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Fractal Analysis of Mining Wastewater Time Series Parameters: Balkhash Urban Region and Sayak Ore District

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Abstract: The population life and health quality are significantly reduced due to water resources pollution caused by heavy metals, especially in urban agglomerations located close to metal ore mining and processing facilities. The greatest environmental pollution occurs during the extraction of Cu, Zn, and Pb. In this study, a fractal R/S analysis of wastewater discharge indicators time series from a metal ore mining facility located in the Sayak ore district in the Republic of Kazakhstan (turbidity, electrical conductivity, flow magnitude, and pH level) was carried out. A sharp increase in the flow rate was recorded from 10 to 15 July 2024 and an increase in the electrical conductivity from 4 to 26 July 2024. However, the latest type of indicator assessment does not exceed the critical level for life. The presence of electrical conductivity indicators time series long-term memory and persistence was also recorded (the Hurst exponent for the electrical conductivity time series is fixed in the 0.56 to 0.59 range and does not go below the threshold value for randomness according to the Anis-Lloyd formula). Thus, the value-changing process is controlled and stable, and minor changes in turbidity indicate that these releases do not significantly harm the environment. Despite this, the results obtained do not allow for a comprehensive analysis of the state of releases as the data from all deposits is not available. Therefore, due to the time constraints of the data provided for analysis, it is difficult to fully assess the impact of specific metal ore mining facilities on the environmental safety of the Balkhash urban region. In addition, many studies indicate very high risks of chronic diseases for the population living in this region. The findings of this study enable us to conclude that the application of fractal analysis and the calculation of fractal characteristics for time series of emissions can serve as an indicator of the environmental status within the given area. This information can be used by environmental services to build reliable environmental pollution monitoring systems.

Keywords: mining wastewater; R/S analysis; Balkhash urban region; Hurst exponent; Sayak ore district; time series analysis

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1. Introduction

Environmental degradation due to metal ores extraction and processing is a common fact in the modern world [1]. The mining process is usually done in an open-pit manner by removing part of the earth's rock to a depth of up to 100 m. Also, it can be carried out in a closed manner if the minerals are located deeper under the surface of the earth. Nevertheless, due to the mining, a large amount of waste remains because ore makes up

only a small part of the total extracted material. The greatest pollution of the environment occurs in the case of Cu, Zn, and Pb extraction. In the case of copper mining, large mine wastes and tailings remain. The production of zinc and lead leads to emissions of CO_2, SO_2, and NO_x gasses into the environment. In addition, in both cases, solid particles are released into the air and contaminated process water is released onto the surface relief. Thus, there is significant pollution of both air and soil by mining waste. Some of the pollutants can enter open reservoirs near mining, which can be used by the local population for drinking and farming.

The presence of metallic ore mining and processing regions near the main water resources poses a significant threat to the life quality of the population. In addition, water consumption should be safe, affordable, and free of pollutants. However, several pollutants, including inorganic, organic, pathogens, thermal, and radioactive, should be considered [2]. All of them have a common impact on the health of the population using polluted water. In general, according to the World Health Organization (WHO), any significant changes in the physical, biological, and chemical properties of water that may have negative consequences for human health and other living beings can be defined as water pollution [3]. Water pollution is associated not only with complications in water usage for drinking, washing, and other vital activities. In addition, water is used for agriculture, in particular, for field irrigation, and plays an important role in the formation of biochemical reactions under the surface lands [4,5]. Even apart from the location of ore mining and processing regions, limited water resources have been brought to a crisis state due to population growth, urbanization, chaotic agriculture, etc. According to the World Water Development Report released by UNESCO, the use of freshwater in the world has increased sixfold over the past 100 years [6]. Since the 1980s, the use of freshwater in the world has been growing on average by about 1% per year. At the same time, about 80% of urban wastewater is discharged into the environment without any pretreatment [7,8].

Seven metrics were formulated to evaluate the quality of life in urban environments in [9], utilizing the ISO 37120:2018 standard [10] as a foundation. These include urban services, culture, economy, and recreation, as well as urban mobility, wellness, safety, and environmental comfort. The latter include noise and air pollution, climatic comfort, and the purity of water resources. According to the UNESCO 2021 World Water Development Report [6], about 829,000 people die from drinking contaminated water, including almost 300,000 children under the age of five. This accounts for about 5% of all deaths in this age group. At the same time, the information is presented mainly about organic water pollution. The use of water contaminated with waste from the extraction and processing of metal ore can have long-term consequences for human health, including provoking oncological diseases and generally reducing life quality. Therefore, the research aimed at studying the impact and characteristics of the water waste releases from metal ore extraction is very relevant for urbanism, particularly in terms of ensuring the urban population life quality and environmental prospects in urban development near the mining regions. The analysis of the chemical composition of waste released to the terrain and the introduction of effective systems for water purification and sedimentation before release to the soil should lead to a decrease in the water resources pollution level and, accordingly, lead to a decrease in morbidity and improve the life quality in cities located near the metal ores extraction.

