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MODIFICATION AND DEVELOPMENT OF WATER, SOIL AND VEGETATION POLLUTION INDICES FOR ENVIRONMENTAL MONITORING OF COPPER MINE INFLUENCE ZONE

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The article addresses some methodical questions connected with generalized pollution indices application in the mining enterprise environmental monitoring when assessing their environmental impact. Many large mines include a whole set of studies in their environmental monitoring programs to assess the impact on all natural components to provide full compliance with environmental norms as well as to show the audience their environmental responsibility and commitment to saving nature. In this regard, the article assesses the prospects of generalized indices use when processing complex monitoring data for water, soil and vegetation obtained in the vicinity of copper mine. As a first step widely known weighted arithmetic water quality index was modified using enhanced set of parameters, contemporary Russian norms and corresponding hazard classes for drinking and natural water pollutants. Evaluation of the modified index using environmental monitoring data confirmed that it is an effective tool for comparing river water pollution levels at different sampling points in different years. Using the Safyanovsky copper mine (Middle Urals, Russia) as a case study, it was concluded that mine water discharge into the Rezh River has no noticeable impact on river water quality, which remained virtually constant over the three-year study period (2017–2019) that confirmed by summarized data from Roshydromet's annual reports. On the next step a complex index of soil and vegetation pollution with copper and zinc was assessed. Based on the calculation results using soil and vegetation sampling data, it was found that this index can provide clearer identification of anomalous points for outlining the pollution zone from the waste rock dump, since its amplitude is 30 % greater than for any of individual indices for copper and zinc. In general, the use of environmental pollution indices represents a promising direction for development the methods for processing integrated environmental monitoring data at mining enterprises. They can be recommended to obtain additional generalized information for municipal authorities and local population, confirming the admissibility of an enterprise's impact on the environment and its environmental responsibility.

Key words: pollution index; water quality index; soil; vegetation; copper; zinc.

1. Introduction

Pollution (or quality) indices of natural environment components are widely used in environmental studies. They integrate indicators for individual pollutants in water, soil, vegetation and others to provide a characteristic of each sample of a natural object in the form of a single number [1–3].

Many large mines include a whole set of studies in their environmental monitoring programs to assess the impact on all natural components to provide full compliance with environmental norms as well as to show the audience their environmental responsibility and commitment to saving nature.

Pollution indices application in complex environmental studies allow for a significant reduction in the volume of output data and makes it easier for non-professionals to understand the results of environmental pollution assessments for providing local population and municipal authorities with objective environmental information.

In this concept frames the article assesses the prospects of generalized indices use when processing monitoring data for water, soil and vegetation monitoring in the vicinity of copper mine to possible widen the information outcomes of complex environmental monitoring studies.

Heightened pollution levels are often observed in areas where metal ore mining enterprises are located and pollution indices may be useful in environmental monitoring in these areas [4, 5].

This article presents some results in the field having a scientific and practical meaning including the following:

– assessing the feasibility of using generalized environmental pollution indices when processing integrated environmental monitoring data to significantly reduce the volume of output data;

– modifying a weighted arithmetic water quality index, which is promising for use in Russia, based on incorporation an expanded set of indicators using specific for copper mines parameters, Russian MPC standards, and hazard classes for drinking and surface water;

– assessing the effectiveness of using a water quality index using real data from a copper mine;

– assessing the feasibility of jointly processing soil and vegetation pollution assessment data based on complex pollution index in the impact zone of a copper pyrite mine.

The monitoring studies were conducted under a contract with JSC Safyanovskaya Med, under which the contractor may use only summarized data for scientific purposes and publications. Therefore, raw data is not provided in the article.

Sampling of natural environments was carried out by employees of Institute of Industrial Ecology of the Ural Branch of the Russian Academy of Sciences in 2017–2019. In subsequent years, the monitoring program was significantly reduced due to environmental legislation changes, so more recent complex data are absent. Chemical analysis of samples was made in the analytical laboratory of the Safyanovsky mine.

2. Modification of the weighted arithmetic water quality index

The weighted arithmetic water quality index (hereinafter WQI) was proposed in 1965 by Horton R. K. [6] and developed by Brown R. M. and others [7]. It is the sum of a set of pollution indicators normalized to standard values and taken with certain weights. Calculating the WQI does not require multiple measurements of the pollutants content in water, so it is often used to conduct one-time assessment of both surface and groundwater pollution [8–13]. In this regard, we consider the WQI as promising tool for assessing the water quality of natural water bodies in the zone of mining enterprises influence in Russia.

