fairly mild winters with snowfalls and thaws and long summers. The average annual air temperature is +5.4 °C. The frost-free period lasts 155–160 days. The soil warms up and freezes to a depth of about 0.5–1 m. On average, precipitation is 540–550 mm, but decreases to 400 mm in some years. A characteristic feature is a fluctuation in the amount of precipitation not only in different years but also in the seasons of the year. Thus, the period from April to October accounts for more than 60% of the annual rainfall. Long-term data registered by the gauging station (50°35′ N and 36°35′ E) (figure 1) show that the spring flood runoff in high-water years accounts for 77.4% of the annual runoff, in average years – 69.2%, and in low-water years – 55.5%. The intensity of the spring flood level rise in the first two or three days is insignificant, usually does not exceed an average of 10 cm per day, after which it increases to 30–50 cm per day, and sometimes to 80–120 cm per day. The average level of the spring flood is 217 cm. Flood is formed in the spring (69% of the annual runoff) and is the main phase of the hydrological regime, starting from the second decade of March and lasting for 26 days on average. The largest rainfall during the observation period was 231 mm. The annual flow rates are 1.25 and 2.7 m^3 s^{-1} (50% and 1% availability, respectively).

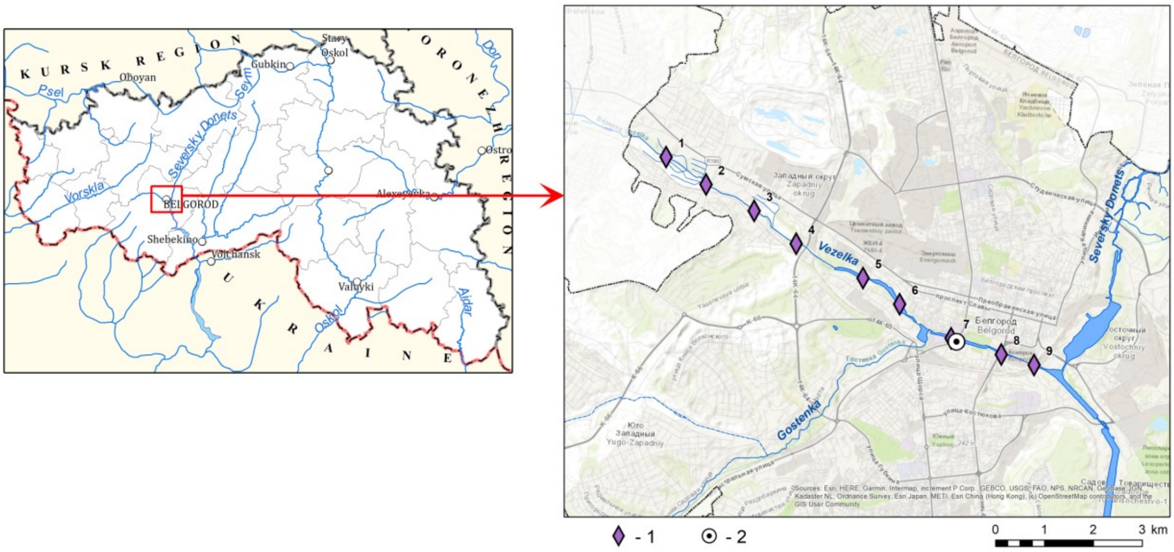

Figure 1. Study area. Designated by numbers: 1 – calculated sites, 2 – gauging station.

