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DIGITAL MODELING OF DECISION-MAKING RISKS IN NATURAL AND MAN-CAUSED CRITICAL SITUATIONS

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ABSTRACT

The purpose of the work is to create mathematical and methodological support for a dynamic digital information-analytical system for operational and situational assessment and forecasting of flood threats in the activities of administrative authorities in emergency conditions. The East Kazakhstan region was chosen as the region under study. A high category highway was chosen as a critical flood object. Operational monitoring satellite information arrives at the analysis center with a frequency of 12 hours, forming an uncontrolled time window. To solve this problem, a simulation model has been developed for predicting the dynamics of flooding in the area and identifying the critical vector of flooding in a 12-hour time interval with a pixel accuracy of 200 meters and a given time lag. A criterion for measuring the danger for a controlled object - a motor road - from the intensity and dynamics of flooding in the mathematical form of the roadway stability coefficient has been selected. It is proposed to evaluate the level and dynamics of danger by reducing the coefficient of roadway stability as a function of the distance to the predicted flood boundary. The stability coefficient depends on the hydrodynamic pressure, which is largely functionally determined by the volume of water in large nearby natural and artificial reservoirs. Long-term changes in the volume of water in natural reservoirs have been studied and empirical models for forecasting volumes for monthly and annual periods have been constructed. A mathematical model for assessing the risk and reliability of decision-making under the conditions of parametric uncertainty of control agents of the road structure stability control system has been developed.

Keywords: *Process, Model, Probability, Flood, Decision Making, Simulation, Distribution Law, Hydrodynamics, Geosystems.*

1. INTRODUCTION

Currently, hard-to-predict natural emergencies, and often catastrophic ones, such as floods, fires, hurricanes, etc., are observed all over the world. These situations are often associated with global climate change, which is further aggravated by man-made factors. In Kazakhstan, critical situations constantly arise in different regions associated with the passage of flood waters, generated in the spring by active snowmelt and additionally heavy rainfall. At the same time, such emergency situations (ES) occur both on large and small rivers [1,2]. Under these conditions, in order to reduce socio-economic damage, the problem of reliable forecasting of situations in terms of time and volume of measures to prevent or mitigate the consequences of these phenomena is of great importance. At the same time, as practice shows, it is of key importance to quickly obtain reliable information, both about the current state of flood zones and the dynamics of their dynamics in the direction of the most important national economic objects. Most often,

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road and rail communications suffer from floods. Figure 1 shows a satellite photograph of a similar situation on the Irtysh River in Pavlodar region [1].

In the figure, from the space monitoring data, one can see the real position of the water surface and the location of the trajectories of the railway and highways. Space monitoring of the state of snow cover and the dynamics of flood waters in real time provides for three levels [2]. The first level at a spatial resolution of 250 m provides for daily analysis, which corresponds to the low resolution of MODIS, while the observation is carried out daily. The second level corresponds to an average spatial resolution of 25-70 m. The third level is possible in especially critical cases, for which high and ultra-high resolution optical and radar systems for remote sensing of the earth (RSD) are used. For operational monitoring of the situation during the passage of flood waters and floods, it is proposed in [3] to use monitoring technologies based on daytime images of EOS-AM TERRA MODIS (250 m resolution) [4, 5].

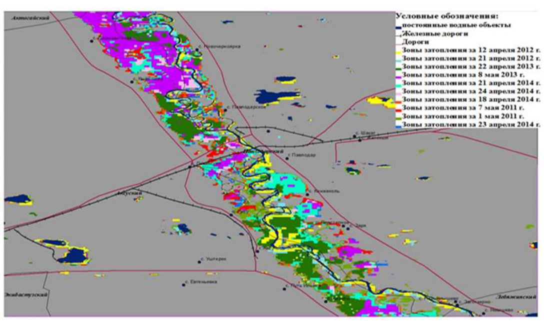

Figure 1. - The results of space monitoring of the passage of flood waters on the Irtysh River at a resolution of 250 m [1].

To identify water bodies, it is proposed to use data in the visible and near infrared ranges. The organizational and technological disadvantage of satellite monitoring is its daily cycle from 2 to 4 times a day. During the time between sessions of communication with the satellite and receiving information with interruptions from 12 to 4 hours, in a real situation (flood, fire), emergency phenomena are out of control, and situational processes are poorly controlled. The solution is permanent optical monitoring based on geostationary observation stations, but such a technology will be extremely expensive, but promising.

Assessment and prediction of the dynamics of geosystemic situations in practice, as a rule, is carried out visually, by analyzing satellite information. Recently, formal methods of forecasting and decision-making based on mathematical modeling have been increasingly involved. Each of these technologies has its own advantages and disadvantages. The visual method is characterized by subjective errors. Formal approaches involving the mathematical apparatus require, in order to ensure a sufficient level of reliability, a large amount of statistical material that comes from ground and space stations and services conducting geodetic and hydrological observations. Mathematical forecasting partially eliminates the shortcomings of monitoring cyclicity by «predicting» the state of the dynamic process in the intervals between monitoring sessions.

