Современная наука и инновации. 2026. № 1. С. 69-76
ТЕХНИЧЕСКИЕ НАУКИ
ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ

Modern Science and Innovations. 2026;(1):69-76
TECHNICAL SCIENCES
INFORMATION, COMPUTING AND MANAGEMENT

Научная статья
УДК 004.724.4
https://doi.org/10.37493/2307-910X.2026.1.5

Исследование гидролитосферных процессов участка Архызский-1 Архызского месторождения питьевых подземных вод

Екатерина Александровна Меркулова[1*]

[1] Южный федеральный университет (105/42, ул. Большая Садовая, Ростов-на-Дону, 344006, Россия)
[1] emer@sfedu.ru
*Автор, ответственный за переписку

Аннотация. ***Введение.*** Рациональное использование подземных вод в условиях возрастающей рекреационной нагрузки требует детального изучения гидролитосферных процессов. Целью работы является исследование фильтрационных характеристик и разработка математической модели для участка Архызский-1 Архызского месторождения питьевых подземных вод. Материалы и методы. Основу исследования составили опытно-фильтрационные работы, выполненные в 2024 году на скважинах № 131-Э, 131-К-1 и 131-К-бис. Обработка данных выполнялась в соответствии с методиками аппроксимации передаточных функций распределенных объектов. На основе статических коэффициентов передачи определены интегральные параметры гидравлического взаимодействия скважин: D = 0,0135487; K = 0,00075576; Kp = 2,1019758. Построены графики пространственного распределения коэффициентов взаимодействия. Разработана математическая модель неустановившейся фильтрации для двухслойной среды, учитывающая перетекание между пластами, упругие свойства пород и воздействие добывающих скважин. Верификация модели на полевых данных подтвердила её адекватность. Полученные результаты и разработанная модель создают научно-методическую основу для оптимизации режима эксплуатации месторождения и планирования мероприятий по рациональному природопользованию в условиях возрастающей рекреационной нагрузки на регион.

Ключевые слова: гидролитосферные процессы, месторождение подземных вод, опытно-фильтрационные работы, математическое моделирование, фильтрационные параметры, водоносный горизонт, верификация моделей, Архыз.

Для цитирования: Меркулова Е. А. Исследование гидролитосферных процессов участка Архызский-1 Архызского месторождения питьевых подземных // Современная наука и инновации. 2026. № 1. С. 69–76. https://doi.org/10.37493/2307-910X.2026.1.5

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Статья поступила в редакцию 01.12.2025;
одобрена после рецензирования 01.02.2026;
принята к публикации 01.03.2026.

Research article

Study of hydro-lithospheric processes of the Arkhyzskiy-1 site of the Arkhyz drinking groundwater deposit

Ekaterina A. Merkulova[1*]

[1] Southern Federal University (105/42, Bolshaya Sadovaya st., Rostov-on-Don, 344006, Russia)
[1] emer@sfedu.ru
*Corresponding author

Abstract. The rational use of groundwater under conditions of increasing recreational pressure requires a detailed study of hydro-lithospheric processes. The aim of this work is to investigate filtration characteristics and develop a mathematical model for the Arkhyzskiy-1 site of the Arkhyz drinking groundwater deposit. The research is based on experimental filtration works carried out in 2024 at wells No. 131-E, 131-K-1 and 131-K-bis. Data processing was performed in accordance with methods of approximating transfer functions of distributed objects. Based on static transfer coefficients, integral parameters of hydraulic interaction between wells were determined: D = 0.0135487, K = 0.00075576, Kp = 2.1019758. Graphs of the spatial distribution of interaction coefficients were constructed. A mathematical model of unsteady filtration for a two-layer medium was developed, taking into account leakage between layers, elastic properties of rocks, and the impact of production wells. Model verification against field data confirmed its adequacy. The obtained results and the developed model provide a scientific and methodological basis for optimizing the field development regime and planning measures for rational environmental management under conditions of increasing recreational pressure on the region.

Keywords: hydro-lithospheric processes, groundwater deposit, experimental filtration works, mathematical modeling, filtration parameters, aquifer, model verification, Arkhyz.

For citation: Merkulova EA. Study of hydro-lithospheric processes of the Arkhyzskiy-1 site of the Arkhyz drinking groundwater deposit. *Modern Science and Innovations.* 2026;(1):69-76. https://doi.org/10.37493/2307-910X.2026.1.5

Conflict of interest: the author declares no conflicts of interests.

