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DEVELOPMENT OF ENHANCED METHOD OF GEOSPATIAL ELECTRICAL INTELLIGENCE OF NEAR-SURFACE SOIL LAYERS IN NORTHERN KAZAKHSTAN FOR DETECTING POLLUTION SOURCES

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This study focuses on the near-surface soil layers in suburban areas of Astana, Northern Kazakhstan, to address the critical issue of soil pollution caused by anthropogenic activities, particularly coal dust dispersion from open railway freight transportation. Existing geophysical methods for soil conductivity measurement lack precision due to interference from upper soil layers and seasonal moisture variations, limiting reliable pollution source identification.

To enhance the precision of measurements, researchers modified the measuring probes. This improvement, combined with geophysical studies and Global Positioning System topographic referencing, allowed for identifying new patterns in pollutant behavior. A strong correlation was established between electromagnetic anomalies and human activities, including transportation, logistics, and urbanization.

The study revealed that soil electrical conductivity near railway tracks was three times higher due to coal dust, with peak values reaching 4.8 mS/m in spring. Modified probes improved measurement accuracy by 28–32 % depending on the season, enabling precise detection of subsurface pollution patterns.

The findings provide insights into urban pollution dynamics and its long-term effects.

Based on experimental data, recommendations were developed such as transition to renewable energy will reduce coal dependency and pollution.

In conclusion, the study highlights key issues surrounding soil pollution and provides recommendations to mitigate its effects. This approach supports sustainable land management, regulatory enforcement, and pollution mitigation strategies in urban-suburban interfaces worldwide

Keywords: soil electrical conductivity, digital processing, experimental data, coal dust, transport and logistics flows, rail transportation

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1. Introduction

Monitoring the condition of suburban and rural lands, and their level of pollution determines the quality of agricultural products and soil productivity. Comprehensive assessment of soil pollution levels not only ensures food safety but also plays a crucial role in maintaining the sustainability of agricultural ecosystems. The accumulation of heavy metals, pesticides, and other harmful substances in the soil can lead to a decline in crop yield, alteration of soil microbiota, degradation of soil fertility, and poisoning of consumers of agricultural products.

Thus, the agroecological assessment of the condition and monitoring of agricultural lands and urban areas is relevant and has one of the most important problems of modern agrochemistry and soil science. It includes a wide range of issues, including assessment of soil fertility for farming, and determination of the level of soil pollution with toxic elements and chemical compounds.

In this context, the development and implementation of advanced monitoring techniques, such as geophysical methods, remote sensing technologies, and in-situ soil sampling, are essential. These methods enable accurate identification of pollution sources, spatial distribution of contaminants, and their dynamics over time.

By establishing threshold levels for pollutants and introducing real-time monitoring systems, it becomes possible to promptly address contamination issues and implement remediation strategies. Furthermore, the data obtained through such monitoring can serve as a basis for developing environmentally friendly land-use practices, optimizing fertilization strategies, and ensuring compliance with regulatory standards.

For instance, the critical role of household and industrial waste in river pollution and flooding in Southeast Asia in the study [1] was disclosed. Currently, pollution of the soil cover of suburbs is one of the most important environmental problems. Monitoring the content of pollutants in the soil is important both for the hygienic assessment of the quality of the soil of populated areas and for determining the suitability of land for growing plants.

Therefore, studies that are devoted to soil pollution monitoring are scientific relevance especially for megacities and their suburbs, which are often the main suppliers of agricultural products.

2. Literature review and problem statement

Soil structure plays a key role in sustainable production as it influences plant growth, ecological functioning and the flow of water and energy between the soil and the atmosphere. However, due to the complex interaction of biological and anthropogenic activities and limited monitoring capabilities, it is difficult to measure soil structure and internal processes both in time and space. It is also important to take into account the influence of soil on the presence of heavy metals in agricultural products [2].

Geophysical sensing methods are non-invasive ways of measuring the physical properties of the studied environments. These methods are effective in detecting anomalies and various aspects of spatial heterogeneity [3]. However, their accuracy can be limited by indirect measurements, requiring expert interpretation, and the methods often rely on snapshot data that may fail to capture dynamic processes over time. In agriculture, geophysical methods such as electrical prospecting (electrical resistivity tomography of the soil – ERT) and electromagnetic surveys are becoming increasingly important for assessing the spatial variability of soil, which is important for effective management and precision agriculture [4]. ERT, despite its utility, has limitations such as sensitivity to soil moisture and salinity, which can distort results. The setup process, requiring precise electrode placement, is challenging in uneven or rocky soils, and its penetration depth may not always reach deeper soil layers. Moreover, the data processing and creation of 2D or 3D models require advanced computational tools and expertise.

Electrical conductivity measurements are used to monitor soil properties and the impact of agricultural practices such as cover cropping, compaction, irrigation, tillage, and fertilization on soil water dynamics and crop yields [5]. Electrical conductivity measurements have become a standard tool in agronomic research due to their efficiency and reliability in defining soil horizons, estimating water content, and monitoring [6]. The studies are performed using multi-electrode devices that create 2D or 3D models of the electrical resistance distribution in the subsoil. An array of electrodes is connected to the soil, providing galvanic contact, and measurements are then taken using different connection configurations. However, the precision of such measurements is influenced by the electrical properties of the medium, connection schemes, and the need to minimize errors in data collection. The current flow in the soil depends on the electrical properties of the medium, the distance between the electrodes, and the connection scheme [7]. Depending on the objectives of the study, a measurement model can be selected that minimizes errors and satisfies the limitations on data spread [8].

