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METHOD FOR DETERMINING THE OPTIMAL LOCATION OF FIREFIGHTING EQUIPMENT FOR LOCALIZATION OF GROUND FOREST FIRES

Abstract. Localization and forest fire suppression is an urgent problem for the whole world. Given the heterogeneity of forests on the planet, approaches to modeling the spread of fires and their extinguishing are different. In this article a method for determining the required number of forces and means for the localization of ground forest fires is offered, taking into account the location of firefighting equipment in forests. To forecast the spread of fire, equidistant places from the fire departments in forests were chosen using Voronoi diagrams. The results of the calculation make it possible to conclude whether there are enough available forces and means to localize the predicted fire and to suggest additional firefighting equipment locations. The use of Voronoi diagrams for the State Enterprise "Zhovkva Forestry" in the Lviv region showed 12 dangerous areas, which are located the furthest from the fire departments. The method for determining the optimal location of firefighting equipment was applied to the Butynskyi forestry in Zhovkva forestry enterprise. Reducing the time of free spread of ground forest fires by 25% using rational placement of firefighting equipment and machinery, allows to reduce the number of employees for its localization by 53.8%.

Keywords: ground forest fire, fire localization, Voronoi diagram, firefighting equipment.

1. Introduction. On the territory of Lviv region in Ukraine the number of forest fires amounted to 41 in 2019. About 20 hectares of forests were destroyed. It should be noted that according to the legislation of Ukraine, forest users are in charge of forest fire extinguishing and accordingly the management of this process. Despite this, in 2019, 65 units of equipment of the State Emergency Service of Ukraine, 10 units of equipment of local fire brigades and only 10 forest users were involved in firefighting process. Voluntary fire brigades, created on the initiative of forest users, are rarely involved in extinguishing of such fires. Thus, in 2019, only 10% of the total number of people were involved in extinguishing of forest fires. Fires have a negative impact on the environment. Ways to solve environmental problems were considered in [1].

Successful and rapid firefighting is ensured by responding quickly to fires. Most scientific works are devoted to methods of decision-making in case of fires, traffic routing and distribution of forces and means to suppress forest fires [2]. However, the rational placement of firefighting equipment near forests, taking into account the location of existing state, local and forest fire departments, significantly reduces the cost of their elimination. In addition, in order to respond quickly to forest fires, it is advisable to create and involve voluntary fire brigades from settlements that are in close proximity to forests, the distance from the existing units to which is quite large.

To define the location of firefighting equipment near forests, it is necessary to predict the probable spread of fire. A number of analytical and experimental models and techniques are used to determine the speed of flame propagation. The most common way to determine this parameter is the Rothermel model, which has been improved by many scientists in recent years [3]. This model is based on the energy conservation equation, where the flame propagation speed depends on the density of the combustible material layer, the particle size of the forest combustible materials and their burning velocity. This model also takes into account the effect of wind speed on the spread of flame along the front, but does not consider the terrain. The slope of the terrain has an impact on the speed of fire propagation that is considered in [4] the fire spread model as a combustion wave based on the Hamilton-Jacobi equations. However, this method can only be used using a computer. An analytical method of the fire propagation speed in forests is presented in [5]. According to the law of conservation of energy for a stable combustion process, the authors developed a method for determining the speed. The model is as follows:

$$V_f = f(I_R, \xi, \rho, \varepsilon, Q, \varphi_w, \varphi_s),$$

where I_R – intensity of combustion reaction; ζ – a coefficient that takes into account the properties of the combustible material; ρ – the density of the combustible material layer; ε – efficiency coefficient of combustible material heating that shows which part of combustible material participates in ignition during its heating by a fire due to all types of heat transfer; Q – heat of ignition; φ_w – coefficient that takes into account the direction of the wind; φ_S – coefficient that takes into account the slope of the terrain.

Based on the forecast of possible fire size depending on the characteristics of the combustible load, fire hazard class, weather conditions, etc., it is possible to determine the optimal location of fire equipment to extinguish a possible fire. Most methods of fire departments location apply to large cities. An example of such methods is given in the article [6], where a mathematical model for determining locations of new fire stations in Istanbul is offered. However, there are works that consider the location of firefighting equipment in rural areas in order to respond in a timely manner to forest fires [7].

