Article

Geoinformation Modeling of Flooded Areas in Settlements in the Example of Lutsk

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Abstract: Floods in Ukraine is a common natural phenomenon that repeats periodically and in some cases it becomes disastrous signs. In an average year in the rivers of Volyn passes from one to three floods with going beyond the limits of the floodplain. 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. Using modern technologies of geodesy and remote sensing allows to quickly determine and predict the floodplain area of settlements. The research results of water level changes on the Styr River and flood zones within the limits of Lutsk is proposed. The mathematical model of short-term forecasting of water level in flood period on the river Styr with implementation of geoinformation modeling of flooded areas using remote sensing data is proposed.

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

1. Introduction

Freshets and flooding is typical for all rivers in Ukraine, whitch watersheds are characterized by irregularity of falling atmospheric precipitation.

The power of floods is largely depends on the amount, intensity and 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, which is characterized by fast, relatively short-lived increase of water levels in the mainstream during heavy rains, prolonged rains, heavy snow melt during the thaw, which is imposed on the rain. Floods in Ukraine is a common natural phenomenon that repeats periodically. However, in some cases it becomes disastrous signs, entails the destruction of dams and buildings, loss of life, significant financial loss.

In an average year in the rivers of Volyn passes from one to three floods with going beyond the limits of the floodplain. Frequencies of floods in many year cut is subordinate to certain laws, which appear in alternating periods of high and low water level, caused by global atmospheric circulation.

The territory of Stir river basin is characterized by flat topography, which complicates a quick passage of floods and causes flooding of large areas, on average, once in 2-3 years.

Economic activities which carried out with violation environmental regulations, significantly reduced the possibility of throughput of river Styr and a number of its inflows, that increased water level and the time of the floods.

The main reasons of spring floods as natural disasters (as well as the fall) is a natural (meteorological) factors that intensified by anthropogenic load of area. That is catastrophic consequences to a certain extent caused by economic activity in recent decades. Enhanced of negative consequences their catastrophic ostent not contributes the location of buildings in the area permanent flooding and intensification of overland flow. So today there is an urgent need for complex planning and implementation of immediate flood protection measures and organize economic activities in watersheds in most exposed to the ravages regions by 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 in 2016-2020 years", 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 in national and foreign scientists. Monitoring of flood processes, with the use remote sensing methods, their forecasting and GIS modeling were considered in the works [1,2], and in combination with mathematical prediction in the works [3-5]. Modeling using discrete Fourier series devoted several articles, including [6,7].

The practical application of geographic information systems in general and QGIS package concretely is covered in the works [8-10].

Questions of mathematical modeling of flood process in river Styr dedicated work [11], but geoinformation forecasting of flooding areas in the city of Lutsk was not considered that`s why proposed research timely and relevant.

2. Research area

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 floods repeating is possible in the following years on the rivers of the entire western region of Ukraine, that must be taken in mind in the performance measures to protect the population from the negative effects of treatment.

Volyn region characterized by flat terrain, whitch making it difficult to rapid completion of 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 and the time of the floods.

The main reasons of spring floods as natural disasters (as well as the fall) is a natural (meteorological) factors that intensified by anthropogenic load of area. That is catastrophic consequences to a certain extent caused by economic activity in recent decades. Enhanced of negative consequences their catastrophic ostent contributes the location of buildings in the area permanent flooding and intensification of overland flow.

Based on the statistical data of the Volyn Regional Center for Hydrometeorology over the past 7 years about water level in the river Styr using a every ten days values water levels (Table 1) we conducted mathematical modeling of fluctuations of water levels in the period within territory of Lutsk. The post of hydrological measurements of Styr river water levels in the territory of Lutsk located on the Shevchenko street and complies an altitude 172.87 meters.

