Dust content in the air: A case study of the Afanasyevsky open pit mine (Russia)

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Abstract. According to experts, the world consumption of mineral raw materials and the rocks extraction have reached about 12 and 100 billion tons per year, respectively. Overall Russian coal production accounts for 259.9 million tons (according to the Ministry of Energy of the Russian Federation and the ‘Rosinformugol’ agency), metallic ores are estimated at 230 million tons, and building materials reach 1.4 billion tons. The overall growth in mineral production and capacity of ore producers cause an increase in the negative environmental impact of mining extraction and processing. It should be taken into account that due to the depletion of reserves of rich mineral raw materials, the volume of mined rock mass and the amount of processing waste of mineral raw materials increase. It results in the formation of mine dumps, consisting rocks, ore beneficiation wastes, ashes, slags, and sludge. Research data describe critical environmental situation within the mining enterprises, and especially mine dumps, as a result of massive dust emissions. In addition, there is a tendency to further environmental degradation, due to the increase in production capacity without complying with effective measures to reduce dust emissions. Considering the fact that fine particles are priority pollutants in the extraction and processing of mineral resources at mining enterprises, it is necessary to develop new environmentally efficient and economically viable methods of dust suppression.

1. Introduction
Anthropogenic sources of aerosols emitted during the extraction and processing of minerals are one of the largest and specific pollutants of almost all components of the biosphere, a high concentration of which is harmful to human health, forests, agriculture, etc. Therefore, from the waste dumps of mines and quarries, more than 8 million tons of dust per year are blown into the atmosphere, including about 1 million tons per year in Russia [1, 5, 10]. As a result, the dustiness of the air increases tenfold compared with the established norms [4, 22, 29].

The greatest environmental hazards are mining enterprises located in close proximity to settlements, as well as to agricultural and forestry areas [2, 3, 8, 13, 24]. The Afanasyevsky open pit mine is an example of such an enterprise. The mining company develops the Afanasyevsky carbonate field, located in the Voskresensky district of the Moscow Oblast, on the right bank of the Moskva river. The enterprise directly borders agricultural territories of farms and Achkasovo village. In addition, the city of Voskresensk is located within 4 kilometers of the mine dump. The company was commissioned in 1964. The overburden rocks are represented by loams, variegated marls, sometimes intersected by fine-grained dense limestones. Bedding rocks are marls and a layer of dolomitized rocks with an average thickness...
of 3.5 m and limestone with a thickness of about 7 m. Marl and limestone are used as raw materials for the cement production, dolomitic rocks are processed for crushed stone and lime flour. The total mineral reserves amount to 300 million tons. There are four developed bench within the deposit: overburden rocks, marl, dolomite, and limestone benches. Stripping operations are carried out with walking and bucket-wheel excavators. The total overburden volume is more than 3 million m$^3$ per year. The annual raw materials output for cement production is more than 4 million tons. Dolomite mining for the production of crushed stone and flour amounts to more than 6 million tons. The development of the Afanasyevsky field is accompanied by aerosol emissions at all stages, leading to air pollution in the nearest settlements, pollution of farm areas with falling dust, which leads to the reduction in yields and products quality. In this regard, the purpose of the research was to assess the state of the components of the natural environment in the impact zone of the Afanasyevsky open pit mine.

2. Methods
In the course of research conducted in 2015–2018, a number of procedures for assessing the state of atmospheric air were carried out. This made it possible to accurately assess the environmental situation in the impact zone of the Afanasyevsky open pit mine.

Analysis of the dust content in atmospheric air in the impact zone of the mine dump was conducted throughout the year, in periods without precipitation under various meteorological conditions. Atmospheric air monitoring points were located directly on the dump territory, on the border of the sanitary protection zone of the production facility and on the residential area of the city in accordance with the average long-term prevailing wind directions [9].

Monitoring of atmospheric air was carried out in accordance with GOST 17.2.3.01–86 Nature protection. Atmosphere. Air quality control regulations for populated areas to analyze the dust content in the atmospheric air of the impact zone of the Afanasyevsky open pit mine [15].

Monitoring sites are located taking into account the natural and technical security of the mine dump (the main directions of the average annual wind rose, significant topographic uplifts and depressions, forested areas, and buildings), which makes it possible to accurately identify the patterns of the formation of the atmospheric pollution halo.

