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# GEOINFORMATION MODELING OF FLOODED AREAS IN SETTLEMENTS (IN THE EXAMPLE OF LUTSK)

**Object.** Flooding in Ukraine is a common natural phenomenon that repeats periodically and in some cases it becomes disastrous. In an average year floods on the rivers of Volyn region take place from one to three times which extend beyond the limits of the floodplain. The floodplain of Styr river is located in the historical center of Lutsk city, that`s why issues of research and forecasting of floods are very important for a given city. **Methodology.** Using modern technologies of geodesy and remote sensing allows to quickly determine and predict the floodplain area of settlements. Based on the statistical data of the Volyn Regional Center for Hydrometeorology during the 7 year period 2011-2017 about water levels of the river Styr. We conducted mathematical modeling of fluctuations of water levels within the territory of Lutsk, based on creating a partial Fourier series for discrete values of middle-ten-day water levels values. The post hydrological measurements of Styr river water levels in the territory of Lutsk located on the Shevchenko Street comply with an altitude 172.87 meters. Based on the data of short-term flood forecasting in February and March, and relief data from the Department of Architecture and Urban Development of Volyn State Administration, we conducted visualization of the results using geographic information system QGIS. **Results.** The results of mathematical processing were the basis for geoinformation simulation of flooded areas using remote sensing data that are publicly available. Use of statistical and geospatial data in this article has great potential for further application in modeling the processes of natural and technogenic origin. **Scientific novelty.** The mathematical model of short-term forecasting of water levels during the flood period on the river Styr with implementation of geoinformation modeling of flooded areas using remote sensing data is proposed. **Practical significance.** The research results of water level changes on the Styr River and flood zones within the limits of Lutsk is proposed. The spring flood in February-March 2018, with the maximum water level 5.33 m, corresponds to an absolute mark of 178.20 m, which is forecasted in this article.

*Keywords:* geoinformation modeling; settlement territory; approximation; digital terrain models; TIN-models; water level; flood process.

## Introduction

Freshets and flooding are typical for all rivers in Ukraine, in which water pools characterized by irregularity of falling atmospheric precipitation.

The power of floods largely depends on the amount, intensity, duration, atmospheric precipitations or water supply in the snow cover and melt water formation intensity [Kovalchuk, 1997].

Flood – phase of the hydrological regime of the river is characterized by a fast, relatively short-lived increase of water levels in the mainstream during heavy rains, prolonged rains and heavy snow melt during the thaw, which is imposed on the rain. Floods in Ukraine are a common natural phenomenon that repeats periodically. However, in some cases it becomes disastrous and entails the destruction of dams and buildings, loss of life, and significant financial loss.

In an average year the rivers of Volyn region has one to three floods which go beyond the limits of the floodplain. Frequencies of floods in many years are subordinate to certain laws, which appear in alternating periods of high and low water levels, caused by global atmospheric circulation.

The territory of Styr river basin is characterized by flat topography, which complicates a quick passage of floods and causes flooding of large

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areas, on average, once in 2-3 years.

Economic activities which were carried out in violation of environmental regulations, significantly reduced the possibility of throughput of river Styr and a number of its inflows, which increased water levels at the time of the floods.

The main reasons of spring floods as natural disasters (as well as in the fall) are natural (meteorological) factors that intensified by anthropogenic loading in an area. In recent decades flooding has had catastrophic consequences on buildings in the area of permanent flooding and on certain economic activities. Their negative consequences are enhanced to a catastrophic extent and contribute to intensification of overland flow. Recently there is an urgent need for complex planning and implementation of immediate flood protection measures and organizing economic activities in watersheds that are most exposed to the ravages of freshets and flooding.

Since 1995, scientists from the Lesya Ukrainka Eastern European National University performed comprehensive regional monitoring study.

Work carried out under the following programs: "Complex regional program protecting the population and territories from emergency situations of technogenic and natural character in the Volyn region from 2016 to 2020", Regional Environmental Program "Environment 2016 - 2020", Regional program for evaluation of state and clearing of major river Volyn beds, Regional program for environmental monitoring of Volyn region, Regional ecological program "Ecology - 2015 and Forecast till 2020".