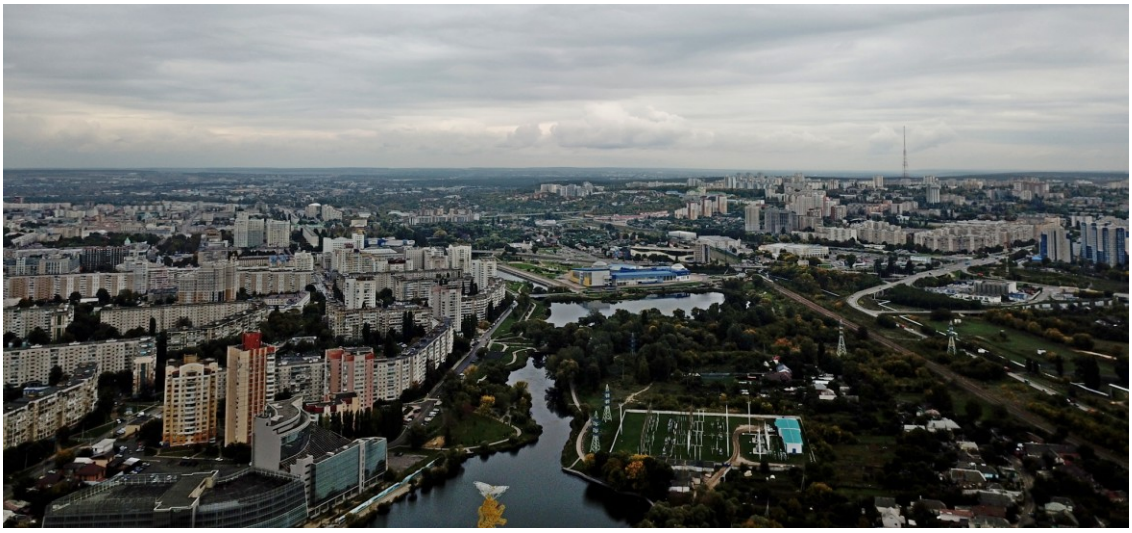

Figure 2. View of the eastern part of the Vezelka River floodplain (the central part of Belgorod).

The key river basin of 409.5 km^2 belongs to the Vezelka River. This is the right tributary of the Seversky Donets River. From the total length of the river (27.4 km) within the boundaries of Belgorod, there is a 9.75 km long section of the lower reaches (figure 2). Vezelka has a relatively narrow floodplain. The absolute elevations of the floodplain vary from 115.5 to 117 m. The average slope of the river is 0.0005. The width of the floodplain varies from 60 to 200 m, the width of the riverbed is 3–6 m. Flooded meadow and flooded marsh soils are formed in the flood zone of Vezelka. A significant part of the floodplain is represented by an urbanised landscape, mainly in the eastern part. At the same time, in the western part of the floodplain, household development is concentrated. The vegetation of the river floodplain within the city is represented by tree-shrub and herbaceous vegetation. In the western part of the floodplain, there is the vegetation of agroecosystems characteristic of household plots; there are also areas of meadow and hydrophilous herbaceous vegetation, and wetlands (figure 3).

Figure 3. View of the western part of the Vezelka River floodplain.

Tree and shrub vegetation are represented by narrow woodlands, mainly of small-leaved species, stretching along the water line on a significant part of the floodplain. In some places, it is almost entirely covered by light forests. From both banks of the Vezelka River, on the site located near its confluence with the Seversky Donets River, there is a park consisting of mixed forest plantations, in which deciduous and coniferous species grow.

2.2. Dataset

The initial data in this study are DEM, materials of observations of the water regime of the rivers in the study area registered by gauging stations of Roshydromet, available in the publications of the water cadastre, as well as in hydrological yearbooks, data of Federal State Budgetary Institution "Central Chernozem Department for Hydrometeorology and Environmental Monitoring".

3. Methods

Information about the terrain of the tide zone was obtained from the results of aerial photography, which was carried out using DJI Mavic Pro unmanned aerial vehicle (UAV), flight tasks were created in DroneDeploy software. The survey was carried out from a height of 180 m to ensure high accuracy of the resolution of the aerial image elements within 5–10 cm on the ground. According to the recommended settings in DroneDeploy software, the longitudinal overlap of aerial photographs (Px) was set to 75%, the transverse overlap (Py) was set to 65%. To ensure that the accuracy of the coordinates of the projection centres of aerial photos is at least 5 cm in plan and 10 cm in height relative to the points of the geodetic network adopted as a horizontal and vertical geodetic basis, ground reference benchmarks of square shape with a side of 1 m were used. The reference benchmarks were distributed evenly, if possible, in a staggered manner, within each site where aerial photography was planned. The distance between the reference benchmarks was about 200–300 m.

