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Original Article

Water Quality Assessment from an Environmental Liability Applying Grey Clustering and Harmonic Mean

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Abstract *- The monitoring of the quality of the mine tailings from the La Tahona mining waste dump in 2018, located east of the city of Hualgayoc, is an important issue that must be analyzed, as it still represents a severe risk to the health of the city's inhabitants. In this way, the Grey Clustering method provides an alternative to evaluate the level of contamination of the sources near the mining tailings, taking into account the monitoring data with file number 0038-2018-DSEM-CMIN, carried out by the Directorate of Environmental Supervision in Energy and Mines of the Environmental Evaluation and Oversight Agency (OEFA), analyzing seven parameters of Prati index and Environmental Quality Standard, pH, Zinc, Suspended Solids, Arsenic, Lead, Iron and Cadmium. The results showed that the monitoring points of the water bodies near the effluent to the environmental liabilities of La Tahona were classified as high risk, which means that the efforts made to remediate the mentioned liabilities by the General Directorate of Mines of the Ministry of Energy and Mines (MINEM) do not comply with the quality parameters. Finally, the results obtained may be of help to OEFA, MINEM and the authorities of the Cajamarca region of Peru in the search for the correct treatment of the tailings effluents mentioned above.*

Keywords *- Grey clustering, Environmental liability, Water quality.*

1. Introduction

The district of Hualgayoc, situated in the province of the same name in the department of Cajamarca in northern Peru, is characterized by a rugged relief, high hills without vegetation, plateaus, hills, mineral reserves, among others. This district, located in the sub-basin of the Arazcorgue River, has irregular soils suitable for pastures and extensive cattle raising between 3,600 and 4,650 m.a.s.l. [1].

Although in Hualgayoc, there is an agricultural tradition that dates back to pre-Hispanic times, the inhabitants of this district are mostly of rural origin, dedicated to the sowing of maize, peas, beans, oca, potatoes, and olluco, and in the livestock area dedicated to the breeding of cattle and pigs [1]. The activity for which the district is known is mining, with the Cerro Corona mine, located about 2 km from the district, currently being in the exploitation stage.

This study focuses on the analysis of the results of study 0038-2018-DSEM-CMIN carried out on the environmental liabilities of the former mining company "Los Negros" in the hamlet of La Tahona located 900m east of the city of Hualgayoc by [2], for which a sanction was subsequently imposed by Directorial Resolution No. 2200-2018-OEFA/DFAI to the Directorate [3].

The assessment will be carried out at the mouths of the mining liabilities through the analysis of the Grey Clustering method. The selected method allows for quantifying the information [4], classifying the sampling points according to established parameters such as [5] quality parameters or the Water Quality Standards published Supreme Decree N° 004-2017-MINAM [6]. In this way, it can be assumed that the grey clustering method can benefit from a better analysis of the intakes in the conditions prior to the programmed restoration [7].

Consequently, our specific objective in the present investigation is the classification of 8 water intakes near the hamlet La Tahona before the treatment process [8]. Consequently, our specific objective in the present investigation is the classification of 8 water intakes near the hamlet La Tahona before the treatment process [8] by the state-owned company Activos Mineros (AMSAC) near the Arazcorgue and Hualgayoc sub-basins coming from the mining liabilities "Los Negros", using the method mentioned above. Section II presents the methodology used in this research, where the details of grey clustering are given. Section III describes the case study explained above, followed by Section IV's results and analysis; the conclusions are in Section V.

2. Methodology

The grey clustering method was developed based on the grey systems theory, originally formulated by Deng in 1985 [4, 9, 10].

In this article, the Grey Clustering procedure is applied to evaluate the impact on the level of contamination under the influence of the La Tahona mining liability. This methodology is normally used when data are uncertain and unquantifiable, but in this case, the grey systems are grouped according to accepted quality parameters... [4]. For the development of the research, it has been elaborated based on the following points.

2.1. Step 1. Setting of Central Points

Identify and delimit the study area; this information was collected from file 0038-2018-DSEM-CMIN. To do this, its values must first be dimensioned. These are applied to the standard values.

$$\mathrm{N}_{ij} = \frac{Zij}{\left(\frac{\sum\_nj=1Ziij}{n}\right)} \quad (1)$$

2.2. Step 2. Triangular Function Determination and their Values

Therefore, the triangular functions (number of grey classes) must be calculated where all the analyzed bodies are located (Figure 1.).