The literature analysis shows that national water quality standards, various sets of pollutants and weight values for each of them are used to calculate the WQI. Therefore, the calculation results are linked to the national regulatory framework in the field of natural water quality control and may differ due to the use of different scales for finding the weights of the same pollutants. In this study, we propose to modify the WQI using Russian drinking water quality standards (maximum permissible concentrations MPC) and hazard classes [14].

2.1. Modification and calculation of WQI: materials and methods

The modification and assessment of the WQI was performed using data of chemical analysis of water samples taken at three points in the Rezh River, which is affected by wastewater from the Safyanovsky copper mine. The mine has two treated wastewater outlets: Outlet 1 – surface water from the copper ore crushing facility site; Outlet 2 – the water from quarry and surface water from the quarry and waste rock dump area. The location of sampling points and wastewater outlets is shown in Fig. 1.

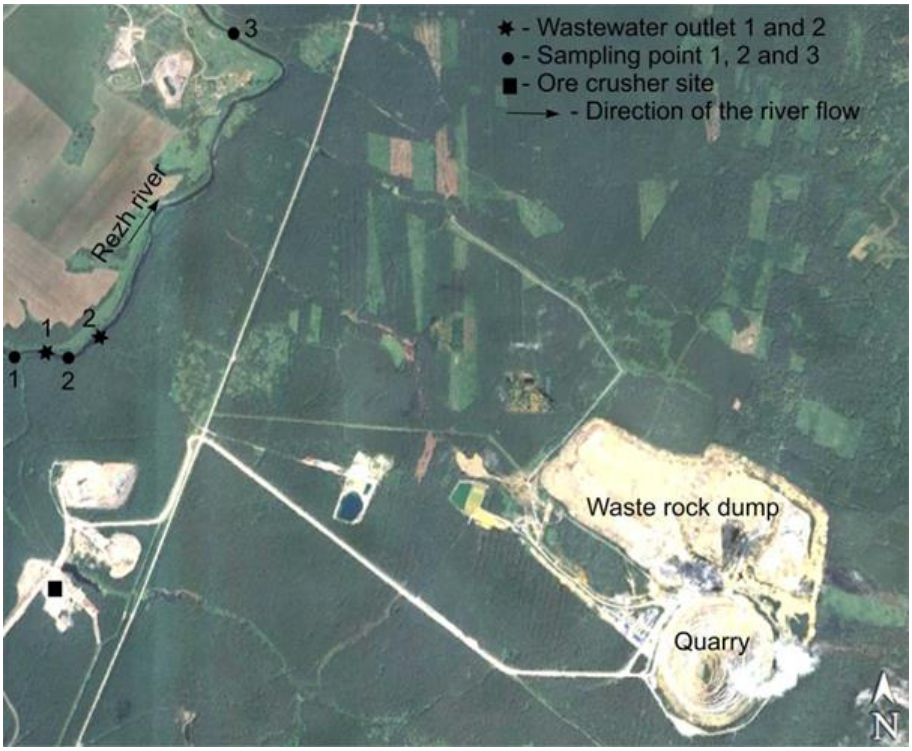

Fig. 1. Location of sampling points and wastewater outlets in the area of the Safyanovsky copper mine, Middle Urals, Russia. The image source – Google Earth Pro, 7.3.6.10201 (64-bit)

To modify the WQI, the following changes are proposed:

1. The list of pollutants used in [8, 13] was expanded by a number of indicators included in the environmental monitoring program of the Safyanovsky mine, for a more adequate assessment of the impact of wastewater on the water body, namely, the following indicators were added: copper, nickel, lead, silicon, oxidizability.

2. To calculate the relative pollution for each pollutant, Russian MPC of chemical substances in water bodies for drinking water are used [14].

3. The weights for pollutants are calculated using the hazard classes of pollutants given in [14]. The weight value for each substance is defined as 1/Hc, where Hc is the hazard class.

The WQI calculation was performed in accordance with [8, 13] using the formulas 1–4 given below for the pollutants listed in Table 1.