This problem concerns urban agglomerations located near the regions of metal mining and ore processing. For example, in the Republic of Kazakhstan, one of such regions, for which the problem of ensuring the environmental safety of cities is acute, is the Northern Balkhash region, or the southern part of the Karaganda region. The Sayak ore district is located in this region, which has about ten deposits of high-quality ore. The main industrial value consists of skarns with gold-copper-molybdenum association deposits. In particular, the copper content in them is about 10–15%, molybdenum from 0.01 to 1%, cobalt 0.15%, etc. The area is directly adjacent to Lake Balkhash, which is one of the largest lakes in the world. Also in this region, on the Lake Balkhash shore and in the southern part of the Aktogay district, there are several urban agglomerations: the city of Balkhash with a population

of more than 78,000 people, and Priozersk with more than 13,000 people [11]. More than 3 million people live in the Lake Balkhash basin or the Balkhash urban region, including residents of Almaty, which is one of the largest cities in Kazakhstan with a population of over 2 million people. Agglomerations are adjacent to regions of intensive mining and processing of metallic ores, particularly the Sayak ore district.

The metal ores extraction and processing require significant water resource consumption. At the same time, a significant volume of water after production is chemically polluted on different scales. This leads to a negative impact on the environment and worsens the life quality and health of the population living near mining facilities. In total, more than eight tons of water are required to process ore and produce one ton of a useful component [12]. The geographical features of the Central Kazakhstan territory led to the massive use of groundwater for mining purposes due to the limited resources of suitable surface waters. At the same time, groundwater in this region is extremely necessary for the water supply for the population of nearby settlements. Lake Balkhash is large in the northern part of ore basins and on the shore large semi-freshwater settlements. Moreover, the water in the western part of the lake is used for food and industrial supplies. The water in the eastern part of the lake has a high salinity from 3 to 6 g/L. Fishing is also economically important in the region, so the ecological stability of the water in the lake is extremely important.

The region around Lake Balkhash has significant environmental problems that have been accumulating since the 1970s. The significant water resources used for the metal ores extraction have led to the rapid shallowing of the Balkhash Lake and other lakes in the region. In particular, only five of the sixteen lake systems remain. One-third of the Balkhash Lake basin has been drained [13]. A significant volume of Balkhash Mining and Metallurgical Combine discharges and wastewater releases led to the fact that 20 years ago, more than 70 tons of copper, 60 tons of zinc, and lead each year were deposited at the bottom of Lake Balkhash [14]. Besides heavy metals, the lake is also polluted by petroleum products and chemical compounds of fluorine with other elements. In addition, the polluted waters flowing into the Balkhash Lake basin from mining enterprises of the People's Republic of China may have an impact on the ecology of the region.

The peculiarity of this region is that it is in a continental climate zone with cold winters and hot summers with strong winds. Intensive extraction of metal ore leads to a violation of the soil cover, which in these climatic conditions is also fraught with the ecological safety of the regional ecosystem. Moreover, in addition to the release of wastewater from production, a large amount of pollution in the region is accounted for by emissions from the Balkhash Mining and Metallurgical combine. One of the solutions that can improve the air quality in the region, especially in a continental climate, is the use of biotechnological filter systems. Such systems use some types of mosses to purify the air from various pollutants, in particular, PM2.5 (particulate matter with a diameter of 2.5 mm). The authors in [15] describe the concept of moss-based biotechnological purification filters used in an urban environment. However, the same concept can be adapted for use in other regions with a high content of pollutants in the air.

In [16], a concept of water quality parameters statistical analysis was proposed using the example of open reservoirs in India, including the calculation of the water quality index (WQI) and fractal analysis to calculate the Hurst exponents of reservoirs pollution parameters time series. In [16], estimates are given for reservoirs from which water consumption by the population directly proceeds. In the case of wastewater release based on the results of metallic ores mining, such estimates should be adjusted. The calculation of the Hurst exponent and the study of the long-term memory presence in the time series structure can be performed based on the Rescaled Range Analysis (R/S analysis) [17,18] or Detrended Fluctuation Analysis (DFA) methods [19,20].

Water quality has a significant number of indicators, the normative indicators of which are determined in accordance with the WHO/EPA standard [21,22]. The procedure for selecting and evaluating water samples is described in [23]. In [24], time series Hurst indicators of hydrological variables and water quality indicators for various watersheds

were calculated. The results obtained indicate the persistence of the Hurst index before and after the deseasonization procedure of the time series. The values of the Hurst index, which are estimated in [24], can be used to develop models for predicting time series of water quality. However, water samples were taken for analysis from the open reservoirs of the Little River and Walker Branch located in Tennessee, USA. The research process and the results of the Hurst index evaluation may have their own characteristics for different waste mine water outlet samplings based on the results of metal ore extraction. The time series study for water flow chemical components concentrations for the hydrological properties analysis has been described in several papers [25–28]. In these works, the presence of such time series random fractal behavior was shown, and the presence of some time series stable persistence was recorded, which makes the prediction of their values possible. In particular, it was shown in [27,29,30] that some water quality indicators may have short-term and long-term persistence.

