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PREDICTABILITY OF MINING WASTEWATER POLLUTION BASED ON FRACTAL TIME SERIES ANALYSIS

Pollution of water resources by heavy metals, especially in areas of ore mining and processing, leads to a deterioration in the quality of life and health of the population. The greatest degree of pollution is associated with the development of deposits of copper, zinc and lead. Within the framework of this study, a fractal R/S analysis of the time series of wastewater indicators (turbidity, electrical conductivity, flow rate and pH) selected at the site of the Sayak ore district (Republic of Kazakhstan) was performed. A substantial increase in flow was noticed from July 10 to July 15, 2024, and an increase in electrical conductivity from July 4 to July 26, 2024, although without exceeding critical levels. The Hurst exponent for electrical conductivity exceeds 0.56, indicating the presence of long-term memory and the stability of the process. Minor variations in turbidity indicate no serious harm to the environment. However, the data are limited and do not allow for an assessment of all deposits in the region, making it difficult to draw conclusions about the impact on the environmental safety of the Balkhash urban region. Despite the high risk of chronic diseases in the area, the results confirm that fractal analysis can serve as a useful indicator of environmental conditions and a basis for monitoring systems.

Keywords: time series analysis, R/S analysis, Hurst exponent, mining wastewater, environmental monitoring.

Introduction

It is well known that the mining and processing of metal ores is one of the main causes of environmental degradation [1]. Ores are extracted using both open-pit (up to 100 meters deep) and underground methods, depending on the location of the deposits. A significant amount of waste remains, as the proportion of ore in the extracted material is low. Some pollutants enter water bodies used by the local population. The proximity of such facilities to water sources poses a serious threat to safety and quality of life. Water pollution may be organic, inorganic, pathogenic, thermal, or radioactive [2]. This complicates water use in households, agriculture, and disrupts biochemical processes in the soil [3]. The problem is particularly relevant for urban agglomerations located near mining regions. In Kazakhstan, this includes the Northern Balkhash region (southern Karaganda oblast), where the Sayak ore district is located, containing a dozen high-quality deposits.

The region around Lake Balkhash has been experiencing significant environmental difficulties since the 1970s. Excessive use of water resources for mining activities has caused the drying up of lake systems: only 5 out of 16 have survived, and about a third of the Balkhash River basin has dried up [4]. Each year, more than 70 tons of copper and around 60 tons of zinc and lead settled into lake [5]. The water is also contaminated with petroleum products and fluoride compounds. Additional impact comes from wastewater discharged by mining enterprises in the People's Republic of China.

In study [6], the example of Indian water bodies, a statistical method for assessing water quality was developed based on the Water quality Index (WQI) and the use of fractal analysis (calculation of the Hurst index). However, such assessments, suitable for drinking water sources, require adjustment when analyzing wastewater from ore mining. To evaluate the long-term memory of time series, methods such as Rescaled Range Analysis (R/S-analysis) [7] and Detrended Fluctuation Analysis [8] are applied. Water quality indicators are determined according to WHO/EPA standards [9], and sampling procedures are described in [10]. Study [11] demonstrates the persistence of Hurst exponent values for hydrological variables before and after deseasonalization, which is important for forecasting. However, it focused on open water bodies (Little River and Walker Branch (Tennessee, USA), while wastewater from mining sites may have distinct characteristics. Several studies [12] have revealed fractal behavior and persistent concentrations of chemical components in mine water flow. As shown in [13, 14], some water quality parameters exhibit both short-term and long-term predictability.

Study [15] examined the quality of drinking water using turbidity as an indicator – a measure of transparency loss due to the presence of suspended particles. Turbidity serves as an important indicator of changes in water quality. When persistent changes in this parameter are observed, it becomes possible to forecast the future state of the water. In the present study, turbidity and electrical conductivity of wastewater generated during metal ore mining are analyzed. Although this water is not used for drinking, its infiltration into groundwater and surface water bodies (e.g., the Balkhash basin) may pose environmental risks and threaten public health. If pollutants exhibit long-term persistence, their concentration can be monitored and predicted. However, in the case of random or antipersistent fluctuations, such predictability is lost, indicating potential violations of technological standards.