The approach of [8, 13] was adopted because it is proposed for groundwater (the authors mean – underground sources of drinking water) and in our case we deal with the river pollution by purified quarry waters, which are underground ones. Therefore, it allows more adequate assessing of the mine impact on the river as the calculation includes ore metals. The use of scale based on the hazard class of a pollutant, in our opinion, allows taking into account, first of all, pollution by more hazardous substances, since they are included in the calculation with bigger weight values, which seems important for the overall assessment of the hazard of pollution using WQI because its value will be bigger too.

$$WQI = \sum_{i=1}^{n} SI_i, \quad (1)$$

$$SI_i = W_i \times Q_i, \quad (2)$$

$$Q_i = 100 \times (C_i/S_i), \quad (3)$$

$$W_i = w_i / \sum_{i=1}^{n} w_i, \quad (4)$$

where,

SI_i – pollution index for each pollutant i, dimensionless;

Q_i – relative pollution for each pollutant, dimensionless;

C_i – measured concentration for each pollutant, mg/dm^3;

S_i – MPC for each pollutant, mg/dm^3 [14];

W_i – relative weight for each pollutant, dimensionless;

w_i – weight for each pollutant equal to 1/Hc, where Hc is the hazard class of the pollutant [14], dimensionless;

n – number of pollutants used.

Table 1. Pollutants, MPC and hazard classes for calculating WQI [14]

Pollutants	MPC, Mg/Dm^3	Hazard Class, Hc
Hydrocarbonates	1000	4
Iron	0,3	3
Hardness	7	4
Calcium	100	4
Silicon	10	2
Magnesium	50	3
Manganese	0,1	3
Copper	1,0	3
Nitrates	45	3
Nickel	0,01	2
Oxidizability	7	4
Lead	0,03	2
Sulfates	500	4
Dry residue	1000	4
Zinc	1	3

2.2. Modification and calculation of WQI: results and discussion

The water quality index was calculated for three sampling points (Fig. 1) using formula (1). At each point, the sampling was performed 3 times during the summer period of 2017, 2018, and 2019. For the calculation, the average values of pollutant concentrations for three samplings in each year were taken. The calculation results are presented in Table 2.

Table 2. Calculated values of WQI for sampling points 1–3 in 2017–2019.

	Year of sampling		
Sampling point	2017	2018	2019
1	28,43	27,81	30,77
2	33,45	33,23	35,70
3	27,26	27,18	35,79

So as the WQI is modified, there is no special scale of pollution ratings for it now. Due to this one can make a very approximate assessment of water quality in terms of its possible use for drinking purposes based on the scale of pollution levels given in [8]. Such assessment may be used for water pollution levels comparison for different points and years. The water quality rating levels depending on the calculated WQI value are there as follows: 0–25 – Excellent; 25–50 – Good; 50–75 – Poor; 76–100 – Very poor; >100 – Unfit for drinking. According to this scale, water in all three points can be classified as "Good", that is, it can be used for drinking purposes after standard water treatment.

For adequate of water quality rating using modified WQI in accordance with Russian norms, additional research is required to develop an appropriate scale.

The data in Table 2 show that the maximum WQI values were obtained in sampling point 2 and 3 in (downstream of the treated wastewater outlets) in 2019 and were equal to 35.70 and 35.79 that may indicate the presence of the river water pollution connected with

mining waters. But in 2017 and 2018 point 3 has minimal values in comparison with points 1 and 3 that doesn't confirm the above.

The average WQI value for all measurements is 31.07 and deviations from the average range from minus 12.5 % to plus 15.2 %, which does not exceed relative measurement error for most pollutants (20 %).

The result obtained allows concluding that discharge of treated wastewater from the copper mine has an insignificant effect on the water quality of Rezh River and the pollution remained almost constant in terms of compliance with environmental norms for drinking water.

This conclusion corresponds to the generalized data of the Roshydromet (annual reports "Quality of Surface Waters of the Russian Federation" for 2017–2019), where it is noted that the water in the Rezh River in the indicated years was consistently classified as "dirty", that is, the quality of the water in the river did not change.

The difference between estimations of Roshydromet and those ones made on the scale [8] confirms the need of development a scale for the modified WQI for providing the possibility of using it as an absolute index.

Thus, the modified WQI can be proposed for use in environmental monitoring of the mining enterprises influence zone in Russia as a relative indicator of water pollution: to compare the results of testing at different points within a year, as well as to assess changes in water pollution levels in different years. The results of WQI calculation can be used by municipal authorities to assess the impact of the mining enterprise on a water body, as well as to inform the local population.

3. Soil and vegetation pollution indices

The operation of mining enterprises is usually accompanied by emissions of ore metals into the environment, which leads to pollution of soil and grassy vegetation in the surrounding areas [15–19].

