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Spatial Evaluation and Modelling of Fire Stations Layout to Access Forest Fires by Roads (Case Study: Krasnoyarsk Region, Russia)

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Abstract

Regional forest fire protection services on the ground usually have a fire station infrastructure with firefighting vehicles capable of moving by public and forest roads. The location of fire stations is a subject of evaluation on the regional scale and a matter of constant research interest. Infrastructure and transport accessibility, as well as the spatial location of fire stations worldwide and in Russia, were discussed. Location-Allocation ArcGIS tool and the access routes database for Krasnoyarsk region (archived data of 2002-2022 forest fires detected by MODIS containing 60637 records) were the base of methodology to evaluate fire station layout. The settlement dataset from Open Street Map (OSM) was used to analyze new locations as candidates for a fire station. Standard Deviational Ellipse ArcGIS tool was applied to define an optimal area for the current fire station from which routes to the nearest fires are built. OSM settlements inside of 1-sd area of the ellipse were used to generate the candidate list of settlements to find new locations instead of the current fire station. Results have been evaluated for 3 groups of access routes: 3 hours and less, more than 3 hours, and access routes of any duration according to the Russian forestry rules. The proposed fire station layout has improved forest fire accessibility with OSM candidates for 39 stations; 20 of 59 remain spatially unchanged. Total regional forest fire accessibility changed from the current to the proposed layout in absolute values from 47331 to 48905 fires. Analysis of 39 relocated stations showed that the new fire station layout is more optimal than the current one because it provides access to an additional 20 % of forest fires with a decrease in average weighted time to reach them by 30 %. The described methodology could make an emergency response during a fire-hazardous period more effective.

Keywords: Forest fires, infrastructure, road network, fire station layout, spatial modelling, Krasnoyarsk region.

1. Introduction

Forest fires are a constant threat in different parts of the world (Loupian et al., 2017; Bondur et al., 2020; Tyukavina et al., 2022; Wu et al., 2022), and their negative influence is a subject of many scientific activities including physical and socio-economic geography (Gubanova, Klesch, 2019). The annual occurrence of forest fires characterizes large areas of Russia (Tarko et al., 2021), and the same trend occurred in 2023 (Kotelnikov et al., 2023).

Rapid access to forest fires requires roads and infrastructure, both for public use and the forest, that varies over time and space. Road infrastructure has some certain influence on regional development (Zander, Koryakova, 2011; Lavrinenko et al., 2019; Louka et al., 2022) and is a factor in human mobility (Virag et al., 2022). Infrastructure often understands as a set of transport objects with associated infrastructure elements (Switala, 2023). Since the very beginning of the geoinformation technology development, road networks have been studied with the help of spatial and GIS tools (Reddy et al., 2016), and then have been developed for the regional scale (Rastorguev et al., 2021). Till now, there has been a constantly evolving trend in the study of transport accessibility (Rubkina and Stoyascheva, 2010; Tokunova, 2018; Savvinova et al., 2021; Sackov, Barka, 2023; Soukhov et al., 2023). Inequalities in infrastructure depend on the level of infrastructure development and urban population size (Pandey et al., 2022). Population and infrastructure are linked and influence each other in many ways and are the subject of research activities. For instance, Rushiti et al. (2022) investigated the population distribution, considering metrics like distance from the nearest cities and distance from the headquarters of the municipalities.

Presently, the fire safety issue in the forests is very relevant to the infrastructure location (Andreev, 1999; Andreev, 2003; Momot, 2014). Fires drifting near settlements carry the risk of fire spreading to residential and outbuildings and can lead not only to material losses but also to human casualties. Limited resources of the forest protection system and significant differences in

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natural and economic conditions predetermine the feasibility of forest funds and the level of fire protection. Such zoning should serve as a basis for organizing structures for forest protection, differentiating forest fire modes of operation services, and allocating allotments (like fire stations) for forest protection as per regions. One of the important tasks in forestry is to detect the dependence of forest fire location on the infrastructure facilities, primarily on settlements and roads (Podolskaia, 2021a; Podolskaia, 2021b; Podolskaia et al., 2020c; Podolskaia et al., 2023a, 2023b). It is well known that a serious number of fires were started near the roads (Armenteras et al., 2017) and close to the settlements. The denser the road network, the more people access the forests, and consequently, the more fires there will be. Only a small part of forest fires has natural causes like dry thunderstorms, for instance, described in the paper (Baranovskiy, 2004). Some country-level research shows that the probability of fires depends on human activity, population density, and distance from settlements and roads (Iran, Poland). Distance from infrastructural objects like automobile roads and railways affects the probability of fire, an example of forest fires and infrastructure in Poland is shown in the paper (Ciesielski et al., 2022). Researchers divide factors of forest fire occurrence into environmental, human, and land parameters (Kaboosi and Majidi, 2018).

