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LEVEL OF FIRE DANGER OF THE LOCAL TERRITORY

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The object of the study is the fire risk of the local area. The problem to be solved is to take into account most of the significant parameters in the territorial placement of fire-rescue units of different functional capacities. As part of the solution to this problem, a technique for assessing the fire risk of a large-scale local area has been developed. The methodology is focused on local territories of a large area with a low population density. A special feature of the proposed method is the differentiated fire risk assessment of each point of the surface plane. For such an assessment, the parameters that are decisive from the point of view of impact on the fire hazard are analyzed and structured. The specified factors include the spatial distribution of population density and buildings, the transport and communication network, the spatial distribution of the density and type of vegetation, and statistical data on landscape fires. The use of existing geo-informational resources in real time is foreseen. A new approach of ranking the fire risk of the elementary plane of the territory in accordance with the necessary number of resources of rescue units to ensure the appropriate level of safety is proposed. Neural network data processing methods were used to compare local area parameters with fire risk ranks. A neural network capable of comparing the fire risk of the territory with its parameters was obtained. The functionality of the developed methodology was tested and the fire risk levels of an arbitrary area were graded with an average degree of correlation of 0.97. The proposed method allows for assessment and correction of the state of provision of local territories with civil protection resources. The developed methodology is especially relevant when creating new fire and rescue units of territorial communities

Keywords: fire risk, local territory, fire station, service area, neural network, population density

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1. Introduction

The development of humankindpredetermines an increase in the level of threats of both man-made [1, 2] and natural nature [3]. The most intense are dangerous events associated with local fires (LF) [4]. LF cause death and injury to people [5], lead to the destruction and damage of industrial [6] and residential facilities [7, 8]. Of particular danger are LF in ecosystems [9]. Combustion products and extinguishing agents [10] cause pollution of water sources [11], soils and atmospheric air [12], which globally provokes acid precipitation and increased greenhouse effect [13]. CounteractingLF is based on two directions. Prevention involves preventive measures [14] and detection of fires in the early stages [15]. Extinguishing implies timely response to LF with a sufficient amount of resources [16]. It is important to optimize the cost of ensuring fire safety (FS). At the same time, optimization is between two factors – material costs that strive to a minimum, and the level of FS, which tends to the maximum but should not be lower than the established norms. Based on this, the optimal way to ensure FS will be the compliance of all fire-fighting measures within the local territory (LT) with the level of FS of this territory.In addition to the large number of factors affecting the FS of a region, its assessment significantly complicates the uneven distribution of such factors throughout the territory. Based on the fact that for fire and rescue units (FRU) the time of arrival at the place of call plays a critical role, their number within the settlement and territorial location is very important. Exceeding the time of FRU traveling to the place of LF leads to an increase in human and material losses, as well as excessive release of combustion products [17, 18]. The main reasons for exceeding the normalized time of arrival of FRU are exceeding the normalized distances [19] to dangerous objects [20], incorrect choice of routes, and inconsistency in the state of the transport network [21]. In addition to a large number of significant parameters, the issue of territorial location of FRU is complicated by the constant change of such parameters. Therefore, the question of the number and location of FRU needs constant clarification. Thus, the imperfection of existing methods and approaches to taking into account significant parameters in the territorial placement of FRU of different functional capacity is an urgent problem.

