A New Approach to Validate a Mixing Zone Study of a Gold Mine Effluent

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Abstract

This study was conducted in a gold mining located at the city of Conceição do Pará/ MG. This study aims to validate the theoretical dimension of a mixing zone with field physical chemical parameter data and to verify the impact of the effluent discharge of this gold mine into the Pará river. Water quality data of parameters such as: arsenic, copper, iron and sulfate were also used for the development of mixing zone dimension. Mathematical modeling of mixing zone was done in accordance to the methodology recommended by the EPA, 1991.

Introduction

Due to the relevant difference between the water quality criteria for effluent discharge and the water quality criteria for receiving water, the national and state environmental regulation for water quality in Brazil (CONAMA 430/2011 and DN-COPAM/CERH-MG 01/08) allow the development of a study to determine the "Mixing Zone". This type of study is very important and applicable for the mining industries that need to discharge its effluent in receiving water.

In order to enlarge the security level of the mining water dam in terms of the increase of the free board and decrease of the probability of untreated water discard disposal, this study was made to determine the mixing zone of the Pará River generated by the Effluent Treatment Plant (ETP) treated effluent in the proportion of 48 m^3/h from the dam and 50 m^3/h from the underground mine. The water that is inside the dam has high concentrations of arsenic, total cyanide, copper, iron, sulfate, and total dissolved solids (water that is not pumped to the ETP).

The objective of the present study is to define the geometry of a mixing zone generated by a mining effluent discharge into Pará River, for the following parameters: arsenic, total cyanide, copper, iron, phosphorus, nitrate, total dissolved solids (TDS) and sulfate. The study area is located in Conceição do Pará, Minas Gerais, Brazil, where a gold mine discharge its effluent into Pará River.

Dam Water Balance: The dam receives 3 m^3/h from the Oil-Water Separator (OWS), 69 m^3/h annually from the gold ore processing plant and 31,7 m^3/h annually from average rainfall (total income of 103,7 m^3/h). The dam loses 26 m^3/h of water by evaporation due to the use of sprinklers, 18,87 m^3/h in solar evaporation and 105 m^3/h by feeding the ore processing plant (total water 149,87 m^3/h). At the end there is a negative balance of 46,17 m^3/h (free board of 1,5 m is very concerning, since torrential rains can make this board even smaller).

There is an Effluent Treatment Plant where aluminum sulfate and flocculants are added to the suspended solids in the water, and then it passes though columns of activated carbon. This ETP works with water from the underground mine, and it directs the effluent to the Carneiro stream.

The current study was developed to calculate the mixing zone in Pará River in a situation where the ETP starts to receive water from the mine and the tailing water dam (approximately 98 m^3/h) and discharge into the river. Furthermore, the study aims to confirm that the treated effluent discharge is environmentally acceptable, increases the free board of the water dam and reduces the need for emergency discharge in case of torrential rains.

Technical Background

To understand the mixing zone of a receiving water, it is necessary to know the water quality of both the effluent and the receiving drainage (at the discharge point), each flow rate and the cross-section geometry of the receiving channel. This data was found throughout the study and made it possible to calculate the geometry and extension of the mixing zone. Furthermore, after the effluent discharge, the river starts the self-attenuation process, where the effluent flow dilutes in the river water.

Methodology

Sample collection: The ETP should operate at least 24 hours before the sample collection to ensure that the effluent gets to the receiving body (effluents flow velocity is unknown). The sample collection was made in 4 different points such as three samples in Pará River (one upstream, one downstream and one at the discharge point) and one last sample in the effluent, right after the ETP treatment.

The samples collected in the Pará River were obtained using a boat in order to better characterize the physical dimension of the mixing zone. The ETP effluent sample was collected on a reservoir where the treated water is stored before being discharged into the river. The temperature, pH, dissolved oxygen (DO), electrical conductivity (EC) and redox potential (Eh) were measured *in situ*.

Chemical analysis: The parameters that were analyzed are: major cations (Ca, Mg, Na, K), trace metals (Fe, Al, Cu, Pb, Ni, Zn, Cd, Mn, Co), non-metal (As), anions (sulphate, carbonate, bicarbonate, total alkalinity, nitrate, nitrite, chloride, phosphorus and cyanide).

Flow rate estimation on the river: The flow rate was estimated using data from the fluviometric station named Velho do Taipa #40330000, which is located downstream in the river in relation to the discharge point. In order to have a conservative analysis in terms of parameters dilution, the study used the minimum monthly flow recorded by the fluviometric station.

Mass balance for the ETP effluent discharge into the Pará River: The arsenic, total cyanide, copper, iron, phosphorus, nitrate, TDS and sulfate concentration on the receiving body were determined through the application of a mass balance between the parameters concentration in the discharged ETP effluent and the concentrations recorded upstream in the Pará River, following the equation (Equation 01):

$$C_{final} = \frac{(C_1 \cdot Q_1) + (C_2 \cdot Q_2)}{Q_1 + Q_2} \qquad (01)$$

Where:
C_{final}: final concentration;
C_1: upstream concentration;
Q_1: receptor flow rate;
C_2: concentration in the ETP effluent;
Q_2: effluent flow rate.

Mathematical modeling of the mixing zones physical length: the physical dispersion of the sulfate was used as basis to model the mixing zone length, since this parameter falls within the category of "inert" elements, and faithfully represents the physical advance of the parameters inside the drainage. Elements which are labeled as "not inert" will dissipate faster in the water and will have a shorter mixing zone when compared with the "inert" ones. In other words, the sulfate dilution depends only on physical processes, while the other elements also depend on chemical processes (adsorption, absorption or simple precipitation). Therefore, the end of the mixing zone of the sulfate shows that all other parameters are already diluted in the receiving water.