Also known for soil mapping and precision farming is the electromagnetic induction (EMI) method [9]. Although ERT and EMI measure the same physical property – electrical resistance (or its inverse conductivity), they do so in different technical ways, namely, with different types of current sources. EMI is widely used in environmental applications [10] for rapid topographic measurement of soil electrical conductivity. However, only frequency domain methods (FDEM) are considered in the work, which limits the scope of application to rocky or mountainous environments. Some practices show that changes in electrical conductivity associated with the salt content in the soil are considered, but in soils with a high degree of heterogeneity or with mineralization, this may lead to incorrect assessment of electrical conductivity data. Although the use of high-frequency alternating current leads to an increase in interference from metal objects, metal structures or power lines, which can significantly distort the results and reduce the reliability of the data obtained. In the paper [11], the influence of soil texture and soil organic matter is studied in detail [12]. In these studies, modern geophysical methods were used, such as electromagnetic induction and georadar data. The combination of geophysical data makes it possible to determine ancient river beds and take into account their dynamics and impact on the modern environment. However, such geophysical studies require significant equipment and research costs, which makes them not suitable for widespread use. The use of electromagnetic induction methods to study hydrogeological structures, discussed in [13], is a relatively new direction, for example, to search for underground rivers. However, it is applicable in environments with high ground contrast and large scanning depths, it is over tens or hundreds of meters and is ineffective for near-surface soil analysis.

There are various approaches to characterizing the spatial variability of the earth, for example, based on radar satellite data [14]. However, they are not as reliable, fast, and easy to use compared to GPS-based mobile measuring equipment [15]. Satellite data are also affected by atmospheric conditions, and access to high-resolution radar data can be prohibitively expensive for regular monitoring.

Modern software allows researchers to construct three-dimensional models of the electrical conductivity of the surface layer based on these data [16, 17]. While these tools are invaluable for understanding soil dynamics, they come with high computational demands, costly licenses, and the risk of errors in data inputs, which can lead to misleading conclusions.

Electrical and electromagnetic methods have been successfully used to characterize soil properties such as bulk density and clay content, as well as state variables including soil salinity and moisture content. However, soil electrical conductivity is influenced by numerous factors, such as porosity, pore water conductivity, and saturation, which vary over time. Some soil properties, such as texture, remain fairly stable, while moisture varies greatly depending on environmental influences. This requires a series of measurements in different seasons using the same types of electrodes and measurement points.

Combining near-surface sounding at different depths can improve the understanding of soil response [18]. While helpful in monitoring processes like seasonal moisture changes or root water uptake, these approaches often focus on shallow soil layers and may fail to capture deeper dynamics. The equipment used in near-surface sounding also has its depth limitations, which could restrict comprehensive analysis. In this context, the geophysical approach helps to highlight the processes of soil moisture change caused by seasonal variations, precipitation and root water uptake [19]. However, the challenges and limitations outlined above emphasize the need for careful selection and integration of methods to address the complexities of soil monitoring and pollution control effectively.

Thus, for the analysis of soil and causes of pollution, the optimal and accurate method is a combination of the geophysical method and the use of GPS. GPS allows data to be linked to specific measurement points with high geographic accuracy, which is especially important for repeated measurements or long-term monitoring.

3. The aim and objectives of the study

The aim of the study is to develop a high-precision geophysical method for measuring soil electrical conductivity with topographic reference to identify pollution sources of the near-surface soil layer of the northern regions of the Republic of Kazakhstan during monitoring of all seasons of the year. This will allow to analyze the reason of source pollution and propose targeted measures to reduce it.

To achieve this aim, the following objectives are accomplished:

– to develop modified probes for high-precision soil conductivity measurements and integrate GPS technology for accurate topographic referencing of surface soil analysis and detecting the pollution sources in suburban areas;

– to conduct field experiments in the northern regions of Kazakhstan to obtain real-time geospatial data on soil electrical conductivity with assess seasonal variations to determine how pollution levels change throughout the year;

– to analyze spatial patterns of soil pollution by identifying key pollution sources and formulate targeted recommendations for reducing soil pollution.

4. Materials and methods

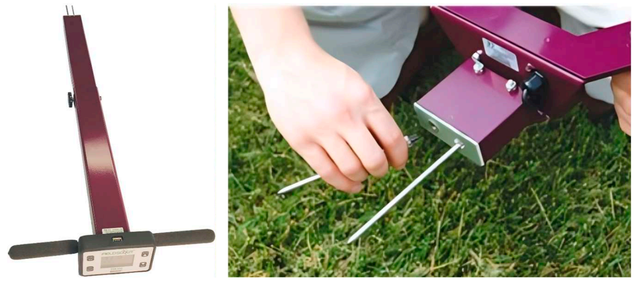
The object of the study is the near-surface soil layers in the suburbs of Astana, Northern Kazakhstan, with a focus on detecting pollution sources linked to railways and highways via developed enhanced method of geospatial electrical intelligence.

As a hypothesis, it is assumed that modifying soil conductivity probes with insulating varnish coatings and integrating GPS-referenced measurements will significantly improve the accuracy of pollution source detection compared to traditional methods.

