GIS-Technologies and Mathematical Simulation as Tools for Lightning-Caused Forest Fire Danger Prediction

Nikolay Baranovskiy[1], Vladimir Barakhnin[2,3], and Elena Yankovich[1]

[1] National Research Tomsk Polytechnic University, Lenina ave. 30, 634050 Tomsk, Russia
[2] Novosibirsk State University, Pirogov st. 2, 630090 Novosibirsk, Russia
[3] Institute of Computational Technologies SB RAS, Lavrent'yev ave. 6, 630090 Novosibirsk, Russia
firedanger@narod.ru

Abstract. New approach to forecasting of forest fire danger caused by storm activity is presented in the article. This approach is based on using the criteria of forest fire danger and physically proved mathematical models of forest fuel ignition. The formula of criterion is based on a probabilistic assessment of forest fire danger and uses the main theorems of probability theory. Data of a forest fire retrospective on the controlled territory are used to assess the members in probabilistic criterion. Timiryazevskiy local forestry of the Timiryazevskiy timber enterprise of the Tomsk region is considered as a typical territory. It is shown that it is not enough to use only statistical information on forest fires for an adequate assessment of the forest fire danger caused by action of storm activity. Visualization of data is carried out with the use of geoinformation technologies.

Keywords: GIS, mathematical simulation, forest fire danger, prediction, lightning.

1 Introduction

The remote areas of forested territories are characterized by a big share of the forest fires caused by action of storm activity [1]. The great value of the area passed by fire is noted for such fires [2]. Such fires in the forests are detected with delay when the ignition center already reached the big sizes. It is either impossible or ineffective to suppress ignitions in taiga zone. Fire fades in case of the beginning of long rains, or at burning out of all forest area before fire came across the natural barrier (for example, river). In such a situation, the most perspective approach is to forecast the forest fire danger and to carry out preventive measures in controlled forested territories [3]. There are various forest fire danger forecast systems taking into account storm activity developed in the different countries of the world [4–6]. However, all these systems have no physical basis and are based mainly on the analysis of statistical information on forest fires and characteristics of the forested territory [7].

2 Background

Storm discharges are one of the reasons for forest fires. Lightning is an electric discharge conditioned by the division into positive and negative discharges in the clouds that leads to a difference in potentials of the range 10-100 mV [8]. In order for the division into discharges to happen, it is necessary that water be present in all three phases solid, liquid and gas [9].

According to the development conditions, storms are divided into the air-mass and frontal ones. Air-mass storms over a continent occur as the result of the local air heating from the ground surface that leads to a development of rising flows of the local convection and to a formation of heavy cumulonimbus clouds in it. The frontal storms occur on the borders of warm and cold air masses [10]. There may be the cloud-to-cloud and cloud-to-ground discharges. Around 90% of cloud-to-ground discharges are negative, and the nature of the remaining 10% of positive discharges is not fully clear [11]. The cloud-to-ground discharges, i.e. ground storm discharges, can cause forest fires [12]. The energy characteristics for positive and negative ground storm discharges are different, and these differences are substantial in terms of igniting the forest fuels. Due to the vast majority of positive discharges, all the energy reaches the surface in one stroke, and a multi-stroke is typical for the negative discharges [13].

Wide statistics on ground storm discharges has been collected within the functioning of the US National Lightning Detection Network [14]. This system may identify most ground storm discharges on USA and Canada territories with the spatial resolution of several kilometers and determination accuracy in time of 1 msec. Due to the system operation, the data on the stroke polarity, stroke peak current and stroke complexity are archived (if it is a single or multi-stroke) [13].

In Russia, between 1992 and 2000, storm-induced forest fires equaled 37 to 53 % of the area where fire had spread, with a relative number of 8.817.5 % [15]. Dry storms, producing mass ignitions on large spaces, often create a very intense situation [16].

Canadian Forest Fire Danger Rating System (CFFDRS) has two main subsystems (modules) Canadian Forest Fire Weather Index (FWI) System and Canadian Forest Fire Behavior Prediction (FBP) System. Two other elements (Fuel Moisture System and Canadian Forest Fire Occurrence Prediction (FOP) System) are not developed for the whole country, but there are regional versions of these systems [17].