2. Literature review and problem statement

Analysis of the state of fire danger (FD) in different countries as a whole and in individual regions is carried out within the national structures for monitoring the state of technogenic and natural safety [22]. The annual reports provide statistics of LF by their nature, the number of dead, injured, and material damage. Using these data, an analysis of fire risks (FR) of individual regions is carried out [23]. However, in this case, FR is determined by the ratio of the number of LF per LT to the number of the population, the number of dead, the number of injured, and material damage, which makes it impossible to estimate FR in areas with a low frequency of fires.A separate factor is the negative impact of large-scale LF on the air ecosystem [24]. The advantage of this method is the ease of calculation and a small amount of necessary input data, which correlates with annual statistics. There are fairly accurate methods for predicting FD, which are based on the processing of a large number of statistical data [25]. But at the same time, this method has significant drawbacks – it is the failure to take into account a number of significant factors, complete dependence on statistical data, and focus on the territory of a large area for which it is possible to collect such an array of data. To realize the possibility of assessing the level of FD on LT of arbitrary size, the calculation of FR is provided as an integrating indicator for a number of hazard factors, which are given a certain rank [26]. The FR criteria include the scope of operation of objects, their area and height, the number of people who can simultaneously be at the facilities, the presence and scale of LF in recent years. But the list of these criteria is insufficient and does not make it possible to fully assess the level of FD of an object or territory. Therefore, ISO 16732-1:2018 proposes a method for calculating the total FR, as an integrating indicator of individual, social, and potential FR. However, this technique defines FR as the probability of an incident. This approach does not make it possible to correlate the level of FD LT and the necessary measures to ensure FS. When analyzing FR on a large-scale LT, additional hazards, such as the type and density of vegetation, terrain, and the presence of water sources, become important [27]. A more complete description of FR is provided by the international standard ISO 31000:2018, where FR is an integrating indicator for assessing the sources of danger, possible consequences, and their probability. But there is no method for numerical evaluation of such parameters for large-scale LT, and the calculation requires a significant array of engineering, social, and statistical data. The level of FR is also affected by the presence and condition of fire protection systems, such as early detection, warning and automated extinguishing systems of LF [28]. However, no general approach has been created to assess the degree of influence of such systems on the level of FR as a separate object and LT as a whole.When choosing a place to place a new FRU or assess the correctness of the placement of already created FRU, it is necessary to take into account the number of fire hazardous objects, the degree of their FD, territorial location, the presence and condition of access roads [29]. In its simplest form, the issue of placing FRU is solved as a problem of placing circles of a certain radius. In this case, the determining parameter is the time of arrival of the unit at the place of LF [30]. The limiting radius of the circle is determined on a condition that this time should not exceed the established values, taking into account the speed of movement of the fire truck. However, the work does not take into account the state of transport communications. Determination of the limits of maintenance of FRU, taking into account the presence and condition of highways, was carried out in [31], where the service area of FRU has the form of a polygon. However, the different level of FD of objects and the different functional capacity of FRU are not taken into account. Automation of the process of placing FRU on the map of a district or city using the GIS program was carried out in [32]. The proposed algorithm allows interactive use of digital maps with additional application of layers with the transport network and FRU [33]. However, when extinguishing complex LF, it is necessary to involve several FRUs, which do not make it possible to make results in [33]. Assessment of the level of FD of the district takes into account many parameters and is carried out by separate methods for the city and forest [34]. Nevertheless, such methods are quite abstract. The method of spatial calibration of territories according to the stages of FR [35] has been widely used. At the same time, this method is well suited only to LT of the same fire load, for example, forests, fields, etc. Taking into account FR in dense diverse buildings requires consideration of the characteristics of each individual object. Thus, the unresolved part of the problem under consideration is the lack of methods and approaches to assessing the level of FDover LT of a large scale with the definition of the necessary fire-fighting forces and means.

3. The aim and objectives of the study

The aim of our work is to develop a methodology for assessing the level of fire danger of a large-scale area with the definition of the necessary fire-fighting forces and means. This technique will make it possible to assess and adjust the state of provision of local territories with civil protection resources.

To accomplish the aim, two tasks have been set:

– to theoretically substantiate the methodology for assessing the level of fire danger of a local area of a large scale by structuring the determining parameters of fire danger, using artificial intelligence methods and GIS technologies;

– to check the operability of the methodology for assessing the level of fire danger of a local area of a large scale.

