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Original article

Justification of the Need to Use the Radiation and Chemical Protection Service as Part of Special Fire and Rescue Units in the Subjects of the Russian Federation

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Abstract

Introduction. Recently, much attention has been paid to the issues of long-term development of specialized fire and rescue units of the Federal Fire Service of the State Fire Service. In this regard, there is a need to develop criteria to justify the use of a particular service as part of specialized fire and rescue units. Therefore, the objective of this study is to develop a mathematical model to justify the need to use radiation and chemical protection services as part of specialized fire and rescue units in the subjects of the Russian Federation.

Materials and Methods. Justification of the need to use radiation and chemical protection services as part of specialized fire and rescue units has been carried out using the theory of fuzzy sets. The mathematical model takes into account the climatic and geographical features of the subjects, indicators of social, technical and economic development, and the risks of emergencies and fires. It also takes into account the availability of forces and means of a Unified State system for the prevention and liquidation of emergency situations in each subject of the Russian Federation. In total, 15 indicators were selected that characterize the need to use radiation and chemical protection services as part of specialized fire and rescue units. A desirability function is defined for each indicator, which shows which values of the indicator are the most acceptable from the point of view of the need to use radiation and chemical protection services as part of specialized fire and rescue units.

Results. Using the developed model, the subjects of the Russian Federation are identified in which the need for radiation and chemical protection service as part of specialized fire and rescue units is the highest. It is proposed to create a radiation and chemical protection service of the 1st category in the Moscow, Sverdlovsk and Rostov regions, in the Krasnoyarsk and Primorsky Territories and in St. Petersburg. In 21 subjects it is proposed to use the radiation and chemical protection service of the 2nd category. In other subjects, it is proposed to assign the 3rd category to the radiation and chemical protection service.

Discussion and Conclusion. The mathematical model developed using the theory of fuzzy sets will allow a more differentiated approach to the creation of a radiation and chemical protection service as part of specialized fire and rescue units and increase the efficiency of the functioning of this service and specialized fire and rescue units as a whole. The presented model can be applied to justify the need to use other services and groups as part of specialized fire and rescue units.

Keywords: fuzzy set, specialized fire and rescue unit, emergency, fire, risk, radiation and chemical protection.

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Научная статья

Обоснование необходимости использования службы радиационной и химической защиты в составе специализированных пожарно-спасательных частей в субъектах Российской Федерации

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Аннотация

Введение. В последнее время большое внимание уделяется вопросам перспективного развития специализированных пожарно-спасательных частей Федеральной противопожарной службы Государственной противопожарной службы (ФПС ГПС). В связи с этим существует потребность в разработке критериев для обоснования использования той или иной службы в составе специализированных пожарно-спасательных частей (СПСЧ). Поэтому цель данного исследования состояла в разработке математической модели для обоснования необходимости использования службы радиационной и химической защиты в составе СПСЧ в субъектах Российской Федерации.

Материалы и методы. Обоснование необходимости использования службы радиационной и химической защиты (РХЗ) в составе СПСЧ проведено с использованием теории нечетких множеств. В математической модели учитываются природно-климатические и географические особенности субъектов, показатели социального и технико-экономического развития и риски возникновения чрезвычайных ситуаций и пожаров. Также учитывается наличие сил и средств РСЧС в каждом субъекте Российской Федерации. Всего отобрано 15 показателей, характеризующих необходимость использования службы РХЗ в составе СПСЧ. Для каждого показателя определена функция желательности, которая показывает, какие значения показателя являются наиболее приемлемыми с точки зрения необходимости использования службы РХЗ в составе СПСЧ.

Результаты исследования. С использованием разработанной модели определены субъекты Российской Федерации, в которых потребность в службе РХЗ в составе СПСЧ наиболее высокая. Службу РХЗ 1-го разряда предлагается создать в Московской, Свердловской и Ростовской областях, в Красноярском и Приморском краях и в г. Санкт-Петербурге. В 21 субъекте предлагается использовать службу РХЗ 2-го разряда. В остальных субъектах предложено присвоить службе РХЗ 3-ий разряд.