The Canadian method of forest fire danger prediction [14] is formed relying on analysis of a large number of statistical data according to which they formed the tables of fire danger dependence on different factors. Within the FWI sub-system, the moisture content of forest fuels is predicted depending on weather conditions; whereas within FBP, forest fire spots behavior is forecasted for different forest plant communities.

A logical structure of the system [15, 16] represents an abstract model of the impact of different factors and conditions on the process of how fire occurs and spreads.

The Canadian and American methods are similar to each other in their structure, approaches and fire danger index formation principles. Therefore, they have both similar advantages and disadvantages. European Forest Fire Information System EFFIS (Europe) [6]. The most progressive component of system repeats the subsystem of the Canadian Forest Fire Danger Rating System. This system has the same characteristics and uses Earth remote sensing data.

The work purpose is to create a new method for geospatial data analysis in order to monitor, assess and forecast the forest fire danger caused by storm activity.

3 Mathematical Methods

Using the basic principles of probability theory, we obtained a formula to assess the probability for the forest fire to occur for the j-th time interval of the forest fire season [18]:

$$P_j = [P(A)P\left(A_j/A\right)P\left(FF/A, A_j\right) + P(L)P\left(L_j/L\right)P\left(FF/L, L_j\right)]\,P_j(D), \quad (1)$$

where P_j is the probability of a forest fire to occur for the j-th interval in the controlled forest area; $P(A)$ is the probability of anthropogenic impact; $P\left(A_j/A\right)$ is the probability of a fire source presence on j-th day; $P_j\left(FF/A, A_j\right)$ is the probability of a forest fire to occur from anthropogenic impact in the forest area; $P(L)$ is the probability of dry thunderstorms to occur in the forest area; $P\left(L_j/L\right)$ is the probability of ground lightning discharge; $P_j\left(FF/L, L_j\right)$ is the probability of a forest fire to occur from lightning in case, if dry thunderstorms can happen in the forest area; $P_j(D)$ is the probability of fire to occur due to weather conditions of forest fire maturation (the probability of the fact that the forest fuel layer will be dry); index j corresponds to a day of the fire danger season. To determine all multipliers in the formula (1), the author offers to use a definition of probability through frequency of events and to use statistical data for a concrete forestry. The formula (1) contains the following members [18]:

$$P\left(A_j/A\right) \approx \frac{N_{FD}}{N_{FW}}, P(A) \approx \frac{N_A}{N_{FS}}, \quad (2)$$

$$P_j\left(FF/A, A_j\right) \approx \frac{N_{FA}}{N_{FT}}, \quad (3)$$

$$P\left(L_j/L\right) \approx \frac{N_{LN}}{N_{LD}}, P(L) \approx \frac{N_L}{N_{FS}}, \quad (4)$$

$$P_j\left(FF/L, L_j\right) \approx \frac{N_{FL}}{N_{FT}}, \quad (5)$$

where N_A is the number of days during the fire danger season when the anthropogenic impact is enough for forest fuel ignition;N_{FA} is the number of fires from anthropogenic impact; N_{FT} is the total number of fires; N_L is the number of days when lightning occurred (during dry thunderstorms); N_{FS} is the total number of days in the fire danger season; N_{FL} is the number of fires from lightning (during dry thunderstorms); N_{FD} is the number of fires on a specific day of the week; N_{FW} is the total number of fires for a week; N_{LH} is a number of ground lightning discharges passed on the concrete hour, starting from 00.00 oclock; N_{LD} is the total number of ground lightning discharges per day. Obviously, the more cases will be considered for this forestry, the bigger accuracy to determine the probability by formulas (2)-(5) will be. Therefore, in forestries, it is necessary to register all fire danger season parameters (N_A, N_{FA}, N_{FT}, N_L, N_{FS}, N_{FL},N_{FD}, N_{FW}, N_{LH}, N_{LD}) every year.