3. Statistical analysis

Analyzing the statistics, we can state that every year in the city of Lutsk observed 1-2 floods. So in 2011 there was a flood in February, when the water level risen to an altitude of 177.85 and in August during torrential rains when the water level has increased from 2.74 m to 3.84 m. The 2012 spring flood was observed in March with the maximum water level 177.05 m, and during the September rains, the water level has increased from 3.13m to 3.77 m. In 2013 on April 15 was observed a record spring flood, when the water level reached 179.00 meters mark, and during September and October rainy season the water level has increased from 2.69 meters to 3.48 meters. In 2014 floods was

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registered in February and June, when over three decades the water level rising from mark 2.89 m to 3.84 m and 2.77 m to 3.78m. In 2015, during the flood in the month of May, the water level risen from a mark 175.59 m to 176.27 m. In 2016 on the territory of Lutsk was observed autumn flood, when in the second week of November, the water level began to rise from the 2.81 m mark to a mark of 3.58 on December 18. In 2017 there was a weak spring flood in the period from February 2 to March 2. At this time, the water level has increased from 3.01 m to 3.99 m. Autumn flood fell to the end of November and continues at the beginning of 2018. At this time, the water level has 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.

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**	419,4	491,1	444,8	391,1	336,9	260,0	289,4	375,7	330,5	269,8	264,6	265,5
	II	458,1	485,0	394,9	382,5	333,9	287,6	311,1	379,0	279,7	266,9	261,8	272,1
	III	481,5	483,8	428,9	358,0	304,8	271,4	302,8	351,6	271,4	270,8	263,6	285,2
2012	**I**	282,2	297,9	398,7	349,4	327,4	291,5	325,6	291,2	324,0	349,9	334,7	286,6
	II	271,1	293,6	365,4	359,2	329,3	352,3	300,4	313,7	317,3	339,7	333,3	309,7
	III	291,9	343,0	342,5	351,2	298,6	356,2	300,6	337,0	352,6	339,7	310,0	341,8
2013	**I**	349,7	421,7	443,8	524,2	533,5	451,9	409,3	349,2	276,6	331,5	326,6	305,8
	II	380,7	441,6	440,8	603,5	492,1	464,9	364,1	280,9	294,3	319,5	305,3	294,3
	III	375,4	453,6	484,8	586,8	443,9	457,5	364,4	277,4	330,9	327,6	307,4	294,2
2014	**I**	304,7	346,7	365,5	285,3	267,5	352,1	289,0	261,3	270,9	267,1	259,2	247,6
	II	300,9	365,7	331,0	286,0	283,3	360,2	295,6	262,4	265,8	273,0	261,7	243,2
	III	351,9	379,6	325,8	285,3	295,2	365,5	271,6	263,9	272,6	256,6	249,9	266,0
2015	**I**	264,8	279,7	272,1	282,3	248,2	306,4	244,3	245,4	241,5	257,4	246,0	253,4
	II	297,9	258,4	277,2	275,1	255,4	260,3	235,8	235,9	242,2	257,8	244,9	252,9
	III	291,6	260,4	275,1	254,3	294,2	250,7	244,0	241,6	240,3	264,2	254,2	252,8
2016	**I**	270,4	298,7	302,8	266,4	256,8	254,6	273,5	275,3	247,3	245,0	292,0	327,0
	II	275,7	289,5	291,3	272,1	264,0	259,3	280,8	275,6	240,1	255,8	291,3	343,0
	III	280,6	298,0	272,6	278,9	268,6	269,0	288,9	261,7	237,8	259,5	326,5	328,6
2017	**I**	322,3	300,9	399,3	357,9	302,6	291,5	308,6	325,6	326,4	380,9	350,9	352,8
	II	329,6	314,4	391,0	311,2	304,5	294,2	321,7	321,7	327,2	352,9	332,1	385,1
	III	305,3	361,3	396,1	297,2	301,6	297,1	324,4	319,4	361,0	332,8	309,4	401,7