In [31], the drinking water quality was studied in terms of turbidity, which is a measure of water transparency degree. The greater the number of solids in the water, the greater the degree of turbidity. It is an important indicator of changes in water quality and with its persistence, appropriate methods can be used to predict water quality in the future. In [31], the R/S analysis method was used to evaluate the time series Hurst indicator for changes in the turbidity of drinking water. For different samples, both the transient behavior of turbidity time series and the unstable change in turbidity values were found, which may indicate unstable releases of substances saturated with solid particles into the water. If such displays are recorded in water, this may threaten the environmental safety and health of people who consume this water. After all, the random nature of fluctuations in the time series does not allow for their change in the future, and at a certain point in time, these indicators may be life-threatening.

Therefore, the time series fractal analysis method application for indicators of wastewater releases from metal ore mining facilities to determine the long-term memory presence and persistence identification is the relevant task to ensure environmental safety and maintain the life quality of the population living near these facilities.

The purpose of this article is to study the long-term memory in pollution by wastewater discharges from metal ore mining facilities indicators time series which affects the environmental safety and life quality of the population living in regions that are near mining areas. The Balkhash urban region, in particular, its northern part and Sayak ore district, was chosen as an example for the study. To achieve the goal, the following tasks were set:

1. Apply the fractal analysis indicators time series method for water releases to the soil surface after extraction of metal ore contamination or to calculate the Hurst exponent and identify long-term contamination.
2. To analyze the value of the electrical conductivity, turbidity, and water quality time series Hurst exponent to assess the pollution level from Sayak ore district deposits.

The long-term stability of pollutant concentrations, turbidity levels, and electrical conductivity of effluents suggests that water quality parameters can be effectively predicted and regulated. These findings are significant for the advancement of urban development, particularly in ensuring environmental safety and promoting the sustainable growth of urban agglomerations, including those in proximity to mining and metal ore processing areas.

2. Materials and Methods

2.1. Calculation of the Hurst Exponent for a Time Series of Water Releases

With the advent of Hurst's work [32] on modeling water accumulation, hydrologists use the described approaches to analyze and model time series of complex structures, especially those that are non-linear in nature. The change in water pollution indicators is a non-linear process, therefore, for this case, a fractal analysis of the time series of releases can be applied to identify the presence of long-term memory in the time series and calculate the

Hurst exponent. As already mentioned, several methods can be used for these purposes. If there is sufficient data, the R/S analysis method can be used.

Let a discrete time series of water release indicators be given, in particular, water from metal ore mining facilities, for example, turbidity, flow, electrical conductivity, pH level, etc. In this case, the values of the indicators are fixed by appropriate sensors at time points $t_1, t_2, \ldots, t_n$, where t_1 is the initial moment, then the time series R can be presented in the following way:

$$R = (r(t_1), r(t_2), \ldots, r(t_n)). \quad (1)$$

Based on the time series R, we will construct a family of cumulative time series $R^h = (r(t_1), r(t_2), \ldots, r(t_h))$, $h = \overline{3,n}$, for each of which the statistical characteristics will be calculated [18,33]:

$$\overline{R}^h = \frac{1}{h}\sum_{j=1}^{h} r(t_j),\ h = \overline{3,n}, \quad (2)$$

where $\overline{R}^h$ are the mean of time series R^h,

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

where $\rho(h,s)$ is a deviation from the arithmetic mean,

$$F_h = \max_{s=\overline{1,h}}\rho(h,s) - \min_{s=\overline{1,h}}\rho(h,s), \quad (4)$$

where F_h is range,

$$\sigma_h = \sqrt{\frac{1}{h}\sum_{j=1}^{s}\left(q(t_j) - \overline{Q}^h\right)^2},\ h = \overline{3,n}, \quad (5)$$

where σ_h is the standard deviation.

Therefore, the next equation can be constructed

$$\lg\left(\frac{F_h}{\sigma_h}\right) = H\left(R^h\right)\cdot\lg(h) + \lg(\delta),\ h = \overline{3,n}, \quad (6)$$

where $H\left(R^h\right)$ is the Hurst exponent. The Hurst exponent for an independent variable can be calculated using the least squares method.