The issue of research, forecasting, and modeling of floods did not lose its relevance with national and foreign scientists. Monitoring of flood processes, with the use remote sensing methods, their forecasting, and GIS modeling were considered in the works [Dorozhynsky, 2011, Liu, 2005], and in combination with mathematical prediction in the works [Voloshyn, 2017, Maat, 2015, Aronica, 2012]. Modeling using discrete Fourier series devoted several articles, including [Voloshyn 2012, Melnyk, 2015].

The practical application of geographic information systems in general and QGIS package is concretely covered in the works [Li ,2014, Knight, 2015 , Maiti, 2015].

Questions of mathematical modeling of flood process in river Styr dedicated work [Shostak, 2011], but geoinformation forecasting of flooding in areas near the city of Lutsk was not considered thus this proposed research is timely and relevant.

## Methodology

The frequency of floods in the multi-years cut formation is subject to certain laws, which appear in alternating periods of high and low water level, caused by global atmospheric circulation.

According to conclusions of Ukrainian Research Hydrometeorological Institute`s scientists high repeating floods are possible in future years on the rivers of the entire western region of Ukraine, that must be taken into consideration for the performance measures to protect the population from the negative effects.

Volyn region is characterized by flat terrain, making it possible for rapid floods and leads to submergence of large territories, on average, once in 2-3 years.

Economic activities that are in violation of environmental regulations, significantly reduced the throughput possibility of Styr river and a number of its inflows, raising the water level at the time of the floods.

Based on the statistical data about water levels in the river Styr using ten day interval values water levels (Table 1), we conducted mathematical modeling of fluctuations of water levels in the period within territory of Lutsk. The post hydrological measurements of Styr river water levels in the territory of Lutsk located on the Shevchenko street comply with an altitude 172.87 meters.

Analyzing the statistics, we can state that every year in the city of Lutsk 1-2 floods are observed. In 2011 there was a flood in February, where the water level increased by 4.98 m to an altitude of 177.85 and in August during torrential rains the water level increased from 2.74 m to 3.84 m. The 2012 spring flood was observed in March, when the water level rose from 2.93 m to 4.18 m (maximum water level 177.05 m), and during the September rains, the water level increased from 3.13 m to 3.77 m. On April, 15 2013 a record spring flood was observed, when the water level rose from 3.11 m to 6.13 m and reached the 179.00 meter mark, and during the September and October rainy season the water level increased from 2.69 meters to 3.48 meters. The 2014 February and June floods registered in, with water levels rising from

*Table 1*

The average ten-day water level of the river Styr within the territory of Lutsk for 2011-2017.