At copper pyrite ore deposits, zones of soil and vegetation pollution with copper and zinc may form near quarries and waste rock dumps, and the accumulation of these metals in soil and vegetation may differ [16, 17, 19, 20]. In this regard, the pollution of both soil and vegetation with ore metals is simultaneously studied for a more reliable identification and assessment of the mining operations' impact on the environment.

To summarize the monitoring data and possibly increase its informativeness, we propose to calculate pollution indices for two environments for copper and zinc individually, as well as a complex index integrating data for two environments and two metals. The assessment and comparison of such indices are presented below.

3.1. Soil and vegetation pollution indices: materials and methods

To calculate the indices of soil and vegetation pollution, we used data from chemical analysis of copper and zinc content in the soil and vegetation samples collected around Safyanovsky copper mine. The sampling was carried out in July 2018 at 8 points located on a profile running near the quarry and waste rock dump (Fig. 2).

The metal concentrations were measured using inductively coupled plasma spectrometry. The relative error in finding of metal content in the samples was 20 %. Russian environmental norms for copper and zinc are as follows: maximum permissible concentration for soil close to neutral, neutral (loamy and clayey) [22]: copper – 132 mg/kg, zinc – 220 mg/kg; maximum permissible level (MPL) for grassy vegetation used as animal feed [23]: copper – 30 mg/kg, zinc – 50 mg/kg.

Fig. 2. Location of soil and vegetation sampling points in the area of the quarry and waste rock dump of the Safyanovsky copper mine, Middle Urals, Russia. The image source – Google Earth Pro, 7.3.6.10201 (64-bit)

3.2. Soil and vegetation pollution indices: results and discussion

Using the measurement data, the individual indices of copper and zinc accumulation in soil and vegetation were calculated (Fig. 3) (all indices are dimensionless).

1. Indices of copper ISCu and zinc ISZn accumulation in soil:

$$ISCu = CSCu/MPCCu, \quad (5)$$

$$ISZn = CSZn/MPCZn, \quad (6)$$

where:

CSCu and CSzn – concentrations of copper and zinc in soil samples,

MPCCu and MPCZn – maximum permissible concentrations of copper and zinc in soil.

2. Indices of copper IVCu and zinc IVZn accumulation in vegetation:

$$IVCu = CVCu/MPLCu, \quad (7)$$

$$IVZn = CVZn/MPLZn, \quad (8)$$

where:

CVCu and CVZn – concentrations of copper and zinc in vegetation samples,

MPLCu and MPLZn – maximum permissible levels of copper and zinc in vegetation.

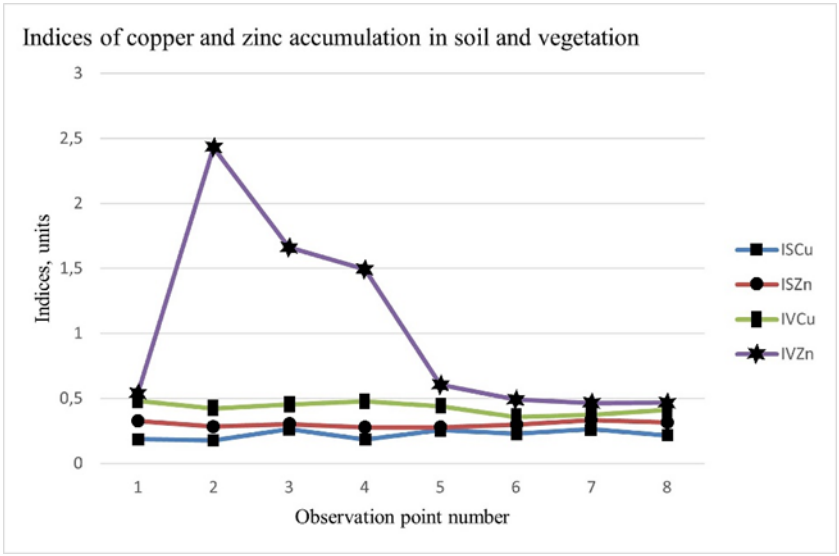

Fig. 3. Indices of copper and zinc accumulation in soil and vegetation

As Fig. 3 shows, the concentrations of copper and zinc in the soil are significantly lower than MPC (by 3–5.5 times). The presence of waste rock dump on the profile at points 2–4 is not seen. The minor (from 5 to 20 %) multidirectional fluctuations in the copper and zinc accumulation indices are observed, not related to the location of the sampling points relative to the quarry and waste rock dump. Relatively high values of the ISCu (5) and ISZn (6) indices are observed both near the waste rock dump (point 3) and at a significant distance from it (points 5 and 7 for copper, 1 and 7 for zinc).