The world practice of effective territorial management is based on system integration and digital transformation of all existing technologies, which include: operational collection, monitoring, generation of big data integrating socio-economic, environmental and natural-technogenic information on the region. Automated systems should have advanced software: mathematical, technical, geoinformation, organizational and methodological, as well as intellectual support for optimal decision-making processes in conditions of fuzzy factor data of control agents;

2. LITERATURE REVIEW

An analysis of the literature in the subject area considered in this article showed that many studies focus differentially and narrowly on certain issues of scientific and practical problems. The article uses experimental and statistical data presented in the reports on the completed grant topic entitled: "Development of a multi-purpose aerospace predictive monitoring system for warning of natural and man-made emergencies in conjunction with semantic and geospatial data" [1,2,5]. In Kazakhstan, the main developer of systems for space monitoring of emergencies is the National Center for Space Research and Technology. The results of monitoring in the "on-line" mode are transmitted to the territorial department of emergency situations and the crisis center of the Ministry of Emergency Situations of the Republic of Kazakhstan, and are also displayed on the geoportal http://emergency.gzi.kz/. Physically, the geoportal is located on a server that is installed in the server center "National Information Technologies" and connected to the Unified Transport Environment, which provides

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prompt access to monitoring results for users of the Internet portal of state bodies of the Republic of Kazakhstan. “The National Center for Space Research and Technology is a member of the JPT Sentinel Asia, which unites the countries of the Asia-Pacific region. Within the framework of this organization, interstate coordination is carried out, the exchange of data from remote sensing of the earth and the products of their processing, necessary for making timely decisions to prevent hazards, is carried out. Satellite information is a photographic image of the area, which must be processed by special software, as well as visually by professional operators.

The methodology of the proposed study is based on the geosystem approach, which was proposed by Academician Sochava V.B. [3]. In this paper, the geosystem is interpreted as - "a special class of control systems, where the individual components of nature are in a system connection with each other and, as a certain integrity, interact with the cosmic sphere and human society." The set of geosystemic factors of influence on the object under study is determined in each specific task by expert methods. In this paper, the subject of research is the controlled quality of the road. Geosystem factors are: hydrological factors - groundwater and the volume of water in natural reservoirs (lakes, reservoirs); natural and climatic factors - the level of snow cover, the level of rainfall, the temperature of the atmosphere, the strength and direction of the wind, the area flooded by flood waters. Natural and climatic conditions in the study area are described in detail in [6,9,21]. All of the listed factors in quantitative measurements are observed and chronologically stored in large databases of relevant public services and organizations.

To assess the quality of the road, an integrated criterion is needed, which is used at all stages of the life cycle of an object, starting from the design stage and controlled during operation until the moment of disposal [7,8,10,11,12].

In [7], as an integrated criterion, the stability coefficient calculated by formula (1) is proposed. In this work, it is indicated that the key influence on the stability coefficient is acquired by the hydrodynamic parameter D in combination with the physical and mechanical properties of building materials. The hydrodynamic pressure D depends both on the level of groundwater and on the flooding of the road embankment by flood waters. At the same time, the author believes that the development of methods for ensuring the stability of road structures under the variability of geophysical conditions is an even less difficult task than ensuring design stability under conditions of a variable water-thermal regime. Therefore, the water-thermal regime of the area is the main prerequisite for road-climatic zoning and is a prerequisite for the design, construction and operation of the road.

$$K = \frac{\sum_{i=1}^{n}\left[\left(\sum_{j=1}^{m} Cij\right)\cos(\alpha_i) tg\varphi + CLi\right]}{D + \sum_{i=1}^{n}\left[\left(\sum_{j=1}^{m} Gij\right)\sin(\alpha_i)\right]} \quad (1)$$

The main attention in [7], as well as in [10], is focused on ensuring the stability of road slopes.

In all known methods for calculating the stability of the roadway, it is considered that the design technical and technological parameters, as well as the standard values, are deterministic values. However, in [8] a new approach based on the stochastically programmable concept is proposed. In this work, a hypothesis is put forward that all physical and mechanical indicators of building road materials are random quantities with certain statistical distribution laws. The calculation of the strength and stability of the roadway proposed in this paper by the simulation method proves that typical well-known deterministic design algorithms give significantly overestimated results.

In [13], the influence of flood water bodies on the resistance of soils to mechanical stress was studied. It was found that flood waters affect the physical and mechanical properties of soils in the road embankment and on the soil, base starting from a distance of 1000 m. The paper provides tabular data and empirical dependencies showing quantitative relationships between moisture content and mechanical characteristics of soils.

Monitoring of natural and technogenic phenomena and processes is based on control and measurement technologies with the active use of tools. The control process contains measurement procedures, comparison of the measured value with the standard and decision making. Measuring tools in any case contain a measurement error, which in many examples has a normal distribution law [20,22]. The composition of the control parameter distribution laws and the error distribution law generate control errors, which are interpreted as decision-making risks - the probability of false and undetected defects, which lead to economic losses [4,14]. The version of the international quality standard ISO 2015 provides for risk assessment on a mandatory basis. In

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systems of space monitoring of natural phenomena, the risks of control and measurement technologies and decision-making are practically not studied.

Based on the results of the analysis of literary sources in the subject area under study, the following conclusions can be drawn:

1. The most important objects of the Republic of Kazakhstan, subject to periodic destructive effects from seasonal floods, are roads. Flood events sharply reduce the main indicator of the quality of the road, quantified by the stability coefficient, which formally integrates geosystemic factors.

2. The overwhelming majority of studies in the field of control and management of natural and man-made emergencies consider the process in a differentiated way in terms of individual components and focus narrowly on certain issues of scientific and practical problems. Particularly acute is the problem of preventing natural hazards with the involvement of space means of earth sounding and digital information processing in ensuring the normative reliability of predicting the dynamics of controlled processes.

3. Applied methods for the formal provision of a digital system for geosystemic emergency forecasting have more than 50 options. In this paper, from the whole variety of formal tools, it is proposed to use: expert assessments, geographical analogies, functional dependencies, probabilistic and simulation models, fuzzy sets.