| Year | Dec. | Water levels on a monthly, cm | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **I** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **VIII** | **IX** | **X** | **XI** | **XII** |
| **2011** | **I** | 419,40 | 491,10 | 444,80 | 391,10 | 336,90 | 260,00 | 289,40 | 375,70 | 330,50 | 269,80 | 264,60 | 265,50 |
| | **II** | 458,10 | 485,00 | 394,90 | 382,50 | 333,90 | 287,60 | 311,10 | 379,00 | 279,70 | 266,90 | 261,80 | 272,10 |
| | **III** | 481,45 | 483,75 | 428,91 | 358,00 | 304,82 | 271,40 | 302,82 | 351,64 | 271,40 | 270,82 | 263,60 | 285,18 |
| **2012** | **I** | 282,20 | 297,90 | 398,70 | 349,40 | 327,40 | 291,50 | 325,60 | 291,20 | 324,00 | 349,90 | 334,70 | 286,60 |
| | **II** | 271,10 | 293,60 | 365,40 | 359,20 | 329,30 | 352,30 | 300,40 | 313,70 | 317,30 | 339,70 | 333,30 | 309,70 |
| | **III** | 291,91 | 343,00 | 342,45 | 351,20 | 298,55 | 356,20 | 300,55 | 337,00 | 352,60 | 339,73 | 310,00 | 341,82 |
| **2013** | **I** | 349,70 | 421,70 | 443,80 | 524,20 | 533,50 | 451,90 | 409,30 | 349,20 | 276,60 | 331,50 | 326,60 | 305,80 |
| | **II** | 380,70 | 441,60 | 440,80 | 603,50 | 492,10 | 464,90 | 364,10 | 280,90 | 294,30 | 319,50 | 305,30 | 294,30 |
| | **III** | 375,36 | 453,63 | 484,82 | 586,80 | 443,91 | 457,50 | 364,36 | 277,36 | 330,90 | 327,55 | 307,40 | 294,18 |
| **2014** | **I** | 304,70 | 346,70 | 365,50 | 285,30 | 267,50 | 352,10 | 289,00 | 261,30 | 270,90 | 267,10 | 259,20 | 247,60 |
| | **II** | 300,90 | 365,70 | 331,00 | 286,00 | 283,30 | 360,20 | 295,60 | 262,40 | 265,80 | 273,00 | 261,70 | 243,20 |
| | **III** | 351,91 | 379,63 | 325,82 | 285,30 | 295,18 | 365,50 | 271,55 | 263,91 | 272,60 | 256,55 | 249,90 | 266,00 |
| **2015** | **I** | 264,80 | 279,70 | 272,10 | 282,30 | 248,20 | 306,40 | 244,30 | 245,40 | 241,50 | 257,40 | 246,00 | 253,40 |
| | **II** | 297,90 | 258,40 | 277,20 | 275,10 | 255,40 | 260,30 | 235,80 | 235,90 | 242,20 | 257,80 | 244,90 | 252,90 |
| | **III** | 291,55 | 260,38 | 275,09 | 254,30 | 294,18 | 250,70 | 244,00 | 241,64 | 240,30 | 264,18 | 254,20 | 252,82 |
| **2016** | **I** | 270,40 | 298,70 | 302,80 | 266,40 | 256,80 | 254,60 | 273,50 | 275,30 | 247,30 | 245,00 | 292,00 | 327,00 |
| | **II** | 275,70 | 289,50 | 291,30 | 272,10 | 264,00 | 259,30 | 280,80 | 275,60 | 240,10 | 255,80 | 291,30 | 343,00 |
| | **III** | 280,55 | 298,00 | 272,64 | 278,90 | 268,55 | 269,00 | 288,91 | 261,73 | 237,80 | 259,45 | 326,50 | 328,55 |
| **2017** | **I** | 322,32 | 300,94 | 399,34 | 357,90 | 302,55 | 291,45 | 308,55 | 325,64 | 326,35 | 380,94 | 350,94 | 352,79 |
| | **II** | 329,58 | 314,36 | 390,99 | 311,18 | 304,52 | 294,24 | 321,70 | 321,67 | 327,19 | 352,94 | 332,09 | 385,06 |
| | **III** | 305,3 | 361,34 | 396,12 | 297,19 | 301,55 | 297,14 | 324,44 | 319,38 | 360,96 | 332,77 | 309,40 | 401,67 |

mark 2.89 m to 3.84 m and 2.77 m to 3.78 m respectfully. In 2015, during the May flood, the water level rose from 175.59 m to 176.27 m. In 2016 the autumn flood occurred in the second week of November. The water level rose from 2.81 m to 3.58 on December 18. From February 2 to March 2 2017 there was a weak spring flood where the water level increased from 3.01 m to 3.99 m. The end of November flood continued to the end of 2017. At this time, the water level increased from 3.03 m (November, 27) to 4.15 (December, 31). Fluctuations of water levels in the river Styr in the past seven years is shown in Figure 1.