One of the classical methods of DC electrical exploration is the method of vertical electrical sensing. A model representing the medium as a horizontally layered model is used for the study. Each individual horizontal layer is assumed to be homogeneous, that is, it has no or negligible differences in resistivity. As the current sinks into the depth, the apparent resistivity to ρ changes stepwise when the next layer is reached. Vertical electrical sounding is based on measuring electrical conductivity at different depths in one place on the soil surface. The advantage of the method is that there is no need to perform soil cuts and boreholes and the integrity of the soil is not disturbed.

For experimental determination of electrical conductivity, humidity and temperature of the soil, a portable TDR 350 meter was used, designed for field measurements (Fig. 1, *a*).

The portable TDR 350 Soil analysis device is designed for quick and easy measurement of soil parameters and is made in the form of a rod with 2 removable electrodes installed in its base and allows to measure all types of soil except stony (Fig. 1, *b*).



a *b*

Fig. 1. Portable conductivity meter: *a* – a general view; *b* – an assembly process

The built-in Wi-Fi system allows to save measurement results on a computer or smartphone, and the presence of a GPS receiver allows to take measurements with georeferencing.

To analyze obtained data the Spyder 6 environment and the Python programming language has been used.

5. Results of developing the method of Geospatial Electrical Intelligence and monitoring of the surface soil layer condition in the suburbs of the capital city of the Republic of Kazakhstan

5. 1. Developing an Enhanced Probes and GPS-integrated analysis for suburban soil pollution detection

To assess the reliability and effectiveness of the measurements, a series was initially conducted (Fig. 2).

The measurements carried out showed a significant shortcoming of these measurements. The existing measurement system involves immersion of probes exposed over the entire surface into the soil. This leads to the summation of the conductivity of all soil layers during the immersion of the probes. At the same time, strong conductivity, often of the upper soil layers in the spring-autumn period, suppresses minor changes in the conductivity of the lower soil layers. In this case, the resistance between these electrodes is determined by Ohm's law in integral form for a non-uniform section of the circuit:

$$R = \int_0^l \frac{\rho}{S} \mathrm{d}l, \tag{1}$$

where S is the area of the interelectrode surface; ρ is the resistivity and l is the distance between electrodes.

Or for the specific conductivity of a soil area:

$$G = \int_0^l \frac{S}{\rho} \mathrm{d}l, \tag{2}$$

where the integration interval is taken from the soil surface to the current depth of immersion of the electrodes.

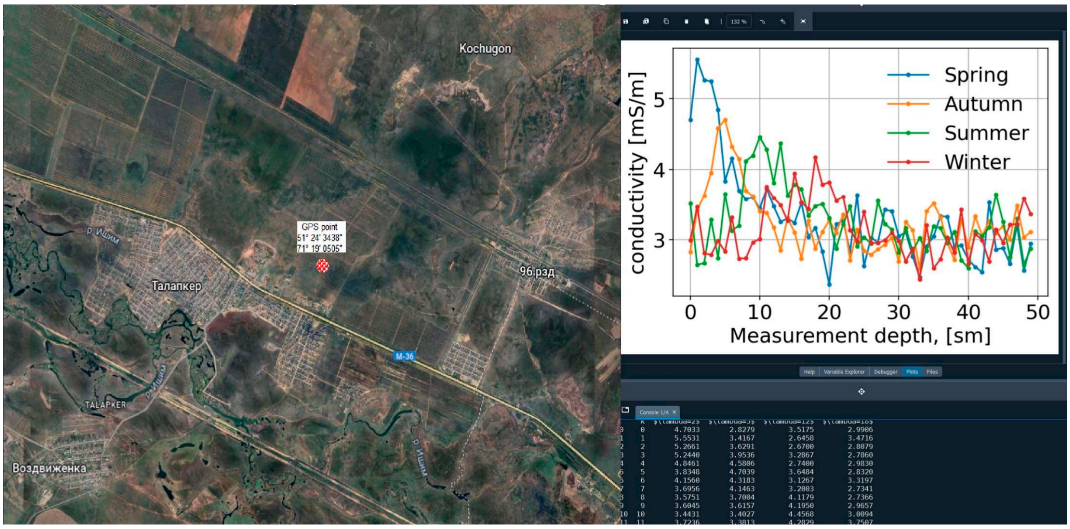


Fig. 2. Electrical conductivity measurements at various depths of the near-surface soil layer

As a result, a significant increase in the conductivity of the upper soil layer when immersing the probes significantly reduces the sensitivity of further measurements. Also, there are large scatters of measurement data associated with the heterogeneity of the soil structure. The reason for this is the soil structure, which in places has a porous semi-air structure or, on the contrary, a wet one, which ultimately leads to sharp jumps in the data of soil electrical conductivity. All this leads to a decrease in the reliability of measurement data at the soil depth.

To solve this problem, it was decided to apply an insulating varnish coating to most of the probe (Fig. 3). And then the formula of specific conductivity for the soil layer will take the form:

$$G = \int_{l_2}^{l_1} \frac{S}{\rho} dl, \quad (3)$$

where integration is carried out on a short probe section l_1: from the beginning of the non-isolated part of the probe l_2 to its final part – the probe tip.