Formula (1) contains the multiplier $P_j(D)$. This is the probability of fire danger from meteorological conditions. In early work, this probability was calculated through the time for the forest fuel layer to dry [19]. However, at present, it is hard to implement the method like this on the whole territory of Russian Federation, because in order to model the process of drying the forest fuel layer, it is necessary to have information about the initial moisture content of forest fuel. The present paper offers to use the compromise variant. We suggest calculating the probability by meteorological conditions using the Complex Meteorological Index, which was approved in the state standard. The range of this index starts from zero and has no upper border. However, it is possible to set its upper border as a maximum possible value during the fire danger season. To estimate the probability of forest fire danger, we normalize the complex meteorological index on figure of one [18]:

$$P_j(D) = \frac{NI_D}{NI_{max}}, \tag{6}$$

where NI_D is a value from the complex meteorological index for the day for which the forecast is realised; NI_{max} is the maximum value of the complex meteorological index. Then, the range of variation of forest fire danger probability by meteorological conditions will be within 0 to 1.

The complex meteorological index is calculated by the formula [7]:

$$NI = \sum_{n} t(t-r), \tag{7}$$

where t is the air temperature; r is the dew point temperature; n is the number of days after the last rain.

The dew point characterises the amount of moisture in the air. The higher the dew point, the greater the humidity is at a given temperature. The dew point temperature is determined as the temperature to which air must be cooled (at the constant pressure and constant water vapour content), in order to reach saturation and in order for its condensation process to start, that is, the dew to appear. The saturation state can exist only as long as the air contains the maximum possible amount of water vapour at the given temperature and pressure.

The work [20] suggests a simple mathematical model of tree ignition by the cloud-to-ground lightning discharge.

Electric current flow is various in the trunk of deciduous and coniferous trees [21]. This is due to the fact that in broad-leaved trees, moisture is transported is in a massive central part. More damp central part is an electric current conductor. The analysis of the known information on wood properties of broad-leaved species shows, that it is necessary to consider moisture presence in the trunk wood structure. Even under the conditions of high-speed processes, moisture presence can essentially change the wood ignition conditions. Therefore, when setting the task for broad-leaved trees, it is expedient to consider the influence of moisture content on thermophysical characteristics of wood.

We consider the following physical model. A cloud-to-ground lightning discharge strikes in a tree trunk at the fixed moment of time. The electric current of the cloud-to-ground lightning discharge flows along the trunk. It is supposed, that the heat emits in the core according to Joule-Lenz law. It is supposed that in various trunk sections, the electric current has the same parameters. It is considered, that one can describe the moisture evaporation by Knudsen-Lengmuir equation [22]. As a result of electric current flow, the wood is warmed up due to the Joule heat emission and the wood ignites when achieving the critical thermal fluxes to ignition surface and critical temperature. It is supposed, that the formed vapor space is filled with water vapor. Changes of volume fractions of phases are reflected on thermophysical properties of internal wood part of the broad-leaved tree. The tree trunk is modeled by the cylinder. We consider the representative section of a trunk. Fig. 1 shows the decision area scheme.

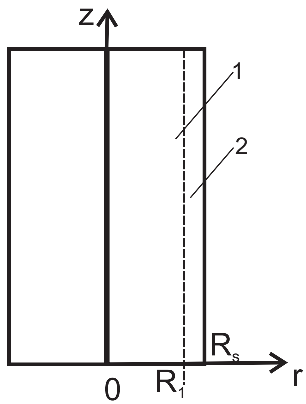

Fig. 1. The decision area scheme: 1 core, 2 - bark.