In the Russian forest practice, transport and forest infrastructure, including forest roads, are necessary for forest protection and regeneration and decisive for overland access when organizing forest fire suppression. Forestry infrastructure includes public roads and particular use, fire stations, seasonal roads, forest roads, glades and firebreaks, and settlements where fire stations are most likely located. In Russian forestry, a list of forestry objects is submitted by the Government of the Russian Federation for the protection of forests, their exploitation and maintenance. Forestry plays a key role in regional and national territorial development (Neverov et al., 2015). One of the challenges of Russian forestry is the insufficiency (or underdevelopment) of its infrastructure. Forest Code of the Russian Federation (dated 2007, with its editions 2007-2024, in force since 01/09/2024), in Article 13 "Forest Infrastructure," describes the necessity of infrastructure for the efficient operation of forests.

Forest fire stations play a key role in the forestry infrastructure as facilities to manage protective, operational, and reserve forests. They are the centers for the organization to access and extinguish forest fires in Russia (Podolskaia, 2022). Fire stations network include stations with different possibilities to manage forest fires; they are classified into three types depending on the purpose, available equipment, workforce, and structure (Order of Rosleskhoz dated December 19, 1997 N 167). Forest fire stations differ from other infrastructural objects. Firstly, they are a part of forestry with its sets of public and forest roads, often used seasonally. Secondly, they are mainly located in settlements and combine human forces with special firefighting equipment. Thirdly, the function of stations is to fight forest fires which have different spatial coverage depending on the hazardous season. There are several methods like non-spatial with an application of Office programs (like Microsoft Excel) and spatial GIS (commercial ESRI ArcGIS and Open Source like QGIS) to evaluate fire station locations. Tjurin et al. (2019) described the placement of forest fire stations intending to minimize arrival time when extinguishing forest fires. For the optimization of placement, a mathematical model and method of rational territorial location of stations have been used; the optimization problem is solved by nonlinear programming in the add-in MS Excel Solver for case study in the forestry of Leningrad region, Russia.

Nowadays, placement and assessment of fire station locations is a complex task at regional and federal levels of countries (Akay et al., 2022; Podolskaia, 2024). Assessment of fire station location and proposals of their possible optimal layout has been studied with recent research (Bugday, 2019; Sakellariou et al., 2020; de Domingo et al., 2021; Ranabhat et al., 2022; Bispo et al., 2023). Bugday, 2019 evaluated visibility of forest fire watch-towers for the Forest Management Directorate (Cankiri) in Turkey. They mainly used spatial cluster analysis (part of classical machine learning) and estimates of forest fire danger and susceptibility. The location of fire stations was discussed by Podolskaia (2021a). The location of fire stations is of research interest in different parts of the world, including countries like Spain (de Domingo et al., 2021), Nepal (Ranabbat et al., 2022), Bosnia and Herzegovina (Sokolovic et al., 2022), and Poland (Grajewski et al., 2019) and others with their specificities of scale and evaluation methods. Researchers actively use GIS tools and methods for fire station reconfiguration and relocation, aiming in each case to propose optimization solutions and improved forest fire accessibility (Akay et al., 2017; Akay et al., 2018; Bugday, 2019; Sakellariou et al., 2020; de Domingo et al., 2021; Podolskaia, 2022; Ranabbat et al., 2022; Sokolovic et al., 2022; Bispo et al., 2023).

The goal of the paper is to present a methodology to evaluate the location of fire stations based on the available accessed routes, namely described as previous research findings (Podolskaia et al., 2020a, 2020b) and infrastructural datasets. Infrastructure with its essential features that support daily life, and economic activity plays a special role in accessing forest fires by ground means. We have used datasets for settlements and roads from the Open Street Map project (OSM, https://www.openstreetmap.org). To reach the goal, a set of tasks was followed: to determine the present state of fire stations' location research tasks at their regional distribution, to develop and to implement a methodology to evaluate current locations of fire stations in the region, and to evaluate their location and to propose new locations within the study region.