Fractal analysis has a number of significant advantages over traditional methods in processing environmental monitoring data, especially in the study of time series of environmental pollution (water, air and soil resources). It is more robust to noise and capable of extracting the underlying structure of a signal even in the absence of clear patterns. Unlike classical methods, fractal analysis enables the development of predictive models for ecosystems with unstable or cyclical dynamics and serves as a foundation for machine learning and neural networks, especially in anomaly detection.

The goal of this research is to examine persistence over time in time series of polluted water, which affects environmental safety and quality of life in areas near mining regions. The Balkhash urban region, particularly its northern part and the Sayak ore district, was selected as the study area. The long-term persistence of pollutant concentrations indicates the potential for forecasting and controlling water quality. This is important for ensuring environmental safety and sustainable development in urban agglomerations, especially those located near mining areas.
Research Objectives:

To apply fractal analysis to time series of pollution indicators (turbidity, electrical conductivity, pH, and flow) to calculate the Hurst exponent and identify long-term memory.

To investigate the values of the Hearst index according to the main parameters for assessing the degree of wastewater pollution in the Sayak ore region.

Materials and methods

A discrete time series of wastewater indicators (turbidity, flow, electrical conductivity, pH, etc.) is considered, with values recorded by the corresponding sensors at specific time intervals $\mathbf{t_1, t_2, ... t_n}$, where $\mathbf{t_1}$ be the initial time point, then the time series can be represented as [16]:

$$R = \big(r(t_1), r(t_2), \dots, r(t_n)\big).$$

Based on the original time series R a family of cumulative time series $R^h = \big(r(t_1), r(t_2), \dots, r(t_h)\big), \;\; h = \overline{3, n}$ is constructed to analyze the aggregated behavior of the observed data over time and [7, 17]:

where $\overline{R}^h$ is the arithmetic mean of a time series R^h,

$$\rho(h,s) = \sum_{j=1}^{s}\left(r(t_j) - \overline{R}^h\right), h = \overline{3,n}, s = \overline{3,n},$$

where $\rho \;\; h, s$ is the deviation from the arithmetic mean,

$$F_h = \max_{s=\overline{1,h}} \rho(h,s) - \min_{s=\overline{1,h}} \rho(h,s),$$

where F_h – range,

$$\sigma_h = \sqrt{\frac{1}{h}\sum_{j=1}^{s}\left(q(t_j) - \overline{Q}^h\right)^2}, h = \overline{3,n},$$

where σ_h is the standard deviation of a time series.

Accordingly, the following equation can be derived:

$$lg\left(\frac{F_h}{\sigma_h}\right) = H\left(R^h\right) \cdot lg(h) + lg(\delta), h = \overline{3,n}$$

where $H\left(R^h\right)$ is the Hurst exponent, as the coefficient of the independent variable, is calculated using the least squares method.

The fractal dimension D of the time series R is calculated using the following formula [7] $D = 2 - H$.

It indicates the extent to which the fractal occupies space when the observation scale is reduced. Based on the fractal dimension D, a predictability index P can be calculated [6] $P = 2|D - 1.5|$. .

The value of P increases with a decrease or increase in the fractal dimension of D relative to the value of 1.5. At $D < 1.5$, stability is recorded in the structure of the time series. At $D < 1.5$, the time series **R** also demonstrates constancy. If P tends to zero, it can be concluded that the time series is random or close to it. The following formula is used to establish a threshold value that makes it possible to distinguish between a stable time series and a random one [18]:

$$H_h^T = \sqrt{\frac{2}{\pi(h-1)}}\sum_{i=1}^{h-1}\sqrt{\frac{h-i}{i}},$$

where H_h^T is the theoretical threshold value for identifying the boundary between random and persistent time series.

