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Mathematical Modelling of Dust Transfer from the Tailings in the Alagir Gorge of the RNO-Alania

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Abstract

Introduction. Mathematical modelling of the aerodynamics of mountain gorges is an actual means of studying possible man-made emissions in various meteorological conditions that increase the transfer of pollutants in the direction of densely populated areas. Aerodynamics and climatic conditions are unique for various mountain gorges. This requires a separate study for each specific case. The paper studies the distribution of dust aerosol from the Unal tailings dump, located near the village of Verkhny Unal (Alagir Gorge, RNO-Alania, RF), with south and south-easterly winds. With these wind directions, the dust of the tailings dump is carried by air currents in the north direction, towards Alagir. The aim of the study is to obtain a forecast for the surface concentration of dust with an increased content of lead, zinc and other elements near densely populated areas of the flat part of RNO-Alania.

Materials and Methods. The model takes into account the terrain, surface wind roses and dust deposition processes. The calculations were carried out for the case of neutral stratification and without taking into account the influence of seasonal factors using a mathematical model previously published by the authors.

Results. The model prediction of the dust concentration distribution obtained from calculations is shown. The frequencies and amplitudes of oscillations of unsteady jet streams in the cross section of the Alagir gorge are analyzed. Based on the data of satellite sensing of the Earth's atmosphere, the frequency of winds leading to the transfer of dust in the direction of densely populated areas is estimated.

Discussion and Conclusion. The Unal tailings dump is a source of pollutants and over many years of its existence, soil contamination can be significant. Field studies of the soil in the Alagir area and, possibly, measures for its reclamation are necessary.

Keywords: mountain ravine, dust, mine tailings, mathematical model, complex terrain

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Научная статья

Математическое моделирование распространения пыли от хвостохранилища в Алагирском ущелье РСО-Алания

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Аннотация

Введение. Математическое моделирование аэродинамики горных ущелий и возможных техногенных выбросов в различных метеорологических условиях, особенно увеличивающих перенос загрязняющих веществ в направлении густонаселенных районов, является актуальным средством исследования этих процессов. Аэродинамика и климатические условия уникальны для различных горных ущелий, что требует проведения отдельного исследования для каждого конкретного случая. В работе рассматривается распространение пылевого аэрозоля от Унальского хвостохранилища, расположенного вблизи поселка Верхний Унал (Алагирское ущелье, РСО-Алания, РФ), в случае возникновения южных и юго-восточных ветров. При этих направлениях ветра пыль хвостохранилища переносится течениями воздуха в северном направлении, в сторону Алагира. Целью исследования является получение прогноза для приземной концентрации пыли с повышенным содержанием свинца, цинка и других элементов вблизи густонаселенных районов равнинной части РСО-Алания.

Материалы и методы. Модель учитывает ландшафт местности, приземные розы ветров и процессы осаждения пыли. Вычисления проводились для случая нейтральной стратификации и без учета влияния сезонных факторов с использованием математической модели, ранее опубликованной авторами.

Результаты исследования. Выполнен модельный прогноз распределения концентрации пыли. Проанализированы частоты и амплитуды осцилляций нестационарных струйных течений в поперечном сечении Алагирского ущелья. На основе данных спутникового зондирования земной атмосферы оценена повторяемость ветров, приводящих к переносу пыли в направлении густонаселенных районов.

Обсуждение и заключение. Унальское хвостохранилище является источником загрязняющих веществ и за годы его существования загрязнение почвы может быть значительным. Авторами сделан вывод о необходимости полевых исследований почвы в районе Алагира и, возможно, принятия мер по ее рекультивации.

Ключевые слова: горное ущелье, пыль, хвостохранилище, математическая модель, сложный рельеф

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Introduction. Tailings contain fine-dispersed waste from mining and processing plants, which, as a rule, are stored in an open manner and enter the atmosphere of mountain gorges in the form of a dust aerosol. Often, meteorological measurements are not carried out in full in mountain gorges or are not available at all, and the available data are insufficient to predict the distribution of pollutants (SV). This disadvantage can be partially eliminated by using mathematical modeling and data from weather satellites. The experience of using mathematical modeling taking into account the data of remote sensing of the Earth is given in [1−4].