To summarize the literature review of this study, a cloud tool for visual representation of papers' topics was used (https://wordscloud.pythonanywhere.com).

Figure 1 graphically shows names of reviewed papers relevent to the spatial modeling of fire station locations accessed by roads. Literature items came from different academic institutions and translated to English.

Figure 1. Most recurrent keywords from References of paper

2. Material and Methods

2.1. Study area

Krasnoyarsk region (Territory, Krai – in Russian) is located in the center of the Siberian federal district and is characterized by a variety of infrastructural features; it is partially covered by road network (Rodikova, Zeer, 2022). As mentioned in the paper (Bredikhin et al., 2020), Krasnoyarsk region is characterized by the least economic development in the Arctic with 95,2% of its territory without economic development. Krasnoyarsk region, an area with constant long-term fire activity in the forests, is selected as a study area.

Regional public roads and transport infrastructure were studied in several papers (Beresnev et al., 2017; Radchenko, Ponomarev, 2019; Goryaeva et al., 2020). According to the indicator of transport availability, Krasnoyarsk region is in the 79th place in Russia (Vladimirova, Zlobin, 2013). One of the assessments of transport network availability for Krasnoyarsk region was presented in Gerasimov et al. (2013). A network of urban-type settlements in Krasnoyarsk has been formed since the beginning of the 17th century (Prokhorchuk, 2007). The rural population in the region is decreasing, and settlements like towns and several cities are becoming more prominent (Parshukov, Shaporova, 2022). There is very little research on the connectivity and links between road and river networks (Istomin, 2020). Forestry and forest resources of Krasnoyarsk region were discussed in several studies (Moskalchenko et al., 2014; Martynyuk et al., 2016; Sokolov et al., 2016; Provin et al., 2021; Sokolov et al., 2021). Geographically, fire stations in rasnoyarsk region are located mainly in the industrial center with the developed networks of settlements and roads; a map of their location with an accessibility zone of 3 hours is shown in Figure 2.

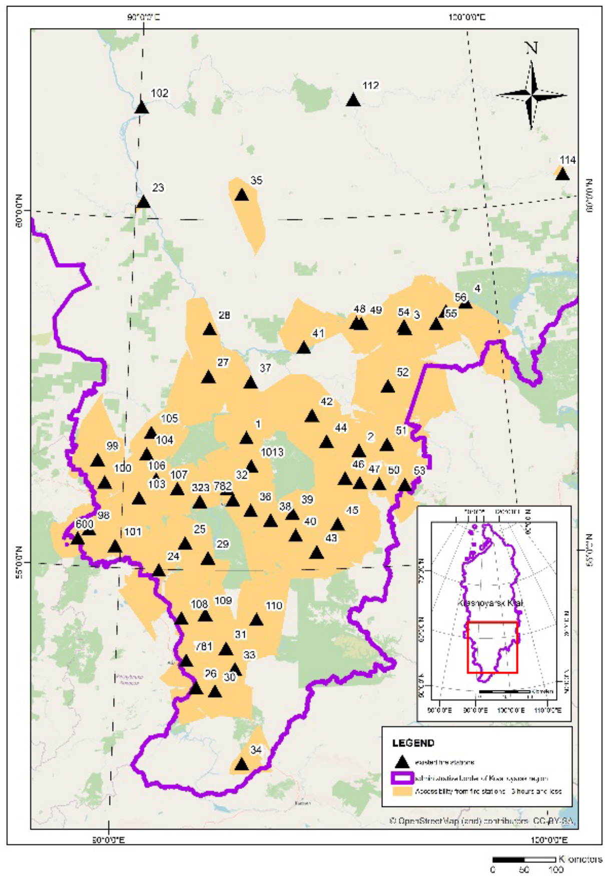


Figure 2. Map of fire station locations in Krasnoyarsk region

Krasnoyarsk region plays a vital role in the socio-economic development of Russian regions (Ketova et al., 2021). Monitoring forest fires on the territory of the Siberian federal district revealed that over the past decades, the number of fires in the region has increased, and their areas have doubled. The main causes of fires were anthropogenic, associated with economic growth and recreational development within forest territories (Ivanova et al., 2022; Ignateva and Baranovskiy, 2022). The forest fires distribution analysis of Krasnoyarsk region's territory ended with a conclusion that the maximum number of forest fires (85%) occurs within a radius of 20 km around settlements. About 45% of fires occur within a radius of 5 km. The most of forest fires (63%) occur in spring (Buchkov and Sukhinin, 2004).