4. The study materials and methods

The object of this study is FRover LT of a large scale. The working hypothesis assumed the difference between the FR of the elementary plane of the territory, depending on the characteristic parameters. The identified differences in the assessment of FR of each surface point will determine the required amount of civil protection resources to ensure the proper level of large-scale FSof LT. The methods of system analysis, statistical data processing, as well as methods of artificial intelligence and GIS technology were used in the work. The implementation of artificial intelligence methods was carried out using the STATISTICA 10 software package (USA). To analyze the spatial distribution of population density, type, and density of vegetation and fire activity over LT, data from the resources of the Fire Information for Resource Management System (FIRMS) [36] and Global Fire Atlas [37] were used.

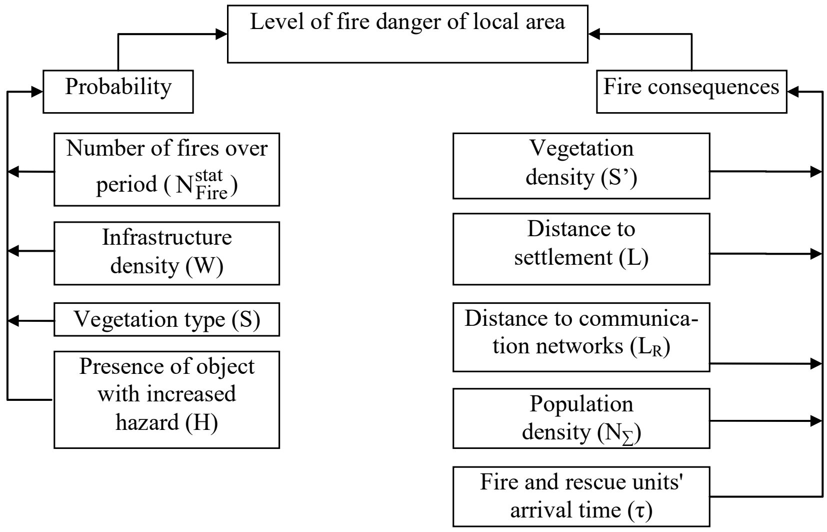

Fig. 1. Integrated structure of factors for comprehensive assessment of the level of fire danger of a local area of a large scale

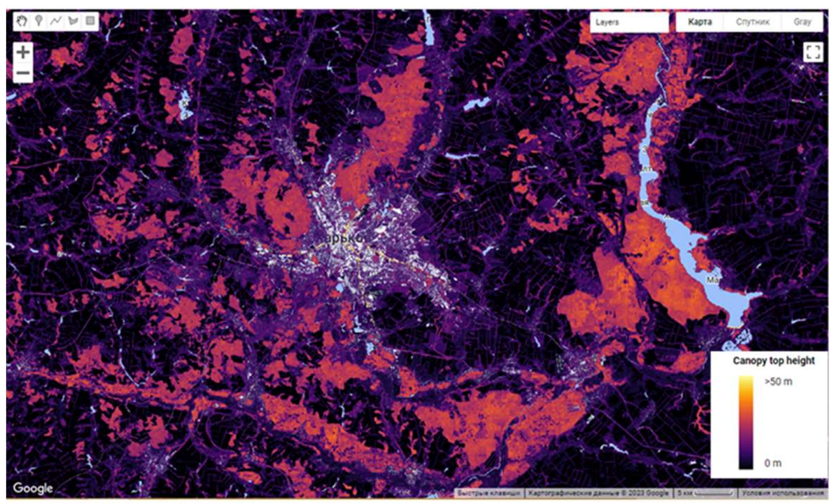

Fig. 2. Vegetation density map of a large-scale local area according to the GEDI and Sentinel-2 satellites

5. Results of the development of a methodology for assessing the level of fire danger of a large-scale area

5. 1. Theoretical substantiation of the methodology for assessing the level of fire danger of a large-scale area

The level of FD by analogy with risk is determined by the probability of the onset of LF and the corresponding consequences [38, 39]. To be able to assess the level of FD, the determining factors for densely built areas and sparsely populated areas were analyzed and structured [40–42]. The complex structure of factors for the integrated assessment of the level of FD LT of a large scale is shown in Fig. 1.