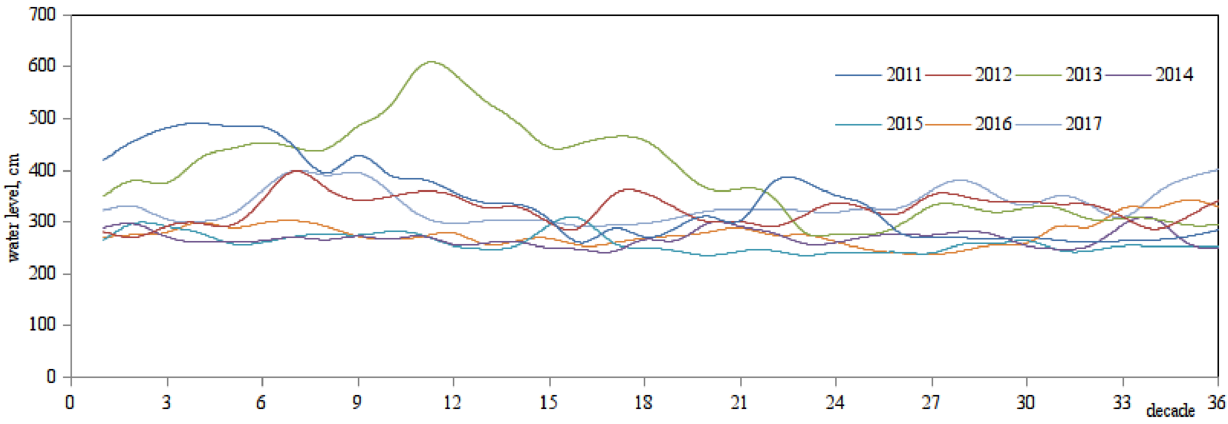


*Fig. 1. Dynamics of water levels on the river Styr in the territory of Lutsk 2011-2017.*

The mathematical model of water levels on the river Styr within the territory of Lutsk is based on the creating a partial Fourier series [Voloshyn, 2012, Melnyk, 2015] for discrete values of middle-ten-day water levels values during the period from 2011-2017.

As the model calculations have shown, the character of the fluctuation of water levels during this period is approximated by the polynomial trend component of the species:

$$H(t) = \sum_{i=0}^{k} a_i t^i \qquad (1)$$

where *H(t)* - value of the Styr river water level; $a_i$ - coefficients of polynomial trend; *t* - time.

The criterion for the best approximation of ten day water level values served coefficient of determination between the actual values and the values of a polynomial trend:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(h_{act_i} - \sum_{j=0}^{k} a_j t^j\right)^2}{\sum_{i=1}^{N}\left(h_{act_i} - h_{mid}\right)^2} \qquad (2)$$

As a result of processing every ten day values, it wasconcluded that the trend component of Styr river water levels fluctuations sufficient to present as a 3 power polynomial. In the process of mathematical treatment we received a trend curve type:

$$H(t) = 0.00007\,t^3 - 0.02128\,t^2 + +1.37259\,t + 336.52133 \qquad (3)$$

For a more detailed study of water levels fluctuations the deviations of observations from the values which have received the trend curve (3) in a finite Fourier series:

$$\bar{h}(t) = a_0 + \sum_{k=1}^{30}\left[a_k \cos(kt) + b_k \sin(kt)\right], \qquad (4)$$

$$a_0 = \frac{1}{n}\sum_{i=1}^{n}\left(h_{act_i} - h_{trend_i}\right),$$

$$a_j = \frac{2}{n}\sum_{i=1}^{n}\left(h_{act_i} - h_{trend_i}\right)\cos(jt_i),$$

$$b_j = \frac{2}{n}\sum_{i=1}^{n}\left(h_{act_i} - h_{trend_i}\right)\sin(jt_i),$$

where - the actual value of water; - the value of water received from the trend component approximating function (3).

Within the above, the mathematical model is:

$$\bar{h}(t) = H(t) + a_0 + \sum_{k=1}^{30}\left[a_k \cos(kt) + b_k \sin(kt)\right] \qquad (5)$$

The proposed mathematical model was used for short-term forecasting of the flood processes. Graphic interpretation of modelling and forecasting at the beginning of 2018 are presented in Figure 2.