The article was submitted 01.12.2025;
approved after reviewing 01.02.2026;
accepted for publication 01.03.2026.

Introduction. The subject of this study is the Arkhyz-1 subsoil site, located in the Arkhyz municipality of the Zelenchuksky District of the Karachay-Cherkess Republic. The village of Arkhyz serves as the economic backbone of a federal resort, which is not only a tourist cluster but also an important resource for the exploitation of hydromineral resources. Conservation and sustainable use of these resources is a key objective for the region, given the annual increase in the number of vacationers and the observed deterioration of the resource base [1, 2].

In this regard, research was conducted at the Arkhyz-1 site of the Arkhyz drinking groundwater deposit, the results of which are intended for implementation in the practical activities of mining organizations.

The aim of the work is to develop the theoretical foundations for managing geological objects under conditions of man-made impact, to improve the accuracy and efficiency of operational processes, and to substantiate development conditions that ensure rational use of natural resources.

Studying groundwater conditions and the factors that shape their resource potential forms the basis of hydrogeological research at all stages of deposit development [3]. The Arkhyz deposit was explored and prepared for commercial production in 1981. Wells were drilled in the Bolshoy Zelenchuk River valley in an intermontane basin composed of glacial and alluvial deposits. At the time of exploration, the area was an undeveloped forested area.

Materials and methods. Geological and hydrogeological characteristics. Quaternary deposits are developed in the lithological-stratigraphic section at depths of 0–150 m. Well-washed alluvial and Holocene boulder-gravel-pebble deposits with sand filler occur in the interval up to 110 m. Below them are virtually anhydrous fine-grained moraine deposits (pilite mixture).

In the section, two aquifers are distinguished: the first in the range of 10–70 m and the second – 80–110 m (Figure 1).

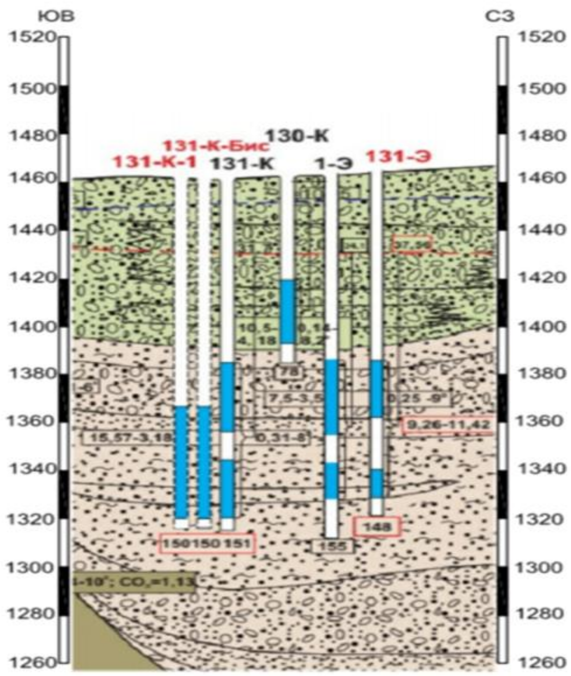

Figure 1. Arkhyz deposit

They are isolated by a clay aquiclude approximately 10 m thick (70–80 m interval). The hydraulic isolation of the horizons is confirmed by drilling and sampling data. The main water inflow is confined to the second horizon (80–110 m), which is better protected from surface contamination, unlike the poorly protected first horizon. Both horizons are characterized by high water content. The well layout diagram for the Arkhyz-1 site is shown in Figure 2.

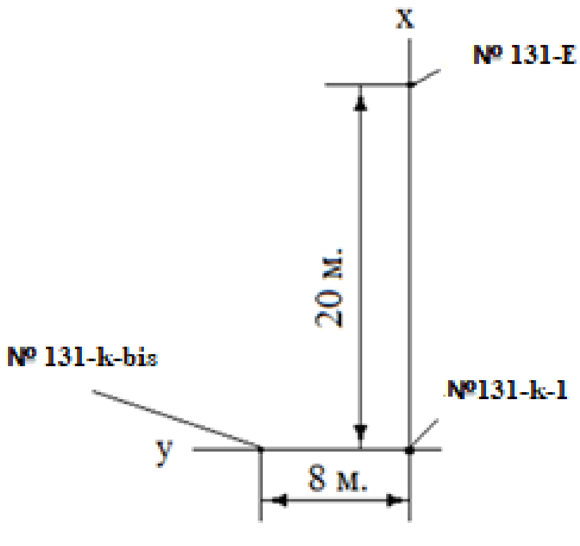

Figure 2. Well location diagram

Research Methodology. The study was based on experimental filtration work (EFW) conducted in 2024 at wells No. 131-E, 131-K-1, and 131-K-bis. The resulting dataset was used to determine filtration parameters and verify the mathematical model. Data processing was performed in accordance with the methods described in [4].