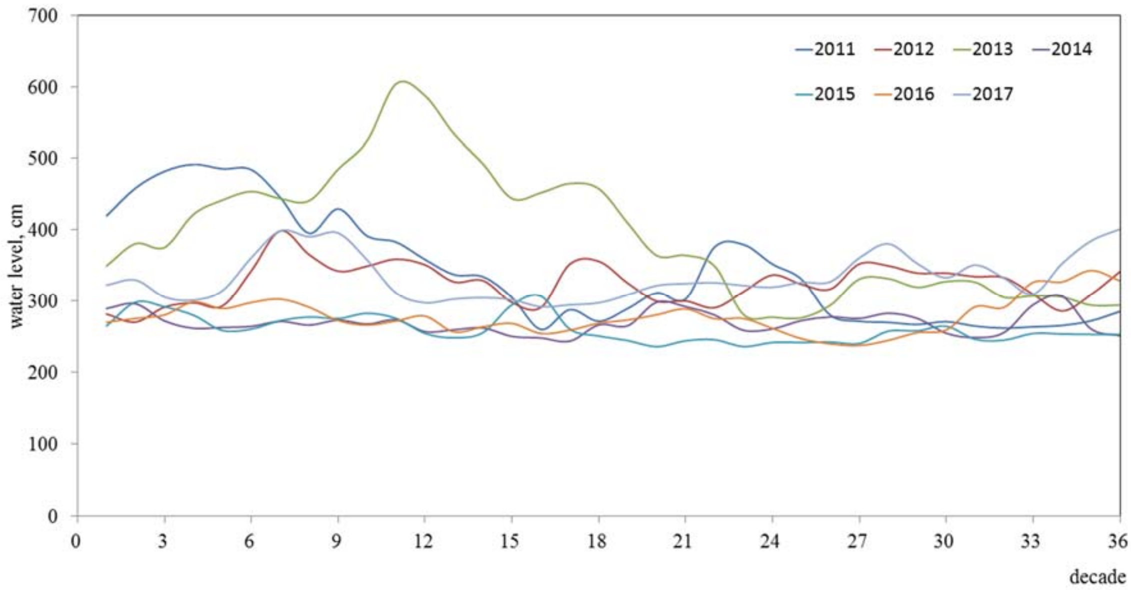

Figure 1. Dynamics of water levels on the river Styr in the territory of Lutsk for 2011-2017.

4. Mathematical modeling

The mathematical model of water levels on the river Styr within the territory of Lutsk is based on the creating a partial Fourier series [6,7] for discrete values of middle-ten-day water levels values during the period 2011-2017 years.

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:

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

where H(t) - value of the Styr river water level; a_i- coefficients of polynomial trend; t — time variable. The criterion for best approximation values every ten days water level of the river Stir served coefficient of determination between the actual values and the values of a polynomial trend:

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

As a result of processing every ten days values of water levels fluctuations, we came to the conclusion that trend component of Styr river water levels fluctuations in the study period sufficient present as a 3 power polynom. In the process of mathematical treatment we received a trend curve type:

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

For a more detailed study of water levels fluctuations present the deviations of observations from the values which have received the trend curve (2) in a finite Fourier series:

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

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

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

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

where $h_{i_{\text{act}}}$ - the actual value of water; $h_{i_{\text{trend}}}$ - the value of water received from the trend component approximating function (2).

Within the above, the mathematical model of water levels values fluctuations in river Styr during the period from 2011 to 2017 will be as follows:

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

Proposed mathematical model we used for short-term forecasting of the flood processes on Styr river in the territory of Lutsk. Graphic interpretation of modelling and forecasting at the beginning of 2018 are presented in Figure 2. As shown in Fig. 2 the spring flooding is forecast in February and March with the maximum water level 4.20 m, corresponding to an absolute mark of 177 m.