Thus, after determining the value of the Hearst indicator, the following interpretation of the results of the analysis of the time series of wastewater discharges can be presented:

1 $H_h^T < H(R^h) \leq 1.$ This may indicate the presence of long-term memory or persistence in the time series. In the case of turbidity or electrical conductivity indicators, this means that high levels of pollution tend to persist or reappear after a temporary decrease. At the same time, the overall trend remains stable, which allows the application of trend-based forecasting methods. For monitoring systems, this is important because persistence signals the stability, predictability, and controllability of water discharges from ore mining facilities.

2 $0.5 \leq H\left(R^h\right) \leq H_h^T$. This indicates the random nature of the time series. In the context of water discharge indicators, it suggests unstable pollution levels that cannot be reliably predicted or controlled. Such a situation may point to disruptions in technological processes, insufficient treatment, or accidental releases. This is especially concerning if the time series previously exhibited persistent behavior.

3 $3.\ 0 \leq H\left(R^h\right) < 0.5$ This indicates ergodicity and anti-persistence in the time series. In the context of water discharge indicators, it means that pollution levels tend to decrease after high values or increase after low ones. Moreover, the trends change more rapidly than in random time series.

The Hurst indicator makes it possible to identify the presence of a long-term relationship in the time series of water flow indicators, which is important for pollution control systems. The present study focuses on process water discharges from mining enterprises; however, this approach can also be used to analyze the quality of drinking water..

Results and Discussion

Data on water discharges from one of the facilities located in the Sayak ore district were used in this study. The data were provided by a private mining company under confidentiality conditions. The facility has been operating for over 50 years and specializes in copper ore extraction. The region is located about 200 km from the city of Balkhash. Three types of groundwater serve as sources of water supply: porous aquifers in loose sediments (with a mineralization of up to 3 g/l), fractured-porous horizons at a depth of up to 50 m and fractured-vein horizons at a depth of 50-60 m. The chemical composition of groundwater is relatively stable, it is dominated by sulfate compounds, and the water is characterized by high hardness (the pH value varies between 6.9–8.5). The analysis covered the period from May 23, 2024, to August 28, 2024, with measurements taken every 20 minutes, resulting in a total of 6,385 observations. The studied parameters included turbidity (NTU), electrical conductivity (in Siemens), flow rate (in m^3/s), and pH. However, the pH data were insufficient for reliable analysis. Turbidity reflected the concentration of suspended particles, electrical conductivity indicated the ionic content of the water, and flow was defined as the volume of water passing through a given area per unit time. A sample of the data and Water Quality Index (WQI) estimates is provided in Table 1 [17]. The full dataset is available at [19].

A fractal analysis of time series data on water discharge indicators was conducted for a facility located in the Sayak ore district. Based on R/S-analysis, Hurst exponents were calculated for electrical conductivity, turbidity, and flow rate – both for the entire observation period and for a shorter period characterized by abrupt changes in these parameters. Additionally, Water Quality Index (WQI) values and the predictability index were determined. As shown in Figure 1, a sharp increase in water electrical conductivity (red line) was observed in July 2024, whereas during the rest of the observation period, the values remained close to zero due to the absence of significant flow. From July 10 to July 15, flow rate (green line) increased sharply, while electrical conductivity had already begun to rise on July 4 and remained elevated until July 26. The significant increase in flow during July 10–15, 2024, may be attributed to both industrial activities and weather conditions, heavy rainfall occurred during this period in the southern part of the Karaganda region (Northern Balkhash region) [20]. The increase in flow was accompanied by the discharge of a large volume of water with high electrical conductivity, while turbidity levels remained almost unchanged. According to [9], even the peak electrical conductivity values in the studied dataset do not pose a serious environmental threat to the region.

