DOI: 10.12731/2658-6649-2025-17-6-2-1586 **EDN: GTJJBW**
UDC 626.8

Original article

IRRIGATION OF SLOPE LANDS BY SUBSURFACE IRRIGATION METHOD USING A SIMULATOR OF HORIZONTAL WELLS

L.V. Kravchenko, A.S. Lebedev, A.E. Khadzhidi, T.Yu. Khashirova

Abstract

Background. To evaluate the effect of different irrigation parameters, a model of a sloping slope was developed for experiments, and different irrigation regimes were investigated using a horizontal well simulator. To consider the process of subsurface irrigation were modeled sloping slopes of sand-soil on the laboratory installation of the author's design, implemented at the Department of Hydraulics and Agricultural Water Supply of Kuban State Agricultural University. Based on the analysis of the results of the experiments, a graph showing the trajectory of irrigation water movement when modeling subsurface irrigation using a simulator of horizontal well was obtained for the first time. The obtained results showed that the main flow of irrigation water in the process of its movement has the trajectory of a downward curve, originating directly from the simulator of horizontal well, then passing at an angle the whole considered area of the slope, and ending at its lower boundary.

Purpose. Purpose of the study to investigate the effectiveness of subsurface irrigation on sloping slope models using a horizontal well simulator.

Materials and methods. Measurement of the indicators of slope angle and soil moisture level were carried out in laboratory conditions, experiments using a simulator of horizontal wells; the method of mathematical modeling was used for the analysis of wetting processes; statistical methods were used for the processing of experimental data. This work is based on the analysis of methods and techniques of irrigation on sloping soil surfaces. To consider the process of subsurface irrigation were modeled sloping slopes of sand-soil on the laboratory installation of the author's design, implemented at the Department of Hydraulics and Agricultural Water Supply of Kuban State Agricultural University. Horizontal well simulators in the form of U-shaped tubes consisting of two vertical parts and one perforated horizontal part were placed in the sand-soil of the author's laboratory installation. A multifactorial experiment was conducted on the experimental laboratory installation to study the technical feasibility of quality irrigation of crops grown on sloping slopes with the help of simulators of horizontal wells equidistantly located down the slope.

Results. The data obtained during the laboratory experiment were processed, and on the basis of their analysis the graphs of dependences of water penetration distances on its volumes at angles of inclination to the plane of 10-30 degrees were plotted.

Conclusion. Based on the analysis of the results of the experiments, for the first time a graph showing the trajectory of irrigation water movement when modeling subsurface irrigation using a simulator of a horizontal well was obtained, which demonstrated the movement of the main flow of irrigation water, which is the trajectory of a downward curve originating directly from the simulator of a horizontal well, then passing at an angle through the whole slope area under consideration, and ending at its lower boundary.

Keywords: subsurface irrigation; simulator of horizontal wells; U-shaped tube; visual inspection; video endoscope

For citation. Kravchenko, L. V., Lebedev, A. S., Khadzhidi, A. E., & Khashirova, T. Yu. (2025). Irrigation of slope lands by subsurface irrigation method using a simulator of horizontal wells. *Siberian Journal of Life Sciences and Agriculture*, *17*(6-2), 626-638. https://doi.org/10.12731/2658-6649-2025-17-6-2-1586

Научная статья

ОРОШЕНИЕ СКЛОНОВЫХ ЗЕМЕЛЬ СПОСОБОМ ПОДПОЧВЕННОГО ПОЛИВА С ИСПОЛЬЗОВАНИЕМ ИМИТАТОРА ГОРИЗОНТАЛЬНЫХ СКВАЖИН

Л.В. Кравченко, А.С. Лебедев,
А.Е. Хаджиди, Т.Ю. Хаширова

Аннотация

Обоснование. Для оценки влияния различных параметров полива была разработана модель наклонного склона для экспериментов, исследованы различные режимы полива с использованием имитатора горизонтальных скважин. Для рассмотрения процесса подпочвенного полива были смоделированы наклонные склоны пескогрунта на лабораторной установке авторской конструкции, реализованные на кафедре гидравлики и сельскохозяйственного водоснабжения Кубанского ГАУ. Полученные результаты показали, что основной поток поливочной воды в процессе своего движения имеет траекторию ниспадающей кривой, берущей свое начало непосредственно от имитатора горизонтальной скважины, далее проходящей под некоторым углом весь рассматриваемый участок наклонного склона, и заканчивающейся у нижней его границы.