One of the methods that takes into account the possible occurrence of fires in forests was proposed in [8], where the number and location of firefighting equipment were determined depending on the risk of fires due to power grid failures. However, considering that the cause of forest fires in most cases is anthropogenic factor, it is necessary to take into account the possible fires occurrence in any place in the forest. This approach is used in the article [9], where determining the location of fire stations and routing them to the place of fire is based on the results of forecasting a possible fire. This method is used for large-scale forest fires. The aim of optimal placement of firefighting equipment should be to minimize the total time of forest fire extinguishing and the number of involved fire engines, the algorithm for this task is given in [10]. Another method of the location optimization of fire equipment is particle swarm method used in [11]. In [12] a model of firefighting equipment placement was developed taking into account the minimization of costs on the example of South Hobart, Tasmania, Australia.

The cost minimization problem in responding to forest fires is also discussed in articles [13] and [14]. The cost of fire suppression will be minimal in case of rational placement of firefighting equipment for rapid response to such fires. Therefore, it is necessary to develop a methodology in order to determine the level of forces for the localization of ground fire at its initial stage.

Given the above, the purpose of this work is to determine the required number of forces for localization of ground fires considering the most remote places in forests from the location of firefighting equipment.

2. Material and method. In this article the forests used by the State Enterprise "Zhovkva Forestry" are considered. The State Enterprise is located in the north-western part of the Lviv region on the territory of three administrative districts - Zhovkva, Sokal and Kamianka-Buzka. Geographically the territory of the forestry is located on the border of two districts: the southern part of the forestry (part of Viazivskyi forestry) belongs to the Opilsko-Roztotskyi district, and the rest of the enterprise to the Malopolisska lowland of Small Polissia. The length of the enterprise from north to south is 57 km, from east to west - 34 km. The total area of the forest fund lands is 33,679 hectares; 28,591 hectares are covered with forest vegetation. The main tree species on the territory of the forestry are Scots pine (54%), Scots oak (17%), European beech (7%), Silver birch (3%) and Black alder (15%). The class of natural fire danger of this forest fund is 3 [15].

According to the Mobilization Plan, 64 employees are involved in fire extinguishing on the territory of Zhovkva Forestry. The time of their readiness to extinguish is 45 minutes. In addition, the following equipment is used to localize and extinguish fires: 2 fire trucks, 1 water tank, a bulldozer and 7 tractors. This equipment is located on the territory of the administrations of 7 forestries. Furthermore, fire units of the State Emergency Service of Ukraine and local fire brigades may be involved in extinguishing the fire.

Determination of equidistant places in forests from the locations of firefighting equipment was carried out using Voronoi diagrams [16]. Forecasting of the forest fires spread was performed according to existing methods, taking into account wind strength and terrain slope. The defining of the number of forces for the localization of the ground forest fire was performed taking into account the time of localization and productivity of one firefighter.

3. Results and discussion. The calculation of the required number of forces and means for extinguishing forest fires must be carried out in several stages. The first stage is to determine equidistant points on the map to the forests from fire rescue units, forest fire stations and strongholds with firefighting equipment. The second stage is forecasting of forest fire spread depending on the terrain and weather conditions. At the same time, the most unfavorable conditions should be considered in order to predict the most dangerous fire spread. The third stage is for calculation of the number of employees and equipment for extinguishing the forest fire. Based on the calculations, a conclusion is made to clarify whether the successful extinguishing of the predicted fire is ensured.

3.1. Determination of the most remote points from the location of fire departments. To determine the most distant points from the location of fire brigades to the place of fire occurrence, Voronoi diagrams are used. The vertices of the diagram are a set of equidistant places between two adjacent locations of fire brigades. Nodes of cell edges are points equidistant from three adjacent locations of fire brigades.

As an example, forests used by the State Enterprise "Zhovkva Forestry" are taken for consideration.

Figure 1 shows the location of forests used by Zhovkva Forestry Enterprise and fire rescue units (state, local stations and strongholds, which have firefighting equipment for extinguishing forest fires).