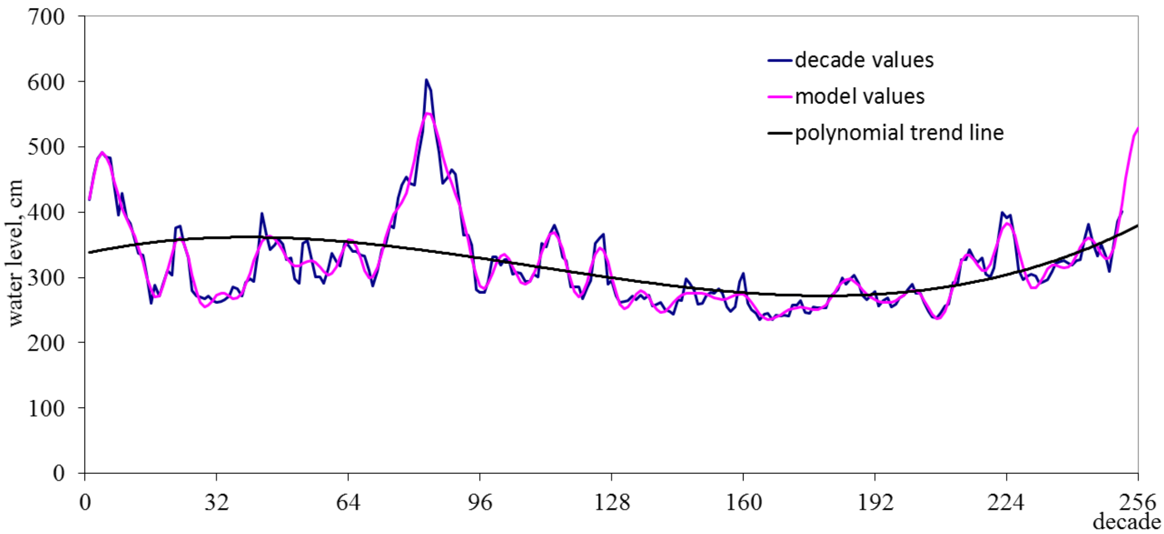


*Fig. 2. Mathematical model for approximation of every ten days water levels of the river Styr.*

As shown in Fig. 2 the spring flooding is forecast in February and March with the maximum water level 5.33 m, corresponding to an absolute mark of 178.20 m.

Further research has focused on identifying areas of flooding within the territory of Lutsk.

**Results**

To build the relief of Lutsk files matrices of heights SRTM v.4 were used, obtained from http://mapgroup.com.ua [SRTM Volyn region, 2018] and the Geological Society of the United States [U.S. Geological Survey, 2018]. Data processing and visualization of the results was performed using a free open source geographic information system QGIS [QGIS. A Free and Open Source Geographic Information System, 2018] in the current at the time of writing long-term support version 2.18.15 (LTR).

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In the first stage, data was obtained by the vector boundary of Lutsk according to City Master Plan approved by The Decision of Lutsk City Council №42 / 1 dated 24.06.2009 [The Decision of the Lutsk City Council, 2009]. For flood process modeling we made vector riverbeds of Styr, Sapalayivka, and Kichkarivka rivers by images obtained from the service Google Maps [Google Maps, 2017] valid for 20.12.2017.

To reduce processing time height files were limited to the territory of Lutsk. According to contours SRTM has been allocated isolines in the study area in increments of 5 meters, and graphical relief was recorded using a single-channel pseudocolor map. For better illustrative purposes of flooding areas in territory of Lutsk was used a picture from Google Maps service [Google Maps, 2017], which was based on a background (Fig. 3).

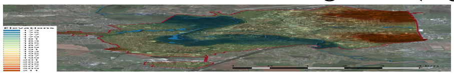

*Fig. 3. Output territory of Lutsk received in geographic information system QGIS.*

Further, we have decided to simulate the maximum level of flood water level in the Styr river as at April 15, 2013, when the water level reached 179.00 meters. Graphically the model is shown in Fig. 4.

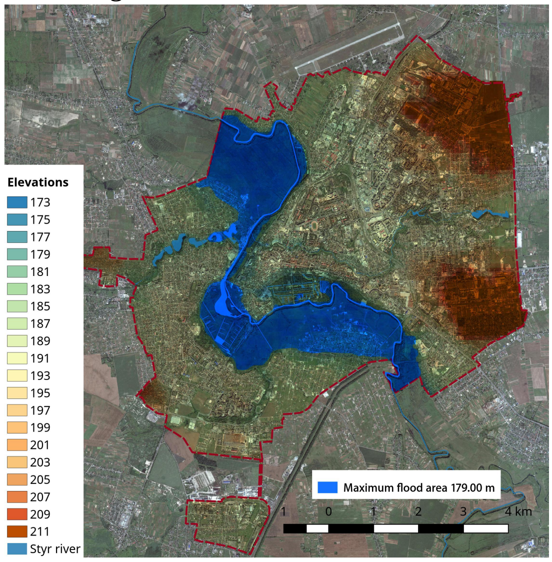


*Fig. 4. Simulating of maximum flood levels as at April 15, 2013 when the water level in the river Styr 179.00 m*

## Practical significance

Based on the data of short-term flood process forecasting in February and March months and relief data from the Department of Architecture and Urban Development of Volyn State Administration, we conducted visualization of the results within the territory of Styr river floodplain using geographic information system QGIS. Graphically, this model with OpenStreetMap [OpenStreetMap contributors, 2017] background is shown in Fig. 5.