The study parameters of the aquifer under consideration, used to describe the static characteristics of the hydrolithospheric process, obtained as a result of the OFR, are given in Table 1.

Table 1. Parameters of the aquifer study

Well flow rate (m3/day)	**Lowering the level in well No. 131-K-1 (m.)**	**Lowering the level in well No. 131-K-1-Bis (m.)**	**Lowering the water level in well No. 131-E (m.)**
600	3.76	0.55	0.38
Static transfer coefficients ((level drop)/ flow rate)			
	3.76/600= 0.00627	0.55/600= 0.000917	0.38/600= 0.000633

Results and discussion. Using the data from experimental filtration works, in accordance with the methodology [1–4], we will determine the hydraulic interaction coefficients (Figure 3) of the wells

$$W_a = \frac{K}{\beta} \cdot \exp(-\beta \cdot (x^2 + (K_n \cdot y)^2)^{0.5}), \tag{1}$$

where: K, D, K_n – parameters determined using the OFR.

The static gain coefficients of the approximating link (assuming $_s = 0$, the radius of the depression funnel $r0 = 0.25m$ $)$ to the values of $_{K1}$ and $_{K2}$ and $_{K3}$ assuming that $L1 \,_- r0 \approx L1$ $_;$ $L2 \,_- r0 \approx L2$ $_,$ *we* obtain a system of equations:

$$\begin{cases} K_1 = \dfrac{K \cdot \exp(-\beta \cdot x_0)}{\beta} \\ K_2 = \dfrac{K \cdot \exp(-\beta \cdot L_1)}{\beta} \\ K_3 = \dfrac{K \cdot \exp\left(-\beta \cdot K_p \cdot L_2\right)}{\beta}, \beta = (D)^{\frac{1}{2}} \end{cases} \tag{2}$$

Substituting the calculated values, we obtain:

$$\begin{cases} 0{,}00627 = \dfrac{K \cdot \exp(-\beta \cdot 0{,}25)}{\beta} \\ 0{,}0000633 = \dfrac{K \cdot \exp(-\beta \cdot 20)}{\beta} \\ 0{,}000917 = \dfrac{K \cdot \exp\left(-\beta \cdot K_p \cdot 8\right)}{\beta}, \beta = (D)^{\frac{1}{2}} \end{cases} \tag{3}$$

Solving the resulting system, we arrive at the following result:

$D=0.0135487$, $K= 0.00075576$, $K_p = 2.1019758$.

The hydraulic interaction of wells is described by the following equation:

$$W_a = \frac{0{,}000135}{\beta} \cdot \exp(-\beta \cdot (x^2 + (2{,}101 \cdot y)^2)^{0.5}), \tag{4}$$