GNSS receiver Acnovo GX9 was used for surveying reference benchmarks with elevations. Point coordinates were determined and registered in MSK-31 coordination system. The survey was carried out in RTK (Real-Time Kinematic) mode, the actual maximum measurement error did not exceed 5 cm. To create the longitudinal profile of the riverbed, an additional ground survey of the water line elevations was carried out, since the results of the survey with the UAV near the water mirror can suffer from strong distortions, as well as be uninformative if the bank is overgrown with dense vegetation.

Photographic materials obtained during aerial photography of the territory were processed in the Agisoft Metashape program. The processing procedure consisted of the following steps:

1) A procedure for aligning photographs based on key points to determine the spatial position of the visual axis of each photograph and obtain a thin cloud of surface points that serves as a basis for further surveys.
2) Coordinate referencing of the model to the local coordinate system. Benchmarks on aerial photographs were referenced to coordinates obtained as a result of instrumental survey on the ground.
3) Reconstructing photographs into a dense point cloud and removal of points with low confidence of coordinates determination.
4) Classification of dense cloud terrain points. The survey area was divided into cells with a side length of 100 m, in which points were screened out with an excess of more than 0.1 m and an angle of more than 25° relative to the expected average terrain surface.
5) Digital Elevation Model (DEM) creation based on classified terrain points.
6) Digital Surface Model (DSM) creation based on a full cloud of points.
7) Creation of an orthophotomap based on DEM.

For additional information on the terrain, DEM was created using digitised topographic maps at a scale of 1:10 000 (contour intervals of 2–2.5 m) with a resolution of 10 m. In the course of vectorisation, vector layers of horizontals, cliffs and ravines, elevations, water line elevations (adjusted for the results of field surveys), reservoirs and watercourses were created. The terrain model was built in the ArcGIS 10.5 program using the "TopoToRaster" tool in the "SpatialAnalyst" module. This tool interpolates the hydrologically correct raster surface using point, linear, and polygonal data. This method imposes special restrictions that ensure the connected drainage structure and correct representation of ridges and watercourses from the input data of the isolines. Also, in the terrain model, it is necessary to account for the cliffs in the water line boundaries, which represent a natural barrier when the territory is flooded. The DEM, which was created in this way, provides a constant descent along the riverbed and accounts for its longitudinal slope.

To determine the zone of flooding of given expected probability of occurrence, the exceedance method was used [14]. It was considered that the slopes of the water surface, when the water level rises, are identical to the slopes of the river obtained by the water lines.

The water elevation level Z_{flooding} can be calculated by the formula (1):

$$Z_{\text{flooding}} = Z_0 + \Delta Z \tag{1}$$

where Z_0 is the water level in the low-water period (m), ΔZ is the layer of flooding of given expected probability of occurrence, m.

Since the work was carried out in autumn, it was impossible to obtain accurate data on low water levels along the length of the surveyed areas. Therefore, during the field work, surveys of current water lines were carried out, including at the nearest gauging station used in the calculations as analogue objects. Thus, uniform data on changes in slopes of river sections were obtained. Based on the results of the water line survey, the longitudinal profile of the river was created, and the points of the calculated sites were set at the points of inflection.

For each calculated site, the level of water rise was determined by transferring the absolute height of flooding from the gauging station, analogue object, accounting for the slope of the channel according to the formula (2):

$$Z_{\text{flooding}} = Z_{\text{floodingGS}} \pm (L \times \text{tg}\,\alpha) \tag{2}$$

where Z_{flooding} is the absolute height of water rise at flooding of the given expected probability of occurrence at the calculated site (m, Baltic System), $Z_{\text{floodingGS}}$ is the absolute height of water rise at flooding of the given expected probability of occurrence at the gauging station, analogue object (m, Baltic System) (the ± sign is selected depending on the position of the calculated site relative to the analogue object, L is the distance along the river profile from the analogue object to the calculated site (km), tgα is the slope between the analogue object and the calculated site, ‰).