This allowed locally measuring conductivity only in the current soil layer, namely, between the probe tips. In this case, let's obtain values of relative specific conductivity of the soil slightly below standard probes. However, the high sensitivity of the device allows for effective measurement of relative changes in conductivity for any soil layers, even with minor changes in the probe immersion depth. Obviously, this preserve jumps in electrical conductivity data associated with the heterogeneity of the soil structure, but this is solved by software smoothing and a series of measurements. Fig. 4 shows a simplified measurement scheme in the form of discrete layers.

Fig. 5 shows the visualized measurement data. The graphs demonstrate the soil's electrical conductivity with standard and modified probes.

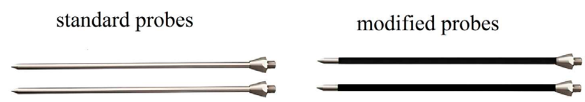


Fig. 3. Appearance of standard and modified probes

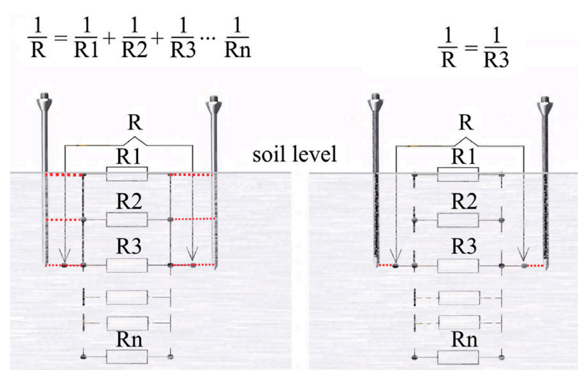
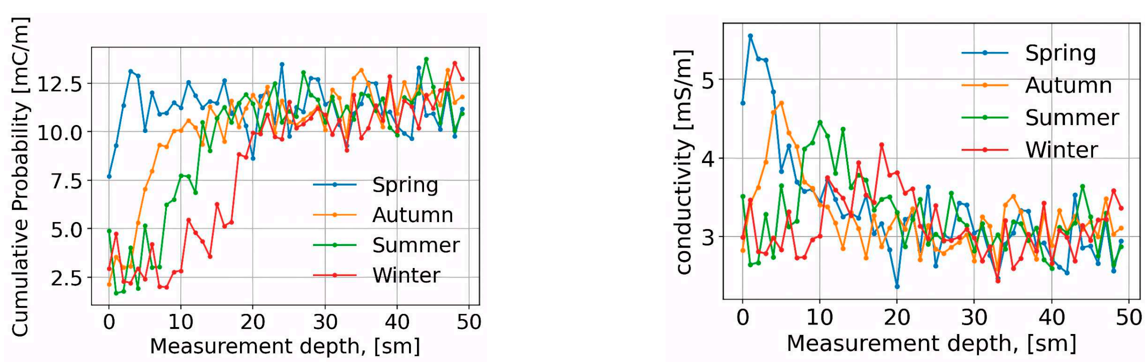


Fig. 4. Simplified scheme for measuring soil in the form of discrete layers



a

b

Fig. 5. Visualized measurement data: *a* — soil electrical conductivity with the standard probe; *b* — soil electrical conductivity with the modified probe

The measurements were carried out in different seasons of the year to demonstrate the dynamics of changes in readings in the same area.

5. 2. Geospatial field analysis of seasonal soil pollution dynamics in Northern Kazakhstan

A series of measurements were taken in different seasons of the year. The measurement point was agricultural land in the suburbs of the city (Fig. 6, *a*) and modified probes were used for the measurements.

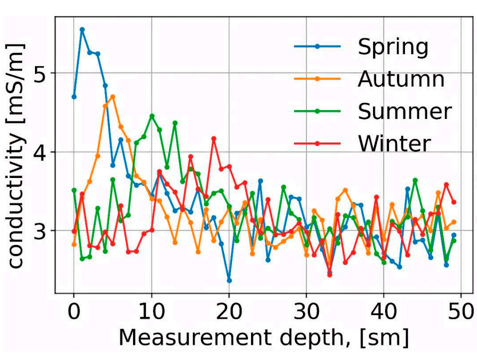
The results are shown in Table 1, and the visualization of the raw data is shown in Fig. 6, *b*. The obtained measurement results were then processed programmatically. The spline interpolation method implemented in the Spyder 6 environment and the Python programming language was used to smooth the data. This allowed to obtain clear graphs of changes in the specific conductivity of the soil (Fig. 6, *c*).

Let's analyze the obtained data. The maximum increase in soil electrical conductivity occurred in the spring, which is associated with the melting of snow and an increase in soil moisture. The consequence is an increase in the electrical conductivity of the upper soil layers. Later, during the summer period, a process of gradual absorption of moisture into the soil occurs. The results of this process are observed on the graphs of this season as a decrease in surface electrical conductivity and its increase in lower soil layers. The minimum electrical conductivity data for a series of measurements were obtained in the winter, when the soil was hidden under a layer of snow. As shown by the measurements, soil electrical conductivity strongly depends on the season of the year and correlates with soil moisture. Deeper than the upper soil layer (>0.3 m), the profiles tend to become uniform, with a monotonous downward growth, so in experimental studies, the emphasis is on the surface soil layer.