Copper concentrations in vegetation are significantly lower than MPL (2–2.8 times) and vary slightly along the profile from 0.36 to 0.48 MPL, i. e. within 14 % of the average with relative error of chemical analysis of 20 %.

Thus, the ISCu (5), ISZn (6) and IVCu (7) indices do not provide reliable information on the pollution of the area near the waste rock dump.

At the same time, on the graph of zinc accumulation index in vegetation IVZn (8), points 2–4, located at a distance of 20 m from the waste rock dump, are clearly visible, where an increase in this index by 2.5–4.5 times is observed. Zinc concentration in points 2–4 exceeds MPL by 1.5–2.5 times. This result shows that the study of vegetation pollution is a more informative type of study in the conditions of the Safyanovsky copper mine compared to the study of soil pollution. Moreover, useful information is provided by the data on zinc pollution, which is consistent with the conclusions of other studies [17, 19, 20]. This fact is explained by the greater mobility of zinc compared to copper in the soil-plant system for many types of grassy vegetation [20, 21].

Next, the indices of copper and zinc accumulation in soil and vegetation were calculated (Fig. 4) and a complex index for two metals and two environments:

3. Complex index of copper accumulation in soil and vegetation ISVCu:

$$ISVCu = ISCu + IVCu. \quad (9)$$

4. Complex index of zinc accumulation in soil and vegetation ISVZn:

$$ISVZn = ISZn + IVZn. \quad (10)$$

5. Complex index of copper and zinc accumulation in soil and vegetation ISVCu-Zn:

$$ISVCu\text{-}Zn = ISVCu + ISVZn. \quad (11)$$

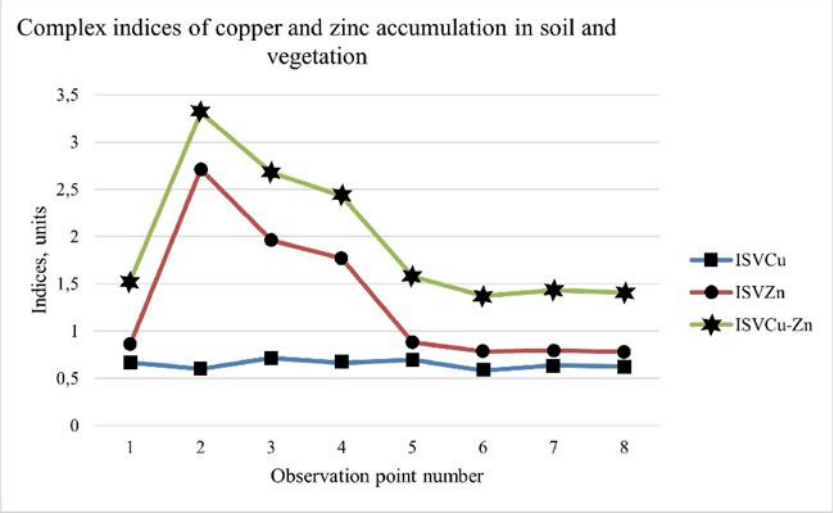

Fig. 4. Complex indices of copper and zinc accumulation in soil and vegetation

As Fig. 4 shows, the graphs of the copper ISVCu (9) and zinc ISVZn (10) accumulation indices practically repeat the shape of the graphs of the individual copper IVCu (7) and zinc IVZn (8) accumulation indices in vegetation with an insignificant increase in the general level by 0.15–0.25 units due to the contribution of the individual copper ISCu (5) and zinc ISZn (6) accumulation indices in soil (Fig. 3).

The ISVCu (9) index does not provide useful information, since the relative changes in its values along the profile are within the error of chemical analysis of 20 %.

The graph of the complex index of copper and zinc accumulation in soil and vegetation ISVCu-Zn (11) repeats the shape of the IVZn (8) (Fig. 3) and ISVZn (10) (Fig. 4) graphs.