The study of the atmosphere of mountainous territories using mathematical modeling is carried out for a wide range of tasks [3−11]. In [5−7; 11−13] modern mathematical models, solution methods and basic laws of aerodynamics of mountain gorges are presented. Due to the multifactorial nature of aerodynamics [7], idealized gorges are often modeled and simplified synoptic conditions are considered [5−6; 8].

The dispersion of dust aerosol in mountain gorges and in flat areas differs [12−13]. In addition, each mountain gorge has a unique climate and aerodynamics, for the study of which a detailed mathematical model must include many arrays of initial data, boundary conditions and weather conditions, which is extremely resource-intensive and often faces a lack of necessary data.

In [3−4], a mathematical model of a mountain gorge is used, which does not require detailed input data, but takes into account the main factors: the mountain landscape of the area, surface wind roses, dust deposition processes, atmospheric turbulence. Standardized algorithms for solving hydrodynamic equations of the OpenFOAM computational package implementing the finite volume method are used.

The authors consider the removal of SV from the bowl of the Unal tailings pond of the Sadon lead-zinc combine, located in the bend of the Ardon River near the village of Unal (Alagirsky district, RNO-Alania, RF), in the Alagir gorge, the Northern part of the Caucasian ridge, at 42.862 s. w. and 44.145 v. d., at an altitude of about 1700 meters above sea level. The width of the gorge near the tailings dump reaches 3000 m, the height of the slopes is 2570 m. The tailings dump was created more than 50 years ago and contains about 2.6 million tons of tailings, which contain 0.21 % wt. Pb, 0.32 % wt. Zn, as well as other elements. Reclamation measures significantly reduce dusting processes, however, a significant amount of dust is contained on the slopes of the gorge and in the soils near the tailings dump. The results of field studies of tailings content on the slopes of the gorge from the Unal tailings dump are devoted to works [14–16].

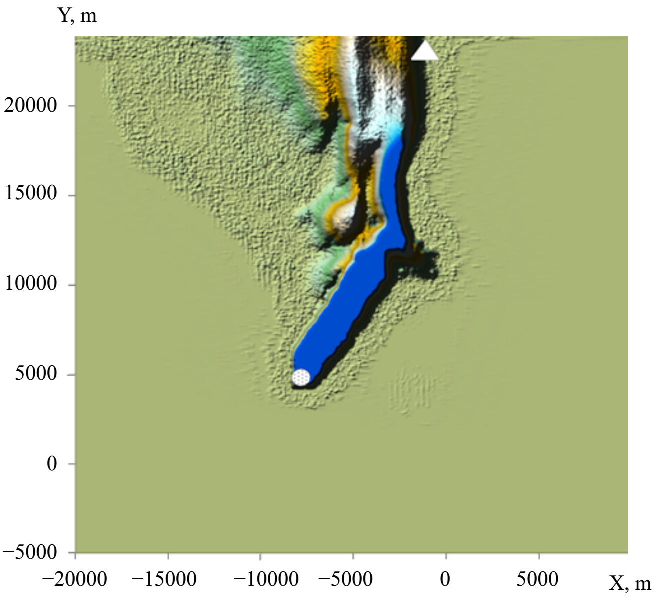
The conditions of separation of dust aerosol particles from the surface obtained in experiments are presented in [17–18]. The determining factors are the strength of the wind and the turbulence of the atmosphere, and the distribution of dust deposited on the slopes is determined by the topography and the wind rose. In [8–9; 19–23], mathematical modeling of aerodynamics and dust propagation is used for real problems.

In this paper, synoptic situations associated with easterly and southeasterly winds over the Alagir gorge are considered, in which dust from the tailings dump spreads in a northerly direction, towards Alagir (RNO-Alania). The occurrence of unsteady jet streams that carry dust in a northerly direction is discussed.

