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Water Quality in Areas Surrounding Mining: Las Bambas, Peru

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Abstract*: Nowadays, it is known that water is a critical issue for human life. For this reason, research in this category is a complex subject. The case chosen for this work is in the district of Tambobamba, Cotabambas province, in the region of Apurimac. This is where Las Bambas mine is operating and the area of influence includes the Challhuahuacho and Ferrobamba rivers. Based on six monitoring points, carried out between February 2017 and March 2019 by ANA, it was possible to know if these rivers would have a low or high degree of contamination. Therefore, the methodology used in this work was the Grey Clustering Method. This method includes vital water parameters established by Peruvian D.S. N° 004-2017-MINAM. The results of these studies show that the Ferrobamba River has a high water quality while the Challhuahuacho River has a poor water quality, which could be associated with spills in the area.

Keywords*: Grey Clustering; Mining project; River water quality; Water quality.

I. INTRODUCTION

One of the largest mining activities in Peru is done in the Apurimac, known as the Bambas, is the mine that produces approximately 2% of the world's copper as it produced 452,000 tons of copper in 2018 [1]. Due to the great volume and scope of the activity, an environmental study is required [2] to analyze the given impacts, especially the influence on the rivers in the surrounding area, since the impacts on water quality and quantity are among the most controversial aspects of mining projects [3]. Especially when this water tends to be used for multiple activities such as agriculture, livestock, among others, as is the case [4].

In regard to methodology, the grey system has been chosen, which is focused on the study of problems with uncertain and small-scale information [5]. There are currently a large number of systems that satisfy the above characteristics. Therefore, it is important to highlight its wide range of method applicability [6].

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For example, application in intelligence studies [7], technological advances [8] and water quality [9].

Thus, depending on the objects to be grouped, the grey clustering method has two methodologies: clustering using grey incidence and clustering using grey whitenization weight functions. The first method is mainly used to group the different present categories into the same factors. Unlike the second one, it is more used to verify whether the objects of study belong to the same category or not, so they can be studied in different ways [6]. In this study, the center-point triangular whitenization weight functions (CTWF) is used [10].

The case study that seeks to know how the mining activities of Las Bambas affect the water of the community will be through the study of two rivers: Challhuahuacho River and Ferrobamba River. The first river is one of the main rivers of the Santo Tomas sub-basin. This sub-basin with the Vilcabamba sub-basin forms the Apurímac river basin [11]. It is located in the district of Tambobamba, which belongs to the province of Cotabambas, one of the provinces of Apurímac [12]. Its geographical coordinates are as follows [13]:

+ Latitude: 14° 7' 18.91" S
+ Length: 72° 15' 32" W

In addition, this micro watershed made sense from northeast to southwest and, beyond the level of 3690 MASL, also had a surface area of 468.7 km^2 [11]. It also belongs to the Atlantic slope.

On the other hand, the Ferrobamba River is located in the district of Tambobamba, province of Cotabambas, one of the provinces of Apurímac. It is one of the main rivers of the Santo Tomás sub-basin. Therefore, it is included in the Apurímac River [14]. It has an altitude of 4364 MASL. And its geographical coordinates are as follows:

+ Latitude: 14° 5' 28.32" S
+ Length: 72° 13' 6.47" W

The present article looks for an awareness about water contamination and those basins can be used for the benefit of the community through programs of regional governments. To achieve it, the objective is to classify the monitoring points of the Ferrobamba River and Challhuahuacho River according to the water quality present in the area. Also, it is wanted to know if social problems presented some months ago are related to the possibility of water pollution [15].

The structure of the present study is as follows: The CTWF methodology is explained in section II, in section III the case study is seen, its results are detailed in section IV, the discussion are shown in section V and the conclusions are presented in section VI.