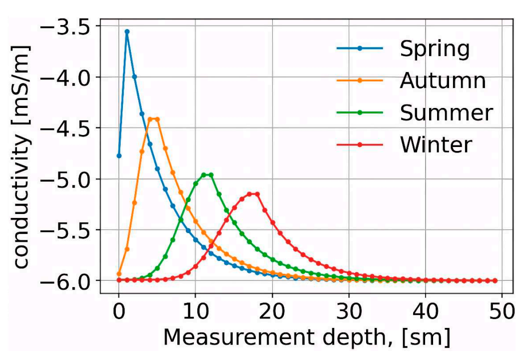
In general, the obtained results in terms of character and numerical values do not contradict the data obtained by other researchers. For example, they are close to the results (Fig. 7) obtained by a group of researchers from the University of the city Padova (Italy) [20].

The study area (Padua city) has a moderately warm climate and a large variation in soil density. Therefore, the stabilization of specific conductivity, which strongly depends on these parameters, for loose soil also occurs at depths up to 50 centimeters, and for dense and stony soil at a depth of 1–4 meters.

a



b



c

Fig. 6. Field data of soil electrical conductivity measurement: *a* – map of the research area; *b* – raw measurement data; *c* – smoothed measurement data

Table 1

The results of field measurements

Depth	Soil electrical conductivity, mS/m			
H, cm	Spring	Autumn	Summer	Winter
0	2.853	0.978	1.668	1.141
1	3.703	1.567	0.796	1.622
2	3.416	1.779	0.820	0.958
3	3.394	2.104	1.437	0.936
4	2.996	2.731	0.890	1.133
5	1.985	2.854	1.798	0.982
6	2.306	2.468	1.277	1.470
7	1.846	2.296	1.350	0.884
8	1.725	1.850	2.268	0.887
9	1.755	1.766	2.345	1.116
10	1.593	1.553	2.607	1.159
11	1.874	1.531	2.433	1.901
12	1.626	1.322	1.956	1.746
13	1.405	1.005	2.516	1.641
14	1.451	1.460	1.774	1.417
15	1.389	1.256	1.937	2.094
16	1.675	0.886	1.872	1.685
17	1.194	1.419	1.490	1.584
18	1.316	1.023	1.629	2.322
19	0.986	1.261	1.655	1.933
20	0.515	1.426	1.461	1.969
21	1.371	1.250	1.025	1.703
22	1.420	1.511	1.371	1.764
23	0.980	0.860	1.623	1.287
24	1.787	1.294	1.057	1.127
25	0.777	0.994	1.187	1.544
26	1.179	0.939	1.096	1.105
27	1.113	1.013	1.701	1.105
28	1.575	1.082	1.374	1.142
29	1.556	1.178	1.295	1.249
30	1.199	0.846	0.970	1.132

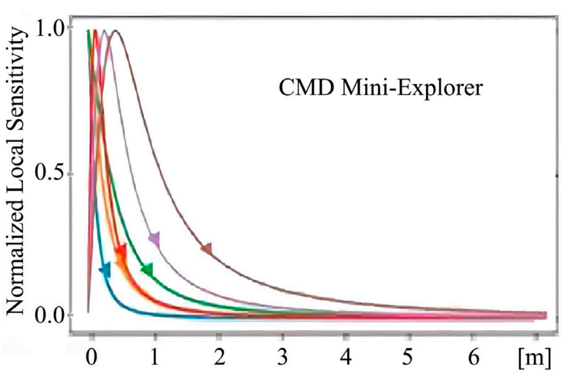


Fig. 7. Results obtained by a group of researchers from the University of Padua [20]

5. 3. Pollution source identification and targeted mitigation strategies

When analyzing the electrical conductivity and moisture of the soil, it is necessary to take into account the seasonality of precipitation, otherwise, an error in the interpretation of the observation results may occur. Thus, the growth of soil moisture averaged in the spring period in a series of measurements was about 50 per cent, while the growth of electrical conductivity at this measurement point and in the same time interval was more than 3 times. Also, the results of comparing the data for other seasons of the year in the lower layers of the soil, where the growth of moisture was no more than 10 per cent, more than a twofold increase in electrical conductivity do not correlate. And in the winter period, when the growth of moisture became minimal, the growth of electrical conductivity in the deep layers of the soil continues.

The reason for this increase, according to the experimental data obtained, could only be external particles on the soil surface, seeping deeper over time. It is known from the literature [3, 6] that traditional sources of pollution can be residential buildings, public utilities, industrial enterprises, agriculture, transport, etc. Therefore, in order to find the source of the sharp increase in soil electrical conductivity in the territory of this rural district, a series of measurements were taken along lines intersecting possible sources of pollution (Fig. 8, *a*). These are agricultural lands, where the sources could be fertilizers applied to the soil, residential areas with possible sources in the form of household waste, power lines and transport and logistics lines. In order to ensure the reliability of the data, five series of measurements were taken (Table 2). The digitized and smoothed data are shown in Fig. 8, *b*.