In this case, the fractal dimension D of the time series is found by the formula [18,34]:

$$D = 2 - H, \quad (7)$$

To indicate how much the fractal fills the space after zooming out, the predictability index P can be calculated based on the indicator D [17]:

$$P = 2|D - 1.5|, \quad (8)$$

In this case, the P value increases when the value of D is less than or greater than 1.5. If $D < 1.5$, then there is a persistence in the structure of the time series R. If $D > 1.5$, then the time series R is persistent. If the value is close to 0, then it can be argued that the time series is random or close to random. A formula can be applied to identify a threshold value that allows you to identify a time series as persistent or random [35]:

$$H_h^T = \sqrt{\frac{2}{\pi(h-1)}}\sum_{i=1}^{h-1}\sqrt{\frac{h-i}{i}}, \quad (9)$$

where H_h^T is the theoretical threshold value utilized to define the boundary between stochastic and persistent time series.

In addition to these estimates, which make it possible to analyze water release time series structure, another indicator can be calculated that determines water quality [17] using the formula:

$$WQI = e^{\sum_{j=1}^{k} \alpha_j \ln\left(\frac{100 \cdot v_j}{v_j^*}\right)}, \quad (10)$$

where v_j is the value of the j-th indicator, v_j^* is the normative value of the j-th indicator, k is the number of indicators, and α_j is weight coefficient.

According to the WHO/EPA standards [21], the standard value of electrical conductivity is 400 microsiemens per centimeter (μS/cm). Conductivity above 300–500 μS/cm in freshwater streams may begin to stress sensitive aquatic species, but thresholds vary based on location and ecological needs. It was noted in [17] that when calculating QI for electrical conductivity, it should be used. However, in our study, a smaller number of indicators were used, namely, k = 1. Therefore, the weighting coefficients need to be normalized. After normalization, the value of the weighting coefficient for electrical conductivity $\alpha_j = 1$.

Therefore, after calculating the Hurst exponent, it is possible to determine such an interpretation of the analysis results for a time series of water releases:

1. In case $H_h^T < H\left(R^h\right) \leq 1$, long-term memory is present, indicating that the time series is persistent. In the context of analyzing water release indicators, such as turbidity or electrical conductivity, Hurst exponent values of this magnitude suggest that high pollution levels are likely to remain elevated for extended periods or may return to high levels following periods of decline. The main trend regarding the indicator's values or the water pollution level remains. For such time series, traditional trend forecasting methods can be used. This is important for the operation of water pollution monitoring systems because the case of water parameters time series persistence is a sign of stability, predictability, and controllability of releases, in particular, water releases from metal ore mining facilities.
2. If case Hurst exponent is $0.5 \leq H\left(R^h\right) \leq H_h^T$, then the time series is random. In the time series analyzing context water release indicators, this may mean that the pollution level varies unstable, and harmful substance concentrations in water cannot be regulated and predicted. This may be due, for example, to a violation of technological processes and a violation of the sedimentation and water purification norms. Most likely, the water is either insufficiently purified before being released to the ground surface or the release is carried out abnormally in an emergency. The latter can be established if, prior to this, a temporary series of indicators of water releases had a persistent nature of fluctuations.
3. In case $0 \leq H\left(R^h\right) < 0.5$, the time series can be classified as ergodic, indicating that the process is anti-persistent. Within the context of analyzing water discharge indicators, this suggests that pollution levels tend to decrease temporarily following high values or, conversely, to increase after low values. The dynamics of such a time series change more rapidly than that of a random time series.

Constructing the Hurst indicator for the time series of water discharge indicators facilitates the analysis of long-term delays in the mechanisms generating these time series. This is crucial for developing effective water pollution monitoring systems. While this study focuses on the discharge of non-potable water from mining facilities, applying these assessment methods is equally important for evaluating drinking water pollution in urban agglomerations. Similar reasoning has been applied in the analysis of air pollution time series as discussed in [33]. If the Hurst exponent value of such a time series falls below a certain threshold, it may signal a critical situation or indicate instability in pollution levels. This could suggest the emergence of critical conditions regarding water pollution, necessi-

tating timely intervention. Conversely, if the time series exhibits persistence, traditional models that account for trend components may be suitable for forecasting.

2.2. Experimental Methods and Area of Study

To conduct the study, data from the releases of one of the Sayak ore district deposits owned by a private mining company were analyzed. Since the data of the releases are confidential and can be used by competitors, the company provided the data without distributing its name and the exact geographical location of the facility and water sampling stations for analysis. However, since research is critically important to ensure the environmental safety of the region, the company is interested in developing new methods for monitoring and analyzing releases. Taking this into account, this paper will give a general description of the region in which ore is mined and its features, which affect, among other things, the technological process of extraction.

This deposit has been specializing in the extraction of copper ore for more than 50 years. The location of the Sayak ore district is shown in Figure 1. The region of the deposits is located 200 km from the city of Balkhash. The use of water in the extraction process is carried out from the groundwater deposit. According to hydrological studies, there are three types of groundwater in this region. The first type is the groundwater of loose sediments, which are located in river valleys south of rock dumps. Such waters have a significant mineralization up to 3 g/L and pH = 6.6–7.0. The second type of groundwater is deep groundwater, which is widespread everywhere at depths up to 50 m. The water supply is infiltrated. Unloading is carried out for intra-soil evaporation and transpiration by plants. The third type of groundwater in the region is deep vein waters, which are recorded at a depth of 50–60 m. The supply of such groundwater occurs mainly due to atmospheric precipitation in the winter season. The chemical composition of groundwater deposits despite large fluctuations in mineralization (from 1.2 to 5.3 g/L) is relatively constant, changes insignificantly over time, and mainly has a sulfate, sulfate-chloride, sodium-calcium, or calcium-sodium composition. Groundwater usually has a pH between 6.9 and 8.5 and is defined as very hard.