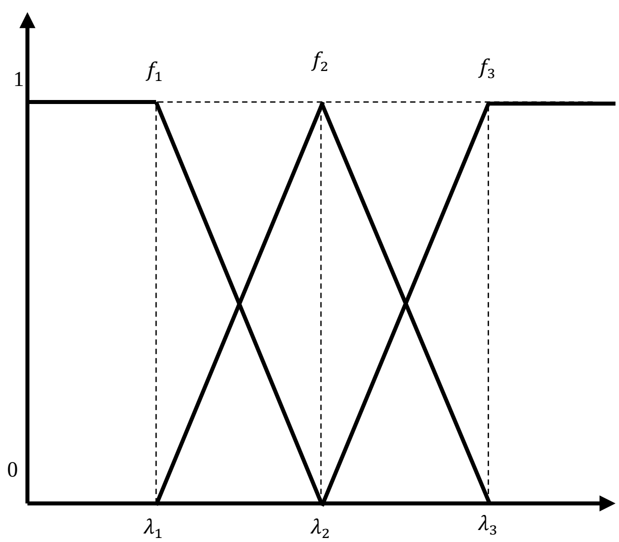

Fig. 1 CTWF Representation

$$f_j^1\,(\mathrm{x}_{ij}) = \begin{cases} 1,\ x\ \ni [0, \lambda 1] \\ \frac{\lambda 2 - \mathrm{x}}{\lambda 2 - \lambda 1}, x\ \in [\lambda 1, \lambda 2] \\ 0\ ,\ \in [\lambda 2\ , +\propto] \end{cases} \quad (2)$$

$$f_j^2\,(\mathrm{x}_{ij}) = \begin{cases} \frac{\mathrm{x} - \lambda \mathrm{K}}{\lambda 2 - \lambda 1}\ ,\ x\ \ni [\lambda \mathrm{k} - 1, \lambda \mathrm{k}] \\ \frac{\lambda \mathrm{k}+1-\mathrm{x}}{\lambda \mathrm{k}+1-\lambda \mathrm{k}}, x\ \in [\lambda \mathrm{k}, \lambda \mathrm{k} + 1] \\ ,\ \in [0, \lambda \mathrm{k} - 1] \mathrm{U}\ [\lambda 2\ , +\propto] \end{cases} \quad (3)$$

$$f_j^3\,(\mathrm{x}_{ij}) = \begin{cases} \frac{\mathrm{x} - \lambda 4}{\lambda 5 - \lambda 4},\ x\ \ni [\lambda 3, \lambda 4] \\ 1\ , x\ \in [\lambda 3, \lambda 4] \\ 0\ ,\ \in [-\ , \lambda 4] \end{cases} \quad (4)$$

These new triangular functions are then plotted.

2.3. Step 3. Calculation of the Weighting of each Criterion

The weighting method must be carried out by first searching for information in the environmental impact studies (Assessment of surface water quality by a unique pollution index). These values will give us the actual field data. Then, apply the following harmonic mean in equation (1), allowing me to calculate the weight of the grey class parameters λ.

$$n_j^k = \frac{\frac{1}{\lambda \mathrm{jk}}}{\sum_{j=1}^{n} \frac{1}{\lambda_j^k}} \quad (5)$$

2.4. Step 4. Clustering Coefficient Determination

The clustering coefficient σ_i^k by object i,i = 1,2,…,m, with regard to Grey classes k,k=1,2,…,s, is determined by (6).

$$\sigma_i^k = \sum_{j=1}^{n} f_j^k(x_{ij}) n_j \quad (6)$$

Where $f_j^k(x_{ij})$ is the CTWF of the $k - th$ grey class of $j - th$ criterion, y n_j is the weight of criterion j, the harmonic mean method, explained in step three, will be used to establish these weights.

2.5. Step 5. Maximum Coefficient Determination

Evaluate the results by determination of the Max Coefficient.

$$Max\ 1 <\ h < s\{\{\sigma k\}\ =\ \{\sigma k\} \quad (7)$$

3. Case Study

The information used in the present analysis of La Tahona Mining's Environmental Liabilities was taken from the Supervision Report that is based on the report of the Ministry of the Environment on facts verified in a field supervision action, with file number 0038-2018-DSEM - CMIN, from February 13 to 23, 2018.

