Flood Forecasting on River Lena During Spring High Water in Area of Location of Potentially Dangerous Objects

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Abstract. The most characteristic for Yakutia natural emergency situations (ES) are spring-summer high waters causing extensive, more than 70%, floods of territories and objects of infrastructure. The article presents the application of the methodology of risk analysis, interpretation of space images and geoinformation technologies (GIS) to develop a mathematical model that predicts flood hazards from spring floods based on statistical data obtained over 50 years and GIS simulation of flooding zones. There is presented an application of methodology of risk analysis, deciphering of satellite images and geoinformation technologies (GIS) to develop a mathematical model, which allows predicting danger of flooding from spring floods on the basis of statistical data obtained over 50 years and GIS modelling of flood zones. The proposed methodological approach allows one to obtain estimates of water level during spring floods in a certain period of time, and build models of studied dangerous process (a trend, harmonic and noise components) with sufficient accuracy and visualize flooded areas. Research of this region will allow considering one of aspects of provision of security of construction of bridge, and also the underwater passage of gas pipeline operating since 2004.

1. Introduction

The Republic of Sakha (Yakutia) having a vast territory located in different climatic zones and a developed network of water bodies is exposed to a wide range of natural emergency situations (ES). The most characteristic of them are spring and summer floods, causing extensive inundations of territories, objects and infrastructure.

Among Russian rivers, the Lena ranks second in length, and third according to a catchment area. The length of river is 4400 km, a basin area is 2490 thousand km², an average water flow is 16,500 m³/s. Duration of freezing-over is about 7 months, the flooding period is the second half of May. An opening of river is accompanied by numerous ice jams and floods, causing extensive more than 70 % floods of territories and objects of infrastructure and causing huge material damage to a population and agriculture of the Republic [1]. Therefore, a prediction of maximum water levels especially in the period of spring flood is an actual problem.

The jams are usually formed in the same places and have a length up to 100 and more kilometers. Duration of existence of jams is on average 3-5 days, and the duration of the most powerful ones is up to 10 days [2-6].
Jam formations on the rivers of Yakutia are due to the following factors: formation of thick ice cover in winter, reaching 150-200 cm; large current velocities, being on the average 1.0 to 1.5 m/s; sinuosity of riverbed and presence of islands.

A choice of part of solution of problem of prediction is conditioned based on locations of already constructed and planned potentially dangerous objects that may be in the area of flooding during the flood.

In the area of Tabaga Cape in 2003 there was built the longest underwater crossing of pipeline on the bottom of the Lena river. Only the crossing of the main river bed of the Lena river was 2.3 km. To maximally decrease a load from water, the pipeline was laid on the bottom with penetration and ground landslide, the depth of river is 14-15 meters. Throughput of pipeline is 528 million m³/year; the maximum working pressure of pipeline is 55 kgf/cm² [4].

At the same time on this part a frequency of jam formation and floods during the considered period of time is greater than 0.8. During the spring flood wash-out of ground of bottom and bank of river in the area of crossing during the formation and destruction of jams may result in denudation of gas pipelines and its damage under influence of hydrodynamic effect of stream and pressure of jam ice.

Near the underwater passing of gas pipeline it is projected creation of the main strategic object of transport construction of the Republic of Sakha (Yakutia) – a rail-and-road bridge crossing over the Lena river with a length of 3.2 km.

Engineering-geological surveys have shown that almost the entire area of planned construction belongs to a continuous permafrost zone.

Riverbed deposits are represented by uneven-grained sands and pebbles, below which fine-grained sandstones with layers of sandy siltstones lie and in some cases coal. Seismicity of building site has a magnitude of 7.

During the spring floods there is a high probability of erosion of banks, river bed of foundation of pillars of bridges.

Ice jam levels of water are formed under the influence of factors common to the whole of Lena: 1) intensity of growth and height of spring flood; 2) ice and meteorological conditions during the formation and destruction of ice cover.

2. Methods
There was created a Database of floods of previous years for a period from 1936 to 2012, which contains data on the maximum levels of water, dates of opening of rivers and other hydrological and meteorological factors affecting the process of passage of spring flood. The database is indexed by time and place of hydrological event, it is used for an analysis of spring floods and a prediction of risks of floods.

The problem of forecasting consists in that on the basis of observations \( y_1, y_2, ..., y_t \) to obtain \( y_{t+1}, y_{t+2}, ..., y_{t+T} \), where \( t \) is the time. Here an assumption is used that patterns peculiar to a phenomenon in the past will remain in the future. This assumption is true when building short-term or operational forecasts. A great contribution to development of methods based on a probabilistic theory of description of river runoff as a stochastic process was made by N.A. Kartvelishvili, Yu.M. Alekhin and V.A. Lobanov [7-20].

A statistical approach to a study of time series is that in a development of process component parts can be identified:

\[
Y(t) = f(t) + u(t) + e(t),
\]

where \( f(t) \) is a function of trend (a tendency of development), \( u(t) \) is a cyclic component, \( e(t) \) is a residual component.

The prediction of danger of flood for some period of time boil downs to carrying out the following stages [7-8]:
1. A preliminary analysis of data;
2. Construction of model, i.e. a choice of curves describing the phenomenon, and a numerical estimation of parameters of model;
3. Testing of adequacy of models and an estimation of their accuracy;
4. Determination of point and interval prediction.
   
   In a preliminary data analysis there happens detection of presence of trend, smoothing of time series. Selection of coefficients and a choice of models of trend is carried out on the basis of method of least squares.

   After removal of trend it is necessary to carry out an analysis of time series for stationarity.