Materials and methods. The mathematical model used, presented in [3–4], is a fairly simple and workable tool useful for estimating the concentration of polluting substance (PS) in the mountain atmosphere. The comparison of forecast values and field measurement data showed satisfactory accuracy sufficient for practical applications.

Research results. Sixteen calculations were carried out with different boundary conditions for wind at the upper boundary of the calculated area with a step of 22.5°: north, north-north-west, north-west, etc. In each calculation, the aerodynamic fields and the concentration of PS from the model source located in the bowl of the Alagirsky Gorge tailings pond were calculated. As a result of averaging and rationing of these calculations, the average concentration of PS is obtained, given in [3]. The normalized PS concentration fields obtained for the south-east, south-south-east and south directions of the external wind are shown here. In other calculated cases, the SV is moved not towards Alagir, but in the direction of sparsely populated areas, reaching which the concentration of PS decreases below the MPC (indicated according to the Federal Law of the Russian Federation "On Sanitary and Epidemiological Welfare of the population" No. 52-FZ of March 30, 1999).

Figure 1 *a* shows the concentration of SV obtained by calculating the south-easterly wind direction; Figure 1 *b* shows the south-south-easterly wind; Figure 1 *c* shows the south wind; Figure 1 *d* shows a topographic map of the calculated area exported from the computational grid. The location of the source is marked with a white circle; the values $0 < C < 0.1C_{max}$ are shown, where C_{max} is the concentration near the source. The triangle marks the southern suburbs of Alagir. The normalization used in [3] was applied. In the areas marked in blue, the concentration exceeds the value of $0.1C_{max}$.



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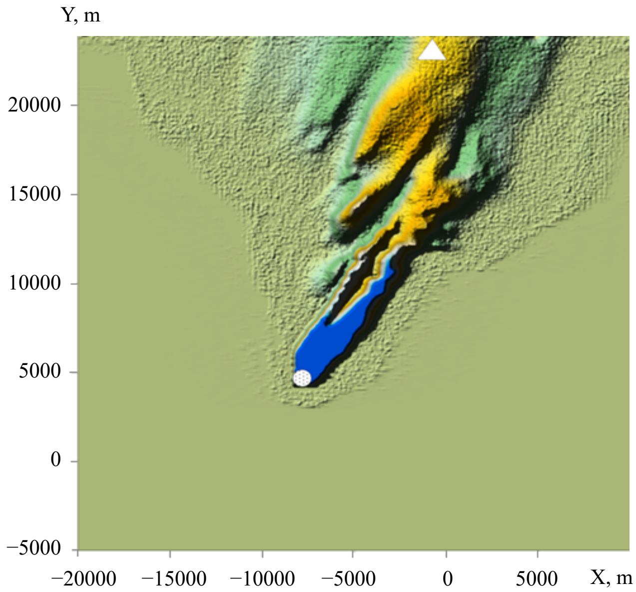