Обсуждение и заключения. Разработанная с использованием теории нечетких множеств математическая модель позволит более дифференцированно подходить к созданию службы РХЗ в составе СПСЧ и повысить эффективность функционирования данной службы и СПСЧ в целом. Представленная модель может быть применена для обоснования необходимости использования других служб и групп в составе СПСЧ.

Ключевые слова: нечеткое множество, специализированная пожарно-спасательная часть, чрезвычайная ситуация, пожар, риск, радиационная и химическая защита.

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Introduction. Specialized fire and rescue units of the Federal Fire Service of the State Fire Service (hereinafter referred to as SFRU) in the territorial garrisons of fire departments are assigned the tasks of extinguishing xs in settlements and facilities, carrying out emergency rescue, diving and other special engineering works related to the elimination of fires, the elimination of the consequences of technogenic and natural emergencies [1, 2].

According to the standard staffing table (Order of the Ministry of Emergency Situations of 21.03.2014 No. 129 "On Amendments to Order of the Ministry of Emergency Situations of Russia of 30.12.2005 No. 1027 and Invalidation of the Orders of the Ministry of Emergency Situations of Russia and Certain Provisions of the Orders of the Ministry of

Emergency Situations of Russia") the following services and groups may be part of SFRU:

– diving service;

– medical and psychological service;

– telecommunications and communications service;

– engineering service;

– radiation and chemical protection service;

– fire extinguishing and emergency rescue service;

– cynological group;

– pyrotechnic work group;

– technical support and maintenance group;

– robotics and unmanned aerial vehicles group.

Currently, much attention is paid to the issues of the SFRU long-term development [2]. In this regard, it became necessary to formulate criteria for justifying the use of a particular service as part of the SFRU.

The study objective is to develop a mathematical model using the theory of fuzzy sets [3-6] to determine the need to use the radiation and chemical protection service (RCP) as part of the SFRU to ensure fire safety and protect territories from emergencies in the subjects of the Russian Federation.

The RCP service in the SFRU of Chief Directorates of the Ministry of Emergency Situations of Russia for the subjects of the Russian Federation is created to ensure safety measures and improve the SFRU readiness for emergency situations to extinguish fires, eliminate emergency situations at facilities with chemically hazardous substances, as well as extinguishing fires and conducting primary emergency-rescue works related to them at facilities with radioactive substances and other sources of ionizing radiation.

Materials and Methods. In order to develop a mathematical model, a list of indicators was formed that characterize the need for the use of SFRU and individual services (groups) of SFRU in the subjects of the Russian Federation. A total of 34 indicators were selected. From these indicators, those that characterize the need to use the RCP service are highlighted. All indicators are divided into three groups.

Natural-climatic and geographical features of the subject characterize the following indicators:

– area of the territory;

– seismic hazard;

– presence of mountain ranges;

– social, technical and economic factors, which include the following indicators:

– share of industrial production in the total volume of production;

– degree of depreciation of basic production assets;

– length of highways;

– length of railways;

– number of radiation-hazardous objects;

– number of chemically hazardous objects;

– number of explosive and fire-hazardous objects.

The third group includes the risks of emergencies and fires, as well as indicators characterizing the availability of forces and means of the Russian System of Prevention and Response to ES (RSChS) in the considered and neighboring subjects of the Russian Federation:

– average distance to the nearest SFRU, in which there is a RCP service;

– average distance to the nearest unit of the RSChS forces, in which there is a RCP service;

– presence of the RCP service in the SFRU in the subject of the Russian Federation under consideration;

– risk of emergencies related to chemical and radiation hazards;

– risk of emergencies related to explosions, collapses.

For each indicator, a desirability function is determined [7, 8], the values of which lie in the range from 0 to 1. The desirability function demonstrates which values of the indicator are the most acceptable from the point of view of the need to use the RCP service as part of the SFRU.