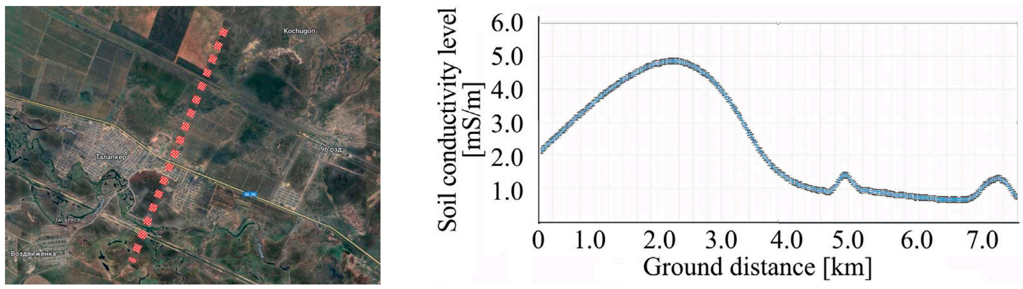
The obtained data revealed a significant increase in electrical conductivity in the first third of the measurements.

To localize the sources of abnormal growth of soil electrical conductivity, a combination of measurements taken with recording of GPS coordinates of measurement points was carried out with a topological satellite map of Google (Fig. 9).

Table 2

Measurement data of soil electrical conductivity along the lines

Measurements 1		Measurements 2		Measurements 3		Measurements 4		Measurements 5	
L, km	*G*, mS/m	*L*, km	*G*, mS/m	*L*, km	*G*, mS/m	*L*, km	*G*, mS/m	*L*, km	*G*, mS/m
0.001	2.038	0.059	2.158	0.118	2.243	0.177	2.329	0.235	2.414
0.294	2.483	0.353	2.568	0.412	2.637	0.471	2.723	0.530	2.791
0.589	2.894	0.647	2.962	0.706	3.048	0.765	3.151	0.824	3.219
0.883	3.288	0.942	3.339	1.001	3.425	1.059	3.493	1.118	3.579
1.177	3.664	1.236	3.716	1.295	3.801	1.354	3.870	1.413	3.921
1.471	3.990	1.530	4.041	1.589	4.110	1.648	4.161	1.707	4.247
1.766	4.298	1.825	4.349	1.883	4.401	1.942	4.435	2.001	4.486
2.060	4.538	2.119	4.589	2.178	4.606	2.237	4.675	2.295	4.709
2.354	4.726	2.443	4.795	2.501	4.777	2.560	4.812	2.619	4.829
2.678	4.846	2.737	4.863	2.796	4.863	2.855	4.863	2.913	4.846
2.972	4.829	3.002	4.812	3.061	4.795	3.119	4.760	3.178	4.726
3.237	4.675	3.296	4.640	3.355	4.589	3.414	4.521	3.473	4.469
3.502	4.435	3.561	4.349	3.620	4.281	3.679	4.178	3.737	4.110
3.796	3.990	3.855	3.904	3.914	3.784	4.002	3.596	4.061	3.459
4.120	3.356	4.179	3.202	4.238	3.048	4.297	2.911	4.356	2.757
4.414	2.620	4.473	2.466	4.503	2.397	4.562	2.243	4.620	2.140
4.709	1.952	4.768	1.866	4.826	1.695	4.885	1.661	4.944	1.575
5.003	1.507	5.062	1.438	5.121	1.387	5.180	1.318	5.239	1.250
5.297	1.216	5.356	1.182	5.415	1.113	5.474	1.130	5.533	1.079
5.592	1.045	5.650	1.027	5.709	0.993	5.768	0.993	5.827	0.942
5.886	0.959	5.945	0.942	6.004	0.908	6.062	0.908	6.121	0.976
6.210	1.130	6.298	1.336	6.386	1.421	6.474	1.336	6.533	1.216
6.622	1.079	6.710	0.976	6.798	0.959	6.857	0.959	6.917	0.668
7.005	0.736	7.095	0.688	7.175	0.688	7.240	0.688	7.328	0.688



a *b*

Fig. 8. Series of measurements along the line with data visualization: *a* — measurement trace; *b* — digitized and smoothed data

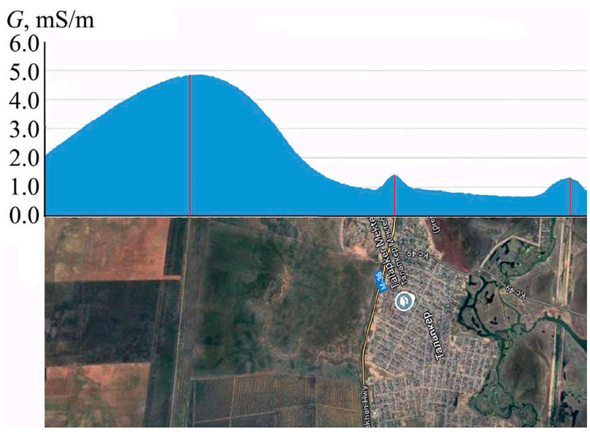


Fig. 9. Survey area profile with superimposed conductivity measurement data

According to the graph, it should be noted that the highest peak values of electrical conductivity were observed near the railway track and a moderate increase in value near highways.

The cause of the abnormal increase in the electrical conductivity of the surface soil layer has been identified scattered coal dust from freight cars with coal transported by rail across the territory of the republic. Based on the results of the study, it is possible to formulate global decisions and current activities.

The main shareholders of our coal resources, as well as part of the railway resources, are foreign companies whose interests are only in obtaining super profits and they are little concerned about the environmental problems of our republic. An example of this is the Indian company «ArcelorMittal Temirtau» in 15 years of operation in the mines of the republic more than 100 people have already died. For comparison, Fig. 10 shows data from the US Department of Labor.