The system of non-stationary differential equations mathematically describes the process how a cloud-to-ground lightning discharge warms up a tree trunk before ignition [20]:

$$\rho_{ef} c_{ef} \frac{\partial T_1}{\partial t} = \frac{\lambda_{ef}}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_1}{\partial r} \right) + JU - QW\varphi_2, \tag{8}$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \frac{\lambda_2}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right), \tag{9}$$

$$\rho_3 \frac{\partial \varphi_1}{\partial t} = 0, \tag{10}$$

$$\rho_4 \frac{\partial \varphi_2}{\partial t} = -W, \tag{11}$$

$$\sum_{i=3}^{5} \varphi_i = 1, \tag{12}$$

$$W = \frac{A(P^5 - P)}{\sqrt{\frac{2\pi RT}{M}}}, \tag{13}$$

$$\rho_{ef} = \rho_3\varphi_3 + \rho_4\varphi_4 + \rho_5\varphi_5, \lambda_{ef} = \lambda_3\varphi_3 + \lambda_4\varphi_4 + \lambda_5\varphi_5. \tag{14}$$

Boundary conditions for the equations (1) - (2):

$$r = 0, \lambda_{ef}\frac{\partial T_1}{\partial r} = 0; \tag{15}$$

$$r = R_1, \lambda_{ef}\frac{\partial T_1}{\partial r} = \lambda_2\frac{\partial T_2}{\partial r}, T_1 = T_2; \tag{16}$$

$$r = R, \lambda_2\frac{\partial T_2}{\partial r} = \alpha(T_e - T_{Rs}). \tag{17}$$

Initial conditions for the equations (1) – (5):

$$t = 0, T_i(r) = T_{i_0}), \varphi_i(0) = \varphi_{i_0}. \tag{18}$$

Where T_i is temperature of internal part of tree trunk ($i = 1$) and bark ($i = 2$); φ_i - volume fraction: organic substance ($i = 3$), water ($i = 4$) and water vapor ($i = 5$); ρ_i, c_i, λ_i is density, thermal capacity and heat conductivity of bark ($i = 2$), organic substance ($i = 3$), water ($i = 4$) and water vapor ($i = 5$); ρ_{ef}, c_{ef}, λ_{ef} - effective density, thermal capacity and heat conductivity of wood for internal part of trunk; λ - heat transfer factor; J current strength; U - voltage; Q - thermal effect of moisture evaporation; r - coordinate; t - time. W - mass speed of water evaporation, A - accommodation coefficient, P^s - pressure of saturated water vapor, P - partial pressure of water vapor in air, R - universal gas constant, M - molecular weight of water. Indexes Rs, e and 0 correspond to the parameters on the external border of tree trunk, the environment and to the parameters at the initial moment of time.

Formulated system of equations (8) – (14) with boundary and initial conditions (15) – (18) is solved by the finite difference method [23]. The double-sweep method in combination with the fixed point iteration method [23] was used to decide the difference analogues of one-dimensional equations.

The following ignition scenario was considered. The negative cloud-to-ground lightning discharge, with duration of $500ms$, with peak current of stroke in $23.5k$ and voltage $100kV$, influences on a wide-leaved tree, for instance, birch. Fig. 2 shows the temperature distribution on the tree trunk radius in various moments of time before and at the moment of igniting by electric current (initial temperature $300K$).

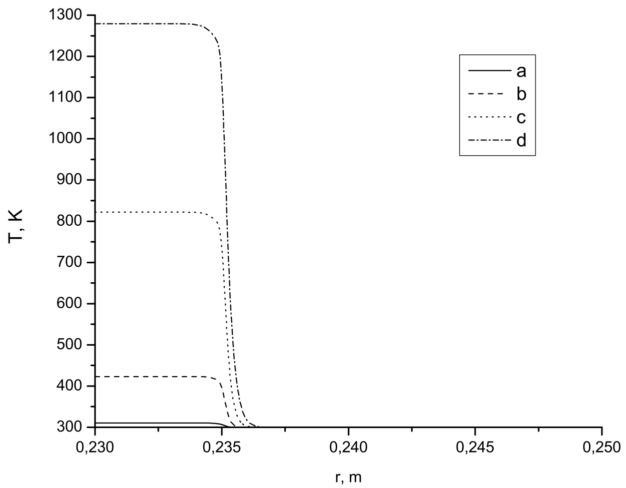

Fig. 2. Temperature distribution on the tree trunk radius at the various moments of time (discharge action duration is $500ms$): a - $t = 0.01s$; b - $0.1s$; c - $0.3s$; d - $0.5s$ [20].