If, with an increase in the value of the indicator, the demand for the RCP service increases, the desirability function has the form:

$$\mu_1(x) = \begin{cases} 0, & x < x_1, \\ \frac{x-x_1}{x_2-x_1}, & x_1 \le x \le x_2, \\ 1, & x > x_2. \end{cases} \quad (1)$$

If a higher value of the indicator corresponds to a lower demand for the RCP service, the desirability function has the form:

$$\mu_2(x) = \begin{cases} 1, & x < x_1, \\ \frac{x_2-x}{x_2-x_1}, & x_1 \le x \le x_2 \\ 0, & x > x_2. \end{cases} \quad (2)$$

Boundary values of x_1 and x_2 are determined by analyzing statistical data for each indicator. Functions $\mu_1(x)$ and $\mu_2(x)$ are used for indicators, the values of which change continuously.

To formalize the indicators set at the qualitative level, linguistic assessments of the degree of expressiveness of the indicator are used. The desirability function for such indicators takes discrete values.

For the "seismic hazard" indicator, the desirability function has the form:

$$\mu_3(\mathrm{y}) = \begin{cases} 0, & \mathrm{y} < 6, \\ 0{,}2, & y = 6, \\ 0{,}4, & y = 7, \\ 0{,}6, & y = 8, \\ 0{,}8, & y = 9, \\ 1, & y \ge 10, \end{cases}, \quad (3)$$

where value *y* characterizes the presence in the subject of the Russian Federation of settlements with the specified seismic intensity for the C degree of seismic hazard (according to the set of rules of SP 14.13330.2011 "Construction in Seismic Areas").

For the "presence of mountain ranges" indicator, the desirability function has the form:

$$\mu_4(z) = \begin{cases} 0, & z = 0, \\ 0{,}25, & 0 \le z < 0{,}2, \\ 0{,}5, & 0{,}2 \le z < 0{,}4, \\ 0{,}75, & 0{,}4 \le z < 0{,}6, \\ 1, & z \ge 0{,}6, \end{cases}, \quad (4)$$

where value *z* characterizes the share of the territory of the subject of the Russian Federation occupied by mountain ranges.

For the "availability of the RCP service in the SFRU" indicator, the desirability function has the form:

$$\mu_5(r) = \begin{cases} 0, & if\ the\ \text{RCP}\ service\ is\ created, \\ 1, & if\ there\ is\ no\ \text{RCP}\ service. \end{cases} \quad (5)$$

The integral assessment of the need to use the RCP service in the SFRU in the subject of the Russian Federation is determined by the formula:

$$W = \sum_{m=1}^{3} \beta_m w_m, \quad (6)$$

where β_m — weight coefficient for the *m*-th group of indicators.

Generalized w_m estimator for the *m*-th group of indicators for the subject of the Russian Federation is determined by the formula:

$$w_m = \sum_{k=1}^{N_m} \alpha_{km} \mu_k(x_k), \quad (7)$$

where N_m — number of indicators in the *m*-th group; α_{km} — weight coefficient for the *k*-th indicator in the *m*-th group; μ_k — desirability function for the *k*-th indicator; x_k — value of the *k*-th indicator for the subject of the Russian Federation.

To determine weight coefficients for each group of indicators, the method of pair-wise comparisons based on the linguistic scale of assessments was used [9, 10]. When comparing the *i*-th and *j*-th indicators, a_{ij} score is set depending on the degree of importance of these indicators from the point of view of the need to use the RCP service in the SFRU from 1 (if the indicators are equally significant) to 9 (if the *i*-th indicator is strictly preferable to the *j*-th). The assessment of the comparison of the *j*- th indicator with the *i*- th i has the inverse value of $1/a_{ij}$.

As an example, Table 1 shows a matrix of pair-wise comparisons for indicators characterizing social, technical and economic features of a subject of the Russian Federation. The names of the indicators are given in Table 2.

The desired values of weight coefficients α_1, α_2, ..., α_N for each group of indicators are the solution to the optimization problem

$$S = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(a_{ij}\alpha_j - \alpha_i\right)^2 \rightarrow min;\ \sum_{i=1}^{N}\alpha_i = 1, \quad (8)$$

which is found by the method of indefinite Lagrange multipliers [11]. Optimization problem (8) is reduced to a system of *N*+1 linear equations, the solution to which is the desired weight coefficients α_i and the Lagrange multiplier λ.