4. Digital methods for the design and operation of geosystem technologies for monitoring natural and man-made threats are based on deterministic approaches, ignoring the stochastic properties of controlled and predictable processes. Decision-making in such systems is carried out according to average statistical estimates. The most acceptable formal method for modeling the studied and controlled natural and man-made processes is simulation, which allows you to fully consider the entire degree of uncertainty in decision-making and quantitative risk assessment.

3. SCIENTIFIC PROBLEM

Kazakhstan has a high-quality road network that is partially or significantly damaged by seasonal floods. To control and monitor these critical situations, space monitoring systems are used, which transmit photos of the earth's surface in digital format to centers for receiving such information at 12-hour intervals. In these systems of control and monitoring of natural emergencies at the decision-making stage, a subjective approach is used based on the past state of the process with a delay of 12 hours. Such technological and technical capabilities of the digital geographic information system used become uninformative, since the time interval of 12 hours becomes uncontrollable. There is a need to predict the dynamics of the process in this time interval, based on the results of the last communication session with the satellite and the estimated rate of flooding of the area. A digital photographic satellite model of the earth's surface makes it possible to carry out calculations and forecasts in pixel format with an accuracy of 200 m. Mathematical and software that implement this approach is currently absent in the current digital geoinformation system.

The second problem and task are to choose a criterion for assessing the level of danger for a socio-economic object, in this case, a road. Currently, the growing danger is not quantified, for example, by risk level or another criterion. The assessment is carried out only by the volume of the destruction that has occurred. The problem arises of developing mathematical or simulation models for the quantitative assessment of the predicted risk in the real dynamics of the natural process. As it was established in the literature review above, the main design and operational indicator of the quality of a road facility is sustainability. The sustainability index is a calculated multi-factor quantitative assessment. One of the factors influencing the stability of a road object is the hydrodynamic pressure D, which is present in the calculation formulas for assessing the stability of a road structure in formula (1). Factor D is closely related to groundwater and the volume of water in large lakes and reservoirs. The predicted volume of water in reservoirs has a long history and a pattern of variation and can be described by a regression model. The predicted volume should enter expression (1) as a correction factor and be implemented in the software application. The adoption of practical measures upon reaching the level of danger, quantitatively measured by the risk, is determined in the organizational and methodological support of the system.

Research methods. The research methodology is based on the geosystem approach, which was proposed by Academician Sochava V.B. [3]. In this interpretation, «a geosystem is a special class of control systems, where the individual components of nature are in a system connection with each other and, as a certain

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integrity, interact with the cosmic sphere and human society». Applied methods of geosystem forecasting include more than 150 approaches, in this work, from the whole variety, we will use: expert estimates, geographical analogies, functional dependencies, probabilistic and simulation models, fuzzy sets. The problem of predicting the stability of a road object as a function of hydrodynamic factors is solved in two ways. The first method considers the impact of large natural and artificial reservoirs on the road object under study, for example, the Bukhtarma reservoir. The second method, in the presence of space monitoring tools, investigates and evaluates the impact of flood waters. In both options, the stability coefficient K_p is calculated. In the first option, the level of the Bukhtarma reservoir changes, and K_p, found by formula (1), also changes. The minimum value of the stability coefficient K_p found in this way is calculated for a given subgrade and geosystem conditions. It is compared with the normative $K_r>=K_n$ and, if it turns out that $K_r>=K_n$, then the subgrade stability is ensured. It is assumed that K_p and K_n are random quantities, the statistical characteristics of which also change depending on the hydrodynamic conditions.

Research result. Conducted literature studies and experiments in the conditions of Rudny Altai confirm the assumption of a strong variability of hydrological and weather conditions in the areas of roads along the entire territory of Rudny Altai [7, 8]. In the scope of this work, statistical and normative data of state organizations were used. The East Kazakhstan region in terms of hydrogeological, climatic and relief conditions is an extremely heterogeneous territory, which includes numerous water sources of natural and artificial origin, about 3600 rivers and rivers, the Bukhtarma reservoir, which is the largest mirror of «artificial water» in the CIS, Ust -Kamenogorsk reservoir, Shulba reservoir and Zaisan lake, one of the largest lakes in the world. A significant part of the area of East Kazakhstan Region (EKR) is covered with mountains. *which creates additional difficulties in the process of designing road communications.* A hydroelectric power plant (Hydroelectric Power Station) was built on the Bukhtarma reservoir, which regulates the discharge of water depending on the needs of the business, which leads to fluctuations in the water level in the Bukhtarma reservoir and, accordingly, groundwater. The water level in this basin is subject to rather strong seasonal and weather influences, which also complicates the general external background of the process of designing and operating roads in this area. Therefore, considering hydrological and hydraulic factors in solving the tasks set is a prerequisite that creates additional scientific, technological and economic problems. Works on monitoring the water regime of the EKR basins have been carried out by various organizations for a long time. In this work, the collection, systematization, analysis and interpretation of the results of this monitoring was carried out with the involvement of scientific achievements in the field of mathematical statistics, computer modeling and special software. Annual fluctuations in water volumes in the Bukhtarma reservoir are presented graphically in Figure 2 [9].

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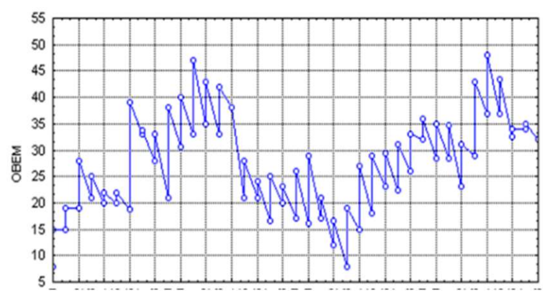

Figure 2. Annual fluctuations in water volumes in the Bukhtarma reservoir (million cubic meters) [7]

As can be seen from the temporary empirical model, the volume of water in the reservoir is of a random nature, but at the same time, the graph shows a pronounced periodicity with a cycle of 11-12 years, which is of scientific interest, especially when solving forecast problems.