Цель. Цель исследования изучить эффективность подпочвенного полива на моделях наклонных склонов с использованием имитатора горизонтальных скважин.

Материалы и методы. Измерение показателей эффективности угла наклона и уровня увлажненности почвы проводились в лабораторных условиях, эксперименты с использованием имитатора горизонтальных скважин; для анализа процессов увлажнения использовался метод математического моделирования; для обработки экспериментальных данных – статистические методы. Данная работа основана на анализе методов и способах полива на наклонных поверхностях почвогрунта. Для рассмотрения процесса подпочвенного полива были смоделированы наклонные склоны пескогрунта на лабораторной установке авторской конструкции, реализованные на кафедре гидравлики и сельскохозяйственного водоснабжения Кубанского ГАУ. В пескогрунт авторской лабораторной установки были помещены имитаторы горизонтальных скважин в виде П-образных трубок, состоящие из двух вертикальных частей и одной перфорированной горизонтальной. На опытной лабораторной установке был проведен многофакторный эксперимент по изучению технической возможности осуществления качественного полива сельскохозяйственных культур, выращиваемых на наклонных склонах, при помощи имитаторов горизонтальных скважин, эквидистантно расположенных вниз по склону.

Результаты. Полученные в ходе лабораторного эксперимента данные были обработаны, на основании их анализа были простроены графики зависимостей расстояний проникновения воды от ее объемов при углах наклона к плоскости 10-30 градусов.

Заключение. На основании анализа результатов проведенных экспериментов впервые получен график, отображающий траекторию движения поливочной воды при моделировании подпочвенного полива при помощи имитатора горизонтальной скважины, продемонстрировавший движение основного потока поливочной воды, представляющего собой траекторию ниспадающей кривой, берущей свое начало непосредственно от имитатора горизонтальной скважины, далее проходящей под некоторым углом весь рассматриваемый участок наклонного склона, и заканчивающейся у нижней его границы.

Ключевые слова: подпочвенный полив; имитатор горизонтальных скважин; П-образная трубка, визуальный осмотр; видеоэндоскоп

Для цитирования. Кравченко, Л. В., Лебедев, А. С., Хаджиди, А. Е., & Хаширова, Т. Ю. (2025). Орошение склоновых земель способом подпочвенного полива с использованием имитатора горизонтальных скважин. *Siberian Journal of Life Sciences and Agriculture*, *17*(6-2), 626-638. https://doi.org/10.12731/2658-6649-2025-17-6-2-1586

Introduction

Cultivation of agricultural structures is largely determined by the timeliness and sufficiency of irrigation water volumes delivered to the fields. If the first, the timeliness of irrigation, is solved mainly by organizational and logistical methods, then the second condition, i.e., provision of necessary volumes of irrigation water, often has problems associated with both its physical deficit, including due to changes in climatic conditions, and with the complexity of water delivery to agricultural lands located at sufficiently large distances from water supply sources [1-5].

This becomes especially important for the conditions of growing agricultural products on sloping slopes, the percentage of which is used in agriculture in Krasnodar Krai (and not only) is quite high.

Materials and methods

It should be noted that the organization of supply and distribution of irrigation water at the top of the slope is a complex technical task, in addition, it is necessary to develop a set of measures for its retention and uniform distribution over the entire area of the slope.

Currently, there is a significant number of studies devoted to the study and development of irrigation technologies on sloping surfaces, but the problem remains relevant and requires further study and solution [6-12].

In order to solve the problem of developing the technology of subsurface irrigation of agricultural structures grown on sloping slopes, as well as to identify and take into account as many factors influencing this process as possible, a multifactor laboratory experiment was designed to study different variants of application of this technology on the laboratory unit of the author's design and implementation.

The main factors influencing the technological process of subsurface irrigation were determined, as well as the functional values obtained as a result of the experiment (Table 1).

Table 1.