The study is based in the district of Hualgayoc, province of Hualgayoc, Cajamarca, Peru. The ubication is shown in Figure 2.

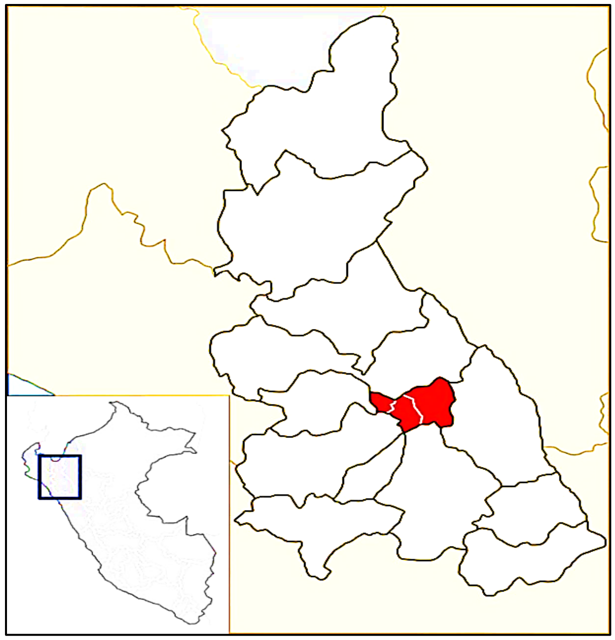

Fig. 2 Province of Hualgayoc, Peru

In the area, there are 55 environmental liabilities; La Tahona is between the two mi-cro-watersheds of Arazcorgue and Hualgayoc.

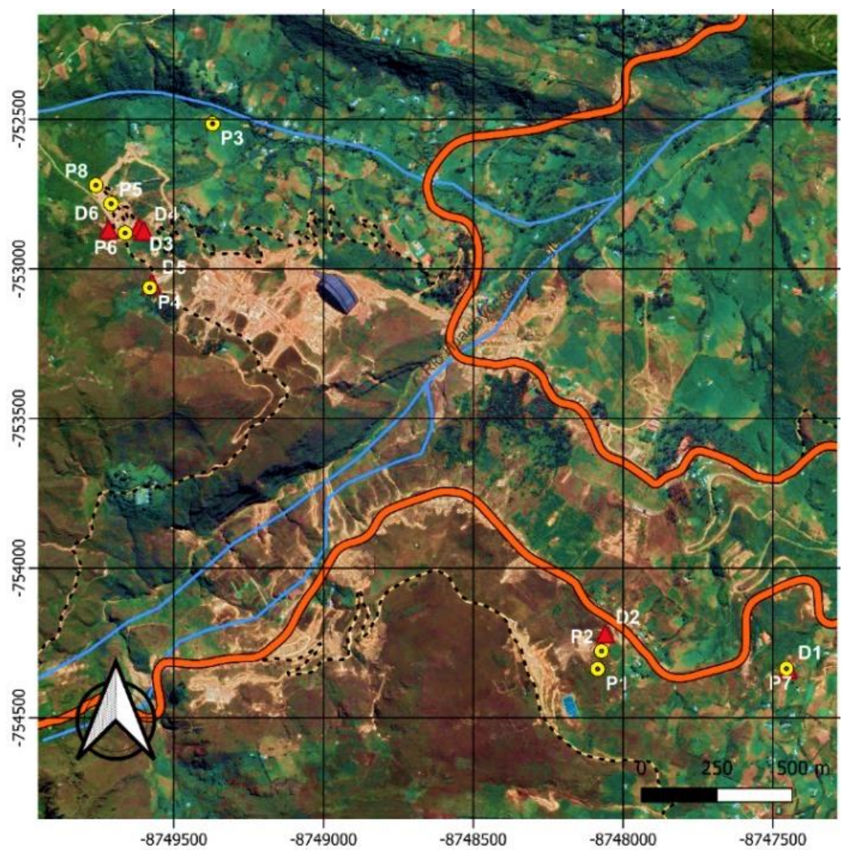

Fig. 3 Location of sampling points (mining tailings) of the tahoma environmental liabilities approximately 2km east of the city of hualgayoc in the department of cajamarca