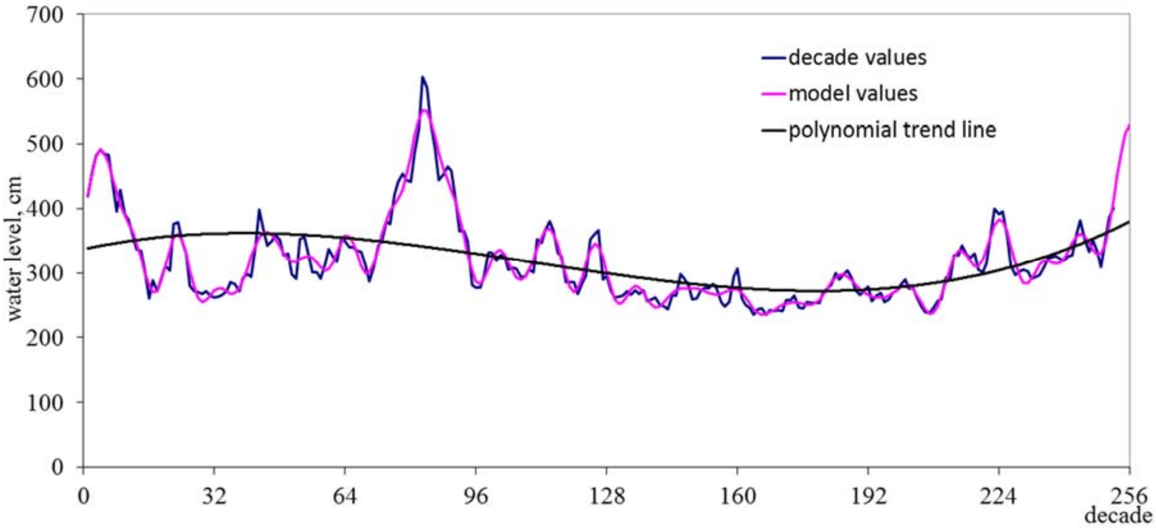

Figure 2. Mathematical model for approximation of every ten days water levels of the river Styr on the Lutsk post observation

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

5. Geoinformation modeling

To build the relief of Lutsk were used files matrices of heights SRTM v.4, obtained from http://mapgroup.com.ua [12] and the Geological Society of the United States [13]. Data processing and visualization of the results was performed using a free open source geographic information system QGIS [14] in the current at the time of writing long-term support version 2.18.15 (LTR).

In the first stage data was obtained by the vector boundary of Lutsk according to City Master Plan approved by the The decision of Lutsk City Council №42 / 1 dated 24.06.2009 [15]. For flood process modeling we have made vector riverbeds of Styr, Sapalayivka and Kichkarivka by images obtained from the service Google Maps [16] valid for 20.12.2017.

To reduce processing time heights files were circumcised on the territory of Lutsk. According to contours SRTM has been allocated isolines in the study area in increments of 5 meters, graphically 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 [16], which was based on a background (Fig. 3). 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 mark. Graphically the model shown in Fig. 4.

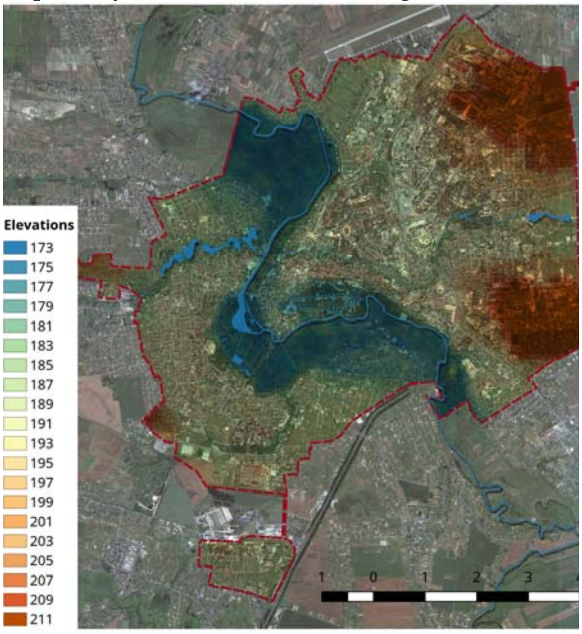

Figure 3. Output territory of Lutsk received in geographic information system QGIS.