   For an assessment of relationship between consecutive values of the same series an autocorrelation coefficient can be used. It is obvious that in an assumption about a random nature of fluctuations of observations in the studied series the relationship between their levels should not be. In addition, a magnitude of autocorrelation coefficient allows making some conclusions about a period of oscillations.

   There are currently quite a sufficiently large number of methods of prediction of danger of floods from the spring inundations. For construction of statistical model there was used a method of control of assessment of danger of flood [9-10], which is based on processing of data with the help of nonlinear multivariable regression.

\[ H = b + c \sum_{j=1}^{M} \sin(\phi_j + \omega_j x) \]

\( H \) is an output, \( x \) is an input, \( b, c, \phi, \omega \) are adjustable parameters; \( M \) is a number of harmonics of approximating function.

   Numerical data charactering the object of study (floods) are documented in a form of table in an Excel workbook. For obtaining a desired result initial data were subjected to a transformation. The preliminary transformation of investigated data of observations for regression modelling was carried out according to the formula:

\[ F(H) = \ln\left(\frac{\pi(H - a)}{b}\right) \]

where \( H \) is water levels during the floods over the period of observation, \( a = b/2 \), \( b = H_{\text{max}} \cdot k \), \( H_{\text{max}} \) is the maximum level of water in the selection (registration of level in a point of observation), \( k \) is a coefficient depending on modes and character of river runoff, it is found with the help of iterative minimization of error.

   As an example for the regression modelling of data on floods there were taken the observations of maximum water level on the Lena river near the village of Tabaga in the period from 1936 to 2012. A model is built on 72 points, on four points a retro-forecast is built. For building models data of Yakut office of hydrometeorological service are used.

   The first stage of data modelling is construction of regression model. After synthesis of models results of prediction are obtained in a form of value of logarithm function. Water levels are obtained by an inverse transformation. Accuracy of prediction is determined by comparing the original data with the results of prediction. The results of regression modelling of data are presented in a form of decomposition of time series into three components: trend, harmonic and random components.

   Analysis of adequacy and reliability of constructed models. A very important element of analysis of time series is research of remainders obtained after a procedure of removal of trend and the cyclic component. Significance of this stage is determined by a fact that it allows assessing the adequacy of chosen model of process to the initial observations.

   To test the model there will be used visual methods presented in a system STATISTICA.

3. Results
   According to the transformed initial data a model №1 is constructed - the trend, i.e. the general trend of development of process. A kind of trend is polynomial. For construction of model №2 (the harmonic component) a difference is taken between the original data and the trend. The data for a
model №3 (the random component) is a difference between the original data, on which the model №2 was built, and the prediction according to the model №2. The model №3 is a model of noise.

The method can be recommended for use if it satisfies the conditions of accuracy and quality.

A criterion of validity and quality of method is taken as a ratio of the mean square error of verifying predictions to the quadratic deviation of predicted value. Accuracy of hydrological predictions is established by comparing the prediction errors with an allowable error. The prediction is considered as justified if its error is less than or equal to the allowable error.

Calculations showed that the allowable error is 75 cm, the criterion of applicability of method is 0.5, the correlation coefficient is 0.8, i.e., this method belongs to a category of good methods.

The remainders are normally distributed, i.e., the constructed model is significant and is suitable for further analysis.

Table 1. Comparative characteristic of results of retro-predictions of water level in Lena river near village Tabaga.

| Level of water, cm | 2009 | 2010 | 2011 | 2012 |
|-------------------|------|------|------|------|
| prediction        | 861  | 921  | 878  | 907  |
| observations      | 823  | 956  | 935  | 943  |
| Error absolute, cm| 38   | 35   | 57   | 36   |
| relative, %       | 4    | 3    | 6    | 4    |

As can be seen from Table 1, as a whole the errors of prediction with advance time of 1 year showed the sufficient adequacy of selected statistical model.

The adequacy of used model is determined by the analysis of remainders (the errors of prediction), representing differences between the predicted and actual values. In the STATISTICA system there are specialized tools of analysis of remainders, in particular, an estimation and graphic representation of their autocorrelation and partial autocorrelation functions.

For the modeling of zone of inundation in the flood with the help of satellite images and GIS a Database of satellite images of floods of previous years was used, indexed by time, place, and level of hydrological event.

![Figure 1. Flood zones near village Tabaga at maximum water levels obtained by retro-prediction. 1 - river Lena with flooded islands, 2 - prediction of 2009, 3 - prediction of 2011, 4 - prediction of 2010.](image-url)
For creation of Database of satellite images there were collected archival images from satellites Landsat TM5, Landsat TM7 and Landsat-8 OLI, which were deciphered and analyzed. Decryption was performed on a software package ENVI (32-bit), and then on ArcMap 10.2. Radiometric calibration was made, then an atmospheric correction was made. Further a training selection of several classes and classification was carried out. For accuracy of classification postclassification processing and vectorization was done. Figure 1 presents zones of inundation near the village Tabaga during the spring flood at the maximum water levels obtained by the retro-prediction.

4 Conclusion
The proposed method will allow obtaining the estimate of excess of level of spring flood during the period of prediction in the presence of database on the water levels over the previous years.

The modelling of flooding with the help of Database of satellite imagery of GIS and regression modelling can give a visual presentation of the overall picture of flood and the size of damage. The use of proposed method in the construction and exploitation of significant objects will allow determining conformity of location and safety of these objects to correctly assess the situation for planning of protective measures against the flood, as well as to carry out preventive measures to significantly reduce the damage.

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