II. METHODOLOGY

The CTWF method, its steps, calculus and procedure are explained as follows [7][16]:

Step 1:

First, it's required to define the variables:

- The objects of study are coded as o_i where $i=1, 2, 3, \dots, m$.
- A set of quality parameters are coded as c_j where $j=1, 2, 3, \dots, n$.
- A set of grey classes to categorize the objects are coded as λ_k where $k=1, 2, 3, \dots, s$.
- The set of standard category values are coded as λ_j^k and referred as the value of the j^{th} parameter to be categorized as λ_k
- The set of monitoring values are coded as x_{ij} and referred as the monitoring value of the j^{th} parameter evaluated on the i^{th} object.

The former must be defined according to the objective of the study. The parameters should be defined according to the data available. Grey classes or categories and standard values are taken from current legislation. Finally, the monitoring values correspond to the object data.

Step 2:

Non-dimensioning the categories defined to parameters of the grey classes and monitoring data.

Step 3:

Define and calculate the center-point triangular whitenization weight functions, or CTWF, of grey classes on monitoring data using Eq. 1-3.

$$f_j^1(x_{ij}) = \begin{cases} 1\,, & x \in [0, \lambda_j^1] \\ \dfrac{\lambda_j^2 - x}{\lambda_j^2 - \lambda_j^1}, & x \in (\lambda_j^1, \lambda_j^2) \\ 0\,, & x \in [\lambda_j^2, \infty) \end{cases} \quad (1)$$

$$f_j^k(x_{ij}) = \begin{cases} \dfrac{x - \lambda_j^{k-1}}{\lambda_j^k - \lambda_j^{k-1}}\,, & x \in (\lambda_j^{k-1}, \lambda_j^k] \\ \dfrac{\lambda_j^{k+1} - x}{\lambda_j^{k+1} - \lambda_j^k}\,, & x \in (\lambda_j^k, \lambda_j^{k+1}) \\ 0\,, & x \in [0, \lambda_j^{k-1}] \cup [\lambda_j^{k+1}, \infty) \\ & k \neq \{1, s\} \end{cases} \quad (2)$$

$$f_j^s(x_{ij}) = \begin{cases} \dfrac{x - \lambda_j^{s-1}}{\lambda_j^s - \lambda_j^{s-1}}\,, & x \in (\lambda_j^s, \lambda_j^{s-1}) \\ 1\,, & x \in [\lambda_j^s, \infty) \\ 0\,, & x \in [0, \lambda_j^{s-1}] \end{cases} \quad (3)$$

Where $f_j^k(x_{ij})$ is the kth CTWF of the j^{th} parameter for monitoring value x_{ij}.

Step 4:

Calculate the clustering weight of the parameters of the grey classes using Eq. 4.

$$n_j^k = \frac{\dfrac{1}{\lambda_j^k}}{\sum_{j=1}^{n} \dfrac{1}{\lambda_j^k}} \quad (4)$$

Where n_j^k is the clustering weight of the j^{th} parameter for the λ_k grey class.

Step 5:

Calculate the clustering coefficient for monitoring points with respect to the corresponding grey class using Eq. 5.

$$\sigma_i^k = \sum_{j=1}^{n} f_j^k(x_{ij}).\, n_j^k \quad (5)$$

Step 6:

Determine the class of the object based on maximum clustering coefficient criteria (Eq. 6).

$$\forall \sigma_i^{k*} : \sigma_i^{k*} = \max_{1 \le k \le s} \{\sigma_i^k\} \rightarrow o_i \text{ belongs to } \lambda_k \quad (6)$$

III. CASE STUDY

Water quality assessment in the Ferrobamba and Challhuahuacho rivers was conducted through six monitoring points. It is important to mention that Las Bambas mine is located around these rivers. For this reason, it could be possible to cause a variation in the components of these rivers, since - as the Las Bambas mine said - a spill of concentrates had occurred in its area during 2017 [17]. Therefore, the Environmental Assessment and Control Agency (OEFA by its Spanish acronym) imposed a sanctioning process, which claimed not to have covered non-hazardous solid waste or preserved hydraulic structures within a sanitary landfill in accordance with R.S. N° 0113-2018-OEFA/DS-MIN [18]. In addition, there was petroleum contamination in the area during October 2018 [19]. Finally, the information to be used was obtained from Peru's national water authority (ANA by its Spanish acronym). Data were collected monthly from February 2017 to March 2019. In this way, we propose to evaluate whether the water is suitable for human consumption or irrigation.