The results of the statistical analysis of monthly observations during 2020 are presented in Figure 3.

Empirical models (Fig. 2; Fig. 3) reflect «smoothed» annual and monthly changes in the data on the dynamics of water volumes in the Bukhtarma reservoir. It follows from the figures that the water level is subject to annual, weekly and daily fluctuations. Daily fluctuations are not illustrated, but are taken into account by the calculated coefficient in the model statistical estimates.

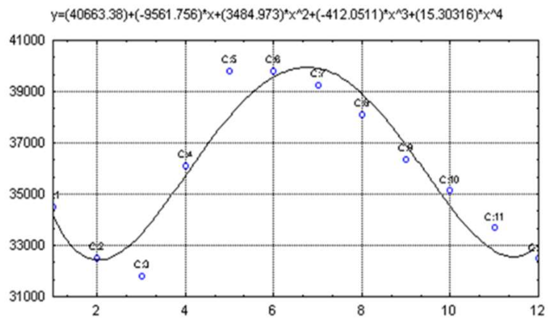

Figure 3. Monthly changes in the volume of water in the Bukhtarma reservoir for 2021.

The average sample coefficient of variation, according to experimental data, is 28%. The maximum level of water volume falls on the spring-summer time, and the minimum level drops to 10-15 million cubic meters, and the maximum rises to 40-42 million cubic meters. The regression model of water volumes in the reservoir with monthly control has the following form:

$$Y = 4533 - 18130x_1 + 7753x_2 - 1267x_3 + 89.455x_4 - -2.32x_5 \quad (2)$$

Figure 4 shows a histogram of the distribution of fluctuations in monthly water volumes in the Bukhtarma reservoir in 2020.

Statistical analysis of the observational results obtained above showed the following: the empirical distribution presented in Figure 4 is approximated by the theoretical normal law, the density function of which has the form.

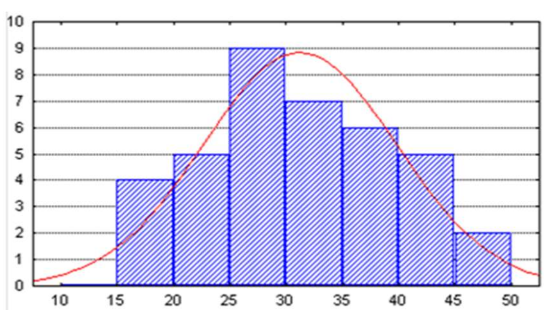

Figure 4. Shows a histogram of the distribution of fluctuations in monthly water volumes in the Bukhtarma reservoir in 2020.

$$f_1(x, \sigma_1, x_{CP1}) = \frac{1}{\sqrt{2\pi 10700}} e^{-\frac{(x-37031)^2}{228000}} \quad (3)$$

where σ_1 is the standard deviation of the distribution; X_{cp1} is the arithmetic mean of this distribution.

The stability coefficient is found from formula (1). The parameters included in the calculation formula are considered as random variables that are found by simulation. The simulation model of the computer experiment is shown in Figure 5 [16,17].

At the same time, it is considered that the level of flooding can change its value daily within certain limits. The average value of the level of flooding is determined from expression (3). Since this empirical expression was found for monthly variations in the level of the reservoir, it can be assumed that the level of flooding is proportional to the level of the reservoir, which is quite correct and has been proven by studies [10-13]

In block 1 of the model (Fig. 5), data on the distributions of the flooding level, adhesion coefficient, angle of internal friction, hydraulic gradient, embankment height, etc. are entered. In order to improve accuracy, the number of simulations is set. Within each cycle, the values of all random numbers are «played out» according to the corresponding distribution laws, and for these values, according to formula (1), the value of the Kp coefficient is calculated. If the calculated value is greater than the normative value, which is also «played out» due to its uncertainty, then this is regarded as a normal outcome and the cycle is repeated, otherwise, when Kp<Kn, the case is considered erroneous and one is added to the «error» counter.

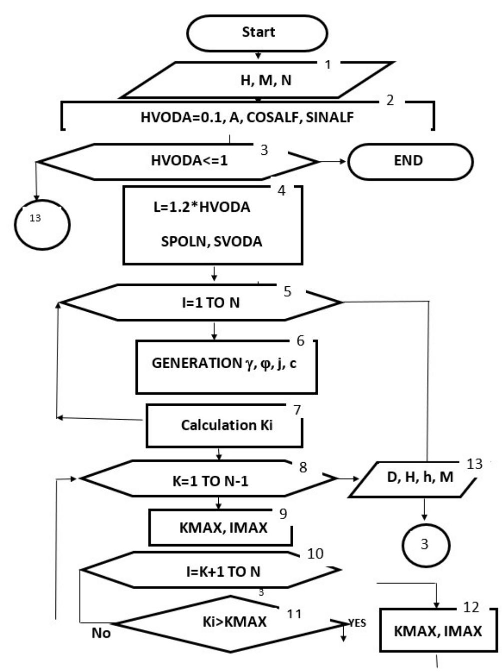

Figure 5. Algorithm of the simulation model for calculating the reliability of the stability coefficient of the road

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At the end of all cycles, the number of false «solutions» is counted. Reliability is calculated and printed out: the average value of the stability coefficient, risk values and reliability. [14,15]
The results of the computer experiment are shown in Figure 6.