2.2. Data

The availability of infrastructural data for research plays a key role in forestry. There is a lack of freely available datasets in some countries for several reasons. Thus, infrastructural open data portals and projects are in high demand for forestry projects. A recent study on the territories of Central European countries used open data sources like MODIS, OpenStreetMap, and WorldClim. The accuracy and completeness of these data have been investigated for the national forest fire probability evaluation (Milanovic et al., 2023), and the research confirmed that open data are of use for regional forest fire management projects. For the present study infrastructural data on settlements and roads were obtained from OSM.

2.3. Methods

The methodology presented in this paper aims to evaluate fire station location at the regional level (administrative division of the Russian Federation) based on the current data on fire stations, settlements and roads. The research question is how transport accessibility of forest fires can be improved by relocating current stations to the nearest settlements. Hence there is a need to estimate the current and new number of routes created from the stations. There are accessibility routes from every station in its current location to the forest fires from 2002-2022 (Podolskaia et al., 2020a, 2020b). The research methodology is shown schematically in Figure 3. It consists of 4 steps: identification of mass centers for the route's datasets and assessment of current fire station location, then use of Location-Allocation tool to select settlements as new candidates to replace current fire stations, and final evaluation of proposed location with changed and unchanged fire stations.

The Location-Allocation analysis has been used for several decades already. This method in GIS is of forestry interest to model and optimize the fire station's location for accessing forest fires by ground means. Location-Allocation tool for fire station locations is used to select stations from the candidate locations that are as close as possible to the places of forest fire occurrence.

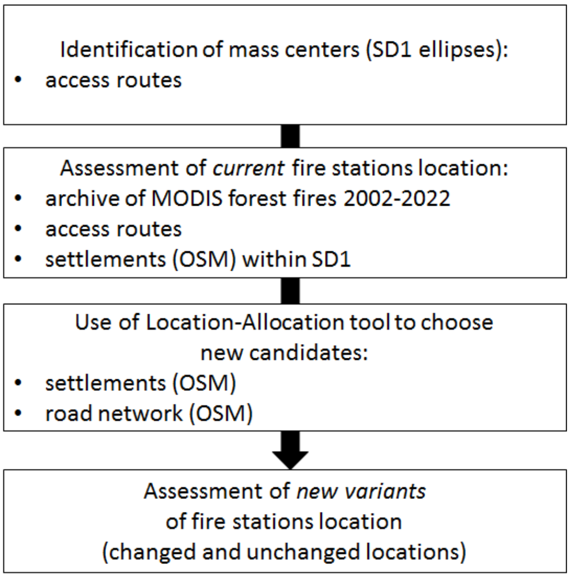


Figure 3. Research methodology

As input data for Location-Allocation analysis, the routes dataset was created for forest fires between 2002 and 2022 using the study by Podolskaia et al. (2019) for Krasnoyarsk region. Fire stations and settlements (OSM) have been prepared as candidates to relocate. Location-Allocation analysis has been performed in ArcGIS software for the created routes divided into 3 groups by time: 3 hours and less, more than 3 hours, and routes of any duration. Groups by time were chosen following forestry rules in Russia (Methodological recommendations on the use of forces and means…,2014), mentioning that forest fire should be accessed within 3 hours of its detection. While selecting OSM candidates, Standard Deviational ellipse 1 (SD1) from Directional Distribution was implemented as a selection parameter for the settlements nearest the ellipse center. Fire stations are considered candidates for selection if (1) they are located within the ellipse SD1 and (2) they are not located in the OSM settlement.

3. Results and Discussion

The spatial location of 59 fire stations and forest fire access routes from the 2002-2022 geodatabase was analyzed. 48905 routes created to access 60637 fires, but only 3033 of them have a duration of more than 3 hours, so the majority of accessible fires were located close to the current fire stations.