To simulate flooding on the ground, we used DEM and the flooding horizon model $Z_{\max}$, which accounts for the difference in the water level of flooding along the survey area (figure 4). To create a model of the flood horizon, linear transverse profiles were used at each calculated site. The length of the profile line was selected so as to cross the nearest horizontal with a height corresponding to the maximum flooding elevation.

Figure 4. Scheme for obtaining a flood zone raster in a GIS: DEM (1), flood horizon (height of water rise) (2), derived difference raster, where values less than zero are the flooded area (3)

Each profile was assigned an attribute with the maximum flooding height at the calculated site. The lines of the profiles were converted into sets of points, which were interpolated by the method of inverse-weighted distances (IDW) to create a raster model of the maximum flooding horizon with a resolution of 10 m.

To determine the location of the points of intersection of the flood horizon with the terrain, simulation was performed using the RasterCalculator tool (formula (3)), as a result of which a flood model adjusted for terrain was obtained:

$$\mathrm{DEM} - Z_{\max} < 0. \quad (3)$$

The flood zone model was converted to a vector format. Then an additional check and adjustment using topographic maps were carried out to identify artificial barriers to flooding – causeways, cliffs, fillings for new construction. The riverbed of the Vezelka River was divided into 9 calculated sites (figure 1), for each of which the absolute heights of the water level were determined in flooding scenarios with different levels of the expected probability of occurrence: 1, 3, 5, 10, 25 and 50 %.

4. Results and Discussion

The calculated highest water levels of the Vezelka River from the calculated sites (analogue object – gauging station “Bolkhovets” – Belgorod) are shown in Table 1, the calculated water levels are plotted on the longitudinal profile (figure 5).

Table 1. Calculation of the maximum water levels of a given expected probability of occurrence for the monitoring sites along the Vezelka River in Belgorod.

Monitoring site	Distance from the mouth, km	Distance from the gauging station, km	Water surface slope, ‰	Maximum water levels of a given expected probability of occurrence, m (Baltic System)					
				1%	3%	5%	10%	25%	50%
1	9.4	7.3	1.18	126.69	126.38	126.18	125.91	125.43	124.74
2	8.4	6.2	1.28	126.10	125.79	125.59	125.32	124.84	124.15
3	7.3	5.1	1.28	124.68	124.37	124.17	123.90	123.42	122.73
4	6.2	4.0	1.38	123.62	123.31	123.11	122.84	122.36	121.67
5	4.6	2.4	0.37	119.02	118.71	118.51	118.24	117.76	117.07
6	3.6	1.4	0.28	118.55	118.24	118.04	117.77	117.29	116.60
7	2.3	0.1	0.67	118.23	117.92	117.72	117.45	116.97	116.28
gauging station	2.2	0	-	118.14	117.83	117.63	117.36	116.88	116.19
8	1.2	1.0	0.49	117.68	117.37	117.17	116.90	116.42	115.73
9	0.5	1.7	0.78	116.85	116.54	116.34	116.07	115.59	114.90

Based on the results of the calculation of the maximum water levels, the flooding boundary of 1% expected probability of occurrence for the city of Belgorod was plotted based on a spatial analysis of the digital terrain model (figure 6).

Absolute flooding elevations of 1% expected probability of occurrence in the Vezelka River basin range from 127.8 m to 116.6 m at the mouth, and the difference in flooding height is 11.2 m. The flooded area is 377 ha, which covers 2.3% of the city territory.