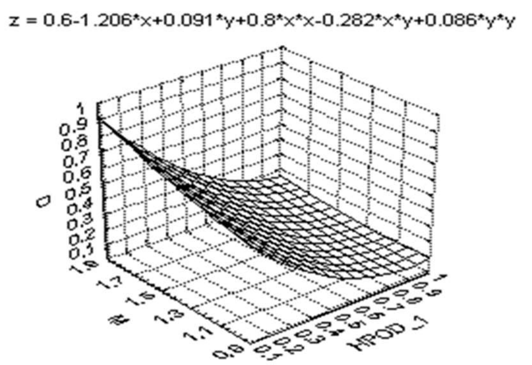

Figure 6. Spatial interpretation of the statistical reliability model of the design stability of the road embankment

Analyzing the results of the calculation, we can draw the following conclusions: in real conditions of high variability in the physical and mechanical properties of building materials, the level of moisture content of the soil of the embankment and its flooding, the statistical uncertainty of the limiting values, the probable level of reliability does not exceed 80%.
In the case of the availability and use of space monitoring tools, it becomes possible to predict the situational danger in the process of flooding territories and risks for important socio-economic facilities, such as roads. At the same time, the results obtained in the first task are not rejected, but are an addition to the current problem. To solve the current problem, it is necessary to use the information coming from the satellite monitoring system, which is shown in Figure 1.
To assess and predict the dynamics of flooding of the area by flood waters, a graphical model has been developed, which is interpreted by Figure 7.

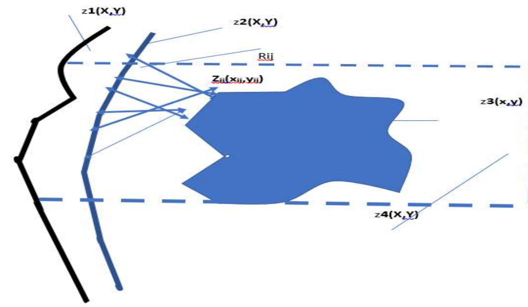

Figure 7. Digital model interpretation of a satellite photograph of the flood sector in 2D format

In this figure, the following designations are accepted: $z_1(x,y)$ - design coordinate digital trajectory of the road in 2D format; $z_2(x,y)$ - calculated digital trajectory of the permissible integral geodynamic risk in 2D format coordinates; $z_3(x,y)$ is the observed flood field in real time; $z_4(x,y)$ – raster digital sector of study in 2D format; Zij(xij,yij) – current i-th; j-th pixel coordinate in the flood field; Rij is the distance from the i-th j-th point of the flood field to the i-th j-th point of the trajectory of the admissible integral hydrodynamic risk.

Hypothetically, it becomes possible, in addition to visual analysis, but also automated control of the flooding process. One of the operational tasks is to identify the critical areas of flooding, assess the marginal risk of flooding, current operational assessment of the probable coefficient of stability of the road object. It was [16-23] proved in that changes in soil bases that are dangerous for the road structure begin at a distance of one kilometer from water sources. With a decrease in this distance, the danger increases sharply, as the physical and mechanical characteristics of the soil base and building materials of the roadway deteriorate. Mathematically, this is reflected in the increase in the uncertainties in the distribution of the parameter, in this case, the coefficient K_p.

The idea of modeling is to develop an algorithm for estimating the distance from the critical point of the leading edge of the flood field (Fig. 7) to the calculated digital trajectory of the permissible integral geodynamic risk in coordinates of the 2D format of the controlled object - z2(x, y) (in this case, to the road section in studied flood sector). All digitized design and studied objects in a raster image have a "pixel" format in 2D coordinates on a selected working model sector z4(x,y).

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The simulation algorithm consists in «measuring» the distance from each i-th; j-th pixel in the 2D format of the flood field up to each i-th; j-th pixel of the calculated virtual trajectory of the admissible geodynamic risk of the road route. By enumeration of all the given estimated distances in each cycle «pixeli-pixelj» is the shortest value from some point of the flood field to some point of the road trajectory (in this case, the digital vector of the road). Cycling through the entire array of pixels of the flood field, the most critical coordinate in the flood field, closest to the road, is found, and a decision is made on further measures. By registering and accumulating data on the dynamics of the spread of critical coordinates of the flood field, a model is built to predict the spread of the entire flood area towards the most important socio-economic objects. Modeling and quantitative solution of this problem seems to be the most effective with the help of simulation methods. Decision-making acts can be implemented expertly - subjectively, or automatically in the presence of an artificial intelligence unit based on neural technology.

In the process of modeling, the problem of determining the digital virtual calculated trajectory of the geodynamic risk arises. This trajectory is defined as a boundary line, beyond which the coefficient of stability of the road structure decreases sharply and the probability of destruction of the roadway increases. Since the value of $K_{н}$ and K_p values are statistically uncertain with the distribution laws $f(K_{н})$ and $f(K_p)$, then in reality the ratios $K_{нi}$ and K_{pj} are estimated. Therefore, the limiting digital trajectory of the permissible integral geodynamic risk has an uncertainty corridor with the calculated risk value, which was described above. To quantify this risk, we will use Figure 8.

Figure 8: $f(K_H)$ - distribution density of the standard value of the stability coefficient; $f(K_P)$ - distribution density of the calculated stability coefficient; $f(K_p)$ - distribution density of the calculated value of the stability coefficient, K_{pi} - i-th value of the calculated value of the stability coefficient, $f(K_{н})$ - distribution density of the standard value of the stability coefficient, K_{nj} - j-th value of the standard value of the stability coefficient. The calculated value of Ki is obtained for the averaged values of all indicators included in the calculation formula for a given section of the road.