$$\beta = 0{,}0135^{\frac{1}{2}}$$

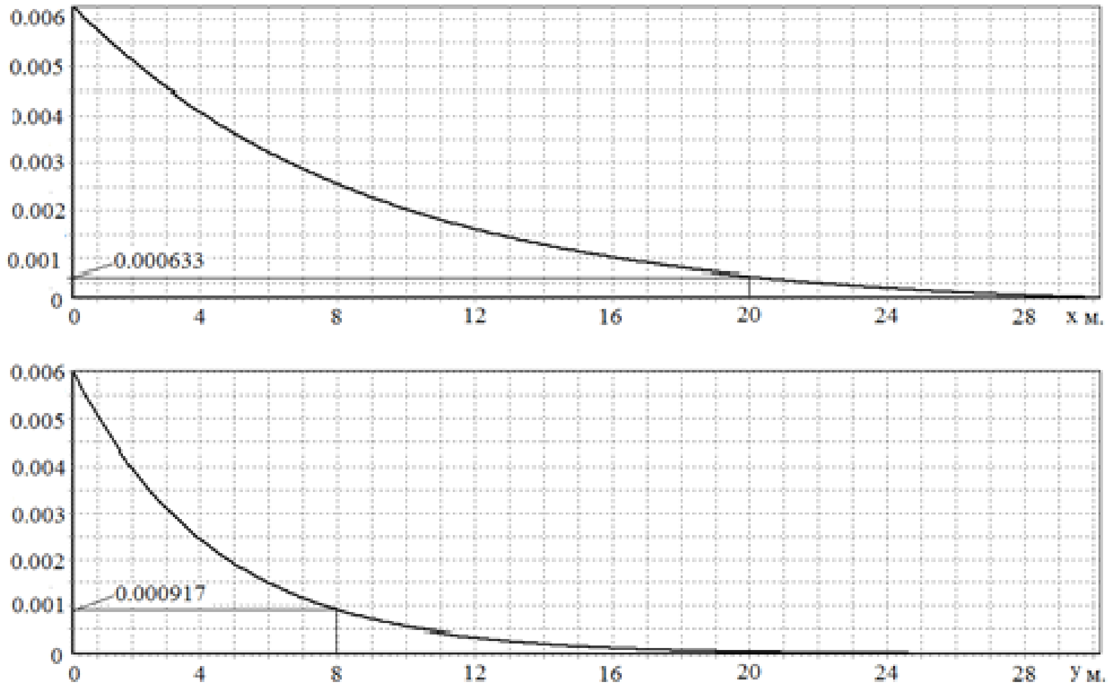

Figure 3. Graphs of the hydraulic interaction coefficients of wells by spatial coordinates x, y

Let us write equation (4) using cylindrical coordinates:

$$W_a(r) = \frac{0{,}000135}{\beta} \cdot \exp(-\beta \cdot \mathrm{r}), \tag{4}$$

$$\beta = 0{,}0135^{\frac{1}{2}}$$

$$\mathrm{r} = (x^2 \cdot (2{,}101 \cdot \mathrm{y})^2)^{\frac{1}{2}} \tag{5}$$

The mathematical model of hydrolithospheric processes of the considered deposit can be presented in the form

Groundwater

$$\frac{\partial h_1(x,y,z,\tau)}{\partial \tau} = k_{1,x}\frac{\partial^2 h_1(x,y,z,\tau)}{\partial x^2} + k_{1,y}\frac{\partial^2 h_1(x,y,z,\tau)}{\partial y^2} + k_{1,z}\frac{\partial^2 h_1(x,y,z,\tau)}{\partial {z_1}^2}$$

$$0 < x < L_x, 0 < y < L_y, 0 < z < L_{z_1},$$

Upper layer

$$\frac{\partial H_1(x,y,z,\tau)}{\partial\tau}=\frac{1}{\eta_2}\left(k_{2,x}\frac{\partial^2 H_2(x,y,z,\tau)}{\partial x^2}+k_{2,y}\frac{\partial^2 H_2(x,y,z,\tau)}{\partial y^2}+k_{2,z}\frac{\partial^2 H_2(x,y,z,\tau)}{\partial {z_2}^2}\right)+V\cdot\delta(x_0,y_0,z,)$$

$$0<x<L_x, 0<y<L_y, L_{z_1}<x<L_{z_2},$$

where: h_1 – pressure in the groundwater horizon;

H_2 – pressure in the studied aquifer;

$k_{2,x}, k_{2,y}, k_{2,z}$ – filtration coefficients by spatial coordinates in the aquifer,

$k_{1,x}, k_{1,y}, k_{1,z}$- coefficients of level conductivity by spatial coordinates in the groundwater horizon;

η_2– elastic capacity of the formation;

$V = Q \cdot K_f$ – the impact of the production well on the pressure (Q is the flow rate of the production well, $K_ф$ is the specified coefficient);

Δ $(x_0, y_0, z,)$ is a function equal to one if $x=x_0$, $y=y_0$, $z_1 \leq z \leq z_2$ (where x_0, y_0 – coordinates of the production well) and equal to zero in other cases;

x, y, z – spatial coordinates;

τ - time.