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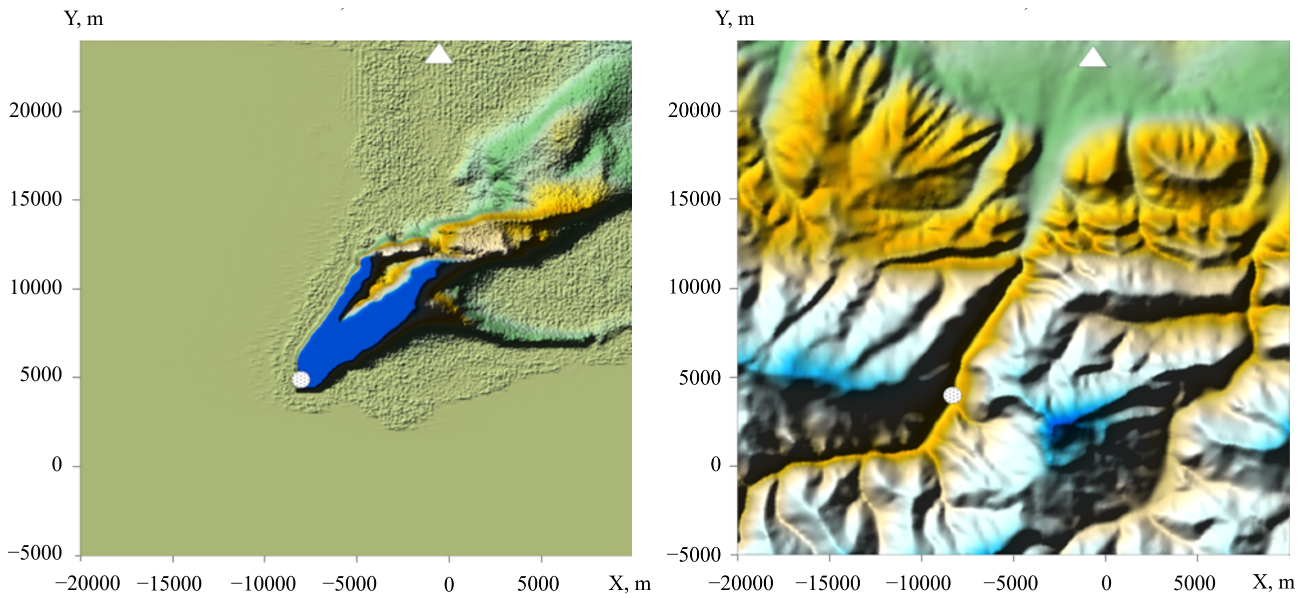


Fig. 1. Forecast maps of the concentration of polluting substance (PS): *a* — south-easterly wind; *b* — south-south-easterly wind; *c* — south wind; *d* — heights.
The *x*-axis is directed to the east, *y* — to the north; the reference point is chosen on the topographic map arbitrarily, near the tailings dump

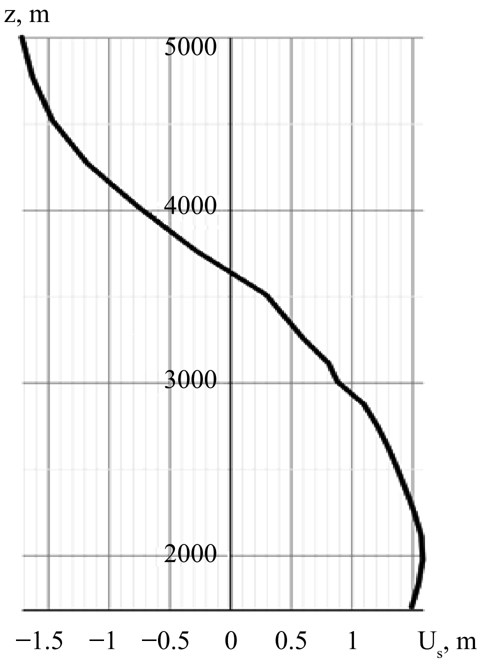
Fig. 1 shows the predicted value of the concentration of PS on the slopes of the Alagir gorge and in the area of the gorge›s exit to the plain near Alagir for synoptic situations in which the concentration of PS will be maximum. The concentration of PS $0.1C_{max}$, shown in Fig. 1, exceeds the MPC (for lead and zinc) by 2−3 times.

Fig. 1 *a* shows that the concentration of PS on the slopes of the gorges tracks the topography of the surface: the dust aerosol spreads along the axis of the gorge, and is also captured by areas of increased turbulence and carried by the wind. Fig. 1 illustrates the spread of PS to the northeast with a southerly wind, with only a small number of them falling into the suburbs of Alagir. For the south-eastern and south-south-eastern cases near Alagir, the number of PS is reached, exceeding the MPC by 2−3 times for both lead and zinc.

1. Jet streams. The propagation of PS along the gorge is determined not only by the external wind, but also by the jet stream, which occurs in a direction perpendicular to the cross-section of the gorge. In all calculations, a geostrophic approximation is used, in which a balance is maintained in the free atmosphere between the pressure drop and the Coriolis force, which makes it possible to calculate stationary air flows over a flat surface. Inside the cross-section of the gorge, this balance is disturbed, as a result, an air flow is formed inside the gorge with a power depending on the baric gradient.