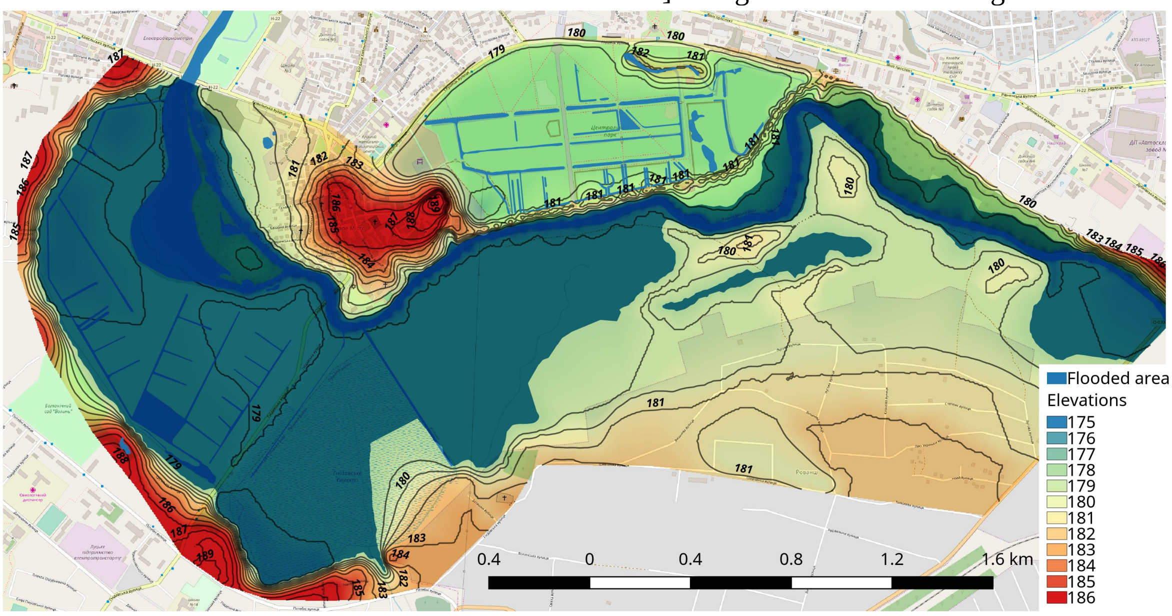


*Fig. 5. Simulation of flood forecast February-March 2018 when the water level in the river Styr was 178.20 m*

Output data is correspond to topographical plans with a scale of 1:500. According to these data, a TIN and raster model with a spatial resolution of 1 m was created. The terrain clearance is 0.5 m, which corresponds to a topographic scale of 1:500.

The flood encompasses historic Lutsk areas such as the Gnidava swamp, the Rovantsi lowlands and the Lesya Ukrainka Central Park of Culture and Recreation. Due to the soil dam exceeding 3 m, which was built in 1933, the Central Park does not relate to the flood zone, however, due to raising the level of groundwater and filtration properties of the dam during the flood period there is insignificant flooding of the territory.

## Conclusions

Based on the analysis of water levels statistical data on the river Styr by Volyn Regional Center for Hydrometeorology for years 2011-2017 we proposed a mathematical model which is based on the building a partial Fourier series for discrete values of the average ten-day water levels values.

This mathematical model is the basis of short-term forecasting of rising water levels within the floodplain of Styr River in the territory of Lutsk, according to which spring floods are forecasted in February-March 2018 with the maximum water level 5.33 m, corresponding to an absolute mark of 178.20 m.

The results of mathematical processing were the basis for geoinformation simulation of flooding areas using remote sensing data that are publicly available. Used in article set of statistical and geospatial data there is great potential for further application in modeling the processes of natural and technogenic origin.

The simulation of flood processes in terms of complexity is not possible without taking into account other meteorological elements such as precipitation, temperature regime, amount of snow, and period of snow. Flood forecast model refinement process in the city of Lutsk in the account of these meteorological elements will be devoted to further research.

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