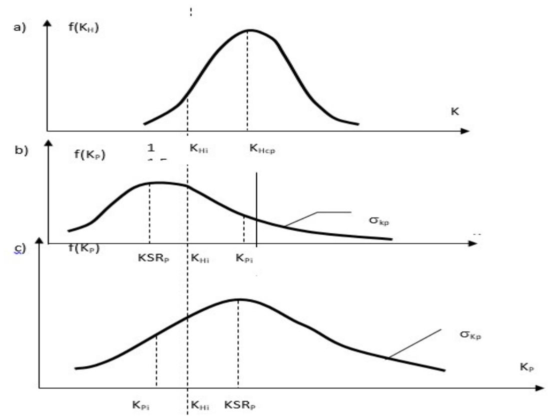

Figure 8. Graphical scheme for calculating statistical reliabilityRoadway stability

It was noted above that the strength of the roadway is subject to strong changes from the impact of variable weather and climatic factors, in particular, from fluctuations in soil moisture. The cumulative coefficient of normative stability K_n varies in the range from 1 to 1.5. according to the recommendations [10,11]. In a real situation, for the case of flooding of the road embankment, the stability coefficient can vary from 2 to 3 [12,13]. If the calculated value of K_p>=K_n, then it is considered that the stability of the subgrade is ensured. Thus, the moisture content of the soil base is the most important indicator of the stability of a road object in complex hydrological zones and is a random value in the calculation models [24]. From this it follows that the calculation methods of K_p should consider the uncertainty factor and be based on the mathematical apparatus of probability theory.

In fact, the actual value of K_p can differ significantly from K_{pi} due to variations and uncertainty in the level of flooding of the embankment. K_{ni} is also a random value and can range from 1 to 1.5 and higher in accordance with the distribution law $f(K_n)$.

$$Pi(Ai) = \int_{Kpi-\frac{\Delta Kp}{2}}^{Kpi+\frac{\Delta Kp}{2}} f(Kp)dKp = \int_{\theta_{1i}}^{\theta_{2i}} f(Kp)dKp, \quad (4)$$

Where,

$$\theta_{1i} = Kpi - \frac{\Delta Kp}{2}$$

$$\theta_{2i} = Kpi + \frac{\Delta Kp}{2}$$

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The assessment of the reliability of calculating the stability of the subgrade should be carried out according to the following algorithm: sequentially set the values of Kи over the entire range of its dispersion within $K_p \pm 3\sigma_{кр}$.To do this, the range $K_p - 3\sigma_{кр} \div K_p + 3\sigma_{кр}$ is divided into N intervals, each with a width of $\Delta K_{р.т.е.}$

$$\Delta K_P = \frac{6\sigma_{KP}}{N}, \qquad (5)$$

where $\sigma_{кр}$ is the standard deviation of the calculated stability factor K_p. The probability of events A_i in the interval ΔK_P is denoted as the product P_i,, which consists of the product of 2 probabilities. The probabilities of the event A_i, i.e. finding K_{pi} in the interval ΔK_p is denoted as P_i, and the probability value can be calculated from the expression Similarly, we will consider the random value of the normative coefficient of roadway stability $K_н$ as an event B_i, the probability of which, i.e. falling into the interval ΔK_{ni}, where $\Delta K_Н = \frac{6\sigma н}{M}$, and M is the number of intervals, will be

$$P_j(B_j) = P_j\left(K_{Hj} - \frac{\Delta K_H}{2} \langle K_{Hj} \langle K_{Hj} + \frac{\Delta K_H}{2}\right) = \int_{\theta_{3j}}^{\theta_{4j}} F(K_H)dK_H \qquad (6)$$

where
$$\theta_{3j} = K_Нj - \frac{\Delta K_Н}{2}$$
$$\theta_{4j} = K_Нj + \frac{\Delta K_Н}{2}$$

The probability of the event Ci, consisting in the fact that the events A_i and B_j will occur simultaneously, will be found as the product of the probabilities

$$Pi(Ci) = Pi(Ai) \cdot Pj(Bj) = \int_{\theta_{1i}}^{\theta_{2i}} f(Kp)dKp \cdot \int_{\theta_{3j}}^{\theta_{4j}} f(K_Н)dK_Н \qquad (7)$$

Then, the current values of K_{pi} are compared with the normative K_{Hj} and if $K_{pi} < K_{Hj}$, then one is added to the counter, where the «less» cases are summed up, otherwise, one is added to the «more» counter. In the next step, the normative value of KHi is increased by $K_н$ and the whole procedure is repeated. Summing up the products over the entire range of P_{Hi} variation within the three-sigma interval for j=1÷m, we obtain the following expression

$$P_i(C_i) = \sum_{j=1}^{m} P_i \cdot P_j = P_i \sum_{j=1}^{m} P_j =$$
$$= P_i \sum_{j=1}^{m} \int_{\theta_{3j}}^{\theta_{4j}} f(K_H)dK_H \qquad (8)$$

When all probabilistic values КНj are enumerated, the counters registering the number of cases «less» or «more» will contain the numbers N_{im} (less than K_{nj}) and $N_{iвб}$ (greater than K_{pj}) corresponding to these cases. These numbers are equivalent to the frequencies of the cases $K_{pi} < K_{нj}$ and $K_{pi} \geq K_{нj}$, respectively. If we divide these frequencies by the total number of outcomes, we get

$$\omega_{iн} = \frac{Niм}{Niм + Niб}; \omega_{iб} = \frac{Niб}{Niм + Niб}, \qquad (9)$$

where $\omega_{iм}, \omega_{iб}$ - the frequency of cases is less or more than the standard coefficient of stability.