In the points 2–4 closest to the dump, there are 1.6–2.2 times higher ISVCu-Zn (11) index values compared to the background values (points 1, 6–8), which is less than for the IVZn (8) index (2.5–4.5 times higher than the background values, Fig. 3), but the amplitude of the ISVCu-Zn (11) index is up to 30 % greater than for the IVZn (8) index. Thus, the results of assessing the indices of soil and vegetation pollution with copper and zinc show that the most informative type of research at the copper pyrite mine is the study of vegetation pollution with zinc. If one has the data on soil and vegetation, it is advisable to use the proposed complex index, which can provide a clearer allocation of anomalous points on the profile for outlining the pollution zone from the waste rock dump.

4. Conclusion

This article addresses some methodical issues related to the potential application of generalized environmental pollution indicators in processing complex environmental monitoring data, using the example of a mining enterprise.

As a first step, the widely known weighted arithmetic water quality index was modified using an expanded set of indicators, Russian MPC and hazard classes for pollutants in drinking and natural waters.

Evaluation of the modified index using environmental monitoring data confirmed its effectiveness as a tool for comparing river water pollution levels at different sampling points in different years. Using the Safyanovsky copper mine (Middle Urals, Russia) as a case study, it was concluded that mine water discharge into the Rezh River has no noticeable impact on river water quality, which remained virtually constant over the three-year study period (2017–2019). This is confirmed by summarized data from Roshydromet's annual reports, "Quality of Surface Waters of the Russian Federation".

The next step involved evaluating the proposed integrated index of copper and zinc contamination of soils and vegetation. Calculations revealed that this index allows for more precise identification of anomalous points for delineating contamination zones in the area of overburden and host rock dumps, as its amplitude is 30 % greater than that of any of the individual copper and zinc indices.

Overall, it can be concluded that the use of environmental contamination indices represents a promising direction for development the methods for processing integrated environmental monitoring data at mining enterprises. Such indices can be recommended to obtain additional generalized information in particular for municipal authorities and local population, confirming the admissibility of an enterprise’s impact on the environment, its environmental responsibility and commitment to the development of cleaner production.

5. Acknowledgments

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МОДИФИКАЦИЯ И РАЗВИТИЕ ИНДЕКСОВ ЗАГРЯЗНЕНИЯ ВОДЫ, ПОЧВЫ И РАСТИТЕЛЬНОСТИ ДЛЯ ЭКОЛОГИЧЕСКОГО МОНИТОРИНГА ЗОНЫ ВЛИЯНИЯ МЕДНОГО РУДНИКА

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В статье рассматриваются некоторые методические вопросы, связанные с применением обобщенных индексов загрязнения в экологическом мониторинге горнодобывающих предприятий при оценке их воздействия на окружающую среду. Многие крупные рудники включают в свои программы экологического мониторинга комплекс исследований для оценки воздействия на все природные компоненты, чтобы обеспечить полное соблюдение экологических нормативов, а также продемонстрировать общественности свою экологическую ответственность и приверженность делу сохранения природы. В этой связи в статье оцениваются перспективы использования обобщенных индексов при обработке комплексных данных мониторинга воды, почвы и растительности, полученных в районе медного рудника. В качестве первого шага широко известный взвешенный арифметический индекс качества воды был модифицирован с использованием расширенного набора параметров, современных российских нормативов и соответствующих классов опасности для загрязняющих веществ питьевых и природных вод. Оценка модифицированного индекса с использованием данных экологического мониторинга подтвердила, что он является эффективным инструментом для сравнения уровней загрязнения речной воды в разных точках отбора проб в разные годы. На примере Сафьяновского медного рудника (Средний Урал, Россия) сделан вывод о том, что сброс шахтных вод в реку Реж не оказывает заметного влияния на качество речной воды, которое за трехлетний период исследований (2017-2019 гг.) оставалось практически неизменным, что подтверждается обобщенными данными ежегодных отчетов Росгидромета. На следующем этапе была проведена оценка комплексного индекса загрязнения почв и растительности медью и цинком. На основании результатов расчетов с использованием данных опробования почв и растительности установлено, что данный индекс позволяет более четко идентифицировать аномальные точки для оконтуривания зоны загрязнения от отвала пустой породы, поскольку его амплитуда на 30% больше, чем у любого из отдельных индексов для меди и цинка. В целом, использование индексов загрязнения окружающей среды является перспективным направлением развития методов обработки данных комплексного экологического мониторинга на горнодобывающих предприятиях. Они могут быть рекомендованы для получения дополнительной обобщенной информации для органов местного самоуправления и населения, подтверждающей допустимость воздействия предприятия на окружающую среду и его экологическую ответственность.

Ключевые слова: индекс загрязнения; индекс качества воды; почва; растительность; медь; цинк.

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