Table 1 represents the lightning discharge parameters and ignition conditions depending on voltage of ground-to-cloud lightning discharge obtained by solving the problems (8) – (14). The analysis of dependences presented on Fig. 2 shows, that tree trunk is warmed up to ignition temperature (more than $1000K$) by the action of the considered cloud-to-ground lightning discharge. The analysis of results shows that for a typical cloud-to-ground lightning discharge, ignition conditions of wide-leaved tree are reached on critical temperature ($801K$) and value of thermal flux ($268kW/m^2$).

We established the ignition limits for tree trunk during the action of the electric discharge at various voltages (Table 1) and current. When the current is less than $15kA$ and voltage is $1 - 50kV$, ignitions fail to occur during the action of cloud-to-ground lightning discharge.

Table 1. Ignition condition of tree depending on voltage of the discharge at current $J = 23.5kA$ [20]

Voltage, U, kV	Ignition conditions	Surface temperature,	Heat flux from core to surface, k kW/m^2
1–45	No	< 801	< 201
50	No	< 801	252
55	Yes	801	268
60	Yes	801	268
80	Yes	801	268
100	Yes	801	268
110	Yes	801	268

3.1 GIS System

Program realization of mathematical model for quantitative assessment of probability of forest fire danger caused by storm activity is enabled in GIS.

Algorithms of geographical information system for quantitative assessment of forest fire danger are implemented in the Python language embedded into ArcGIS [24]. The quantitative assessment is carried out relying on the remote sensing data, land mensuration of forests and statistical information. The criteria to assess the forest fire danger are defined relying on the probability theory, and its values are within the range from 0 to 1. Calculations are made with accuracy up to 0.0001.

Below are the tables in the MS Excel format with forest mensuration descriptions on stratums (Table 2). Russian database on stratums description is used.

The program tool *"FFstormactivity.tbx"* solves the problem to forecast the fire danger of forest quadrant relying on the information about stratum composition and statistical information on fires caused by storm activity and the display of the obtained information on the electronic map. Python is the source language of the *"FFstormactivity"* program [24].

The program tool *"FFstormactivity"* contains 7 forms. It provides two variants to solve the task: complex and stage-by-stage with the control of result. Main stages:

1. Data import from the table Excel to the autonomous geodata base table.
2. Determination of fire danger for forest stratum.
3. Assessment of fire danger probability for forest quadrant according to forest mensuration descriptions.
4. Import of statistical data to geodata base.
5. Assessment of fire danger probability caused by storm activity.
6. Connection of attributive and autonomous tables.
7. Formation of the map according to a legend.

Table 2. Tables of forest mensuration data in the MS Excel format.

forestry	quarter	site	area	composition	age
Kaltayskiy	1	1	43.7	Grass	
Kaltayskiy	1	2	2	Wetland	
Kaltayskiy	1	3	7.6	7B2L1P	B – 75,L – 120, P – 120
Kaltayskiy	1	4	14.8	7W3B	W – 30, B – 35
Kaltayskiy	1	5	19	7W3B	W – 30, B – 35
Kaltayskiy	1	6	18.3	8B2L	B – 65, L – 120
Kaltayskiy	1	7	5.5	7B2L1P	B – 75, L – 120, P – 120
Kaltayskiy	1	8	5.6	5P21L2B	P – 140, C – 160, L – 140, B – 75
Kaltayskiy	1	9	5.3	5C2F1P2B	C – 180, F – 140, P – 140, B – 85
Kaltayskiy	1	10	1.2	Lake	

First step is data import from the table Excel to the autonomous geodata base table.

Next step is determination of fire danger for stratum according to forest mensuration descriptions and assessment of fire danger probability of forest quadrant according to forest mensuration descriptions.

Third step is import of statistical data on storm activity to geodata base.

Algorithm of assessment of probability of the fire danger caused by storm activity presented on Fig. 3.