For example, in Fig. 2 and the profile of the northern component of the wind speed (perpendicular to the external wind) above the tailings dump for the case of an easterly wind is given. The northern component of the wind speed directed along the gorge reaches a value of 1.5 m/s, while the wind over the gorge does not have a northern component. In Fig. 2 *b* for the same case, the spatial distribution of the northern component of wind speed is presented. At the exit of the gorge, the jet stream turns to the west under the influence of an external wind. In almost all calculated cases, a similar jet stream occurs, inside of which the source PS is located, which changes the pattern of their scattering, which spreads mainly to the north or south along the gorge.

2. Pulsation frequencies of jet streams. At the point of the computational grid located above the tailings dump, all calculated fields were recorded after each time step. The analysis of these data showed that the flow over the tailings dump in most calculations is non-stationary under constant boundary conditions. For the southeast wind, the frequency is 0.0005 Hz and the pulsation amplitude is ≈0.18 m/s; for the southeast — 0.00024 Hz and ≈0.07 m/s, respectively; for the south wind — 0.00037 Hz and ≈ 0.06 m/s.



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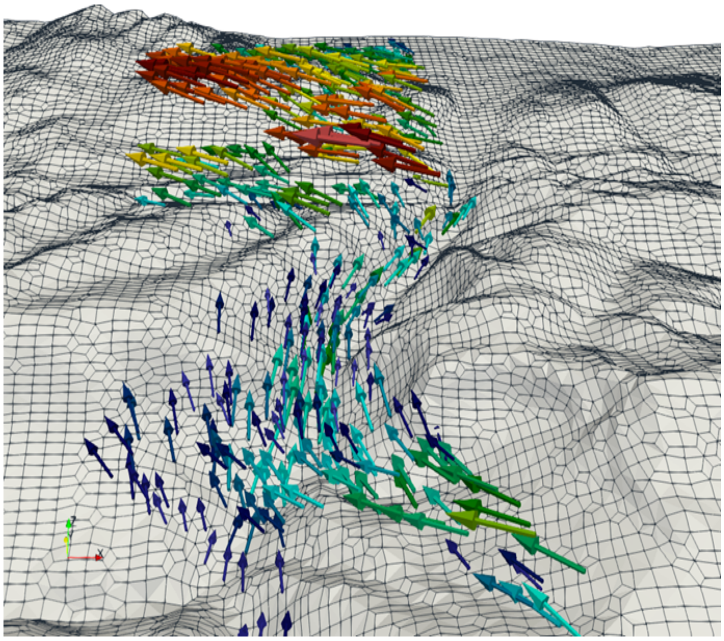
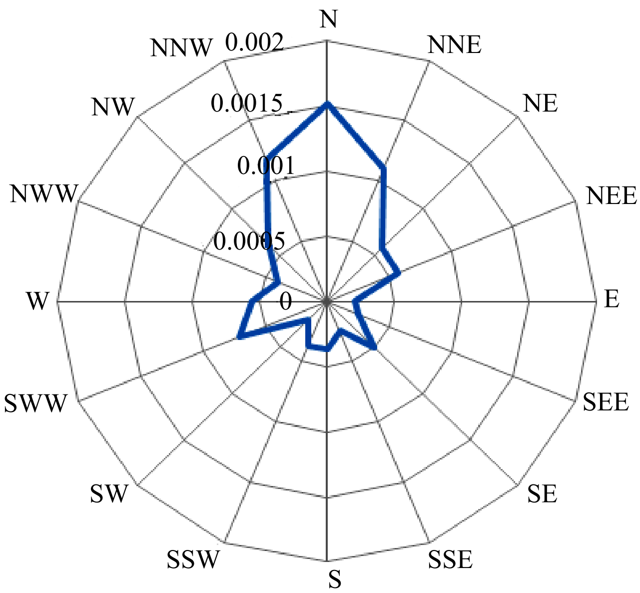


b)

Fig. 2. Jet stream in the Alagir gorge: *a* — profile of the northern component of the wind speed over the tailings dump; *b* — spatial behavior of the jet stream (view from the south of the Alagir gorge in the area of the tailings)