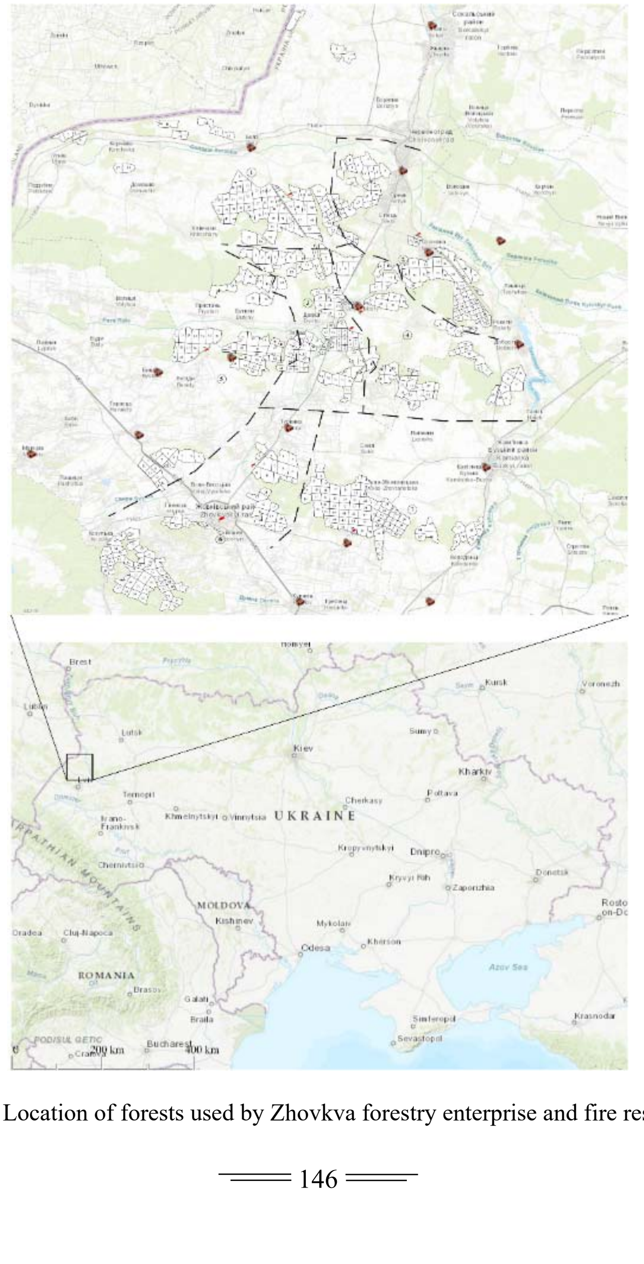

Figure 1 – Location of forests used by Zhovkva forestry enterprise and fire rescue units

For this area the Voronoi diagram is applied. The top of the Dirichlet cells is the location of fire departments and strongholds with firefighting equipment. To build the diagram, the Fortune's algorithm is used. The Voronoi diagram for our case is shown in figure 2.

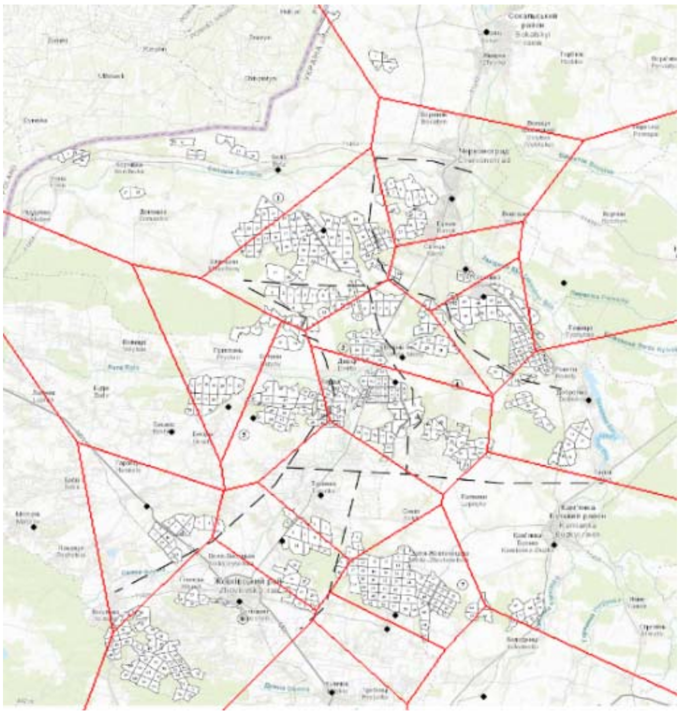

Figure 2 – Construction of Voronoi diagram for forests of Zhovkva forestry enterprise taking into account the location of fire departments and strongholds with firefighting equipment:
1 – Nyzivskyi; 2 – Sosnivskyi; 3 – Butynskyi; 4 – Velykomostivskyi; 5 – Liubelskyi; 6 – Viazivskyi; 7 – Zibolkivskyi forestry

Considering the Voronoi diagram, we can conclude that equidistant from the locations of fire departments are 19 and 50 quarters of Butynskyi forestry, 26 and 73 quarters of Sosnivskyi forestry, 11 and 62 quarters of Velykomostivskyi forestry, 34 quarters of Liubelskyi forestry, 5, 23 and 33 quarters of Viazivskyi forestry, 10th and 63rd quarters of Zibolkivskyi forestry. In addition, the forest quarters of the Nyzivskyi forestry near the border, namely 5-10 quarters, are problematic in terms of detecting and extinguishing fires.