Plan for a multivariate laboratory experiment

Rock type Tilt angle	K_1 (sandy soil)		
α_1	L_1	L_2	L_3
	V_1	V_2	V_3
	l_1	l_2	l_3
	t_1	t_2	t_3
	φ_1	φ_2	φ_3
α_2	L_1	L_2	L_3
	V_1	V_2	V_3
	l_1	l_2	l_3
	t_1	t_2	t_3
	φ_1	φ_2	φ_3
α_3	L_1	L_2	L_3
	V_1	V_2	V_3
	l_1	l_2	l_3
	t_1	t_2	t_3
	φ_1	φ_2	φ_3

where $\alpha_{1\text{-}3}$ – tilt angles; $K_{1\text{-}3}$ – permeability coefficients; $L_{1\text{-}3}$ – borehole depth, cm; $V_{1\text{-}3}$ – water volume, ml; $l_{1\text{-}3}$ – liquid penetration distance, cm; $\varphi_{1\text{-}3}$ – measured moisture content within the rock type under study, %; $t_{1\text{-}3}$ – time measurement for determining the moisture content indicator inside the soil, min.

The experiment was prepared and conducted at the Department of Hydraulics and Agricultural Water Supply of Kuban State Agricultural University using a laboratory unit of its own design and execution, scale 1:100. In the process of its realization, works were carried out on the production of a working model of the slope, allowing to change the values of the angles of its inclination to the horizon. In addition, on the slope itself were placed at different depths simulators of horizontal wells, which made it possible to model different variants of subsurface irrigation, according to the given methodology in Table 1.

The 3000 cm long experimental setup was divided into three parts in order to set different tilt angles as shown in Figure 1. Each part of the model was separated from the other by waterproof plates made of PVC material. The modeled tilt angle to the plane was made of PVC plates having struts along the entire length of the arrangement inside each model. On top of the slope plate, 10 cm high sand-soil was poured on top of the slope plate. Then inside the sand-soil was laid U-shaped tube to a depth of 2 cm, consisting of two vertical and 1 horizontal perforated tube. And the horizontal tube has a perforation on the side of 45 degrees. The spacing of the U-shaped tube was carried out for technical reasons, and to prevent hydraulic fracturing and flow of drilling mud on the surface of the sand-soil. In order to determine the fluid movement inside the sand-soil, an observation well for the whole depth of the sand-soil was laid inside at a distance of 5 cm from the U-tube. For the convenience of monitoring the movement of liquid inside the sand-soil, the observation wells were marked with a series of 1-cm-long marks.

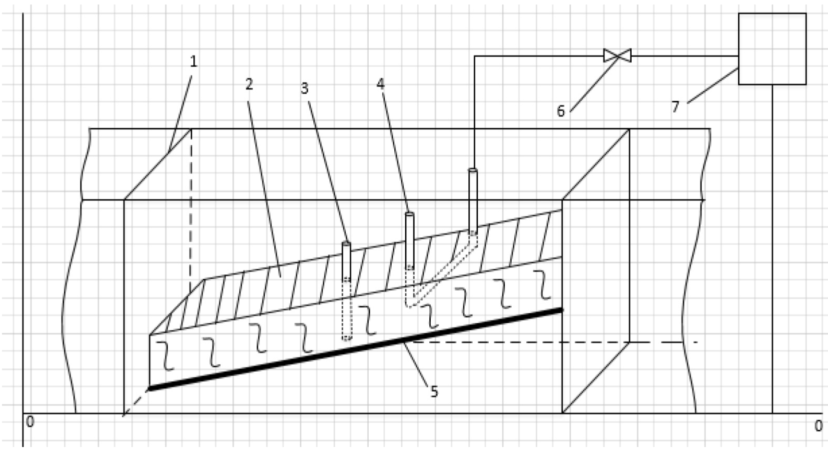

Fig. 1. Schematic diagram of the experimental laboratory setup
1 – Waterproof PVC plate; 2 – Sandy soil; 3 – Observation well; 4 – U-shaped tube; 5 – PVC plate for creating a slope; 6 – Crane; 7 – Measuring container

After placing the above mentioned, equipment in the laboratory setup, the experiment was carried out from the existing measuring tank filled with water up to 1000 ml. After opening the rotary tap, water from the measuring tank started to flow into one vertical tube of the U-tube system.