Table 1. Monitoring points in the area are influenced by mining activity

Point	Description	Coordinates		Altitude
		North	East	
P1	San Agustin former mining unit. Drainage of the BOC-SA-LL-3 pit.	9 252 056	766 908	3 457
P2	Mine mouth of the old LOLA mining unit. Drainage of the mining shaft BOC-LO-LL-4.	9 252115	766 921	3 466
P3	Mine mouth of the old mining unit Los Negros. Drainage of the BOC-LN-LL-6 shaft.	9 253 860	765 640	3 517
P4	Mine mouth of the former Los Negros mining unit. Drainage of the mining shaft BOC-LN-LL-3.	9 253 320	765 429	3 495
P5	Ex-mining unit Los Negros mine shaft. Dewatering of the mining shaft BOC-LN-LL-14.	9 253 598	765 302	3 439
P6	Ex-mining unit Los Negros mine mouth. Drainage of the BOC-LN-LL-17 shaft, which crosses the DESM-LN-LL-11 dump.*	9 253 501	765 348	3 439
P7	Ex-LOLA Mining Unit's mine mouth Drainage from the BOC-LO-LL-10X mine pit is channelled through a concrete channel, which runs along the ground and discharges into a stream.	9 252 054	767 534	3 463
P8	Sampling point downstream of the watercourse watercourse that has contact with the cuttings DESM-LN-LL-21.	9 253 659	765 252	3 449

3.1. Definition of Objects Study

The study analyzed 8 sampling points used in different parts of the area, differentiated by their coordinates [2]. These points are shown in Table 1 and indicated in Figure 3, as well as the nearby mine clearings described in Table 2 so that the relationship with the values obtained can be subsequently evaluated.

The analysis was carried out based on the criteria present in the water quality standards of the Peruvian ECA and Pratti index. The first value (λ1) indicates that the water is not contaminated, so no remediation will be performed in the sample area. This means the water can be used as an alternative for livestock drinking and crop irrigation. The second value (λ2) is acceptable because only disinfection is needed to make it potable. The third value is (λ3), which is moderately polluted, for which advanced treatment is going to be needed, as contaminants affect water quality [11]. The value (λ4) is pol-luted, which cannot be in contact with any population, animals, or plants. Finally, we have the fifth value (λ5), which is highly polluted, highly toxic water for health that generates different diseases that can cause death. These selected definitions are shown in Table 2.

3.2. Identification of the Evaluation Criteria

The Parameters criteria to be assessed for this study are determined by the water quality parameters, which are presented and coded in Table 2.

3.3. Definition of Gray Classes

The classes for the evaluation are five and are focussed on the water quality levels according to the Prati index and the 2017 water quality standards, presented in Table 4.

Table 2. Pratti index parameters and water quality standards for tailings contamination assessment

Parameters Criteria	Description	Code
pH	Hydrogen Potential	C1
Zinc	mg/L	C2
Suspended Solids	mg/L	C3
Arsenic	mg/L	C4
Lead	mg/L	C5
Iron	mg/L	C6
Cadmium	mg/L	C7

Table 3. Definition de grey classes

Grey Classes	
λ_1	Not Contaminated
λ_2	Acceptable
λ_3	Mediumly Contaminated
λ_4	Contaminated
λ_5	Highly Contaminated

3.4. CTWF Calculations

The case study calculations are presented here, following the methodology presented in section II.

3.4.1. Step 1

According to the Water Quality Standard Values, the non-dimensionalized standard values for each parameter were calculated using Eq.1. These values are presented in Table 5.

Table 4. Standard values of water quality

Definition of Water Quality Standard					
CLASSES	λ_1	λ_2	λ_3	λ_4	λ_5
C1	7	6	5	4	3
C2	2	3	5	7	9
C3	10	20	70	189	278
C4	0.1	0.2	0.3	0.4	0.5
C5	0.05	0.06	0.07	0.08	0.12
C6	0.1	0.3	0.9	2.7	3.5
C7	0.003	0.005	0.01	0.05	0.15