According to the complex structure (Fig. 1), the following factors influence the probability:

1. The density of the plant cover determines the intensity of LF and the rate of LF propagation over the surface of LT. The best reflection of the density of vegetation cover is provided by the mapping resource Awesome Gee Community Catalog [43]. This resource providesinformation based on the integration of data from satellite systems GEDI, Sentinel-2 (Fig. 2).

The GEDI satellite system provides resolved altitude data with unprecedented coverage. Optical satellite images such as Sentinel-2 offer dense observations around the world but cannot directly measure vertical structures. Combining GEDI with Sentinel-2, a probabilistic deep learning model for cover height with a quantitative assessment of uncertainty was developed [44].

2. The distance to the settlement has a complex impact on the risk. The main component is the time before the detection of LF and the time of arrival at the place of LFby FRU. Detection times can vary in a very wide range from a few seconds at facilities equipped with automatic alarms up to several hours in the case of landscape LF in the depths of the forest. The same trend applies to the time of arrival. While for densely populated cities the arrival time of FRU is 5–10 minutes, for forest LF in general there is a significant difficulty in delivering LF extinguishing agents to the cell. But the distance to the settlement indirectly affects the likelihood of F. This is explained by the fact that the cause of most landscape LF is the human factor. That is, the distance from the settlement reduces the likelihood of F.

3. The distance from the communication routes directly affects the time of arrival of FRU to the F site. The esti-

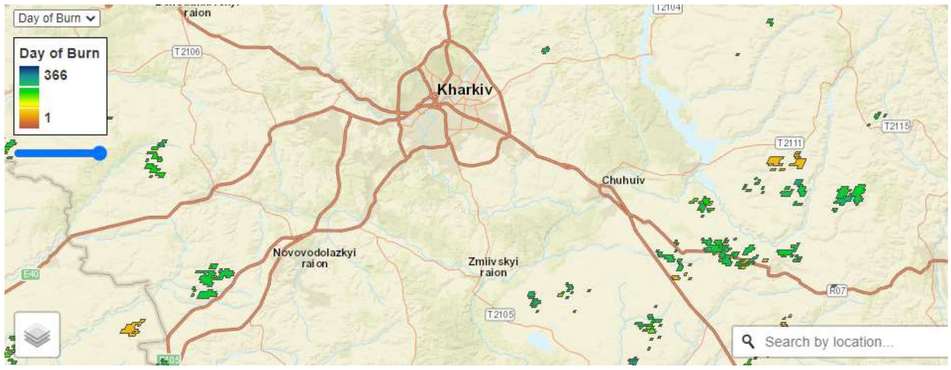

Fig. 3. Duration of landscape fires in the local area in 2022 according to Global Fire Atlas [35]