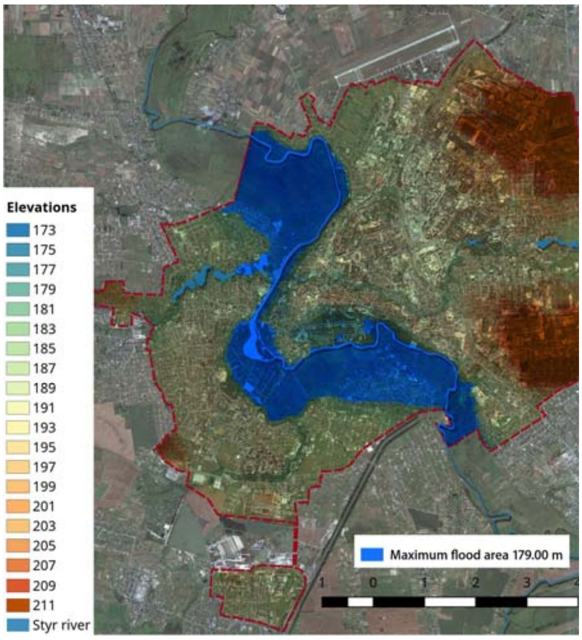

Figure 4. Simulating of maximum flood levels as at April 15, 2013 when the water level in the river Styr 179.00 m**.**

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 teritory of Styr river floodplain using geographic information system QGIS. Graphically, this model with OpenStreetMap [17] background is shown in Fig. 5. 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.

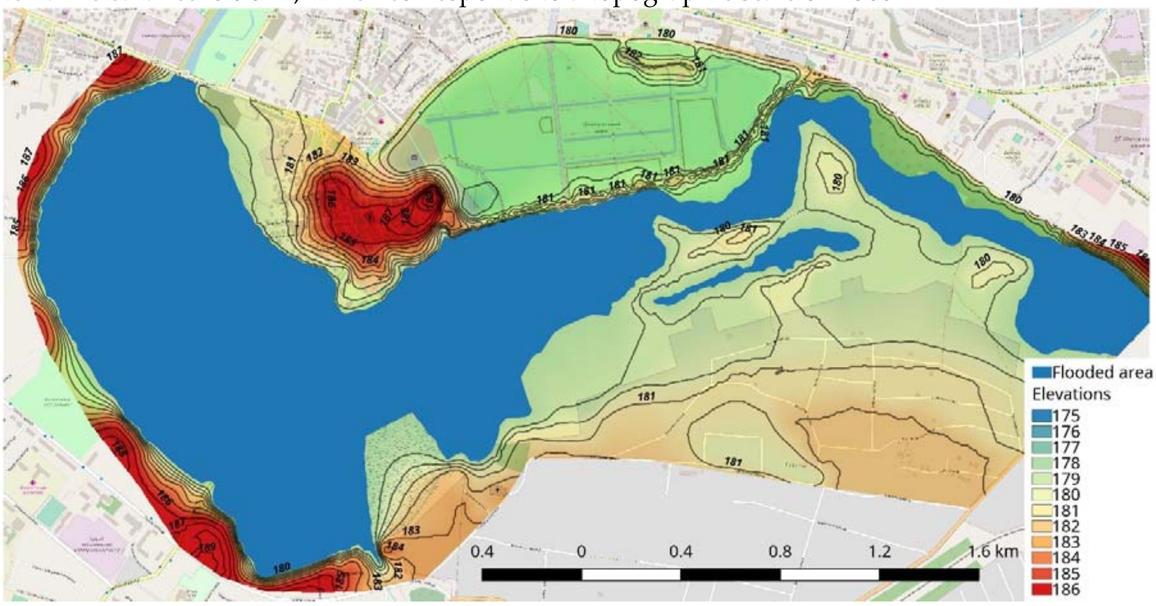

Figure 5. Simulation of flood forecast as of February-March 2018 when the water level in the river Styr 178.20 m

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 groundwater and filtration properties of the dam during the flood period there is insignificant flooding of the territory.

6. Conclusions

Based on the analysis of water levels statistical data on the river Styr by Volyn Regional Center for Hydrometeorology for 2011-2017 year 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 flood processes forecasting whereby forecasted the spring flood in February-March 2017 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 has great potential for further use in modeling the processes of natural and technogenic origin.

Author Contributions: Anna Shostak and Volodymyr Voloshyn performed statistical analysis and mathematical modelling; Oleksandr Melnyk and Pavlo Manko performed GIS simulation.

Conflicts of Interest: The authors declare no conflict of interest.

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