Figure 1. The location of the studied area is the Northern Balkhash region and Sayak ore district, which is located in the Balkhash Lake basin (marked in yellow) in the Republic of Kazakhstan.

The mine discharge of wastewater at this mining facility is organized in such a way as to reduce the negative impact of pollution on the region's ecology. When the mine workings are drained, the mine water flows by gravity through the tunnel to the bottom point, i.e., the

sump or storage tank. As the mine waters accumulate and settle in the reservoir, they are pumped out by a pipeline using pumping equipment of the K130-65 brand (Kataisk pump plant, Kataisk, Russia) into an intermediate storage tank with a volume of 800 m^3. Further, as it accumulates, the mine water is pumped through a pipeline with a diameter of 159 mm by a CNS-180 pump (Pinsk pilot mechanical plant, Pinsk, Belarus) into the next intermediate storage tank with a volume of 7000 m^3. As the sedimentation tank is filled to certain levels, the mine waters are pumped through the pipeline with a pump of the 180/297 brand to the surface, followed by their discharge to the terrain. Sump and intermediate mine water storage are primary settling tanks where pre-treatment processes take place by settling water under the influence of gravitational forces (mechanical cleaning). The use of mine waters can be carried out at any stage, both in the mine and on the surface, depending on the technological needs of the enterprise. The unnecessary volume of mine waters discharge, previously purified by stepwise sedimentation, is carried out by a pipeline with a diameter of 159 mm to the terrain located in a southerly direction relative to the rock dumps of this deposit. The flow of discharges occurs in the direction of the Balkhash Lake.

In this paper, a water release indicators time series fractal analysis for a metal ore mining facility located in Sayak ore district was carried out. In particular, the value of the Hurst exponent was calculated based on R/S analysis for electrical conductivity, turbidity, and flow. At the same time, the value of the Hurst exponent was calculated for a number of observations and for a time series corresponding to a rapid change in these values over a certain period of time. In general, the values of the indicators were stable during the observation period, but a short period of time was recorded when the values of these indicators increased. Fractal analysis was also performed for local time series corresponding to this time period. In addition, this work identified water quality assessments (WQI) and predictability index.

3. Results

3.1. Collection of Data

The data of the releases for the study were provided by one of the companies leading the production of copper ore in the Sayak ore district (see Supplementary materials). The location of the mining area can be seen in Figure 1 [36]. The outlet intake station is located at the outlet of the pipeline before the exhaust water is released to the ground surface based on the results of ore extraction. Since the data of the releases are confidential and can be used by competitors, the company provided the data without distributing its name and the exact geographical location of the field and the water extraction station for analysis. However, in Figure 2, the location of metal ore mining facilities can be seen in the region using Google My Maps (Map data 2024) service [37].

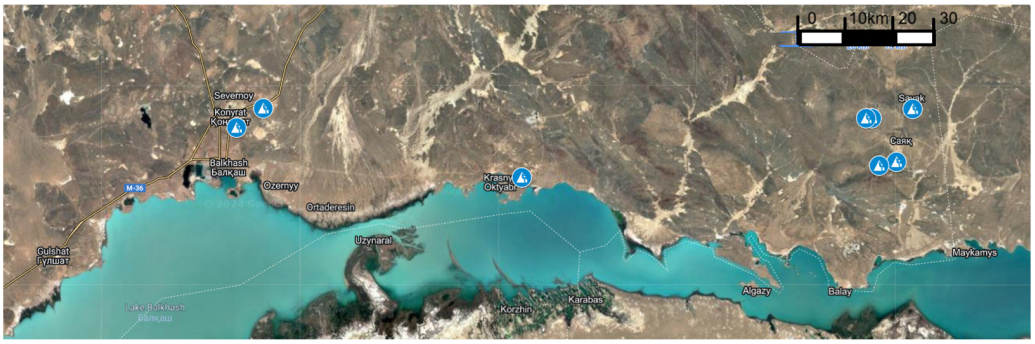


Figure 2. Placement of metal ore mining facilities in the Northern Balkhash region.