Measurements of sand-soil moisture indices were carried out with the help of a tare moisture meter. Measurement of sand-soil moisture was carried out with the help of a calibrated probe sensor, the error of which did not exceed 5%. At the time of the experiment, the movement of liquid was observed using a moisture meter and a video endoscope in the observation well. The time of each experiment was measured using a stopwatch, the time of which was synchronized with the NTP server MSK-IX.

Results

According to the above described, methodology and algorithm of the experiment, experiments with the P-tube placement at a depth of 4 cm and 6 cm were carried out. The results of experiments with the U-shaped tube at a depth of 2 cm, 4 and 6 cm are presented in Table 2.

Table 2.

Experimental results

Tilt angle, degree	Liquid volume, ml	Distance of observation well location from the U-tube, cm	Depth of U-tube placement 2 cm		
			Humidity, %	Fluid passage distance, cm	Depth of water penetration into the observation well, cm
10	200	5 cm	5.3	4.5	5.5
	400		5.7	5	
	600		7.5	6	
20	200		4.4	5.3	3
	400		6.2	6.7	
	600		8.8	9	
30	200		4.8	5	5
	400		7	6.2	
	600		9	7.3	
Tilt angle, degree	Liquid volume, ml	Distance of observation well location from the U-tube, cm	Depth of U-tube placement 4 cm		
			Humidity, %	Fluid passage distance, cm	Depth of water penetration into the observation well, cm
10	200	5 cm	7	3.7	6.5
	400		13.2	6	
	600		14.1	7.5	
20	200		7.5	4.5	7.5
	400		12.9	6.4	
	600		14.1	7.5	
30	200		5.3	4.3	6.5
	400		9	5	
	600		11.5	6.6	
Tilt angle, degree	Liquid volume, ml	Distance of observation well location from the U-tube, cm	Depth of U-tube placement 6 cm		
			Humidity, %	Fluid passage distance, cm	Depth of water penetration into the observation well, cm
10	200	5 cm	9.5	4.5	7
	400		13.7	6.5	
	600		15.3	6.5	
20	200		9.4	4	8
	400		10.4	4.5	
	600		13.7	6.3	
30	200		7.1	4.6	7.5
	400		8.9	7	
	600		12.8	7.5	

Based on the data given in Table 2, a graph of dependencies of water penetration distances on its volume at angles of inclination to the plane of 10-30 degrees was plotted. Thus, on the example of laying a U-shaped tube at a depth of 2 cm, we will build a 3D model in the programming language Python, as well as calculate the error in Python [11]. Figure 3 shows the graph of water penetration distance dependencies on its volume at angles of inclination to the plane of 10-30 degrees at a depth of 2 cm of the P-shaped tube.

At the end of the experiments, an evaluation of the obtained metrics was performed:

– Root-mean-square error MSE:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2, \quad (1)$$

where y_i – true value; $\hat{y}_i$ – predicted value; n – number of data points. The closer the MSE is to zero, the better the model.

– Root-mean-square error MAE:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (2)$$

The smaller the MAE, the more accurate the model.

– Determination coefficient R^2:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2}, \quad (3)$$

where $\tilde{y}_i$ – average of the true values.

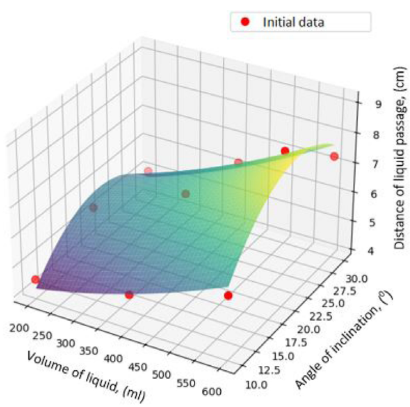

Fig. 3. Graph of dependences of water penetration distance on its volumes at angles of inclination to the plane of 10-30 degrees at the depth of U-tube embedment by 2 cm

Value of R^2 is characterized by the following conditions:

1) $R^2 = 1$ (model perfectly predict the data);

2) $R^2 = 0$ (model predicts no better than the mean value);

3) $R^2 < 0$ (model is worse than the prediction of the mean).

An algorithm implemented in Python was developed to determine the values of the metrics and the results obtained are shown in Table 3.

Table 3.