Table 5. Non-dimensional standard values of water quality

No dimensioned Definition of Water Quality Standard					
CLASSES	λ_1	λ_2	λ_3	λ_4	λ_5
C1	1.4	1.2	1	0.8	0.6
C2	0.38	0.58	0.96	1.35	1.73
C3	0.09	0.18	0.62	1.67	2.45
C4	0.33	0.67	1.00	1.33	1.67
C5	0.66	0.79	0.92	1.05	1.58
C6	0.07	0.20	0.60	1.80	2.33
C7	0.07	0.11	0.23	1.15	3.44

Table 6. Monitoring data in the case study

Criterion	P1	P2	P3	P4	P5	P6	P7	P8
C1	3.54	2.18	3.93	3.07	6.15	3.19	6.38	2.87
C2	112.4	598.1	13.89	5.227	34.73	24.21	4.779	13.24
C3	12	58	65	7	122	20	9	0
C4	0.7074	11.2	0.02836	0.0077	0.14911	0.00508	0.00241	0.12284
C5	0.1541	7881	0.3779	3.241	0.102	1.381	0.2540	1.071
C6	112.4	598.1	13.89	5.227	34.73	24.21	0.2610	0
C7	0.5014	2.906	0.10439	0.03698	0.05991	0.21134	0.05075	0.08667

Table 7. Non-dimensional monitoring data in the case study

Criterios	P1	P2	P3	P4	P5	P6	P7	P8
C1	0.71	0.44	0.79	0.61	1.23	0.64	1.28	0.57
C2	21.62	115.02	2.67	1.01	6.68	4.66	0.92	2.55
C3	0.11	0.51	0.57	0.06	1.08	0.18	0.08	0.00
C4	2.36	37.33	0.09	0.03	0.50	0.02	0.01	0.41
C5	2.03	103697.37	4.97	42.64	1.34	18.17	3.34	14.09
C6	74.93	398.73	9.26	3.48	23.15	16.14	0.17	0.00
C7	11.50	66.65	2.39	0.85	1.37	4.85	1.16	1.99

Also, based on the monitoring results of Mine Entrance Effluents during the 2018 periodic supervision of the auditable unit 55 Mining Environmental Liabilities La Tahona. These values are presented in Table 7.

3.4.2. Step 2

Substituting the values from Table 6 into Equations 2, 3 and 4, the triangular bleaching functions of the five grey classes were obtained for each parameter. As an example, for the first parameter (pH), equations 8-12 and figure 4 are shown[13].

$$f_5^1\,(x) = \begin{cases} 0\,;\; x \nsubseteq [0\,;0.8] \\ 1\,;\; x \in [0\,;0.6] \\ \frac{0.8-x}{0.2}\,;\; x \in [0.6\,;0.8] \end{cases} \quad (8)$$

$$f_4^1\,(x) = \begin{cases} 0\,;\; x \nsubseteq [0.6\,;1] \\ \frac{x-0.6}{0.2}\,;\; x \in [0.6\,;0.8] \\ \frac{1-x}{0.2}\,;\; x \in [0.8\,;1] \end{cases} \quad (9)$$

$$f_3^1\,(x) = \begin{cases} 0\,;\; x \nsubseteq [0.8\,;1.2] \\ \frac{x-0.8}{0.2}\,;\; x \in [0.8\,;1] \\ \frac{1.2-x}{0.2}\,;\; x \in [1\,;1.2] \end{cases} \quad (10)$$

$$f_2^1\,(x) = \begin{cases} 0\,;\; x \nsubseteq [1\,;1.4] \\ \frac{x-0.1}{0.2}\,;\; x \in [1\,;1.2] \\ \frac{1-x}{0.2}\,;\; x \in [1.2.\,;1.4] \end{cases} \quad (11)$$

$$f_1^1\,(x) = \begin{cases} 0\,;\; x \nsubseteq [1,2\,;1.4] \\ 1\,;\; x \in [1.4\,;\propto] \\ \frac{x-1.2}{0.2}\,;\; x \in [1.2\,;1.4] \end{cases} \quad (12)$$