Last stages are connection of attributive and autonomous tables and formation of the map according to the legend.

The program tool FFstormactivity uses the following methods:

1. *AddField* is to add a field. The program adds a field.
2. *CalculateField* is to calculate the field value. To determine the fire danger of the stratum, to assess the probability of forest fire danger on the quadrant, of the level.
3. *Statistic_analysis* is the total statistics. To calculate the total quantity of stratums in each quadrant and quantity of the fire-dangerous ones.
4. *JoinField* is to connect the fields. A connection of two tables takes place on the basis of a key field
5. *ApplySymbologyFromLayer_management* is to add the layer symbols. To form the layer of quadrants according to the fire danger level.

The start-up of the program tool comes from ArcToolbox. It is necessary to specify the initial data in the dialog window that appears after start-up. Russian interface is used in current version of GIS-system.

Structures of tables with initial data on forest fires and forest mensuration descriptions of the territory are given below (Table 3 and Table 4).

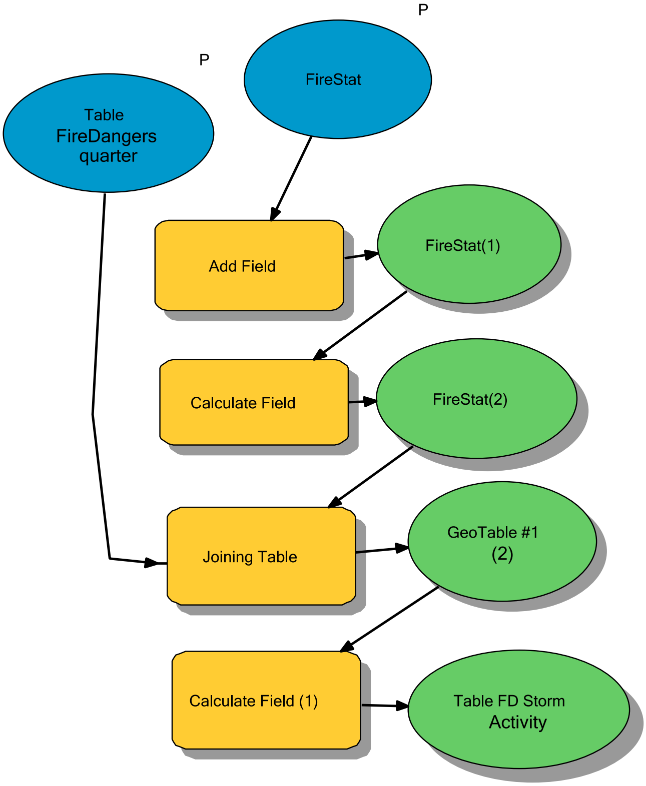

Fig. 3. Assessment of probability of the fire danger caused by storm activity.

The tool implementation results in creating the table with an assessment of probability of fire danger of forest quadrant caused by storm activity with regard to the forest vegetation conditions and the thematic map displaying the fire danger levels of forest quadrants (Fig. 4).

The forest fire danger levels in Fig. 4 correspond to the following gradation: 1 - 0,001852 - 0,030000 2 - 0,030001 - 0,060000 3 - 0,060001 - 0,090000 Minimum - 0,001852; maximum - 0,08333.

4 Discussion

The analysis of foreign forest fire danger forecast systems shows that in the territory of their states they show high operational qualities. However, it is difficult to apply them in the territory of other states, as it is necessary to carry out all range of works on the analysis and adjustment of empirical formulas for new forested territories.

All foreign systems finally offer an abstract index of forest fire danger. The present paper offers the new probabilistic approach to assess the most probable

Table 3. . Structure of the table with statistical data on the fires in the MS Excel format.