Multiplying the probability Pi(Ci) by $\omega_{iн}$ and $\omega_{iб}$ we obtain the probability of events fulfilling the conditions $K_{pi} < K_н$ and $K_{pi} \geq K_н$ for the i-th value of K_{pi}

$$P_i(C_i)\omega_{iM} = \left(P_i \sum_{j=1}^{m} (f(K_H)dK_H)\right)\omega_{iM} =$$
$$= \left(\int_{K_{pi}\frac{\Delta K_p}{2}}^{K_{pi}\frac{\Delta K_p}{2}} f(K_p)dK_p \sum_{j=1}^{m} \int_{K_{Hj}\frac{\Delta K_H}{2}}^{K_{Hj}\frac{\Delta K_H}{2}} f(K_H)dK_H\right)\omega_{iM}$$

After that, K_i increases by ΔK_p and the entire computational cycle is repeated. The number of cycles is n (i=1÷n). Summing up n times by expression (10) we get

$$P_1(C) = \sum_{i=1}^{n} \omega_{Mi} \int_{\theta_{1i}}^{\theta_{2i}} f(Kp)dKp \sum_{j=1}^{m} \int_{\theta_{3j}}^{\theta_{4j}} f(Kн)dKн \qquad (11)$$

Arguing similarly, we arrive at the expression $P_{II}(C)$.

$$Pi(Ci)\omega_{iб} = \left(Pi\sum_{j=1}^{m} F(Kн)dKн\right)\omega_{iб} = \left(\int_{\theta_{1i}}^{\theta_{2i}} f(Kp)dKp \sum_{j=1}^{m} \int_{\theta_{3j}}^{\theta_{4j}} F(Kн)dKн\right)\omega_{iб}$$

$$P_{II}(C) = \sum_{i=1}^{n} \omega_{iб} \int_{\theta_{1i}}^{\theta_{2i}} f(Kp)dKp \sum_{j=1}^{m} \int_{\theta_{1j}}^{\theta_{2j}} f(Kн)dKн$$

(12)

For the numerical solution of these integrals, various methods are used, for example, the expansion of the integrand in a power series, or other methods are used. More acceptable in this case is the Monte Carlo method [4,17].

The purpose of computer modeling is to identify patterns of change in the coefficient K_p when varying the parameters of the distribution laws $f(K_p)$ and $f(K_n)$. To reduce the amount of programming, it is advisable to bring expression (12) to the standard form by replacing the variables K_p and $K_н$, as well as the operations of centering and normalizing by σ_{Kp} and σ_{Kn}. The variables after their replacement will acquire the following analytical form.

$$f(Kp) = \frac{1}{\sqrt{2\pi\sigma_{Kp}}} e^{\frac{-(Kp-\overline{K}p)^2}{2\sigma^2_{Kp}}}$$

$$f(K\textit{н}) = \frac{1}{\sqrt{2\pi_{K\textit{н}}}} e^{\frac{-(K_{\textit{н}}-\overline{K}_{\textit{н}})^2}{2\sigma^2_{K\textit{н}}}} \quad (13)$$

Then, expression (13) after transformations will look like

$$P_I(Kp \geq K\textit{н}), P_{II} = (Kp < K\textit{н})$$

$$P_I = P_I(C) = \sum_{i=1}^{n} \omega_{i\textit{м}} \int_{\theta_{1i}}^{\theta_{2i}} \frac{1}{\sqrt{2\pi}\cdot\sigma_{Kp}} e^{-\frac{(Kp-\overline{K}p)^2}{2\sigma^2_{Kp}}} dKp \sum_{j=1}^{m} \int_{\theta_{3j}}^{\theta_{4j}} \frac{1}{\sqrt{2\pi}\cdot\sigma_{K\textit{н}}} e^{-\frac{(K\textit{н}-\overline{K}\textit{н})^2}{2\sigma^2_{K\textit{н}}}} dK\textit{н}$$

$$P_{II} = P_{II}(C) = \sum_{i=1}^{n} \omega_{i\textit{б}} \int_{\theta_{1i}}^{\theta_{2i}} \frac{1}{\sqrt{2\pi}\cdot\sigma_{Kp}} e^{-\frac{(Kp-\overline{K}p)^2}{2\sigma^2_{Kp}}} dKp \sum_{j=1}^{m} \frac{1}{\sqrt{2\pi}\cdot\sigma_{K\textit{н}}} \int_{\theta_{3j}}^{\theta_{4j}} e^{-\frac{(K\textit{н}-\overline{K}\textit{н})^2}{2\sigma_{K\textit{н}}}} dK\textit{н}$$

(14)

For the numerical solution of these integrals, various methods are used, for example, the expansion of the integrand in a power series, or other methods are used. More acceptable in this case is the Monte Carlo method [17].

The purpose of computer modeling is to identify patterns of change in the coefficient K_p when varying the parameters of the distribution laws $f(K_p)$ and $f(K_n)$. To reduce the amount of programming, it is advisable to bring expression (14) to the standard form by replacing the variables K_p and $K_н$, as well as the operations of centering and normalizing by σ_{Kp} and σ_{Kn}. The variables after their replacement will acquire the following analytical form.

$$t = \frac{Kp - \overline{K}p}{\sigma_{Kp}}$$

$$z = \frac{K\textit{н} - \overline{K\textit{н}}}{\sigma_{K\textit{н}}} \quad (15)$$

Then, expression (13) after transformations will look like

$$P_I = P(Kp \geq K\textit{н}) = \sum_{i=1}^{n} \omega_{i\textit{б}} \frac{1}{2\pi} \int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}} dt \sum_{j=1}^{m} \int_{z_j}^{z_{j+1}} e^{-\frac{z^2}{2}} dz$$

$$P_{II} = P(Kp < K\textit{н}) = \sum_{i=1}^{n} \omega_{i\textit{м}} \frac{1}{2\pi} \int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}} dt \sum_{j=1}^{m} \int_{z_j}^{z_{j+1}} e^{-\frac{z^2}{2}} dz \quad (16)$$

determining the estimated risk of flooding of critical facilities (roads) and automated decision-making when intelligentizing the emergency control and management system [26-28].