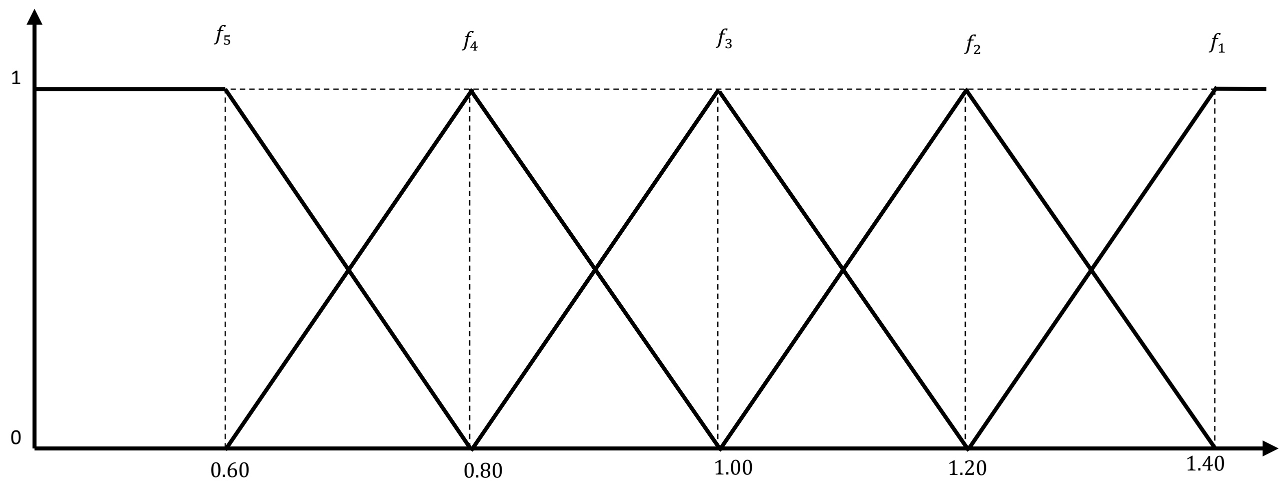

Fig. 4 CTWF for the first parameter

Table 8. Values de CTWF of P1and P2 points

***P*1**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
f_1	0	0	0.78	0	0	0	0
f_2	0	0	0.32	0	0	0	0
f_3	0	0	0	0	0	0	0
f_4	0.55	0	0	0	0	0	0
f_5	0.45	1	0	1	1	1	1
P2	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
f_1	1	0	0	0	0	0	0
f_2	0	0	0.25	0	0	0	0
f_3	0	0	0.75	0	0	0	0
f_4	0	0	0	0	0	0	0
f_5	0	1	0	1	1	1	1

The values in Table 8 were then evaluated for the triangular bleaching functions of the five Grey classes for the eight parameters considered. For example, the results obtained from P1 and P2 are shown in Table 8.

3.4.3. Step 3

The cluster weight (ηi) of every parameter was determined following the harmonic mean using the equation (5).

3.4.4. Step 4

The cluster coefficient results (σ_i^k) was calculated using equation 6. For example, the results from P1 and P2 points are presented in Table 10.

3.4.5. Step 5

The condition was applied: $Max\, 1 < h < s\{\sigma k\} = \{\sigma k\}$, it is determined that the object i of the grey class k*; for each control point. The values are presented in Table 11.

Table 9. Clustering weight of each parameter

Criterion	λ_1	λ_2	λ_3	λ_4	λ_5
C1	0.0150	0.0334	0.0851	0.2186	0.3620
C2	0.0553	0.0691	0.0886	0.1295	0.1255
C3	0.2336	0.2226	0.1372	0.1047	0.0886
C4	0.0637	0.0598	0.0851	0.1315	0.1300
C5	0.0318	0.0507	0.0925	0.1665	0.1375
C6	0.3003	0.2003	0.1418	0.0971	0.0932
C7	0.3003	0.3642	0.3698	0.1521	0.0631

Table 10. Values of CTWF and σ_i^k for the monitoring points

$P1$	C_1	C_2	C_3	C_4	C_5	C_6	C_7
f_1	0	0	0.182	0	0	0	0
f_2	0	0	0.071	0	0	0	0
f_3	0	0	0	0	0	0	0
f_4	0.120	0	0	0	0	0	0
f_5	0.163	0.126	0	0.130	0.137	0.093	0.063
P2	C_1	C_2	C_3	C_4	C_5	C_6	C_7
f_1	0.015	0	0	0	0	0	0
f_2	0	0	0.056	0	0	0	0
f_3	0	0	0.103	0	0	0	0
f_4	0	0	0	0	0	0	0
f_5	0	0.126	0	0.130	0.137	0.093	0.063