Table 1 – Descriptive statistics of time series for wastewater discharge indicators from a metal ore mining facility

Indicator	Turbidity (NTU)	Electrical conductivity (S/m)	Flow Rate (m^3/s)	pH	WQI
Number of observations	6386	6386	6386	55	6386
Mean	7.23	81.95	1.42	5.86	0.20
Std	1.72	206.70	3.82	0.70	0.52
Min	0.00	0.00	0.00	2.17	0.00
Max	8.98	2422.73	20.85	6.62	6.06

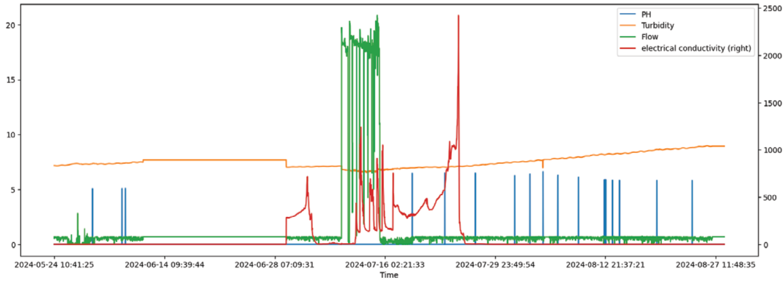

Figure 1 – Time series of water discharge indicator values (flow rate, electrical conductivity, turbidity, and pH level) were recorded at one of the metal ore mining facilities in the Sayak ore district during the period from May 23, 2024, to August 28, 2024.

The Hurst exponent value for the time series of electrical conductivity during the period from May 23, 2024, to August 28, 2024, is $H_1(R^{6386}) \approx 0{,}59$, For the period from July 4, 2024, to July 26, 2024, the Hurst exponent is According to the study [18] $H^T_{6386} < 0.5065$, and $H^T_{1583} < 0.5141$. This means that the time series of electrical conductivity for both time periods are persistent, since $H_1(R^{6386}) < H^T_{6386}$ and $H_2(R^{1583}) < H^T_{1583}$. Based on the dataset, Water Quality Index (WQI) values were calculated, indicating persistence in the corresponding time series. At the same time, turbidity and flow rate exhibited anti-persistent behavior: the flow rate fluctuated sharply, particularly between July 10 and July 15, 2024, while turbidity showed only minor variations, reflecting short-term fluctuations.

The analysis showed that the time series of electrical conductivity in water discharges from the metal ore mining facility in the Sayak district exhibit long-term memory properties. This indicates the stability, predictability, and controllability of this parameter. Considering the regulatory limits for electrical conductivity [9], it can be concluded that the facility complies with the requirements for water treatment and settling prior to discharge.

Information

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Conclusions

This research examined the time series of discharges of treated wastewater from a metal ore mining enterprise in the Sayak ore region (Kazakhstan) for the period from May 23 to August 28, 2024. Using the fractal R/S analysis method, Hurst indices were determined for parameters such as turbidity, electrical conductivity, and flow velocity. The pH analysis proved impossible due to insufficient data.

In the period from July 10 to July 15, a sharp increase in runoff was recorded, and from July 4 to July 26, an increase in electrical conductivity was observed due to intense precipitation. Despite the fact that the values of electrical conductivity did not reach critical levels, their increase may indicate the likelihood of contamination at high concentrations. The Hearst index for electrical conductivity (0.56–0.59) indicates the presence of stability and long-term memory, which characterizes the process as predictable. The Water Quality Index (WQI) also indicates a stable condition. Turbidity values remained in the range of 0.43–0.49, reflecting their unstable and stable nature, which does not pose an environmental threat.

Thus, the process of change in electrical conductivity at the studied facility appears to be controllable, with limited impact on the surrounding environment. However, potential risks from other facilities in the region should be considered, as previous cases of heavy metal concentrations exceeding acceptable levels have been recorded in the waters of Lake Balkhash. This highlights the relevance of fractal analysis as an effective tool for environmental monitoring and for protecting public health.