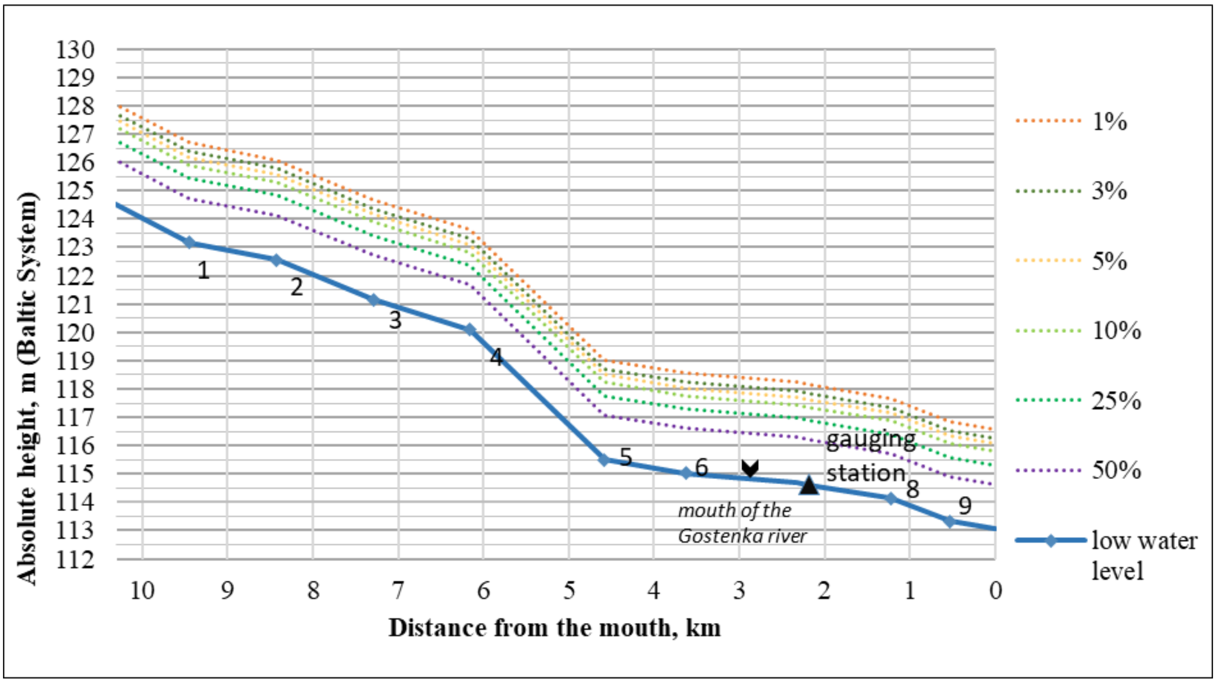

Figure 5. Longitudinal profile of the Vezelka River in Belgorod.