Therefore, in the long term, an alternative to moving away from global coal dependence is the development of our own nuclear energy. This is a rather complicated but necessary path, taking into account the country's historical experience associated with the consequences of long-term nuclear weapons tests at the Semipalatinsk test site, the accident at the Fukushima Daiichi nuclear power plant, etc. However, nuclear power plants have an undeniable advantage – they are environmentally friendly in operation and in the long term generate cheap electricity. It is also important to consider that the Republic of Kazakhstan is the world leader in the production of nuclear energy sources. By a strange coincidence, the Republic of Kazakhstan does not have nuclear power plants, unlike all developed world powers, but continues to destroy the ecology of its country and even increases the rate of coal supplies abroad. And if to talk about the danger to life, it is not nuclear power plants, but primarily coal mines, which today have taken many more lives in the Republic of Kazakhstan alone than all nuclear power plants in the world.

If to talk about the current plan of events, these are, first of all:

– the need to reduce production for export and the use of coal for domestic use;

– a ban on open methods of transporting angles by rail. This includes, for example, the use of awnings or protective films on wagons;

– reduction in the number of coal-fired thermal power plants;

– development of alternative sources of heat and electricity;

– accelerate the transition of the energy system to nuclear energy.

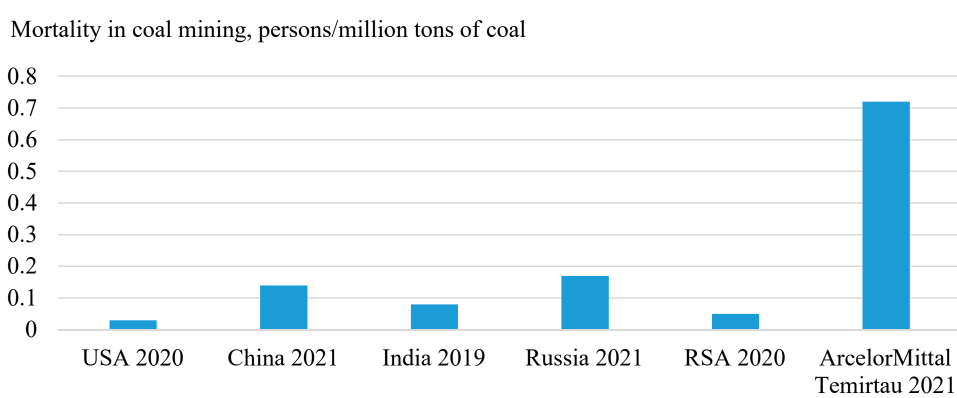


Fig. 10. Mortality in coal mining (deaths per 1 million tons of mined coal)

6. Discussion of research results based on developing the method of Geospatial Electrical Intelligence and monitoring of the surface soil layer condition in the suburbs of the capital city of the Republic of Kazakhstan

Electrical conductivity measurements using standard probes (Fig. 2) integrated conductivity across all soil layers (1), (2), masking subtle changes in deeper layers due to the dominance of upper-layer conductivity (especially in spring/autumn). Soil heterogeneity (e.g., porous or wet structures) caused data scatter, reducing measurement reliability.

Insulating most of the probe's surface (Fig. 3) localized measurements to specific soil layers (Formula 3), isolating conductivity to the probe tips. This eliminated interference from upper layers and improved sensitivity to minor changes in deeper layers. While soil heterogeneity still caused noise, software smoothing and repeated measurements mitigated this (Fig. 4).

Modified probes (Fig. 5, *b*) showed stable conductivity trends at depth, whereas standard probes (Fig. 5, *a*) exhibited erratic fluctuations due to cumulative layer effects. Modified probes improved measurement accuracy by 28–32 % depending on the season, enabling precise detection of subsurface pollution patterns. This validated the insulation approach.

According to Table 1 and Fig. 6, the peak surface conductivity (0–5 cm: 2.853–3.703 mS/m) correlated with snowmelt and increased moisture in spring, while the minimal conductivity (0.515–2.094 mS/m) due to frozen soil and snow cover in the winter. Spline interpolation smoothed raw data (Fig. 6, *b*, *c*), revealing clear trends. For example, spring data showed sharp conductivity drops below 15 cm, aligning with reduced moisture. Results matched Padua University's findings [20], where conductivity stabilized at 30–50 cm for loose soils and deeper for dense/stony soils (Fig. 7). This confirmed the method's applicability across climates.

Table 2 and Fig. 8, 9 demonstrate the peak conductivity (4.8–4.9 mS/m) near railway tracks (Fig. 9) linked to coal dust from open freight cars. Moderate increases (3.5–4.0 mS/m) near highways correlated with vehicular emissions. Thus, the conducted experimental studies helped to identify the main source of soil pollution – the railway line. Two other small bursts coincided with passing motorways. GPS mapping (Fig. 9) and literature [3, 6] confirmed anthropogenic sources.