Name_forest	Name of fores district	
N_F	A total number of the fires during a fire-dangerous season	
N_FA	Number of the fires from storm activity during a fire-dangerous season	
N_D	Total number of days of a fire-dangerous season	
N_A	number of days during a fire-dangerous season when there is a storm activity sufficient for ignition of forest fuel	
N_1	Monday	
N_2	Tuesday	
N_3	Wednesday	
N_4	Thursday	
N_5	Friday	
N_6	Saturday	
N_7	Sunday	
N_W	Total number of fires per a week	

Table 4. Structure of the table with initial data on stratums in the MS Excel format.

forestry	quarter	site	area	compisition	age

scenarios of forest fire danger. The definite scenario can be calculated using a deterministic mathematical model of how the cloud-to-ground lightning discharge ignites a tree.

We developed GIS-system for forecasting the forest fire danger caused by storm activity. The system reserves the layers for the subsequent implementation of a deterministic component based on the mathematical model of tree ignition by cloud-to ground lightning discharge.

Conclusion. As a result of research, we offered the new physically proved approach to forecast the forest fire danger caused by storm activity. The analysis of the methods based on statistical data shows that it is impossible to adequately assess the probability of forest fires caused by storm activity. We offered to use the deterministic models of tree ignition by a cloud-to-ground lightning

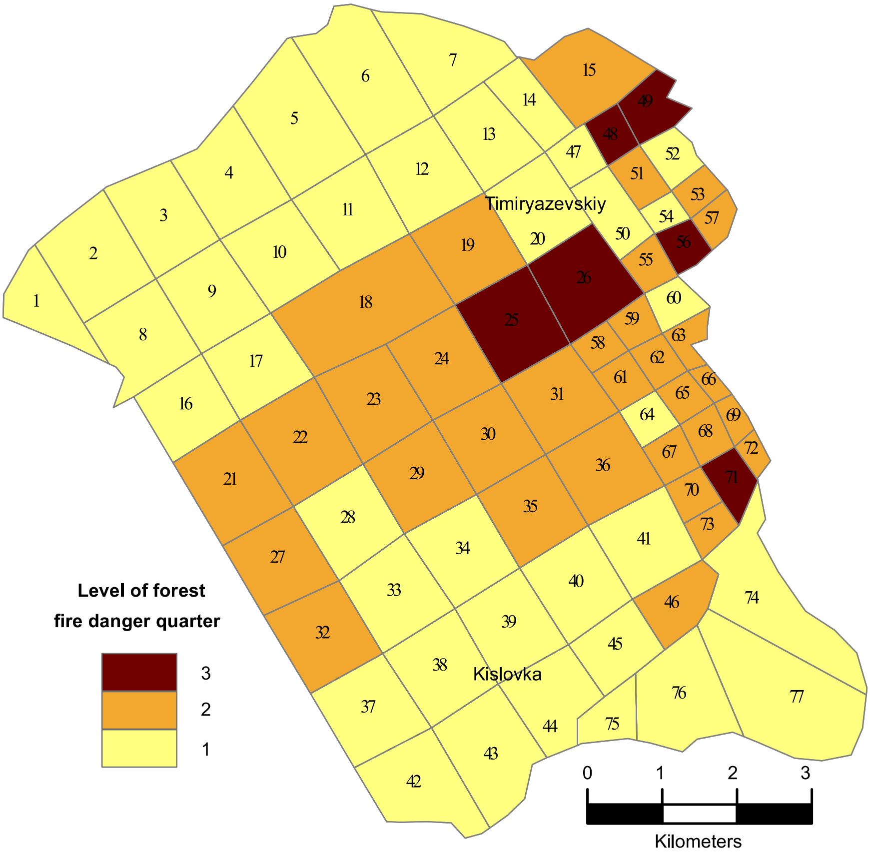

Fig. 4. Map of forest fire danger caused by storm activity in the territory of the Timiryazevskiy local forestry of the Timiryazevskiy forestry of the Tomsk region.

discharge and probabilistic criterion of forest fire danger assessment. The analysis of statistical approach is carried out in the territory of the Timiryazevskiy local forestry of the Timiryazevskiy forestry of the Tomsk region. Technologies of geographic information systems are used to visualize the spatial data. The program implementation of algorithms is enabled in the ArcGIS software.

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