The boundary conditions between the layers are given in the form (Darcy's law)

Groundwater - upper layer

$$h_1(x,y,L_{z_1},\tau)=h_1(x,y,L_{z_1},\tau)+b_1(H_2(x,y,0,\tau)-h_1(x,y,L_{z_1},\tau))\cdot\partial\tau$$

$$H_2(x,y,0,\tau)=H_2(x,y,0,\tau)-b_1(H_2(x,y,0,\tau)-h_1(x,y,L_{z_1},\tau))\cdot\partial\tau$$

$$\frac{\partial H_2(x,y,L_{z_1},\tau)}{\partial z}=0$$

where b_1 – flow parameter.

Lower boundary of the aquifer

$$\frac{\partial H_2(x,y,L_{z_1},\tau)}{\partial z}=0$$

Lateral faces.

$$h_1(0,y,z,\tau)=h_{1,0}; H_2(0,y,z,\tau)=H_{2,0}$$

$$\frac{\partial h_1(L_x,y,L_{z_1},\tau)}{\partial x}=0$$

$$\frac{\partial H_1(L_x,y,L_{z_1},\tau)}{\partial x}=0$$

$$h_1(x,0,z,\tau) = h_1(x,L_y,z,\tau) = h_{1,0}(x,y,z,\tau);$$

$$H_2(x,0,z,\tau) = H_2(x,L_y,z,\tau) = H_{2,0}(x,y,z,\tau);$$

where: $h_{1.0}$, $H_{2.0}$, $H_{3.0}$, $H_{4.0}$ – initial states of undisturbed groundwater and the formation, which are given in the form:

$$h_{1,0}(x,y,z,0) = z, 0 \leq z \leq L_{z1}$$

$$H_{2,0}(x,y,z,0) = 32 - \frac{10 \cdot x}{L_x}, 0 \leq x \leq L_x, 0 \leq y \leq L_y, 0 \leq z \leq L_{z2}$$

Verification of the model using field data from the 2024 OFR confirmed its adequacy.

Conclusions. The Arkhyz-1 site contains two high-yield, hydraulically isolated aquifers, located at intervals of 10–70 m and 80–110 m, separated by a regional confining bed. The second aquifer (80–110 m) is the primary water supply source, being better protected from surface contamination.

Based on the data from experimental filtration work in 2024, the static transmission coefficients for three observation wells were determined to be 0.00627, 0.000917 and 0.000633 m/(m³/day) for wells No. 131-K-1, 131-K-bis and 131-E, respectively.

Based on the experimental data processing method, integral parameters characterizing the hydraulic interaction of wells in the reservoir were obtained: D = 0.0135487, K = 0.00075576, K_p = 2.1019758. Graphs of the spatial distribution of interaction coefficients were constructed, which allows for the visualization of pumping influence zones.

A mathematical model of hydrolithospheric processes has been developed in the form of a system of unsteady flow equations for a two-layer medium (groundwater and production horizon), taking into account flow between layers (Darcy's law), the elastic properties of rocks, and the localized impact of production wells. The model is supplemented with appropriate initial and boundary conditions.

The verification of the model on a field data array confirms its adequacy and applicability for predictive calculations of changes in the hydrodynamic regime during field operation.

The obtained results and the developed model create a scientific and methodological basis for optimizing the operating mode of the Arkhyz field, assessing groundwater reserves taking into account the natural protection of horizons, and planning measures for rational nature management in the context of increasing recreational pressure on the region.

Список литературы

1. Малков А. В., Першин И. М. Системы с распределёнными параметрами. Анализ и синтез. М.: Научный мир, 2012. 476 с.
2. Дубогрей В. Ф., Королев Б. И., Малков А. В., Першин И. М., Першин М. И., Помеляйко И. С., Уткин В. А., Хмель В. В. Кисловодское месторождение углекислых минеральных вод: системный анализ, диагностика, прогноз и управление. М.: Наука, 2015. 283 с.
3. Першин И. М., Шестопалов М. Ю. Проектирование распределённых систем. Теория и практика: учебное пособие. 2-е изд., перераб. и доп. Пятигорск: СКФУ, 2023. 252 с.
4. Першин И. М., Веселов Г. Е., Першин М. И. Методы аппроксимации передаточных функций распределённых объектов // Системный синтез и прикладная синергетика: сборник научных трудов VII Всероссийской научной конференции. Таганрог: ЮФУ, 2015. С. 106–117.
5. Першин М. И. Особенности распределенных объектов // Материалы научно-практической конференции «Университетская наука – региону». Пятигорск: СКФУ, 2017. С. 138–143.