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ФРАКТАЛДЫҚ УАҚЫТ ТІЗІМЕСІН ТАЛДАУ НЕГІЗІНДЕГІ ТАУ-КЕН АЗАМАТТАРЫНЫҢ АҒЫНДЫ СУЛАРЫНЫҢ ЛАСТАНУЫН БОЛЖАУ

Тау-кен өндірісі мен кен байыту нысандарының жанында су көздерінің ауыр металдармен ластануы халықтың денсаулығына кері әсер етіп, өмір сүру сапасының төмендеуіне әкелуде. Ең ауыр ластану Cu, Zn және Pb алумен байланысты. Бұл зерттеу Саяқ кенді ауданындағы (Қазақстан Республикасы) ағынды сулардың уақыттық қатары деректеріне (лайлылық, электр өткізгіштік, ағын және pH) фракталдық R/S-талдау жүргізді. Ағынның күрт өсуі 2024 жылғы 10 шілдеден 15 шілдеге дейін және электр өткізгіштіктің 2024 жылғы 4 шілдеден 26 шілдеге дейін ұлғаюы сыни деңгейден аспаса да байқалды. Электр өткізгіштіктің Херст көрсеткіші 0,56-дан асады, бұл ұзақ мерзімді жадының болуын және процестің тұрақтылығын көрсетеді. Лайланудың шамалы ауытқуы қоршаған ортаға айтарлықтай зиян келтірмейтінін көрсетеді. Дегенмен, деректер шектеулі және аймақтағы барлық кен орындарын бағалауға мүмкіндік бермейді, бұл Балқаш қалалық аймағының экологиялық қауіпсіздігіне әсері туралы қорытынды жасауды қиындатады. Аудандағы созылмалы аурулардың жоғары қаупіне қарамастан, нәтижелер фракталдық *талдау қоршаған орта жағдайларының пайдалы көрсеткіші және мониторинг жүйелері үшін негіз бола алатынын растайды.*

Кілтті сөздер: уақыт қатарын талдау, R/S талдау, Херст көрсеткіші, тау-кен ағынды сулары, қоршаған ортаны бақылау.

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ПРОГНОЗИРУЕМОСТЬ ЗАГРЯЗНЕНИЯ СТОЧНЫХ ВОД ГОРНОДОБЫВАЮЩИХ ПРЕДПРИЯТИЙ НА ОСНОВЕ ФРАКТАЛЬНОГО АНАЛИЗА ВРЕМЕННЫХ РЯДОВ

Загрязнение водных ресурсов тяжелыми металлами, особенно в районах, прилегающих к горнодобывающим и перерабатывающим предприятиям, приводит к ухудшению качества жизни и состояния здоровья населения. Наиболее сильное загрязнение связано с добычей Cu, Zn и Pb. В данном исследовании проведен фрактальный R/S-анализ временных рядов данных (мутность, электропроводность, расход и pH) сточных вод с участка Саякского рудного района (Республика Казахстан). Резкое увеличение расхода наблюдалось с 10 по 15 июля 2024 года, а увеличение электропроводности – с 4 по 26 июля 2024 года, хотя и без превышения критических значений. Показатель Херста для электропроводности превышает 0,56, что свидетельствует о наличии долговременной памяти и стабильности процесса. Незначительные колебания мутности свидетельствуют об отсутствии серьезного вреда для окружающей среды. Однако имеющиеся данные ограничены и не позволяют оценить все месторождения в регионе, что затрудняет выводы о влиянии на экологическую безопасность Балхашского городского округа. Несмотря на высокий риск развития хронических заболеваний в этом районе, полученные результаты подтверждают, что фрактальный анализ может служить полезным индикатором состояния окружающей среды и основой для систем мониторинга.

Ключевые слова: анализ временных рядов, R/S-анализ, показатель Хёрста, сточные воды горнодобывающих предприятий, экологический мониторинг.

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