Computer experiment. By means of computer modeling, the tasks are set to identify and build a spatial 3D picture of the degree of influence of the laws of distribution of the calculated coefficient $f(K_p)$ and the standard coefficient $f(K_n)$ and statistical characteristics of uncertainties on the risks of decision-making in systems with artificial intelligence on the example of emergency situations with the threat of flooding of objects. The range of variable values of the studied indicators in the models was taken from the literature [7,8,13]. The selected ranges are typical for real conditions. As a result of computer simulation, a general picture was obtained in the form of graphic 3D illustrations of the influence of various compositions of the laws of distribution of stability coefficients and the standard value for given tolerances on the standard. In all cases, the normal law was adopted as the law of distribution of the calculated stability coefficient. This is justified by the fact that the value of this coefficient is influenced by a large number of both external and internal factors, and in accordance with the law of large numbers, the resulting distribution, and in this case the distribution K_p, will obey the normal law.

Three distributions were studied as distribution laws for the norm K_n: normal distribution, Weibull distribution, as one of the most common in reliability theory and a uniform law, since in practice, as a rule, there is no information about the actual conditions in which the road will be operated due to the impossibility of predicting humidity fluctuations at the location of the road. Figure 9 shows one example of a distribution model for K_p and K_n according to the normal law.

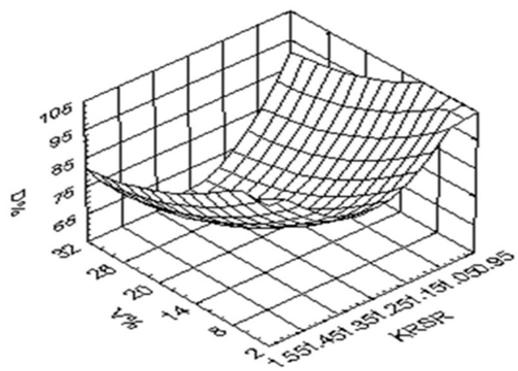

Figure 9 - The level of reliability (risk) of decision-making under the conditions of statistical uncertainty of emergency management factors

A spatial 3D model of the dependence of the reliability of decision-making under the uncertainty of the calculated coefficient Kp and the standard value Kn, with various combinations of their numerical values, gives a general idea of the probable quality of decisions. In contrast to 2D constructions, the region of minimum reliability is distinguished here for some numerical combinations of Kp and Kn. The 3D model is a picture of the risk of decisions. Quantitative assessment of the reliability of decisions under the conditions of uncertainty of all decision agents in practice seems to be possible only with the use of digital technologies. The mathematical models presented above are the software for digital diagnostic and control systems in complex multi-parameter control systems, as well as an integral part of the knowledge base of intellectual support**.**

Conclusion. Based on the results of the study, the following conclusions can be drawn:

Kazakhstan has a high-quality road network that is partially or significantly damaged by seasonal floods. To control and monitor these critical situations, space monitoring systems are used, which transmit photos of the earth's surface in digital format to centers for receiving such information at 12-hour intervals. In these systems of control and monitoring of natural emergencies at the decision-making stage, a subjective approach is used based on the past state of the process with a delay of 12 hours. Such technological and technical capabilities of the digital geographic information system used become uninformative, since the time interval of 12 hours becomes uncontrollable. There is a need to predict the dynamics of the process in this time interval, based on the results of the last communication session with the satellite and the estimated rate of flooding of the area.

To solve this problem, a simulation model has been developed for predicting the dynamics of flooding in the area and identifying the critical vector of flooding in a 12-hour time interval with a pixel accuracy of 200 meters and a given time lag.

A criterion for measuring the danger for a controlled object from the intensity and dynamics of flooding has been chosen, which in mathematical form implements the coefficient of stability of the roadway. It is proposed to evaluate the level and dynamics of danger by reducing the coefficient of roadway stability as a function of the distance to the predicted flood boundary. The stability coefficient depends on the hydrodynamic pressure, which is largely functionally determined by the volume of water in large nearby natural and artificial reservoirs. Long-term changes in the volume of water in natural reservoirs have been studied and empirical models for forecasting volumes for monthly and annual periods have been constructed.

A probabilistic mathematical model for assessing the risks and reliability of decisions under the conditions of parametric uncertainty of agents for controlling the quality and stability of the road structure has been developed. As a result of computer simulation, a graphical model was built in 3D format, representing a 3-dimensional image of the reliability of decisions with varying uncertainties in the values of the stability coefficient and the standard.

Visual analysis of the calculated 3D surface indicates the presence of a clearly visible isoline of the minimum. The line of minimum statistical reliability of decision-making under normal distribution laws Kp and Kn passes through the points 82.15%, 70.3%, 63.05%, 62.1%, 59.5% and 57.95%. Each point corresponds to a certain level of variation of the calculated coefficient of stability, starting from 5% with a step through 5% and ending at 30%. This range is typical for normal laws. All minimum points correspond to the average value of the calculated stability factor in the range from 1.2 to 1.3. The analysis of computer simulation data shows on the response surface the maximum line passing for the case of a normal distribution of Kp and Kn over the values of 10.58%, 16.5%, 25.95%, 27.05%, 29.63%, 31.3%. The mathematical explanation of mini-max levels should be explained by the conjugation of two smooth non-

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linear forms, as a result of which a third, more non-linear form is formed.

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