The data were analyzed for the period from 23 May 2024 to 28 August 2024. The screenings were recorded every 20 min. In total, 6385 values of pH, turbidity, electrical conductivity of releases, and flow values were analyzed during the period under review. Turbidity was measured in the nephelometric turbidity unit (NTU), which characterizes

the number of suspended particles in water. Turbidity was measured by analyzing the amount of light that is scattered by particles in the eyes. The water flow was measured by the volume of water passing through a certain area per unit of time in cubic meters per second. The electrical conductivity was measured in μS/cm. Electrical conductivity determines the ability of water to conduct electric current and depends on the amount of ions dissolved in it. The dataset provided for the study also contained data on the pH level of water, but the volume of data did not allow for reliable analysis of this indicator for the tasks formulated in the study. The dataset of indicators in CSV format can be found at the link [38]. Table 1 shows some descriptive statistics of time series data and WQI estimates.

Table 1. Descriptive statistics of time series of indicators of wastewater releases from a metal ore mining facility.

Indicator	Turbidity, NTU	Electrical Conductivity, μS/cm	Flow, m^3/min	pH Level	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

3.2. The Results of the Hurst Exponent Calculation for Time Series of Water Release Indicators

Based on the R/S analysis, for each time series of water discharge indicators (flow rate, electrical conductivity, and turbidity), the value of the Hurst exponent was calculated and the presence of long-term memory in the time series for the established period from 23 May 2024 to 28 August 2024 was investigated. Figure 3 shows the change in indicators for the entire specified period of time. The value of the Hurst exponent for all 6385 points is calculated for them. The calculation results are shown in Table 2.

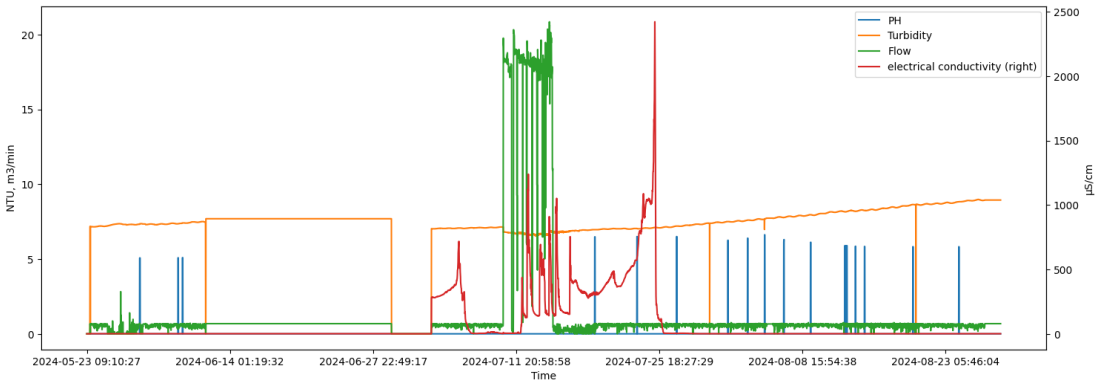


Figure 3. Time series of values of water discharge indicators (flow rate, electrical conductivity, turbidity, and pH level) which were recorded at one of the metal ore mining facilities in Sayak ore district for the period from 23 May 2024 to 28 August 2024.

As can be seen from Figure 3, in July 2024, a significant increase in the value of the water's electrical conductivity was recorded (red curve). In other periods of observation, the value of electrical conductivity is close to zero. Such values are explained by the absence of a significant flow of water from the metal ore mining facility in other time periods. However, as can be seen from Figure 3, in July, the value of the flow increased sharply from 10 July 2024 to 15 July 2024 (green curve). Accordingly, the water's electrical conductivity increased in the time interval from 4 July 2024 to 26 July 2024. During this period of time (a total of 1583 points), estimates of the Hurst exponent of the corresponding

water indicators were separately investigated and constructed. The results are shown in Table 2. Figure 4 shows the corresponding time series for the period from 4 July 2024 to 26 July 2024.

Table 2. Values of the Hurst exponent.

Indicator	Observation Period	
	23 May 2024 to 28 August 2024	**4 July 2024 to 26 July 2024**
Number of observations	6386	1583
Electrical conductivity, μS/cm	0.59406	0.55968
Turbidity, NTU	0.42972	0.48980
Flow, m^3/min	0.38568	0.34991
WQI	0.59406	0.55968