Metrics values

№	Metrics	Values
	Root-mean-square error MSE	0,1284
	Root-mean-square error MAE	0,3062
	Determination coefficient R^2	0,9265

Conclusion

Based on the analysis of the results of the experiments, a graph showing the trajectory of irrigation water movement when modeling subsurface irrigation using a simulator of horizontal well was obtained for the first time. The obtained results showed that the main flow of irrigation water in the process of its movement has the trajectory of a downward curve, originating directly from the simulator of horizontal well, then passing at an angle the whole considered area of the slope, and ending at its lower boundary.

Conflict of interest information. The authors declare that they have no conflict of interest.

References / Список литературы

1. Albaji, M., Golabi, M., Boroomand Nasab, S., & Zadeh, F. N. (2015). Investigation of surface, sprinkler and drip irrigation methods based on the parametric evaluation approach in Jaizan Plain. *Journal of the Saudi Society of Agricultural Sciences*, *14*(1). DOI: https://doi.org/10.1016/j.jssas.2013.11.001
2. Devika, N., Narayanamoorthy, A., & Jothi, P. (2017). Economics of drip method of irrigation in red chilli crop cultivation: an empirical study from Tamil Nadu. *Journal of Rural Development*, *36*(3), 293–310. DOI: https://doi.org/10.25175/jrd/2017/v36/i3/118062
3. Ramah, K., Santhi, P., & Thiyagarajan, G. (2011). Moisture distribution pattern in drip irrigated maize based cropping system. *Madras Agricultural Journal*, *98*(1–3), 51.
4. Reyes-Cabrera, J., Zotarelli, L., Dukes, M. D., Rowland, D. L., & Sargent, S. A. (2016). Soil moisture distribution under drip irrigation and seepage for potato

production. *Agricultural Water Management*, *169*, 183–192. DOI: https://doi.org/10.1016/j.agwat.2016.03.001
5. Selim, T., Berndtsson, R., & Persson, M. (2013). Simulation of soil water and salinity distribution under surface drip irrigation. *Irrigation and Drainage*, *62*, 352–362. DOI: https://doi.org/10.1002/ird.1739
6. Fan, W., & Li, G. (2018). *IOP Conference Series: Earth and Environmental Science*, *121*, 052402.
7. Muršec, M., Leveque, J., Chaussod, R., & Curmi, P. (2018). The impact of drip irrigation on soil quality in sloping orchards developed on marl – A case study. *Plant, Soil and Environment*, *64*(1), 20–25. DOI: https://doi.org/10.17221/623/2017-PSE
8. Too, V. K., Omuto, C. T., Biamah, E. K., & Obiero, J. P. (2014). Review of soil water retention characteristic (SWRC) models between saturation and oven dryness. *Open Journal of Modern Hydrology*, *4*, 173–182. DOI: http://dx.doi.org/10.4236/ojmh.2014.44017
9. Perkins, K. S. (2011). Hydraulic conductivity – Issues, determination and applications (pp. 419–434). London: IntechOpen.
10. Rowshon, M., Muhammed, H., Mojid, M., Ruediger, A., & Soom, M. (2019). Two-dimensional modeling of water distribution under capillary wick irrigation system. *Pertanika Journal of Science & Technology*, *27*(1), 205–223.
11. Maksimov, I., Alekseev, V., & Chuchkalov, I. (2019). Erosion resistance potential as a soil erodibility characteristic based on energy approach. *IOP Conference Series: Earth and Environmental Science*, *226*, 012067.
12. Alekseev, V. V., & Maksimov, I. I. (2013). Aerodynamic method for obtaining the soil water retention curve. *Eurasian Soil Science*, *46*(7), 751–757. DOI: https://doi.org/10.1134/S1064229313070028. EDN: https://elibrary.ru/RFJCDX
13. Sholihah, U. M., Pulungan, N. A. H. J., & Rizqi, F. A. (2023). Soil erodibility: influence factors and its relation to soil fertility in Nawungan, Selopamioro, Bantul Regency. *BIO Web of Conferences*, *80*, 03017. DOI: https://doi.org/10.1051/bioconf/20238003017
14. Alekseev, V., Chuchkalov, S. I., Philippov, V., et al. (2020). Simulation of drip irrigation on slope lands. *BIO Web of Conferences: International Scientific-Practical Conference "Agriculture and Food Security: Technology, Innovation, Markets, Human Resources" (FIES 2019)* (Kazan, 13–14 November 2019), 00218. DOI: https://doi.org/10.1051/bioconf/20201700218. EDN: https://elibrary.ru/JIHCJF
15. Ilyinskaya, I. N., & Gaevaya, E. A. (2021). The productivity of crop rotations on the eroded slope of ordinary chernozems depending on agricultural prac-