A. Context description

The Challhuahuacho River and Ferrobamba River belong to the upper Apurímac basin, located in the Apurímac department, southeast of Lima, Peru, as shown in Fig. 1.

Fig. 1 Calhuahuacho and Ferrobamba rivers

Six monitoring points were available to analyze the water quality of Chalhuahuacho and Ferrobamba rivers. Table I details the monitoring points corresponding to those rivers.

TABLE I: Monitoring points of Challhuahuacho and Ferrobamba rivers

River	River Code	Monitoring Points	Code
Challhuahuacho	R1	PV-01	O1
		V-01	O2
		V-02	O3
Ferrobamba	R2	EF-FU01	O4
		SW-FU-120	O5
		W-FU-80	O6

B. Las Bambas mine

Las Bambas mine is located among a variety of districts: Challhuahuacho, Tambobamba and Coyllurqui. All of them belong to Apurímac. It has an altitude between 3800 - 4600 MASL; in addition, it is located about 75 km southwest of Cusco [20].

Actually, the Ferrobamba deposit is being exploited. Both Chalcobamba and Sulfobamba fields will be exploited some time later. Its concentrator plant has a capacity to process 145 kt per day and generates two types of concentrates: copper and molybdenum, as products. Throughout 2017, its production exceeded 450 kt of copper concentrate [20].

C. Area of influence

There are several ways in which Las Bambas can have an influence, but, for the purposes of this article, two areas of influence will be developed: social and hydrology [4].

On the one hand, the area of direct social influence is close to the mine. It is composed of 18 campesino communities: Huancuirem Pampua, Cconccacca, Carmen Alto de Chalhuahuacho, Manuel Seoane Corrales, Quehuira, Chuicuini, Chicñahui, Choquecca, Pumammarca, Huanacopampa, Ccasa, Allahua, Ccahuarpirhua, Chumille, Huayulloc, Arcospampa, Congota and Sasahuilca.

On the other hand, the area of indirect social influence is only 2: Challhuahuacho and Progreso.

In the case of hydrology influence, there are two impacts: the first is related to the quality of surface water. The second impact is that the quality of sediments is altered by the increase of the quantity of metals.

D. Calculations using CTWF method

Step 1:

Objects of study were defined as it is indicated in Table I. Parameters were defined based on the properties analyzed in each monitoring point. Due to the fact that different types of analysis were performed, two sets of parameters were defined to this study, one to do the CTWF analysis for Challhuahuacho river and the other for Ferrobamba river. See Table II for details.

Table II: Set of parameters defined for the study of Challhuahuacho and Ferrobamba rivers

River	Parameter	Symbol	Code
R1	Biochemical Oxygen Demand	DBO_5	C1
	Chemical Oxygen Demand	DQO	C2
	Hydrogen Potential	pH	C3
	Thermotolerant Coliforms	Coliforms	C4
	Oils and Fats	MEH	C5
R2	Hydrogen Potential	pH	C6
	Arsenic	As	C7
	Cadmium	Cd	C8
	Mercury	Hg	C9
	Lead	Pb	C10
	Zinc	Zn	C11
	Oils and Fats	MEH	C12

In this table, C3 is the same parameter as C6 and C5 of C12. This happens, because those correspond to two different sets of parameters that are going to be analyzed to different rivers.

Grey classes were defined according to Peruvian law DS N° 004-2017-MINAM, Subcategory A. In this case, water quality is evaluated according to its potability. Three categories were defined according to Peruvian law: A1, A2 and A3 (which corresponds to λ_k for $k=1, 2,$ and 3).