3.2 Predicting the spread of ground forest fire. To calculate the number of employees needed to be involved in extinguishing a fire, it is necessary to know the speed of the forest fire spread and the perimeter of the fire. To calculate these parameters, we use the method described in [17].

The general formula for determining the speed of the fire propagation edge is as follows:

$$V_f = V_o \cdot K_\delta \cdot K_\varphi \cdot K_w \,,$$

where V_0 – base speed, m/min; K_δ, K_φ, K_w – influence coefficients of surface slope, relative humidity of air and wind. These coefficients are given in the work [17].

For example, the spread of a ground fire around the perimeter in case of its occurrence in the 19th quarter of Butynskyi forestry of Zhovkva forestry enterprise is considered. The basis of the forest litter burning is fallen pine needles and tree leaves. In accordance with [17], the velocity of burning of such combustible material is 0.41 m / min. The angle of inclination of the terrain in this area does not exceed 10°, so the coefficient K_δ is equal to 1.2. Humidity is taken as for the driest period, then the coefficient K_φ will be 1.7. According to the Ukrainian Hydrometeorological Center, the wind speed is 4.0 m/s, then the coefficient K_w will be 7.0 for the head, 1.6 for the rear and 4.5 for the flanks. Based on the results of the calculation the speed of spread of the head, flanks and rear of the forest fire, it is possible to determine the geometric parameters of the fire in a certain period of time. We shall calculate the geometric parameters of the fire for 30, 60, 90 and 120 minutes. The results of the calculation are shown in figure 3.

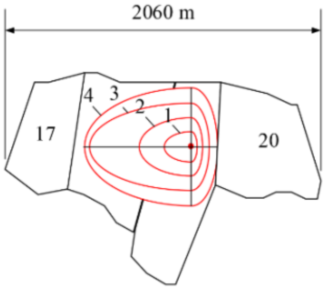

Figure 3 –
Forecasting of the fire spread in the 19th quarter
of Butynskyi forestry of Zhovkva forestry enterprise
for 1 – 30 minutes; 2 – 60 minutes; 3 – 90 minutes;
4 – for 120 minutes

The perimeter of the fire was defined as the perimeter of the two half-elipses. In the first half-ellipse, the semi-major axis is the distance from the fire occurrence area to the edge of the fire at the head, the semi-minor axis is from the fire occurrence area to the edge of the fire on flanks. In the second half-ellipse, the semi-major axis is the distance from the fire occurrence place to the edge of the fire on flanks, the semi-minor axis is from the fire occurrence place to the edge of the fire at the head. The obtained values of the fire perimeter at certain points in time allow to calculate the growth speed of the perimeter.

3.3. Determining of the required number of forces to localize a ground forest fire. In order to determine the number of employees needed to extinguish a ground fire in the forest around the perimeter using hand tools, following formula is used [18]:

$$n_{\Pi} = \frac{\dfrac{L}{\sqrt{W_1^2 - V_p^2}} - \dfrac{L}{V_m}}{\tau_{loc} - \dfrac{L}{V_m}},$$

where L – the length of the edge of the fire, m; W_1 – productivity of work of one firefighter, /min [17]; V_m – average movement speed of firefighters in the forest, m/min; V_p – speed of fire propagation, m/min; τ_{loc} – time of fire localization, min.

Figure 4 shows the results of calculating the required number of firefighters for localization and subsequent successful elimination of the fire depending on the time of free fire spread and estimated time of localization of the fire.

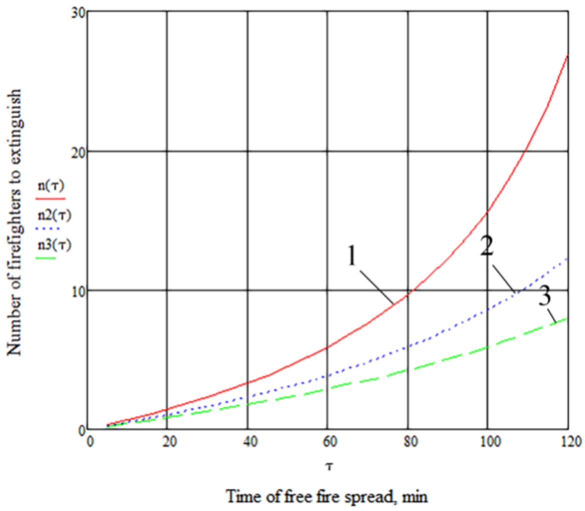

Figure 4 –
The required number of firefighters to extinguish
a ground forest fire, depending on the time of free fire spread
and estimated time of localization of the fire:
1 – 30 minutes; 2 – 40 minutes; 3 – 50 minutes