Measurement of fine particle concentration in the ground-level air was carried out according to a specially developed program. This program is aimed at identifying areas with the maximum surface concentration of inorganic dust with SiO$_2$ content from 70 to 20 % under various meteorological conditions. Strict periodicity of measurements was not taken into account. Measurements were carried out using DustTrak TSI-8533 aerosol monitor. This size-segregated mass fraction measurement technique is superior to either a basic photometer or optical particle counter (OPC). It delivers the mass concentration of a photometer and the size resolution of an OPC. Thus, this aerosol monitor provides mass concentration of fine particles with dimensions of $–1$, $–2.5$, $–4$ and $–10$ μm. Measurement of suspended substances is carried out in a wide concentrations range (0.01–150 mg/m$^3$), and the relative measurement error does not exceed 20 %. To determine the airflow velocity, atmospheric pressure, temperature, and relative air humidity, the MES-200 meteo-analyzer was used.

During the whole time of field observations, the wind speed changed from 1–2 m/s to 14 m/s (with gusts up to 20 m/s), and the frequency of its directions, on average, corresponded to the wind rose for this region. Such a wide range of changes in the intensity and direction of the wind load and a large number of measurements allowed obtaining reliable data on the dustiness of the ground-level air impact zone of the mine dump under various meteorological conditions. This allowed assertion with a high degree of accuracy on the substantial technogenic load of the Afanasyevsky open pit mine on the atmospheric air of the region.

Over the entire period of field observations of the ground-level air, the air temperature varied from $–10$ to $+30$ °C, air humidity did not exceed 65 %, and the atmospheric pressure corresponded to normal values.
3. Results
The assessment and forecast of the state of atmospheric air in the territory of the Afanasyevsky open pit mine were carried out on the basis of the conducted monitoring observations, taking into account the influence of meteorological parameters on the dust distribution in the environment.

The impact of mine dumps dusty surfaces on the environment is closely related to the climatic characteristics of the dumps area [20, 28]. The climate of the region predetermines the intensity and degree of atmospheric pollution, the distance and propagation direction of dust particles depending on the prevailing wind directions. Fig. 1 shows the annual curves of several meteorological factors of the study area, based on the recent 30-years-data. Of particular importance is the consideration of the natural and climatic conditions of mine dumps in identifying agrometeorological phenomena dangerous for the agrarian business (Table 1).

![Figure 1](image_url)

**Figure 1.** Annual temperature and relative humidity dynamics: 1 – average daily temperature; 2 – relative humidity; 3 – wind speed

Data analysis allows conclusion that temperature, speed, and relative humidity of the air favor dust blowing from the dumps [16]. The monitoring studies showed that fugitive dust emissions (mg/(m²·s)) parameter make it possible to predict dust dispersion and determine the concentration at any distance (Fig. 2), based on the graphs (Fig. 3, 4) plotted for dust with a particle size of 0–100 μm.

The graphs show that when the wind speed is in the range of 0–5 m/s, the fugitive dust emissions with a particle size of 0–100 μm is insignificant and varies linearly. With an increase in speed above 5 m/s, the fugitive dust emission increases along a parabola.

Thus, all other things being equal, the least air dustiness at any distance from the dump should be expected at wind speeds of up to 5 m/s. This is confirmed by the results of special measurements of the fugitive dust emissions from the dumps surface.
Table 1. The principal agroclimatic indicators of the Afanasyevsky mine impact zone

| Indicators                                         | Period of the year | Characteristics |
|---------------------------------------------------|--------------------|-----------------|
| 1. Climate type: boreal                          |                    |                 |
| 2. Sum of active temperatures, °C                 | V-IV               | 2365            |
| 3. The temperature of the warmest month, °C       | VI-VII             | 18.3            |
| 4. The temperature of the coldest month, °C       | XII-II             | -10.8           |
| 5. Precipitation, mm                              | I-XII              | 550             |
| 6. Moisture balance, mm                           | IV-IX              | 117             |
| 6. Probability of dry years, %                    | year               | 8.8             |
| 7. Season duration                                 |                    |                 |
| spring (5–15°C)                                   | beginning          | 17.04           |
|                                                   | end                | 05.06           |
|                                                   | days               | 49              |
| summer (15–20°C)                                  | beginning          | 6.06            |
|                                                   | end                | 27.08           |
|                                                   | days               | 83              |
| autumn (5–15°C)                                   | beginning          | 28.08           |
|                                                   | end                | 11.10           |
|                                                   | days               | 45              |
| winter (0–15°C)                                   | beginning          | 3.11            |
|                                                   | end                | 2.04            |
|                                                   | days               | 152             |
| 10. The main vegetation period (10–15°C)          | beginning          | 3.05            |
|                                                   | end                | 18.09           |
|                                                   | days               | 138             |
| 11. Frost-free period                             | beginning          | 12.05           |
|                                                   | end                | 20.09           |
|                                                   | days               | 130             |
| 12. Biological productivity, points               |                    | 60–70           |