Table 11. Values of σ_i^k for the monitoring points

Point	λ_1	λ_2	λ_3	λ_4	λ_5
P1	0.182	0.071	0.000	0.120	0.712
P2	0.015	0.056	0.103	0.000	0.549
P3	0.064	0.024	0.122	0.278	0.408
P4	0.297	0.000	0.199	0.130	0.575
P5	0.034	0.058	0.077	0.258	0.301
P6	0.064	0.223	0.000	0.044	0.709
P7	0.366	0.161	0.080	0.238	0.355
P8	0.597	0.014	0.000	0.096	0.286

4. Case Study

It is shown in Table 11 that of the 8 control points performed on the intake effluents, 6 are highly contaminated, and 2 are not contaminated [13].

According to the results, 75% of the monitored points are classified as highly polluted, while two are classified as not polluted [14].

Table 12. Water quality according to grey clustering criteria based on [3] **index and water quality standards 2017**

Point	$\lambda_1(20)$	$\lambda_2(40)$	$\lambda_3($	λ_4	λ_5	Definition of Classes
P1	0.182	0.071	0.000	0.120	0.712	Highly contaminated
P2	0.015	0.056	0.103	0.000	0.549	Highly contaminated
P3	0.064	0.024	0.122	0.278	0.408	Highly contaminated
P4	0.297	0.000	0.199	0.130	0.575	Highly contaminated
P5	0.034	0.058	0.077	0.258	0.301	Highly contaminated
P6	0.064	0.223	0.000	0.044	0.709	Highly contaminated
P7	0.366	0.161	0.080	0.238	0.355	Not Contaminated
P8	0.597	0.014	0.000	0.096	0.286	Not Contaminated

Table 12. Comparison of the quality of the pit effluents according to the Grey Clustering value

Point	Color Scale
P8	**Better Water Quality**
P7	
P5	
P3	
P2	
P4	
P6	
P1	**Lower Water Quality**

It can be observed that point 8 has a better water quality, being classified according to the table as not polluted, while point 1 is the most polluted [5]. Although different factors may be involved in the higher contamination, if we take into account the proximity of the points and their height, we must also consider that all the mine mouth points except for point 8 (which is a point of a river where tailings and a water channel of the Hualgayoc sub-basin converge) are located on high slopes; also the density of mining waste, described in a characterization study carried out in the same year [6], could also be related to the high levels of contamination recorded, since according to a report by the OEFA in 2017, it describes all the mine entrances as poorly sealed, exposed to rainfall, being all in contact with mining waste that generates acid drainage, with the exception of waste dump 1 near point 7, which is classified as not generating acid drainage, as well as not possessing hydraulic structures, its effluents being mixed with residual material and tailings dispersed near the gabion walls [7].

4.1. About the Methodology

The method offers an objective assessment and classification in cases where it is possible to work with parameters, standard criteria and objects of study, thus offering an assessment with low uncertainty regarding the results[15].

Although the grey grouping method is nowadays increasingly used [16, 17], there is a lack of a legal basis for a better application by specifying environmental quality standards by levels, thus determining the results by legally recognized quality standards.

Also, the harmonic mean method is an objective way of determining cluster weights, as it does not require the consultation of experts processing standard data, which saves costs and evaluation time, but other types of weight generation, such as centralized[10] weights or the Shannon Entropy method could be tested as well.

5. Conclusion

The level of contamination of the effluents from the mouths of the "La Tahona" min-ing liability could be evaluated using the Grey Clustering method, so it was possible to classify the 8 monitoring points in this area to the east of the Hualgayoc district. The results obtained can be useful for their use as an antecedent and later comparison after the remediation commissioned to the state company Activos Mineros, which would be programmed in 2023.

This, in turn, would serve to prioritize the most contaminated effluent points. Likewise, the Grey Clustering methodology could be more effective in avoiding uncertainty within the analysis, as the method of finding the weight of the criteria using the Harmonic Mean allows one to calculate them objectively without necessarily resorting to expert judgment. Also, the standards used from the Prati Index and Water Quality Standards 2017 give some advantages when comparing whether the remediation activities are effective to determine the feasibility of the methods used.

In future monitoring in the area, the present calculations could be used as a baseline or background to determine progress and changes in the parameters considered for water quality analysis.

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