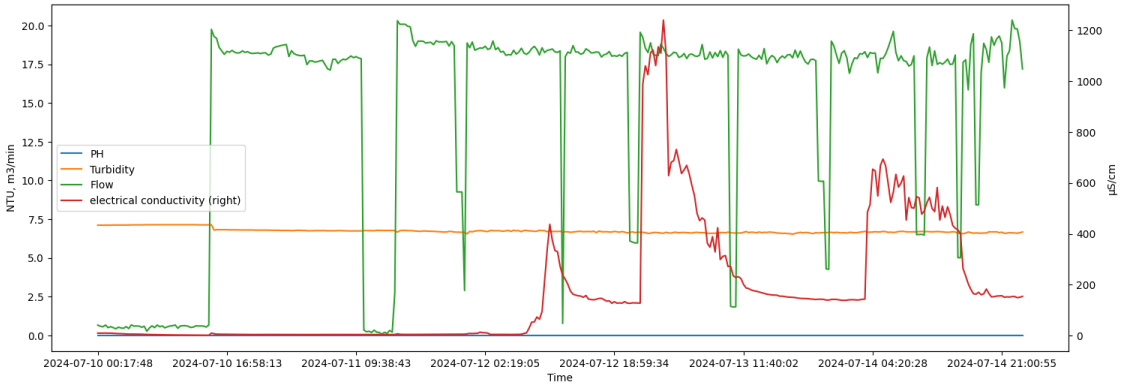


Figure 4. Time series of values of water discharge indicators (flow rate, electrical conductivity, turbidity, and pH level) which were recorded at one of the metal ore mining facilities in Sayak ore district for the period from 4 July 2024 to 26 July 2024.

In general, a significant increase in the value of the flow was revealed from 10 July 2024 to 15 July 2024 which may be due to both the company's activities and weather conditions. Since, according to [39], heavy rains continued in the southern part of the Karaganda region (Northern Balkhash region) during this period. However, in any case, the increase in the flow rate is associated with the wastewater release of a significant volume with a high-level electrical conductivity. At the same time, the turbidity of the water has not changed significantly. In general, the value of the water's electrical conductivity, even at peak values, is estimated [21], and according to this dataset does not pose a significant threat to the ecology of the region. The value of the Hurst exponent for the time series of the electrical conductivity indicator for the period from 23 May 2024 to 28 August 2024 is $H_1\left(R^{6386}\right) \approx 0.59$, for the period from 4 July 2024 to 26 July 2024 is $H_2\left(R^{1583}\right) \approx 0.56$. According to [35], $H^T_{6386} < 0.5065$ and $H^T_{1583} < 0.5141$. This means that the time series of electrical conductivity for both time periods is persistent, since $H_1\left(R^{6386}\right) < H^T_{6386}$ and $H_2\left(R^{1583}\right) < H^T_{1583}$. Also, based on this dataset, water quality indices (WQI) were calculated. It was found that the WQI time series for both time periods are also persistent. The turbidity and flow values are antipersistent. The magnitude of the flow is explained by sharp changes in the flow from high to low values, especially in the period from 10 July 2024 to 15 July 2024. Turbidity does not change significantly, but during almost the entire observation period, alternating growth and decrease are recorded for very short periods of time.

Therefore, based on the results of the analysis, it can be concluded that the time series of water electrical conductivity release indicators that were recorded at one of the metal ore mining facilities in the Sayak ore district are characterized by the presence of long-term memory. Such results are a sign of stability, predictability, and controllability of the electrical conductivity values of the releases. Taking into account the permissible regulatory parameters for electrical conductivity [21], it can be argued that this enterprise fulfills the requirements for the purification and sedimentation of water coming directly from the mining facility.

4. Discussion

4.1. Findings

In this study, the indicators of turbidity and electrical conductivity of wastewater releases after the technological process of mining metal ores are investigated. The water from the outlets is not used for drinking, however, it can penetrate into groundwater and open reservoirs during the release onto the soil, such as lakes of the Balkhash water basin. If the solid particle concentration and the electrical conductivity level are high, the environmental safety of the region can be threatened, and the life quality and local residents' health worsened. The long-term stability for pollutant concentration, turbidity indicators, and water release electrical conductivity means that water quality parameters can be predicted and controlled. Therefore, at any given time, environmental monitoring can verify the permissibility of the pollutant concentration in releases. If the change in the concentration of pollutants in releases, turbidity, and electrical conductivity indicators is accidental or antipersistent, then it is impossible to assert confidently the stability and acceptability of environmental pollution indicators. Moreover, if the instability of such a time series is recorded, it can be argued that the technological norms for the use and release of wastewater from ore mining facilities are not being fulfilled. This analysis can be performed based on a time series R/S analysis for water release indicators and the Hurst exponent calculation.

The results obtained by applying the fractal R/S analysis method for wastewater discharge indicators time series from a metal ore mining facility located in the Sayak ore district in the Republic of Kazakhstan indicate a satisfactory state of releases, which does not harm the environmental safety of the Northern Balkhash region. A sharp increase in the flow rate was recorded in the period from 10 July 2024 to 15 July 2024 and an increase in the water's electrical conductivity from 4 July 2024 to 26 July 2024, which depends on the amount of ions dissolved in it. High values of electrical conductivity may indicate contamination of water with metals, and water cannot be consumed for drinking. In addition, contaminated water in high concentrations can be harmful to the environment. According to estimates [21], the values of the electrical conductivity indicators do not interfere with environmental safety. In addition, the value of the turbidity index is stable. The persistence of time series and the presence of long-term memory of electrical conductivity indicators indicates the predictability and manageability of water pollution levels, which is important for building appropriate monitoring systems.