Based on the Location-allocation analysis by using candidates (OSM-settlements and fire stations if they are not superposed each over) for 3-time intervals (3 hours and less, 3 hours and more, any time), a total 39 stations could be moved to OSM settlements, and 20 stations remain at their current locations. Maximize Coverage setting (special for fire station location problem) with '1' from the Advanced Settings tab was implemented as a parameter to select 1 fire station ("Facilities to") and customize "Impedance Cutoff" in minutes. Calculations were made for all stations. Examples for different cases (remaining fire station N1 and OSM-settlement replacing N43 and N98) are shown in Table 1.

The layout of current and new (proposed) fire stations with detailed accessibility zones of 1-2-3 hours is shown in Figure 4. Red dots on the map show OSM-settlements that are candidates to replace stations, white triangles are for the replaceable stations, and black triangles are for stations with no change.

Table 1. Results of Location-Allocation analysis for the fire stations N1, N 43 and N98 of Krasnoyarsk region

Number of the fire station	Candidates for fire station	Access routes number			% all access routes	% access routes of 3 hours and less	Decision
		Till 3 h	More than 3 h	All routes			
N 1	Current fire station	775	4	779	-2	-13	Fire station remains
	Maluy Kantat	677	88	765			
N 43	Current fire station	1105	12	1117	+27	+4	Papikovo
	Papikovo	1151	265	1416			
N 98	Current fire station	1878	0	1878	+24	+2.5	Rosinka
	Rosinka	1926	411	2337			

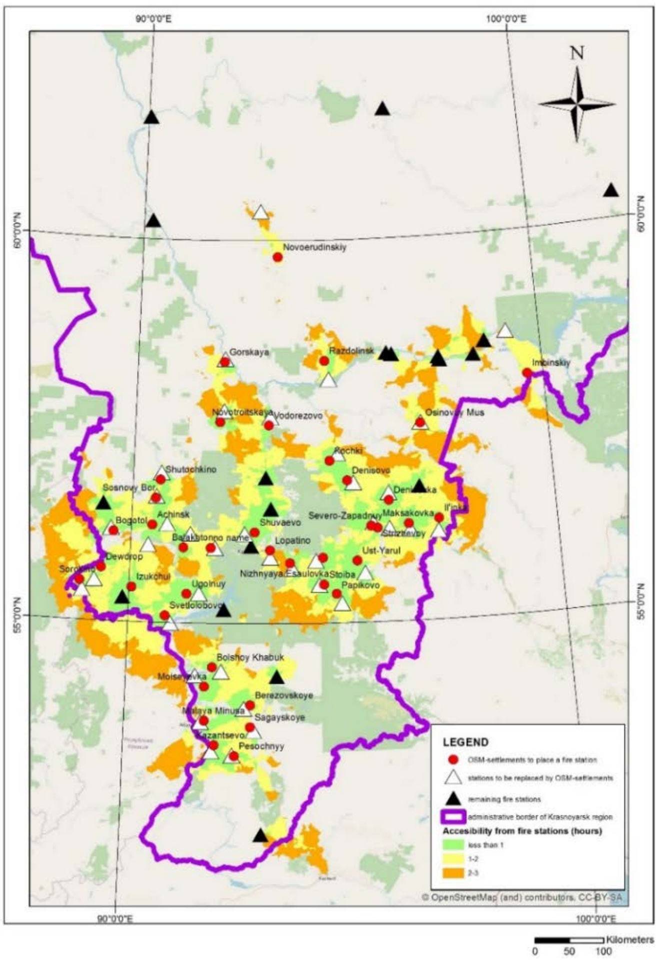
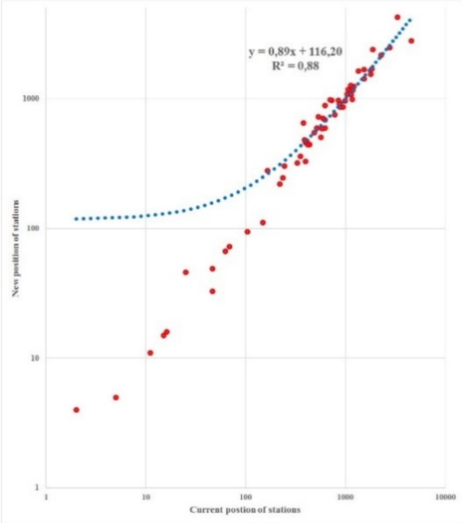