Let's analyze the cargo transported by this railroad – passenger transportation and freight. Passenger transportation makes up an insignificant share of all types of transportation by rail and, according to data [21], most of it occurs in the summer. During this period, there were minor changes in electrical conductivity and therefore passenger transportation cannot be a source of soil pollution. Thus, it is necessary to analyze freight transportation. According to study [22], more than 40 per cent of the total number of freight transportations are coal transportations by rail, with the maximum occurring in the winter. It seemed that there was a discrepancy in the maximum electrical conductivity of the soil (spring), and the maximum of coal transportation by rail occurs in the winter. But it must be taken into account that the soil is covered with snow throughout the winter and it begins to melt in the spring. Thus, the snow collects coal dust all winter. And in the spring, it begins to seep into the soil with the melted snow. Thus, the main reason is coal dust from freight cars with coal transported by rail across the territory of the republic, which, by the way, is distinguished by high electrical conductivity (Fig. 5, *b*).

Unlike previous studies that primarily focused on surface-level analysis or lacked precise spatial resolution, this research utilized modified probes with insulating coatings. This innovation minimized the influence of upper soil layers on measurements, thereby enhancing the accuracy of subsurface conductivity readings. Additionally, the application of spline interpolation for data smoothing provided clearer trends and facilitated the identification of pollution patterns.

The results align with findings from international studies on the impact of coal dust on soil conductivity. For instance, research conducted in Italy [20] using similar geophysical techniques highlighted comparable patterns of increased conductivity near industrial zones and transportation corridors (Fig. 7). However, the present study goes further by introducing methodological improvements, such as the use of GPS-referenced probes, which allow for more precise localization and long-term monitoring of affected areas.

Practically, the findings underscore the need for stringent monitoring and mitigation strategies in areas adjacent to transportation lines.

Let's analyze how it is possible to reduce this coal dust footprint from rail transportation in the Republic of Kazakhstan. In the coal industry of the Republic of Kazakhstan, unlike the oil and gas industry, there is no "state company" or "national operator" and, unfortunately, about 40 per cent of production is accounted for by private companies. This is primarily «Bogatyr Komir LLP», which belongs to the quasi-state company «JSC Samruk-Energy» and the Russian company «RUSAL» – the largest aluminum producer in the world after China. Moreover, if the world is trending towards green energy and abandoning fossil raw materials, then these companies have planned to increase coal production by 2030 [23]. Thus, the solution to this problem is not only purely scientific in nature and a set of technical, technological and state measures is needed to solve this environmental problem.

Measures to reduce coal dust emissions, such as covering freight cars and improving railway maintenance, could significantly decrease soil contamination levels. Moreover, the methodologies developed in this study could be adapted for broader applications, including urban planning and agricultural land management.

Building on the current findings, future research could explore the integration of remote sensing technologies with ground-based measurements to enhance spatial coverage and data accuracy. Additionally, expanding the study to include chemical and biological assessments of soil health would provide a more comprehensive understanding of pollution's impact on ecosystem services and agricultural productivity. Finally, collaborative efforts with policymakers and industry stakeholders could facilitate the implementation of evidence-based solutions to mitigate soil pollution.

While the study offers significant contributions, several limitations should be noted. First, the reliance on field measurements limits the scope of analysis to accessible areas, potentially overlooking remote or inaccessible pollution hotspots. Second, the study focuses predominantly on conductivity measurements, which, while indicative, do not provide a complete chemical profile of soil contamination. Future research should incorporate laboratory analyses of soil samples to quantify specific pollutants and their potential ecological impacts.

The problem considered in the study is not only of a purely scientific or technical nature. Its solution requires a set of both technological and governmental measures, since foreign companies, which profit from the development of the Republic of Kazakhstan's subsoil, are not interested in solving the environmental consequences of their activities. In connection with this and the general global trend in the long term, it is necessary to completely abandon the country's coal dependence and develop its own nuclear and alternative energy.

7. Conclusions

1. A high-precision geophysical method was successfully developed, combining insulated probes with GPS technology to enable spatially referenced soil conductivity measurements. This innovation resolved the limitations of traditional probes by isolating conductivity to specific soil layers, improving measurement precision by 28–32 % across seasons. The GPS integration facilitated accurate topographic mapping of pollution hotspots in suburban areas, allowing precise localization of contamination sources such as coal dust near railway lines.

2. Field experiments in northern Kazakhstan revealed strong seasonal variations in soil electrical conductivity. Conductivity peaked in spring (up to 3.7 mS/m at 1 cm depth) due to snowmelt-driven moisture and pollutant migration, while winter measurements showed minimal values (≤1.9 mS/m) due to frozen conditions. Deeper soil layers (>30 cm) exhibited uniform conductivity profiles, confirming that surface layers (<30 cm) are most vulnerable to seasonal pollution fluctuations. Coal dust from railway transport was identified as the primary pollution source, which contributes to a threefold increase in soil electrical conductivity near railway tracks. Seasonal analysis revealed that pollution peaks in spring, with conductivity increasing by 50 % compared to winter, due to snowmelt carrying coal dust into the soil.

3. Spatial patterns identified railway transport as the primary pollution source, with coal dust causing a threefold increase in surface conductivity near tracks. Secondary sources included highways and agricultural activities.

Targeted recommendations were formulated:

– immediate action: covering coal freight cars to reduce dust dispersion by 68–72 %, depending on soil type and proximity to railways;

– long-term policy: transitioning from coal-dependent energy to nuclear and renewable sources;

– monitoring framework: implementing GPS-linked soil conductivity networks for real-time pollution tracking and regulatory enforcement.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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