Despite the results obtained, it should be noted that the Northern Balkhash region and the city of Balkhash have an extremely high level of chronic health effects from heavy metal pollution. The maximum index of chronic exposure of pollutants to respiratory organs was also recorded in the city of Balkhash [40,41]. It is clear that this concerns emissions of pollutants into the air from ore processing plants. However, the cumulative health effects of heavy metal pollution of both air and water resources should not be discarded. In [42], the analysis of samples of surface waters of the Ili-Balkhash basin was described and a high level of Cu, Pb, and As in the waters of Lake Balkhash was established, exceeding international standards. Lake water samples exceeded safe limits. In particular, As has been identified with a potentially dangerous concentration, which indicates that the consumption of lake water can have a significant negative impact on public health. Therefore, in order to analyze potential threats to the health of the local population, in particular, the population

of Balkhash, it is necessary to monitor the quality of water and releases from metal ore mining facilities. This is the key to ensuring the environmental safety of the region and the life quality of the population living near ore mining and processing facilities.

4.2. Limitations and Future Research Lines

Based on the results of the study, some restrictions can be formed. In particular, the dataset obtained for analysis was collected in a relatively short time interval (from May to August 2024). This to a certain extent complicates the analysis of patterns and the study of possible cyclical or seasonal components in a time series.

At the same time, the data was recorded by sensors quite often—every 20 min. Therefore, the amount of data obtained was sufficient for a general analysis and description of the results obtained. In this case, the inability to track changes in water quality indicators in other time periods does not allow for a more comprehensive assessment of the impact of wastewater releases from mines of metal ore mining facilities in this region on the environmental safety and life quality of the population of the cities of Balkhash urban region.

Another limitation that may affect the conclusion regarding the pollution level is that data on mine water releases from other mining facilities are not available. Accordingly, at the moment, based on the results of a real analysis of soils, air, and water in the Sayak ore district, it is possible to conclude about the complex environmental problems of the region. It is also possible to analyze the state of morbidity in the Balkhash urban region, in particular, in its northern part, and assume that it is associated with emissions and releases of pollutants, including heavy metals. However, in this case, without full information on changes in the values of mine water indicators, which are released to the soil surface by all ore mining facilities, it is difficult to identify those companies or deposits that violate regulatory requirements for environmental safety. Therefore, in the future, it is important to get access to more data on water quality indicators time series in order to analyze them.

The results obtained are important for environmental monitoring services of cities that are located near regions with intensive extraction and processing of metal ores. Rapid response to violations of regulatory requirements regarding the concentration of harmful substances, in particular, heavy metals, in water, air, and soil is the key to maintaining the health and urban residents' life quality and is the environmental safety basis for the region.

5. Conclusions

The long-term memory in the time series of wastewater releases from a metal ore mining facility located in the Sayak ore district in the Republic of Kazakhstan has been studied. For this purpose, the time series fractal R/S analysis method for turbidity, electrical conductivity, flow magnitude, and pH level for the period from 23 May 2024 to 28 August 2024 was used to calculate the Hurst index. Insufficient data did not allow an analysis of the pH level. As for other indicators, a sharp increase in the value of the flow was recorded in the period from 10 July 2024 to 15 July 2024 as well as an increase in the indicator of water electrical conductivity from 4 July 2024 to 26 July 2024. However, the assessment of water's electrical conductivity does not exceed the critical level for life. The presence of long-term memory and the persistence of electrical conductivity indicators time series is also recorded (the Hurst exponent for the electrical conductivity time series is fixed in the range from 0.56 to 0.59 and does not go below the threshold value for randomness according to the Anis-Lloyd formula). It has been established that the WQI time series are also persistent. Also, the turbidity index does not change significantly. The Hurst exponent for turbidity varies from 0.43 to 0.49, which indicates the time series antipersistency for the water turbidity index. It was also recorded that during the period of intensive growth in the flow magnitude and, accordingly, the increase in electrical conductivity, heavy rains continued in the study region. However, in any case, an increase in the flow rate is associated with the wastewater release of a significant volume with a high level of electrical conductivity which can threaten environmental safety in high concentrations.

The results obtained indicate that the process of changing the water's electrical conductivity according to this dataset is controlled and stable, and small changes in turbidity indicate the absence of a significant environmental impact of these releases. However, possible damage from the releases of other deposits or mining and processing facilities of metal ore in this region should not be excluded because many studies indicate very high risks of chronic diseases for the population living in the Balkhash urban region. In general, the results obtained indicate that the fractal time series analysis method can be an indicator of the ecological state in the relevant region. This is important for ensuring the health and life quality of the population of cities living near metal ore mining and processing facilities.

Supplementary Materials: The following supporting information can be downloaded at: https://doi.org/10.5281/zenodo.13899489, accessed on 6 October 2024, Table S1: Data on Water Discharges from Copper Ore Extraction in the Sayak Ore Basin.

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