Table 1

Matrix of pair-wise comparisons for indicators characterizing social, technical and economic features of the subject of the Russian Federation from the point of view of the need to use the RCP service in the SFRU

№ пок.	1	2	3	4	5	6	7
1	1	1	0.33	0,50	0.25	0.25	1
2	1	1	0.33	0,50	0.25	0.25	1
3	3	3	1	3	1	1	5
4	2	2	0.33	1	0.33	0.33	1
5	4	4	1	3	1	1	4
6	4	4	1	3	1	1	4
7	1	1	0.20	1	0.25	0.25	1

Table 2 shows the type of desirability function and its parameters, the calculated values of weight coefficients α_{km} for the indicators included in each group, as well as weight coefficients β_m for each of the three groups of indicators.

Table 2

Parameters of the desirability function and weight coefficients for indicators characterizing the need to use the RCP service in the SFRU

No.	Indicator name	Function	Value x_1	Value x_2	Weight coefficient α_{km}
Natural-climatic and geographical characteristics (β_1 = 0.127)					
1	Area of the territory, thousand km^2	$\mu_1(x)$	20	200	0.583
2	Seismic hazard	$\mu_3(x)$	–	–	0.258
3	Presence of mountain ranges	$\mu_4(x)$			0.159
Social, technical and economic characteristics (β_2 = 0.222)					
1	Share of industrial production in the total volume of production, %;	$\mu_2(x)$	20	50	0.063
2	Degree of depreciation of basic production assets, %	$\mu_1(x)$	40	60	0.063
3	Length of highways, thousand km	$\mu_1(x)$	5	20	0.239
4	Length of railways, thousand km	$\mu_1(x)$	0.5	2	0.084

No.	Indicator name	Function	Value x_1	Value x_2	Weight coefficient α_{km}
5	Number of radiation-hazardous objects, units	$\mu_1(x)$	0	5	0.247
6	Number of chemically hazardous objects, units	$\mu_1(x)$	30	100	0.247
7	Number of explosion- and fire-hazardous objects, units	$\mu_1(x)$	50	150	0.057
Risks of emergencies and fires (β_3 = 0.651)					
1	Distance to the nearest SFRU, in which there is a RCP service, km	$\mu_1(x)$	50	500	0.075
2	Distance to the nearest RSChS unit, in which there is a RCP service, km	$\mu_1(x)$	50	500	0.075
3	Availability of the RCP service in the SFRU	$\mu_5(x)$	–	–	0.703
4	Risk of emergencies related to chemical and radiation hazards, year^{-1}	$\mu_1(x)$	0	0.2	0.085
5	Risk of emergency situations related to explosions, collapses, year^{-1}	$\mu_1(x)$	0	0.4	0.061

Results. The developed mathematical model was applied to determine the need to use the RCP service as SFRU part to ensure fire safety and protect territories from emergency situations in the subjects of the Russian Federation. The values of indicators of socio-economic development of the subjects are determined according to the data of the Federal State Statistics Service. The number of hazardous objects in the subjects is determined using data [12]. The risks of emergencies are determined based on the analysis of data on the types of sources of occurrence and nature of emergencies in the subjects of the Russian Federation for the period from 2010 to 2021.

At the first stage, the subjects of the Russian Federation were identified, in which it is necessary to use the 1st-class SFRU. For these subjects, the condition must be met:

$$W \geq W_{\text{rp}} = \frac{2W_{max}+W_{min}}{3}, \quad (9)$$

where W — value of the integral indicator of the need to use the SFRU in the subject of the Russian Federation; W_{min} and W_{max} — the minimum and maximum values of the integral indicator among the subjects of the Russian Federation. Boundary value W_{rp} was obtained equal to 0.650.

According to the calculation results, the 1st-class SFRU is proposed to be used in six subjects of the Russian Federation: in the Moscow, Sverdlovsk and Rostov regions, in the Krasnoyarsk and Primorsky Territories and in St. Petersburg. In all the 1st-class SFRU, the RCP service is assigned the 1st class.

At the second stage, for the rest of the subjects of the Russian Federation, the values of the indicator "average distance to the nearest SFRU" were determined, taking into account the 1st-class SFRU, and the values of the integral indicator of the need to use the RCP service in the SFRU were calculated.