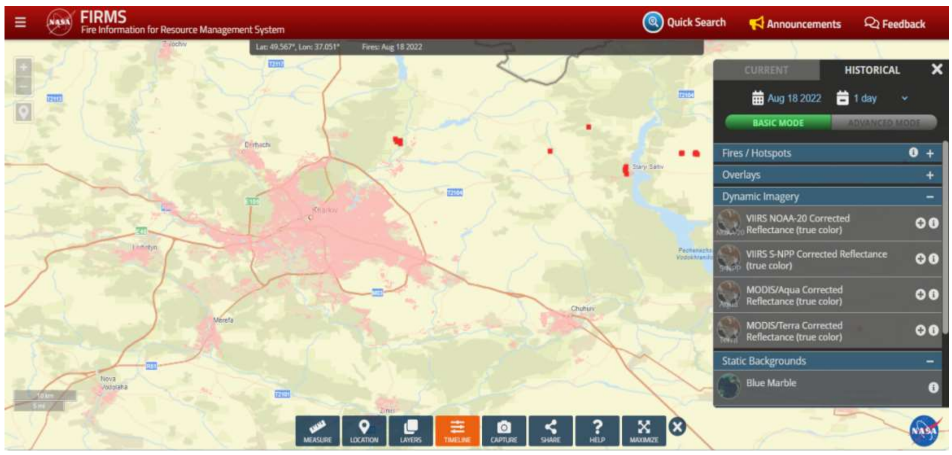

Fig. 4. Spatial distribution of building density in the FIRMS resource

mated speed of a fire truck on an asphalt road is 60 km/h; on unpaved roads – 20 km/h and below.

4. The population density determines the number of people who can get into F site. Accordingly, this indicator will directly proportionally determine the number of dead and injured because of F.

The possible consequences of probable LF are determined by the following factors:

1. The number of LF for a certain period or their duration can be obtained from statistical references. Data collection on landscape LF in steppes and forests is carried out by the Moderate Resolution Imaging Spectroradiometer (MODIS) system. MODIS is a key tool for the Terra and Aqua satellites. These satellites monitor the entire surface of the Earth every 1–2 days, obtaining data in 36 spectral ranges. Such data can improve the analysis of global dynamics and processes occurring on land, in the oceans, and the lower layers of the atmosphere.The results of the analysis of satellite information by the Global Fire Atlas service are shown in Fig. 3. The map (Fig. 3) shows the places of abnormal temperature activity, indicating the occurrence of LF and the duration of such LF by day of the year. The FD of such LF is due not only to the combustion factor but also to a significant environmental threat due to the release of hazardous gases into the atmosphere [45]. To reduce this effect, separate methods are being developed [46].

2. On LTof individual administrative regions, there is a significant uneven density of the population. Within such districts there may be large cities, cities with a population of less than 100 thousand people, and settlements – up to 10 thousand persons. To form the area of departure of FRU, it is necessary to know the spatial distribution of population density. An example of a public database with such information is the FIRMS service (Fig. 4), which contains information on the spatial location of the building in the form of an additional layer of Human Built-up and Settlement Extend.

3. The type of vegetation has a complex effect on several FD factors at once. Firstly, it is the minimum energy of the ignition source, which is sufficient for the occurrence of F. This factor determines the likelihood of LF based on comparison with nearby sources of inflammation. In addition, the type of vegetation determines the rate of spread of LF over the surface of LT. There are two fundamentally different classes of vegetation – steppe and forest.

4. The presence of objects of increased FD determines the concentration of high-energy ignition sources. At industrial facilities, such sources of ignition as a high voltage current arc, friction sparks, an open flame, violation of occupational safety rules and FS are usually present in the aggregate.

However, it is not possible to generate a classic model of FD level from the factors outlined above. This is due to the diversity and uncertainty of the impact of such parameters on the level of FD LT of a large scale. Taking into account the above-mentioned, an approach is proposed to rank the level of FD LT of a large scale, which is based on the need for equipment with personnel to extinguish F. Results of such a ranking are given in Table 1.

Table 1

Ranking of a local area of a large scale according to the level of fire danger, depending on the required number of vehicles with personnel to extinguish fires

Rank, R_{LT}	Required number of vehicles with personnel
I	1
II	2
III	4
IV	6
V	10
VI	15
VII	21
VIII	28
IX	40
X	>40

Further, it is proposed to use an artificial neural network to analyze parameters that affect the level of FD LT of a large scale. The peculiarity of this technology is the possibility of processing large arrays of experimental and statistical data of any complexity in the absence of a priori information on the relationships between them. This became possible due to the ability ofthe network to self-learn when searching for the relationship between input and output parameters.The use of graphic data shown in Fig. 2–4 allows for a pixel-to-pixel analysis of the selected area of large-scale LT. As a result of training a multilayer perceptronic neural network, 4 best predictive models with MLF 12-9-3-1, MLF 12-7-1, MLF 15-5-1, MLF 15-2-1 architecture were obtained. The influence of the main parameters of large-scale LT on the level of FDare given in Table 2.