For successful and rapid localization of the fire, it is necessary to reduce the time of free fire spread that can be achieved by localization of fire brigades near forests. Time of getting from existing fire departments to 19th quarter of Butynskyi forestry is about 30 minutes: from the state fire department of Velyki Mosty - 25 minutes, from the stronghold of Liubelskyi forestry - 27 minutes, form the local fire brigade of Lubelskyi - 38 minutes, from the stronghold of Nyzivskyi forestry – 52 minutes.

The larger is distance to the forests, the larger number of personnel must be involved in fire suppression. According to the mobilization plan in case of fire in Zhovkva forestry enterprise, the time of getting ready and arrival of personnel is 45 minutes. In case of fire detection one hour after its start, taking into account arrival time to the place, the time of free spread of fire will be about 2 hours. Even in case of immediate departure of the state fire brigade from the city of Velyki Mosty, the number of personnel will not be enough to localize the fire. Therefore, for its rapid localization upon arrival of forestry workers, up to 26 people should be involved.

If a stronghold with firefighting equipment is placed in the village Butyn, in order to deliver them to the place of the fire and attract volunteers living in the village, the time of free spread of the fire can be reduced by 1.5 times. In this case only 12 people are needed to be involved for quick localization.

4. Conclusion. Efficient localization of fire equipment can significantly reduce the number of forces and means needed to localize a possible fire in the forests. In addition, it reduces the scale of the fire. Thus, according to the conducted calculations, in case of time decrease of the ground forest fire spread by 25%, the value of the required number of employees is reduced by 53.8%. Similar calculations should be made for other forestries in western Ukraine as well.

This method can be applied only to areas where forests are divided into small sections located near settlements. For large areas of forests, it is advisable to use modern methods of monitoring to detect fires in the early stages and the location of firefighting equipment directly in the forests.

Further development of this method is the study of fire danger in the forests of western Ukraine and forecasting the spread of ground fires in forests using FDS-models to determine the required number of forces and means for their localization and extinguishing.

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ОРМАН ӨРТТЕРІН ОҚШАУЛАУ ҮШІН ӨРТКЕ ҚАРСЫ ТЕХНИКА МЕН ЖАБДЫҚТЫҢ ОҢТАЙЛЫ ОРНАЛАСУЫН АНЫҚТАУ ӘДІСІ

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МЕТОД ОПРЕДЕЛЕНИЯ ОПТИМАЛЬНОГО РАСПОЛОЖЕНИЯ ПРОТИВОПОЖАРНОЙ ТЕХНИКИ И ОБОРУДОВАНИЯ ДЛЯ ЛОКАЛИЗАЦИИ НИЗОВЫХ ЛЕСНЫХ ПОЖАРОВ

Аннотация. Локализация и тушение лесных пожаров – актуальная проблема для всего мира. Учитывая неоднородность лесов на планете, подходы к моделированию распространения пожаров и их тушению различны. В данной статье предложена методика определения необходимого количества сил и средств для локализации наземных лесных пожаров с учетом расположения противопожарной техники в лесах. Для прогноза распространения пожара были выбраны равноудаленные от пожарных частей места в лесах с использованием диаграмм Вороного. Результаты расчета позволяют сделать вывод о достаточности имеющихся сил и средств для локализации прогнозируемого пожара и предложить дополнительные места размещения противопожарной техники. Использование диаграмм Вороного для Государственного предприятия "Жолковское лесное хозяйство" во Львовской области показало 12 опасных участков, которые расположены дальше всего от пожарных частей. Метод определения оптимального расположения противопожарной техники и оборудования применен в Бутынском лесничестве Жолковского лесхоза. Сокращение времени свободного распространения наземных лесных пожаров на 25% за счет рационального размещения противопожарной техники и техники позволяет сократить численность работников по ее локализации на 53,8%.

Ключевые слова: низовой лесной пожар, локализация пожара, диаграмма Вороного, противопожарная техника, противопожарное оборудование.

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