The 2nd-class RCP service is proposed to be used in the SFRU, if the condition is met:

$$W_{\text{PX3}} \geq W_{\text{PX3,rp}} = \frac{2W_{\text{PX3},max}+W_{\text{PX3},min}}{3}, \quad (10)$$

where W_{PX3} — value of the integral indicator of the need to use the RCP service in the SFRU in the subject of the Russian Federation, $W_{\text{PX3},min}$ and $W_{\text{PX3},max}$ — the minimum and maximum values of the integral indicator among the subjects of the Russian Federation in which there is no 1st-class SFRU. Boundary value $W_{\text{PX3.rp}}$ was obtained equal to 0.759.

In the remaining subjects of the Russian Federation, it is proposed to use the 3d-class RCP service in the SFRU.

The obtained values of the integral indicator of the need to use the RCP service in the SFRU in the subjects of the Russian Federation $W_{\text{PX3,}}$ are shown in Fig. 1. It is proposed to use the 1st-class RCP service in 6 subjects of the Russian Federation (highlighted in red in the figure), the 2nd-class RCP service — in 21 subjects (highlighted in yellow), the 3d-class RCP service — in 58 subjects (highlighted in green).

The calculation results based on a mathematical model are compared with the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation. For this purpose, information was collected from the Chief

Directorates of the Ministry of Emergency Situations of Russia in the subjects of the Russian Federation on the availability and need for the RCP service as part of the SFRU.

Of the subjects included in the red group, the RCP service was not created only in the SFRU of St. Petersburg.

Of the subjects included in the yellow group, the RCP service in the SFRU was created in 19 subjects out of 21.