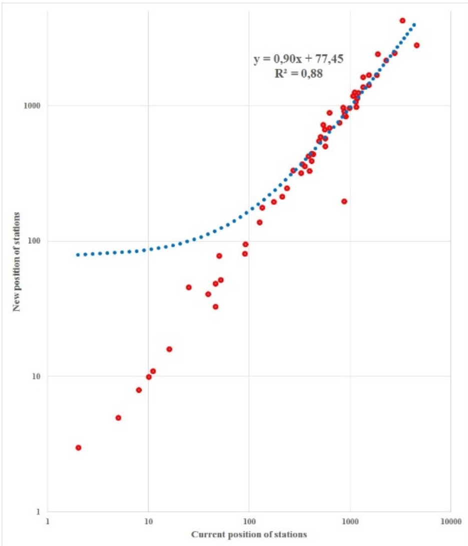
Figure 4. Current and new fire station layouts in Krasnoyarsk region

The number of routes to access forest fires was taken into consideration to evaluate the improvement of the new station's layout. Access routes were built to the 47331 out of 60637 archived forest fires for the current stations' location, and by changing the fire station location, total regional accessibility has been improved up to 48905 fires (from 78 to 80 %). Forest fire accessibility for the current and proposed fire station layouts was measured using a quantitative assessment in relative values. Taking into account the number of accessible fires redistributed spatially from one station to another at the scale of the whole region, the number of routes was rationed by 60637 archived forest fires for each station.

Percentage points are a measurable value that shows the differences between current and proposed fire station locations. Percentage points for 3 cases (all routes, routes of 3 hours and less, routes of more than 3 hours) vary from 0 to +3 and -1.5. The widest variety is for routes of 3 hours and less, and the smallest – for all the routes. Two-dimensional diagrams could help to analyze the change in forest fire accessibility graphically. An algorithmic scale was made to specify the value of the free parameter in the equation y=ax+b. This parameter shows how many routes in addition to the new network could be created, and a linear trend between two datasets, old and new ones, is shown in Figure 5 for the case of (a) all routes and (b) routes of 3 hours.



(a)

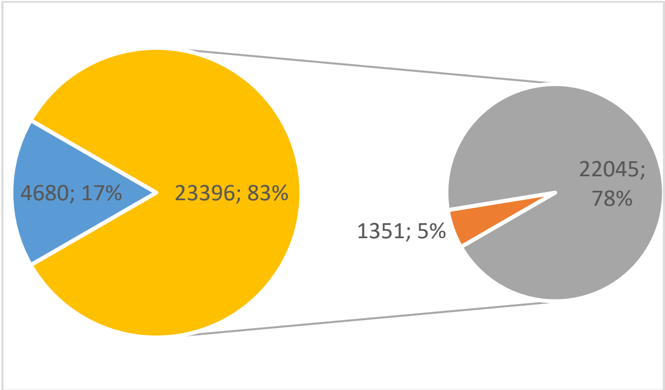


(b)

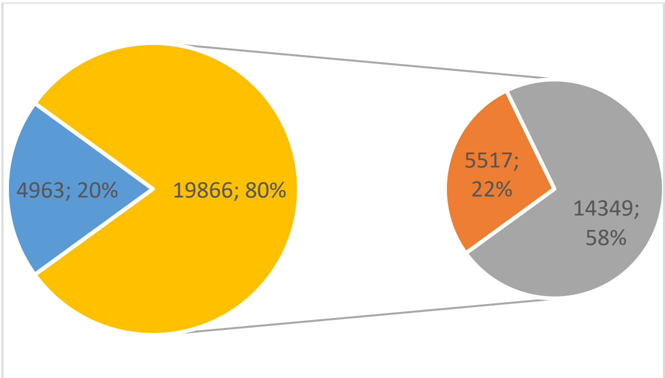
Figure 5. Comparison of routes to fires' numbers in the current and new fire station layouts, where (a) all routes, (b) routes of 3 hours

Analysis of the routes' dataset created to access forest fires of 2002-2022 showed that in the new layout stations, 39 out of 59 stations became reachable. The finding can lead to the understanding of changes in the forest fires accessibility from the current to the new stations' layout. In the new layout of fire stations, 28076 fires would be reachable instead of 23396 in the current one by routes of any time, and 24829 fires would be reachable instead of 19866 by routes of 3 hours and less. The mean value of forest fires has changed from 600 to 720 for the routes of any duration and from 509 to 637 for the routes of 3 hours and less. The maximum of reachable forest fires is 4280 for both groups. The average weighted time (in minutes) of accessing forest fires for the selected group of fire stations was changed from 300 to 230.