Step 2:

Non-dimensioned values were calculated using normalization to the average for standards (Eq. 7) and monitoring values (Eq. 8). Table III shows non-dimensioned standard values. As example, non-dimensioned monitoring values for Challhuahuacho River and Ferrobamba River, in April, 2017, are shown in Table IV and Table V respectively.

$$\lambda_j^{k*} = \frac{\lambda_j^k}{\sum_{k=1}^{s} \frac{\lambda_j^k}{s}} \qquad (7)$$

Table III: Non-dimensioned Standard Values

Parameter	Grey Classes		
	A1	*A2*	*A3*
C1	0.5000	0.8333	1.6667
C2	0.5000	1.0000	1.5000
C3	1.0345	1.0000	0.9655
C4	0.0027	0.2725	2.7248
C5	0.4545	1.0000	1.5455
C6	1.0345	1.0000	0.9655
C7	0.1250	1.0000	1.8750
C8	0.5000	0.8333	1.6667
C9	0.6667	1.0000	1.3333
C10	0.3333	1.0000	1.6667
C11	0.7500	1.0000	1.2500
C12	0.4545	1.0000	1.5455

$$x_{ij}* = \frac{x_{ij}}{\sum_{k=1}^{s} \frac{\lambda_j^k}{s}} \qquad (8)$$

Table IV: Non-dimensioned monitoring data for Challhuahuacho River in April, 2017

Abr-17	O1	O2	O3
C1	0.8333	0.1667	0.1667
C2	1.2000	0.4000	0.2000
C3	0.9200	1.1103	1.1159
C4	0.0003	0.0450	0.4768
C5	2.5455	0.4545	0.4545

Table V: Non-dimensioned monitoring data for Ferrobamba River in April, 2017

Abr-17	O4	O5	O6
C6	1.1862	1.1834	1.1848
C7	0.0121	0.0074	0.0199
C8	0.0317	0.0008	0.0083
C9	0.0333	0.0100	0.1000
C10	0.0333	0.0333	0.9000
C11	0.0075	0.0013	0.0045
C12	0.4545	0.4545	0.4545

Step 3:

Using values of Table III, CTWF were calculated. Graphical representation of CTWF are shown in Fig. 2.

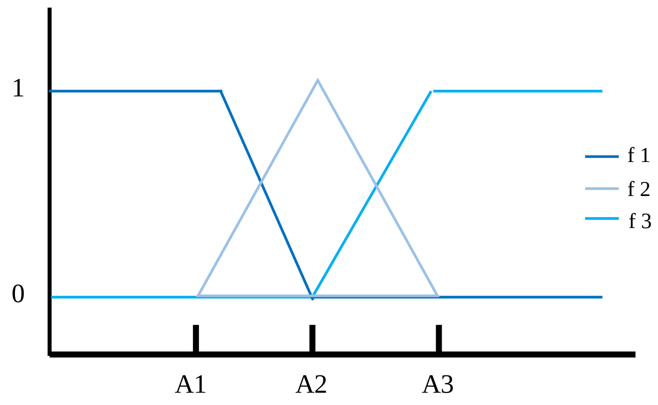

Fig. 2 CTWF according to Peruvian law

As example, equations of CTWF from second parameter for Challhuahuacho River, non-dimensioned monitoring values for Challhuahuacho River and Ferrobamba River in April 2017, are shown in Eq. 9-11, Table VI and Table VII respectively.

$$f_2^1(x_{ij}) = \begin{cases} 1\,, & x \in [0, 0.5] \\ 2 - 2\,x \in & (0.5, 1) \\ 0\,, & x \in [1, \infty) \end{cases} \qquad (9)$$

$$f_2^2(x_{ij}) = \begin{cases} 2x - 1\,, & x \in (\,0.5, 1] \\ 3 - 2x\,, & x \in \ (1\,, 1.5) \\ 0\,, & x \in [0, 0.5] \cup [1.5, \infty) \\ & k \ \neq \ \{1, s\} \end{cases} \qquad (10)$$

$$f_j^3(x_{ij}) = \begin{cases} 2x - 2\,, & x \in \ (1\,, 1.5) \\ 1\,, & x \in \ [1.5\,, \infty) \\ 0\,, & x \in [0, 1] \end{cases} \qquad (11)$$