tices. *BIO Web of Conferences*, *32*, 02007. DOI: https://doi.org/10.1051/bioconf/20213202007. EDN: https://elibrary.ru/EBIIYR
16. Sodikova, G., Shadieva, N., & Saidova, M. (2025). Assessment of mountain soil erosion threat levels based on digital analysis. *BIO Web of Conferences*, *173*, 03003. DOI: https://doi.org/10.1051/bioconf/202517303003. EDN: https://elibrary.ru/WHLSOT

AUTHOR CONTRIBUTIONS

The authors contributed equally to this article.

ВКЛАД АВТОРОВ

Все авторы сделали эквивалентный вклад в подготовку статьи для публикации.

DATA ABOUT THE AUTHORS

Lyudmila V. Kravchenko, Doctor of Technical Sciences, Associate Professor, Head of the Department of Design and Technical Service of Transport and Technological Systems
Don State Technical University
1, Gagarin Sq., Rostov-on-Don, 344000, Russian Federation
lvkravchenko@donstu.ru
SPIN-code: 9684-8955
ORCID: https://orcid.org/0000-0002-9228-3313
ResearcherID: ABD-9790-2021
Scopus Author ID: 57204646125

Alexander S. Lebedev, Postgraduate Student
Kuban State Agrarian University named after I.T. Tribulin
13, Kalinin Str., Krasnodar, Krasnodar Krai, 350044, Russian Federation
lebedev_alex96@mail.ru
SPIN-code: 3173-7300
ORCID: https://orcid.org/0009-0009-8801-5066

Anna E. Khadzhidi, Doctor of Technical Sciences, Associate Professor, Head of the Department of Hydraulics and Agricultural Water Supply
Kuban State Agrarian University named after I.T. Tribulin
13, Kalinin Str., Krasnodar, Krasnodar Krai, 350044, Russian Federation

dtn-khanna@yandex.ru
SPIN-code: 4502-9170
ORCID: https://orcid.org/0000-0002-1375-9548
ResearcherID: HGV-0040-2022
Scopus Author ID: 57194710533

Tatiana Yu. Khashirova, Doctor of Technical Sciences, Associate Professor, Head of the Department of Computer Technologies and Information Security
Kabardino-Balkarian State University
173, Chernyshevskogo Str., Nalchik, Kabardino-Balkarian Republic, 360004, Russian Federation
khashirova@mail.ru
SPIN-code: 5948-9742
ORCID: https://orcid.org/0000-0002-4584-4376
Scopus Author ID: 6504778822

ДАННЫЕ ОБ АВТОРАХ

Кравченко Людмила Владимировна, доктор технических наук, доцент, заведующий кафедрой «Проектирование и технический сервис транспортно-технологических систем»
Донской государственный технический университет
пл. Гагарина, 1, г. Ростов-на-Дону, 344000, Российская Федерация
lvkravchenko@donstu.ru

Лебедев Александр Сергеевич, аспирант
Кубанский государственный аграрный университет имени И.Т. Трубилина
ул. Калинина, 13, г. Краснодар, 350044, Российская Федерация
lebedev_alex96@mail.ru

Хаджиди Анна Евгеньевна, доктор технических наук, доцент, заведующий кафедрой «Гидравлика и сельскохозяйственное водоснабжение»
Кубанский государственный аграрный университет имени И.Т. Трубилина
ул. Калинина, 13, г. Краснодар, 350044, Российская Федерация
dtn-khanna@yandex.ru

Хаширова Татьяна Юрьевна, доктор технических наук, доцент, заведующий кафедрой «Компьютерные технологии и информационная безопасность»
Кабардино-Балкарский государственный университет
ул. Чернышевского, 173, г. Нальчик, Кабардино-Балкарская Республика, 360004, Российская Федерация
khashirova@mail.ru

Поступила 07.07.2025 Received 07.07.2025
После рецензирования 29.08.2025 Revised 29.08.2025
Принята 15.10.2025 Accepted 15.10.2025