can be significantly improved by increasing the number of statistically processed points of a different nature on an arbitrary LT. Since the MLF 15-5-1 neural network has the ability to self-learn, adding new statistics will adjust the predictive model in the direction of clarifying the assessment. Graphic representation of the results is shown in Fig. 5.

Based on the fact that the dimensions of a single pixel are small relative to the distance to FRU, when solving the problems of placing FRU, each pixel can be considered as an elementary point, and its dimensions can be neglected. Cartographic calibration of the territory according to the levels of FD allows for its zoning and determination of the sufficiency of the provision of forces and means. The use of the proposed approach will make it possible to assess the level of FDover LT of arbitrary scale within the city, district, region, state.

Table 2

Characteristics of prognostic models for neural network assessment of the level of fire danger of the local territory

Model architecture	MLF 12-9-3-1	MLF 12-7-1	MLF 15-5-1	MLF 15-2-1
Learning productivity	0.892	0.842	0.827	0.816
Test error	148.5	112.8	76.4	85.9
Learning algorithm	BFGS 2	BFGS 4	BFGS 6	BFGS 9
Activating the hidden layer	Exponential	Identity	Exponential	Exponential
Output activation	Logistic	Exponential	Logistic	Logistic

The construction of models of an artificial neural network was carried out using the statistical software STATISTICA 10 by entering statistical data for 250 points. In order to avoid retraining the network and guarantee high-quality generalization, random separation of observations between samples was carried out. 180 points were used as training, model error testing was carried out at 50 points, and adequacy checks were carried out at 20 points. At the same time, two variants with 12 and 15 input parameters (neurons) were considered. All models had one output parameter (neuron), namely the FD level.

Fig. 5. Graphical interpretation of the calibration of the local area according to the calculated level of fire danger

5. 2. Checking the operability of the methodology for assessing the level of fire danger of a large-scale area

According to the results of analyzing the models in Table 2, it was established that the neural network model MLF 15-5-1 has the smallest error. Training of this neural network was carried out at a speed of η=0.01. Verification of the adequacy of the developed model was carried out by comparing the statistical level of FD at points (the data of which were not used in the training of the neural network $\left(R^*_{LT}\right)$, of the results of assessing the level of FD for the same objects (R_{LTi}), and the corresponding correlation coefficients (r^2) (Table 3). The average correlation coefficient between these indicators based on the results of network training is $r^2 \approx 0.97$. However, based on the fact that the range of 10 levels of the initial data is step-by-step from I to X, each step of the error immediately leads to a decrease in accuracy by 10 %.

Attention should be paid to the results for point 4 (Table 3). As you can see, the error of forecasting results lies within the permissible 10 % but, at the same time, the level of FD is underestimated relative to the real one. This can lead to an underestimation of FD, which is significantly worse than the same error in the direction of revaluation of FD. Therefore, such points need to be monitored to carry out a more thorough analysis. The accuracy of the assessment

Table 3

Checking the adequacy of the neural network model MLF 15-5-1

Parameters	Point 1	Point 2	Point 3	Point 4	Point 5
Coordinates	50.016712, 36.102304	49.920210, 35.953989	49.839046, 36.768428	49.595110, 35.819919	50.215436, 36.401900
R^*_{LT}	II	V	VI	IV	III
R_{LTi}	II	VI	VI	III	III
r^2	1	0.9	1	0.9	1

6.Discussion ofresults of the development of a methodology for assessing the level of fire danger of a large-scale area