Table VI: Values of CTWF of Challhuahuacho River in April, 2017

O1	f1	f2	f3
C1	0.0000	1.0000	0.0000
C2	0.0000	0.6000	0.4000
C3	1.0000	0.0000	0.0000
C4	1.0000	0.0000	0.0000
C5	0.0000	0.0000	1.0000
O2	**f1**	**f2**	**f3**
C1	1.0000	0.0000	0.0000
C2	1.0000	0.0000	0.0000
C3	0.0000	0.0000	1.0000
C4	0.8434	0.1566	0.0000
C5	1.0000	0.0000	0.0000
O3	**f1**	**f2**	**f3**
C1	1.0000	0.0000	0.0000
C2	1.0000	0.0000	0.0000
C3	0.0000	0.0000	1.0000
C4	0.0000	0.9167	0.0833
C5	1.0000	0.0000	0.0000

Table VII: Values of CTWF of Ferrobamba River in April, 2017

O4	f1	f2	f3
C6	0.0000	0.0000	1.0000
C7	1.0000	0.0000	0.0000
C8	1.0000	0.0000	0.0000
C9	1.0000	0.0000	0.0000
C10	1.0000	0.0000	0.0000
C11	1.0000	0.0000	0.0000
C12	1.0000	0.0000	0.0000
O5	**f1**	**f2**	**f3**
C6	0.0000	0.0000	1.0000
C7	1.0000	0.0000	0.0000
C8	1.0000	0.0000	0.0000
C9	1.0000	0.0000	0.0000
C10	1.0000	0.0000	0.0000
C11	1.0000	0.0000	0.0000
C12	1.0000	0.0000	0.0000
O6	**f1**	**f2**	**f3**
C6	0.0000	0.0000	1.0000
C7	1.0000	0.0000	0.0000
C8	1.0000	0.0000	0.0000
C9	1.0000	0.0000	0.0000
C10	1.0000	0.0000	0.0000
C11	1.0000	0.0000	0.0000
C12	1.0000	0.0000	0.0000

Step 4:

From Table III, the clustering weight of each parameter has been calculated using Eq. 4. Details are shown in Table VIII.

Table VIII: Clustering weight values for each parameters

Parameter	Grey Classes		
	A1	*A2*	*A3*
C1	0.0053	0.1525	0.1809
C2	0.0053	0.1271	0.2010
C3	0.0026	0.1271	0.3123
C4	0.9808	0.4663	0.1107
C5	0.0059	0.1271	0.1951
C6	0.0509	0.1389	0.2086
C7	0.4211	0.1389	0.1074
C8	0.1053	0.1667	0.1208
C9	0.0789	0.1389	0.1510
C10	0.1579	0.1389	0.1208
C11	0.0702	0.1389	0.1611
C12	0.1158	0.1389	0.1303

Step 5:

Clustering coefficient values were calculated using Eq. 5. Continuing the example, Table IX shows the results for R1 and R2 in April, 2017.

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Table IX: Values of clustering coefficients for each monitoring point in April, 2017

Abr-17	A1	A2	A3
O1	0.9834	0.2287	0.2755
O2	0.8438	0.0730	0.3123
O3	0.0166	0.4275	0.3215
O4	0.9491	0.0000	0.2086
O5	0.9491	0.0000	0.2086
O6	0.9491	0.0000	0.2086

Step 6:

Finally, we applied the criterion of the maximum clustering coefficient (which are highlighted in Table IX) to determine the category of all monitory points from 2017 to 2019. To conclude with the example, Table X shows the final categorization of monitoring points in April, 2017.

TABLE X: Classification of monitoring points in April, 2017

Date	Object	Class
Abr-17	O1	A1
	O2	A1
	O3	A2
	O4	A1
	O5	A1
	O6	A1

IV. RESULTS

After having processed data of monitoring points from February 2017 to March 2019, results are shown in Table XI.