A secondary pie chart (Figure 6) shows the relative contribution of routes (routes of any duration and routes of up to 3 hours) to the overall picture of forest fires' transport accessibility in the Krasnoyarsk region. The number of reachable fires has changed from 17 in the group of all routes to 20 % in the group of routes within 3 hours. As Figures 6a and b show, the number of fires that could be reachable by redistribution to other fire stations increased from 5 (all routes) to 22 % (routes within 3 hours and less).



(a)



(b)

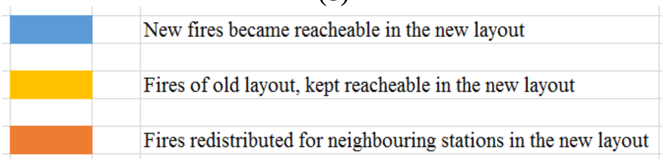


Figure 6. Transport accessibility of forest fires in 2002-2022 in Krasnoyarsk region for a new fire stations layout (group of 39 fire stations with increasing routes number): (a) all routes; (b) routes of 3 hours

The findings of our study show similarities to previous studies. In fact, there is little quantitative regional research of forest fire stations transport accessibility, nor is it discussed in relation to their present and possible location. A study by Ranabhat et al. (2022) proposed 10 fire stations for the extent of Central Nepal. Travel time is the key and very common parameter to estimate fire stations accessibility like any other types of transport accessibility. For example, de Domingo et al., 2021 used machine learning (k-means and DBSCAN, or Density-based spatial clustering of applications with noise) to obtain average and weighted times to reach a fire. Calculations of accessed times in current and proposed fire station layouts differ by 20-25 %. These obtained values show the improvement in the regional accessibility and, even considering size and infrastructural load of Krasnoyarsk region, could be a reference for our research. Countries differ by the size of their administrative division's unit; such relative advantage for a region logistically and economically could be sufficient to be considered as important.

4. Conclusion

This study concludes that the new fire station layout is more optimal than the current one as (1) the number of accessible forest fires increased by 20 % (25 % in case of accessing by routes of 3 hours and less) and (2) the average weighted time of accessing forest fires decreased by 30 %. The results align with forestry studies in other parts of the world. Thus, a methodology to evaluate the location of fire stations has been proposed and implemented at the regional level. The user case of Krasnoyarsk region, which has its fire station location investigated in the present research, is an additional step in using routes geodatabases of the 2002-2022 archive. The content, accuracy, and relevance of the used datasets certainly determine the findings of the present paper. Analysis of the fire station layout could be improved if there are any complimentary (apart from OSM) data on the settlement population. All the settlement candidates to replace fire stations were given same priority; data on their population can lead to a more precise analysis. Time to access forest fires by routes of more than 3 hours varies significantly, and cases of nearly 3 hours of accessibility are present; analysis of this part of the data could lead to the extension of the 3-hour limit in the Russian forestry rules.

Some certain challenges in the location of fire stations could occur in the proximity of administrative or forest management unit borders and these cases should be investigated further. The described methodology could be used to the territory of any regional extent. Thus, analysis at the federal or local level is also possible. Data on the new stations (along with the unchanged stations) locations can be included in economic calculations on the optimal access routes. Such assessments can provide an additional justification for the relocation of stations in the planning of forest fire management activities and can be used in the regional Forest plans. Scenario possibilities and options may consider the unchanged stations as referenced logistical centers for forest fire protection. So, modeling of station relocation leads to accessibility map production for the Forest plans. Relocation of stations can be considered at the federal level as well, and in this case, archived data at the country level will be used. Also, administrative boundaries will be limits of responsibility zones of each administrative unit.

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