When assessing the FRover LT of a large scale, which goes beyond the boundaries of a particular settlement, other factors become important. These are such factors as population density, the presence and density of the plant layer, the likelihood of LF on the ground, and the network of paths that determines the time of the FRU's heading to the place of F occurrence. Ranking the functional capacity of FRU allows us to compare the level of FDover LT to the number of forces and means that make it possible to reduce such a risk. In this case, the rank indicated in Table 1 does not necessarily have to correspond to a separate FRU, this may be the total rank of all FRUs involved in the extinguishing of LFover LT.Ranking the territory by FD level using the developed methodology allows one to get a complete map of FR of any district. The disadvantages of this approach are the need to collect and analyze a large amount of data, which is a rather labor-intensive task within a large-scale LT. Also, with an increase in rastration, the accuracy of the determination increases but the volume of the required input parameters grows exponentially. Shown in Fig. 4, the spatial distribution of buildings is not a complete analog of the spatial distribution of population density since the number of storeys of buildings is not taken into account.In cities with a population of more than 100 thousand people in which the percentage of high-rise residential development exceeds 10 %, the discrepancy between the density of buildings and population density is significant. For such cities, it will be correct to use the methodology for assessing small-scale FRover LT. For areas with predominant one and two-story buildings, exceeding population density can be neglected. When analyzing statistics on landscape LF, in addition to Global Fire Atlas, there are other resources that can represent information in other formats.Such resources conduct their analysis on the basis of data obtained by the MODIS satellite system. However, different approaches to their analysis make it possible to obtain diverse results. But the analysis of the array of satellite data on landscape LF was not considered in our paper and is the direction of future research. A large number of FR factors of a separate LT point with a dimension of a different nature does not make it possible to build an ordinary mathematical model of the dependence of FR level on individual parameters. The solution to this problembecame possible using neural network learning algorithms. To train the neural network and check its performance, characteristics from 250 objects were used. However, it should be noted that although the obtained neural network makes it possible to obtain prediction results with satisfactory accuracy and correlation index $r^2 \approx 0.97$, the minimum allowable amount of data was chosen for its training. Therefore, further research will be aimed at continuing the training of the developed neural network, which will increase its accuracy and versatility. The use in practice of the proposed approaches to assessing the level of FDover LT of a large scale will allow for assessment of the level of provision of LT with the necessary fire-fighting forces and means.

7. Conclusions

1. We have theoretically substantiated the methodology for assessing fire risk in a local area of a large scale. A feature of the proposed technique is a differentiated assessment of the fire risk at each point of the surface plane. For such an assessment, the parameters that are decisive in terms of the impact on fire danger are analyzed and structured. These factors include the spatial distribution of population density and infrastructure, the transport and communication network, the spatial distribution of the density and type of vegetation, and statistical data on landscape fires. It is possible to use real-time geographic information resources such as Fire Information for Resource Management System, Awesome Gee Community Catalog, Global Fire Atlas, and data from the Moderate Resolution Imaging Spectroradiometer satellite system. A new approach to ranking the fire risk of the elementary plane of the territory in accordance with the required amount of resources of rescue units to ensure an adequate level of safety has been proposed. To compare the parameters of the local territory with the ranks of fire risk, neural network data processing methods were used. A neural network model was obtained capable of comparing the fire risk of the territory to its parameters.

2. The operability of the developed methodology was checked and the levels of fire risk of an arbitrary territory, based on a predictive neural network model, with an average degree of correlation of 0.97, were determined. It has been established that the proposed neural network is capable of self-learning, which makes it possible to clarify the results of the assessment when entering new statistical data. Based on the data obtained, a graphical interpretation of the calibration of the local area according to the calculated level of fire danger was created.That is, using this technique, it became possible to build fire hazard maps and to zone a local area of arbitrary scale. In general, the operability of the proposed methodology for assessing and adjusting the state of providing local territories with civil protection resources has been confirmed. Our methodology acquires particular relevance in the spatial placement of new fire and rescue units of communities.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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