Table XI: Results of processed data

	Challhuahuacho			Ferrobamba		
	PV-01	*V-01*	*V-02*	*EF-FU01*	*SW-FU-120*	*W-FU-80*
Feb-17	NO DATA	NO DATA	NO DATA	A1	A1	A1
Mar-17	NO DATA	NO DATA	NO DATA	A1	A1	A1
Abr-17	A1	A1	A2	A1	A1	A1
May-17	A1	A1	A1	A1	A1	A1
Jun-17	A1	A1	A1	NO DATA	NO DATA	NO DATA
Jul-17	A1	A1	A1	NO DATA	NO DATA	NO DATA
Ago-17	A1	A1	A1	NO DATA	NO DATA	NO DATA
Set-17	A1	A1	A1	NO DATA	NO DATA	NO DATA
Oct-17	A3	A1	A1	NO DATA	NO DATA	NO DATA
Nov-17	A1	A1	A1	NO DATA	NO DATA	NO DATA
Dic-17	A1	A1	A3	NO DATA	NO DATA	NO DATA
Ene-18	A1	A1	A2	A1	A1	A1
Feb-18	A1	A1	A1	A1	A1	A1
Mar-18	A1	A1	A1	A1	A1	A1
Abr-18	A1	A1	A1	A1	A1	A1
May-18	A1	A1	A1	A1	A1	A1
Jun-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Jul-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Ago-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Set-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Oct-18	A1	A1	A2	NO DATA	NO DATA	NO DATA
Nov-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Dic-18	A1	A1	A1	NO DATA	NO DATA	NO DATA
Ene-19	A1	A1	A1	NO DATA	NO DATA	NO DATA
Feb-19	A1	A1	A2	NO DATA	NO DATA	NO DATA
Mar-19	A1	A1	A1	NO DATA	NO DATA	NO DATA

V. DISCUSSION

From the results of the Tables shown above, it is appropriate to mention that the Ferrobamba River has an A1 categorization during the entire temporal field of study. On the other hand, the Challhuahuacho River has some lower water quality peaks on specific dates. To illustrate these variations, Fig. 3 shows the results in a binary diagram. In addition, in the Challhuahuacho River, the most critical water quality is observed for two months: October and December 2017. This could happen since, as mentioned in the Las Bambas report, there were 4 spills of concentrates in its area during that year [17]. However, the best water quality is found in the Challhuahuacho River, specifically in the PV-01 during the month of April 2017.

Finally, there could be a relationship between what is described in Fig. 3, during October 2018, and hydrocarbon contamination, since in that month the aforementioned event occurred and was registered by OEFA [19].

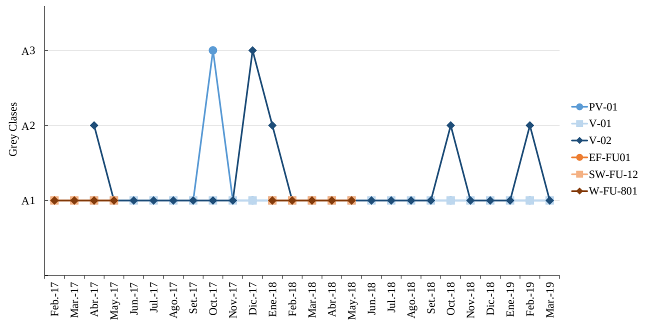

Fig. 3 Binary diagram of results of this study

VI. CONCLUSION

A conclusion of this work refers to the peaks shown in the binary diagram (Fig. 3). These occurred only in the given months, as there could be a relationship with these spills, as has been mentioned above. There was no prolongation of this situation, as the Las Bambas mine probably took control of it. However, future air, soil and other studies would be desirable, as a global environmental report of the area could be created to help citizens better understand the environmental condition of their surroundings.

With this, Las Bambas mine and any other company that performs this activity will probably be more careful with water, air and soil pollution. Finally, the Grey Clustering method evaluated the water quality of six monitoring points of the Challhuahuacho and Ferrobamba rivers, which belong to the Santo Tomas sub-basin. The results obtained in this report could help local authorities in Peru to make the best decisions on water management. Finally, it is important to emphasize that the social problems presented a few months ago in the study area are not related to water pollution, since water pollution problems occurred in 2017, to be precise, during September and December of that year.

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