6. Першин И. М., Малков А. В., Криштал В. А. Построение системы управления параметрами эксплуатации системы добычи минеральной воды регионе КМВ // Современная наука и инновации. 2013. № 1 (1). С. 17–23.
7. Першин И. М., Помеляйко И. С. Системный анализ экологического состояния зоны гипергенеза курорта Кисловодска // Вестник Северо-Кавказского федерального университета. 2013. № 3 (36). С. 74–80.
8. Бондин И. А. Системный анализ гидролитосферных процессов Ессентукского месторождения минеральных подземных вод (Новоблагодарненский участок) // Вестник Санкт-Петербургского государственного университета технологии и дизайна. 2025. № 2. С. 5–15.
9. Першин И. М., Кузьмин Н. Н., Малков А. В. Формирование целевых функций в задачах управления гидролитосферными процессами // 5-я Российская мультиконференция по проблемам управления: Сборник материалов конференции «Информационные технологии в управлении» (ИТУ-2012). Санкт-Петербург: Электроприбор, 2012. С. 622–632.

References

1. Malkov AV, Pershin IM. Distributed Parameter Systems. Analysis and Synthesis: monograph. Moscow: Nauchnyy mir, 2012. 476 p. (In Russ.).
2. Malkov AV, Pershin IM, Pershin MI, Pomelyayko IS, Utkin VA, Korolev BI, Dubogrey VF, Khmel VV. Kislovodsk deposit of carbonated mineral waters. System analysis, diagnostics, forecast and management. Moscow: Nauka, 2015. 283 p. (In Russ.).
3. Pershin IM, Shestopalov MY. Design of Distributed Systems. Theory and Practice: textbook. 2nd ed., rev. and suppl. Pyatigorsk: NCFU, 2023. 252 p. (In Russ.).
4. Pershin IM, Veselov GE, Pershin MI. Methods of approximation of transfer functions of distributed objects. In: System synthesis and applied synergetics: collection of scientific papers of the VII All-Russian Scientific Conference. Taganrog: SFU. P. 106-117. (In Russ.).
5. Pershin MI. Features of distributed objects. In: Materials of the All-Russian Scientific and Practical Conference "University Science to the Region". Pyatigorsk: NCFU, 2017. P. 138-143. (In Russ.).
6. Pershin IM, Malkov AV, Krishtal VA. Construction of a control system for operation parameters of mineral water extraction system in the CMS region. Modern Science and Innovations. 2013;1(1):17-23. (In Russ.).
7. Pershin IM, Pomelyayko IS. System analysis of the ecological state of the hypergenesis zone of the Kislovodsk resort. Newsletter of North-Caucasus Federal University. 2013;3(36):74-80. (In Russ.).
8. Bondin IA. System analysis of hydrolithospheric processes of the Essentuki mineral groundwater deposit (Novoblagodarnensky site). Bulletin of the Saint Petersburg State University of Technology and Design. 2025;2:5-15. (In Russ.).
9. Pershin IM, Kuzmin NN, Malkov AV. Formation of objective functions in the tasks of managing hydrolithospheric processes. In: 5th Russian Multiconference on Control Problems: Collection of materials conference "Information Technologies in Management" (ITM-2012). St. Petersburg: Elektropribor, 2012. P. 622-632. (In Russ.).

Информация об авторах

Екатерина Александровна Меркулова, аспирант кафедры синергетики и процессов управления Института компьютерных технологий и информационной безопасности, Южный федеральный университет, 344006, Россия, г. Ростов-на-Дону, ул. Большая Садовая, 105/42, e-mail: emer@sfedu.ru

Вклад автора:

Екатерина Александровна Меркулова – автор осуществил сбор, обработку и интерпретацию полевых данных, выполнил математическое моделирование и верификацию, подготовил текст рукописи и утвердил окончательный вариант статьи.

Information about the author

Ekaterina A. Merkulova, Postgraduate Student, Department of Synergetics and Control Processes, Institute of Computer Technologies and Information Security, Southern Federal University, 105/42 Bolshaya Sadovaya st., Rostov-on-Don, 344006, Russia, e-mail: emer@sfedu.ru

Author contributions:
Ekaterina A. Merkulova – the author collected, processed and interpreted field data, performed mathematical modeling and verification, prepared the manuscript and approved the final version of the article.