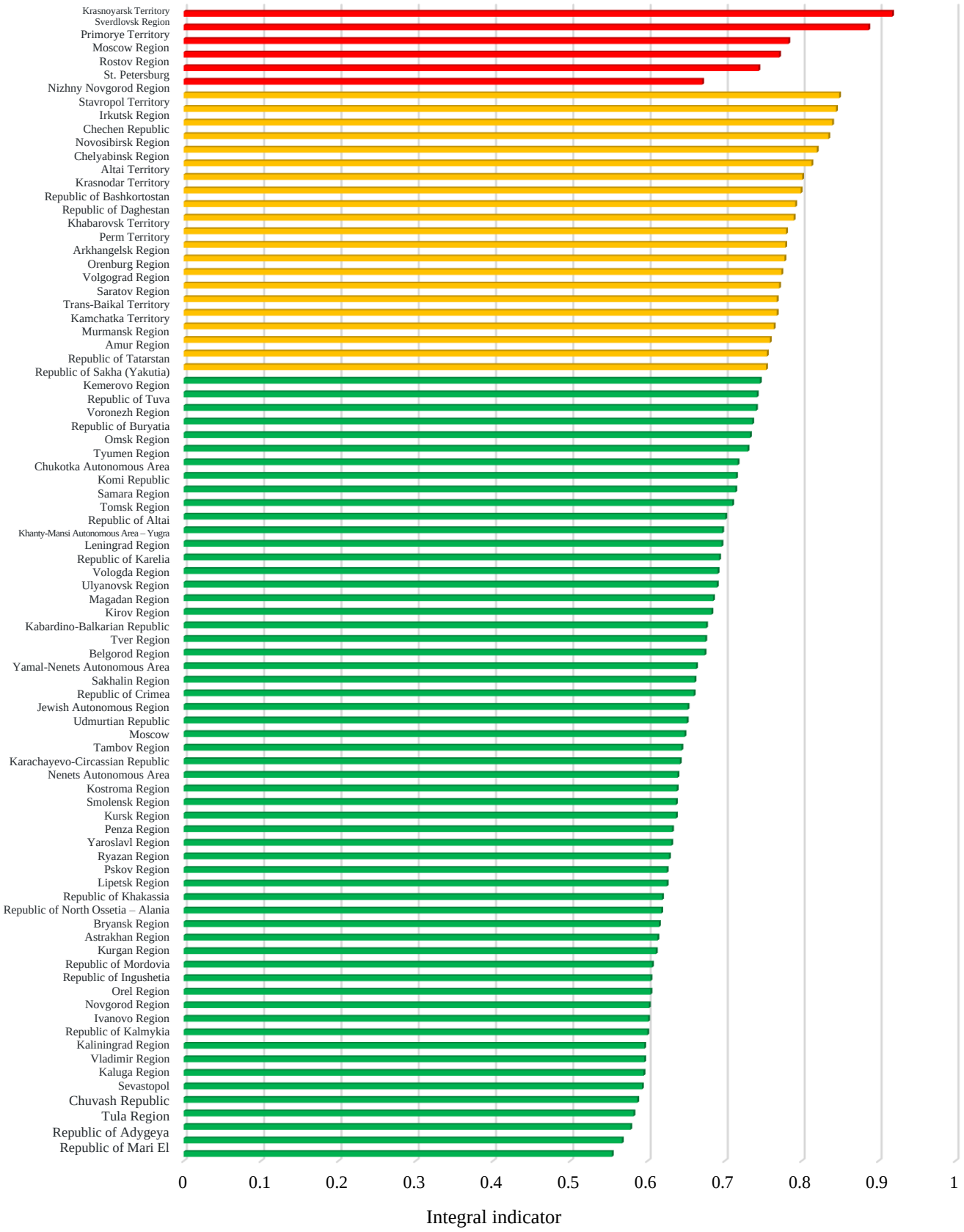

Fig. 1. Distribution of the subjects of the Russian Federation according to the integral indicator of the need to use the RCP service in the SFRU in the subjects of the Russian Federation

Of the subjects included in the green group, there is a RCP service in the SFRU in 40 subjects of the Russian Federation out of 58, 9 subjects declared the need to create a RCP service, 5 more subjects in which this service was created declared no need for it.

The existence of a statistical relationship between the calculation results based on a mathematical model and the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation was verified using the χ^2 Pearson criterion [13, 14]. The results can be displayed as a conjugacy table (Table 3).

Table 3

Conjugacy table to verify the relationship between the calculation results based on a mathematical model and the actual presence or declared need for the RCP service in the SFRU in the subjects of the Russian Federation

Group name	Number of subjects of the Russian Federation in which		Total number of subjects of the Russian Federation
	RCP service has been created or there is a need to do it	RCP service is missing or there is no need	
Red group	5	1	6
Yellow group	19	2	21
Green group	44	14	58
Total	68	17	85

The value of χ^2-statistics for two-field Table 3 is 2.11. The critical value of criterion χ^2 for two degrees of freedom at a significance level of 0.05 is 5.99. The calculated value is less than the critical one, which indicates that there is no relationship between the calculation results based on the mathematical model and the actual presence of the RCP service in the SFRU in the subjects of the Russian Federation. This indicates that the RCP services as part of the SFRU are currently created without taking into account the risks of emergencies and fires and other features of the subjects of the Russian Federation. The use of the approach proposed in the article will allow for a more differentiated approach to the creation of the RCP service as part of the SFRU and increase the efficiency of the functioning of this service and the SFRU as a whole.

Discussion and Conclusion. The mathematical model based on the theory of fuzzy sets has been developed to justify the need for a radiation and chemical protection service as part of specialized fire and rescue units to ensure fire safety and protect territories from emergencies in the subjects of the Russian Federation. The model takes into account the climatic and geographical features of the subjects, indicators of social, technical and economic development, and the risks of emergencies and fires. It also takes into account the presence of forces and means of RSChS in the considered and neighboring subjects of the Russian Federation.

It is proposed to assign a class from the 1st to the 3rd to each SFRU, depending on the scale of the tasks to which the SFRU is involved, taking into account the risks of emergencies and fires. Similarly, it is proposed to assign classes for services and groups as part of the SFRU.

On the basis of the developed model, the calculations of the integral assessment were carried out to justify the need to use the RCP service in the SFRU for each subject of the Russian Federation. The subjects of the Russian Federation are identified in which the need for the RCP service as part of the SFRU is the highest. In these subjects, it is proposed to use the RCP service of the 1st and 2nd classes.

The developed model can be applied to substantiate the need to use other services (groups) as part of the SFRU.

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