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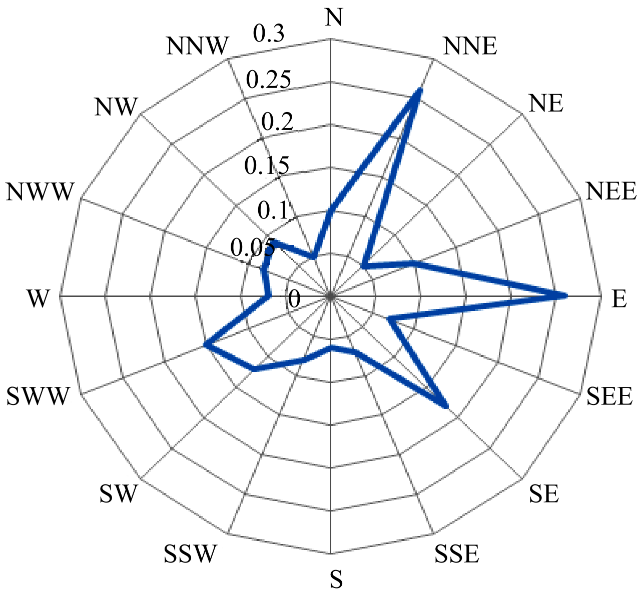

b)

Fig. 3. Frequencies and amplitudes of oscillations at a point located above the tailings dump at a height of about 20 meters: *a* — frequencies and *b* — amplitudes of oscillations

Fig. 3 shows the frequencies (Fig. 3 *a*) and oscillation amplitudes (Fig. 3 *b*) obtained as a result of 16 calculations for different wind directions at the upper boundary, at a point located above the tailings storage at an altitude of about 20 meters. It can be seen that the frequencies (Fig. 3 *a*) are elongated along the northern direction close to the direction of the gorge axis, and the largest pulsation amplitudes (Fig. 3 *b*) are located in the north-northeast direction coinciding with the gorge axis, as well as in the east and south-east directions when jet currents arise.

Probably, such slow and small changes in wind speed inside the gorge do not lead to noticeable changes in the transfer of PS. In the case of a north-northeast wind, the oscillation occurs in 15 minutes at 0.25 m/s, which leads to the appearance of dust clouds, increased turbulence and increased air removal from the gorge.

3. Wind rose. Wind roses and wind strength by direction, based on satellite measurements of atmospheric characteristics provided by the European Copernicus Global Monitoring System (EuMetSAT and Sentinel weather satellites) [24–25] and measurements provided by the NASA weather satellite system (GEOS, Terra, Aqua) [26] for 20 years of measurements, are given in [4] (Fig. 2). The differences observed there can be attributed to the discrepancy of the areas (about 10×10 km or more for different weather satellites) for which measurements are provided, as well as the averaging time of these measurements.

Based on the available data, it is possible to draw conclusions about the repeatability of the synoptic situations considered in this paper: the repeatability of the south wind is 15.0 % according to Copernicus (ERA-5 reanalysis model) and 10.1 % according to NASA (MERRA2 reanalysis model); south-east — 10.4 % and 3.3 %, respectively; south-south-eastern — 20.9 % and 5.2 %. Thus, the synoptic situations under consideration occur quite often, their total repeatability is 46.3 % according to Copernicus and 18.6 % according to NASA, and their consequences need to be analyzed and monitored.

The accuracy of the wind rose obtained from 16 computational experiments for 16 directions of the external wind and the wind rose measured by a weather station located in the Alagir gorge near the Unal tailings dam was compared. This comparison is described in [4] (Fig. 3) and shows satisfactory agreement with the exception of southern winds, which are more winds in the model rose. Both the shape of the wind rose and the repeatability of the other wind directions practically coincide.

Discussion and Conclusion. The results obtained show that the Unal tailing dump is a source of dust containing soil pollutants. During the existence of the tailing dump, pollution can become very large-scale, as a result of which field studies of the soil in the Alagir area are required, as well as measures for its reclamation.

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