Figure 2. Dependence of fugitive dust emissions on airflow velocity
Studies have shown that air pollution varies with the seasons. That why at the Afanasyevsky mine there is an increase in the concentration of dust in the atmosphere, intensively blown off from the dried rocks from April to September (Fig. 6). In addition, on the contrary, from October to March there is a decrease in the dust concentration in the air due to the high humidity of the rocks.

Dust blowing from the dumps surface depends on the humidity of rocks and dust [17]. This dependence is shown in the graph (Fig. 5), curve 2. Analyzing the meteorological factors, it can be concluded that the dumps are one of the key sources of air pollution. Assessment of emission and transfer of dust can be performed on the basis of known techniques [11, 18, 25]. The amount of dust from open areas (dumps) can be determined by the formula (1):

\[ \Pi = S \cdot W_c \cdot \gamma \]  

where \( \Pi \) – the amount of dust, kg/s; \( W_c \) – fugitive dust emissions (taken into account the wind speed on the dump surface, kg/(m²·s); \( S \) – open surface area, m²; \( \gamma \) – coefficient of rock mass change (approximately taken equal to 0.1).

**Figure 3.** Dispersion in the surface layer of dust blown off from mine dump surface, depending on the wind speed: 1 – 3.5 m/s; 2 – 5.3 m/s; 3 – 6.7 m/s; 4 – 7.8 m/s
Figure 4. The dependence of the dust content of the air from the air velocity: 1 – dry dust, 2 – dust moistened with water.

Figure 5. Changing dust concentration in the atmospheric air near the Afanasyevsky open pit mine.

The calculated values of changes in the relative dust content in the air and the $\Delta M$ relative mass of precipitated dust depending on the distance to the source are shown in Fig. 7.

$$\Delta_{\Pi} = \left( \frac{\Pi}{\Pi_0} \right) \times 100 \%,$$  \hspace{1cm} (2)

where $\Pi$ is the actual dust content in the air (mg/m$^3$); $\Pi_0$ is the initial dust content at the formation site (mg/m$^3$).

$$\Delta_M = \left( \frac{M}{M_0} \right) \times 100 \%,$$  \hspace{1cm} (3)

where $M$ and $M_0$ are the deposited dust masses at the calculated point and at the formation site, respectively, t/(ha·year).
Changes in the content of harmful components in the atmospheric air over the seasons are explained [12, 14, 26], mainly by the direction and intensity of the heat and mass transfer processes between the mine dump and atmosphere [7, 27]. Heat and mass transfer is determined by the thermodynamic parameters of the atmosphere (temperature, relative humidity, moisture content, air velocity) and the marginal part of the mine dump (temperature, moisture content) [19, 23]. A change in the temperature or moisture content of the atmosphere during daily oscillations leads to the potential difference (gradient) at the boundary between main dump and atmosphere and the increase of the heat or mass (gas) flow, with vapor-liquid phase transitions during the evaporation or condensation [6, 21, 30]. These phenomena change the intensity of fine particle emission from dumps and dust suppression with condensation.

4. Conclusion
Monitoring in the impact zone of the Afanasyevsky open pit mine has revealed the presence of atmochemical pollution halo with a length of up to 25 km². Dust fallout on the surrounding landscapes led to the formation of lithochemical pollution halo of 10 km², and, as a result, the contamination of agricultural areas. The influence of dust forming surfaces on the environment is closely related to the climatic characteristics of the dumps area. The climate of the region predetermines the intensity and degree of atmospheric pollution, the distance and propagation direction of dust particles. There is a seasonal dynamics of changes in the dust content in the atmosphere, which is explained by the direction and intensity of the heat and mass transfer processes between the mine dump and atmosphere. This study has shown the need to reduce the impact of the Afanasyevsky mine dumps on the environment by reclamation and dedusting system installation in such areas.

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