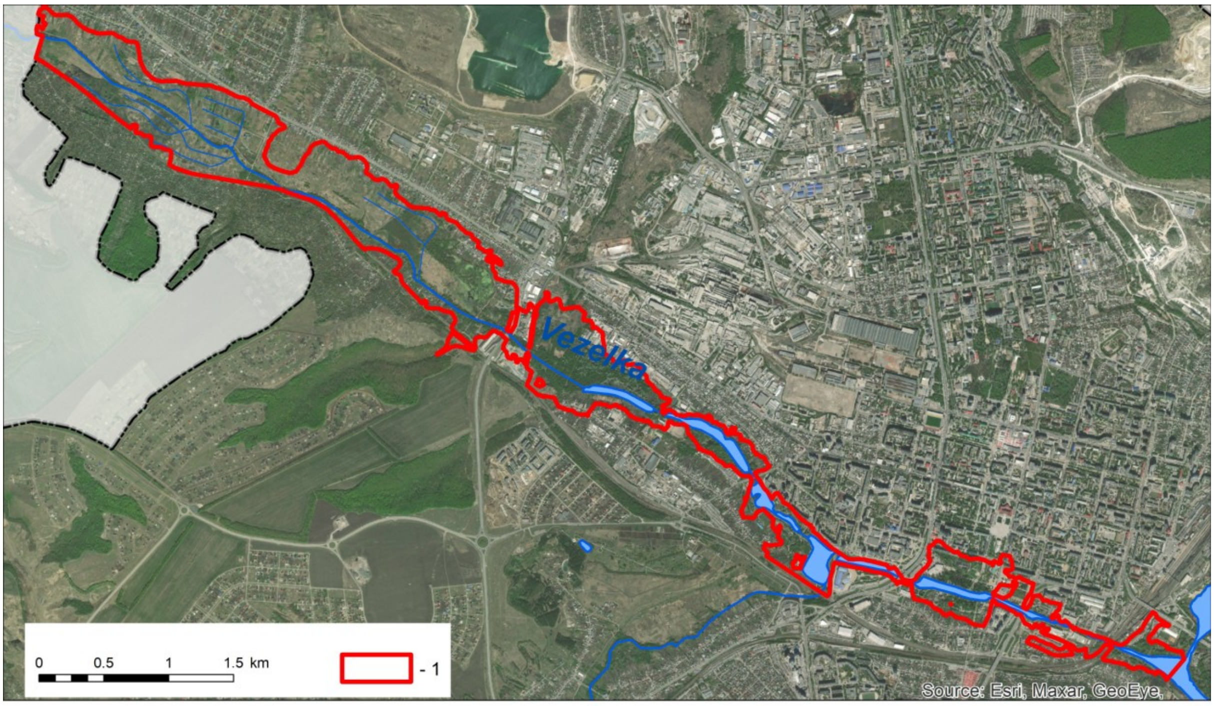

Figure 6. Map of the boundaries of flooding 1% level of a given expected probability of occurrence for the territory of Belgorod.

5. Conclusions

The use of geoinformation technologies in modelling various flooding scenarios with different levels of the expected probability of occurrence and in determining the flood zone boundaries as illustrated by the Vezelka River within the boundaries of the city of Belgorod made it possible to present the modelling results clearly and meaningfully. Replication of the universal geoinformation modelling methodology for flood scenarios and flood zone boundaries for large regional rivers would allow the modelling results to be integrated into a single GIS portal. If the database is continuously updated with current observations, it could assist in the planning and implementation of activities aimed at mitigating the potential damage caused by the flooding of urbanised areas.

References

[1] Lisetskii F N, Zemlyakova A V, Terekhin E A, Naroznyaya A G, Pavlyuk Y V, Ukrainskii P A, Kirilenko Zh A, Marinina O A and Samofalova O M 2014 *Adv. Environ. Biology* **8(10)** pp 536–539
[2] Tucci C E M and Collischonn W 2006 *WMO Bulletin* **55(3)** pp 179–184
[3] Georgakakos K P and Krzysztofowicz R 2001 *J. Hydrol.* **249**
[4] Merkuryeva G, Merkuryev Y, Sokolov B V, Potryasaev S, Zelentsov V A and Lektauers A 2015 *J. Comput. Sci.* **10** pp 77–85
[5] Irimescu A, Stancalie G H, Craciunescu V, Flueraru C and Anderson E 2009 *Threats to Global Water Security* (Dordrecht: Springer) pp 167–177
[6] Skotner C, Klinting A, Ammentorp H C, Hansen F, Høst-Madsen J, Lu Q M and Junshan H 2013 *Proc. of Esri Int. user conf.*
[7] Zueva A, Shamova V and Pilipenko T 2021 *J. of Physics: Conf. Series* **2131(3)** 032069
[8] Petin A N, Petina M A, Lebedeva M G and Dokalova Y I 2015 *Res. J. Pharm. Biol. Chem. Sci.* **6** pp 1787–1792
[9] Kornilov A, Reshetnikov V, Kornilova E and Lebedeva M 2020 *Proc. 20th Int. Multidisciplinary Sci. GeoConf. (SGEM 2020)* **3.1** pp 91–98
[10] Buryak Z and Marinina O 2020 *E3S Web Conf.* **176** 04007
[11] Lisetskii F N and Pichura V I 2020 *Catena* **187** 104300
[12] Chendev Y G, Dudin D I, Belevantsev V G, Fedyunin I V, Inshakov A A and Golotvin A N 2021 *Eurasian Soil Sci*. **54(4)** pp 461–477
[13] Yermolaev O P, Mukharamova S S, Maltsev K A, Ivanov M A, Ermolaeva P O, Gayazov A I, Mozzherin V V, Kharchenko S V, Marinina O A and Lisetskii F N 2018 *IOP Conf. Ser. Earth Environ. Sci.* **107(1)** 012108
[14] Postnova I S, Yakovchenko S G and Dmitriev V O 2005 *J. Comput. Technol.* **10(S3)** pp 39–46