The geometric characteristics of the water drainage is determined by using some parameters in the calculation model of the mixing zone (section width, river slope and river depth for the specific flow rate). The water level determination was made by the HidroWIN software, and the input data were: geometric characteristics of the section, average slope and the Manning's Roughness Coefficient.

The mathematical modeling of the sulfates physical dispersion after the effluent discharge is obtained through the following equation (Equation 02):

$$C_x = \frac{C_e Q_e W}{Q_s \left(\pi \cdot D_y \, X/u\right)^{1/2}} \qquad (02)$$

Where:
C_x: maximum pollutant concentration distance X from the outlet;
C_e: effluent concentration;
Q_e: design effluent flow;
W: stream width;

Q_s: design stream flow;
D_y: lateral dispersion coefficient;
X: distance from the outlet;
u: flow velocity for the design flow.

The Equation 02 is recommended by the *Environmental Protection Agency of United States* (EPA, 1991) for situations where the effluent dispersion is ruled by the receiving body's turbulence (*ambient-inducted mixing*), in other words, when the flow rate of the receiving body is substantially higher than the effluent flow, as showed in this study.

The lateral dispersion coefficient is calculated through the following equation (Equation 03):

$$D_y = 0.6 \cdot d \cdot u^* \pm 50\% \qquad (03)$$

Where:
d: water depth at the design flow;
u^*: shear velocity.

For calculating the shear velocity, the following equation should be used (Equation 04):

$$u^* = (g \cdot d \cdot s)^{1/2} \qquad (04)$$

Where:
g: acceleration due to gravity;
s: slope of the channel;
d: water depth.

Table 1 *Results obtained with the mixing zone's mathematical modeling using a flow rate of 31,7 m^3/s.*

Medium flow rate of 31,7 m^3/s and Q effluent =0,028 m^3/s = 100 m^3/h		
Acceleration due to gravity (g)	9.81	m/s^2
Slope of the channel (s)	0.0005	m/m
Shear velocity (u*)	0.41	m/s
Water depth (d)	7.0	m
Lateral dispersion coefficient (Dy)	1.740215	
Effluent concentration (SO_4)	3,229.16	mg/L
Design effluent flow (Qe)	0,028	m^3/s
Stream width (W)	60	m
Design stream flow (Qs)	31.7	m^3/s
Flow velocity for the design flow (u)	0.12	m/s

Results

Physical-chemical parameters results: The effluent electrical conductivity on the ETP was high. However, these values decrease rapidly when the effluent is discharged into the river and equals with the conditions measured upstream. The other parameters were not so different from the reference values (upstream situation). This is the most important physical-chemical parameter to determine the geometry of a mixing zone in the field

Chemical analysis result: The parameters used for the determination of the mixing zone, in this situation, are: arsenic, total cyanide, dissolved copper, dissolved iron, phosphorus, nitrate, TDS and sulfate. The results were compared with the Brazilian state norm DN COPAM 01/08-Effluent discharge.

Flow rate calculation of the wanted section of the Pará River: This calculation can be done through a maximum, medium and minimum flow analysis, using data collected from the Fluviometric Station Velho do Taipa, which is located downstream in the same river of the ETP effluent discharge. The minimum monthly flows were measured between 1938 and 2016, and its drainage basin is approximately 7,350 km². However, the effluent discharge point is located upstream in the river compared to the fluviometric station, and a ponderation between the two drainage areas must be done. Using a drainage area of 5695 km² for the effluent discharge point, a correction factor of 0.77 was found. After the calculations, the minimum monthly flow (conservative analysis) was 31.7 m^3/s (analysis was made in September, which is a month that the ETP doesn't discharge the effluent on the river since it's when the river has the smallest flow rate).

Mass balance and definition of the effluent discharge mixing zone at the ETP of the Pará River: According to the following table, it becomes clear that one of the most important factors in the mass balance calculation to obtain the final concentration after the dilution is the flow of the receiving water, which is 114,120 m^3/h (31.7 m^3/s). As mentioned earlier in this study, this flow rate is calculated using a conservative method and represents the minimum monthly flow in the Pará River.

Mathematical modeling of the mixing

Table 2 Discharge effluent and receiving body's quality data

Parameter	Unity	DN COPAM 01/08-Effluent discharge	ETP Effluent	DN COPAM 01/08- Class II	Pará River (upstream)
Total Arsenic	mg/L	0.2	0.686	0.01	0.0157
Free Cyanide	mg/L	0.2	0.134	0.005	0.003
Dissolved Copper	mg/L	1.0	0.705	0.009	0.003
Dissolved Iron	mg/L	15	9.73	0.3	1.328
Total Phosphorus	mg/L	-	0.41	0.2	0.23
Sulfate	mg/L	-	3,229.160	250	21.958
TDS	mg/L	-	4,919	500	157
EC	µS/cm	-	6,013	-	92
Nitrate	mg/L	-	30.500	10	1.198

Table 3 Parameter concentration in the mixing zone considering the mass balance concept

Parameter	ETP Effluent		Pará River		Mixing zone's effluent	DN COPAM 01/08- Class II
	C (mg/L)	Q (m^3/h)	C (mg/L)	Q (m^3/h)	(mg/L)	
Total Arsenic	0.686	100	0.016	114,120	0.016	0.01
Free Cyanide	0.134	100	0.003	114,120	0.003	0.005
Dissolved Copper	0.705	100	0.003	114,120	0.004	0.009
Dissolved Iron	9.730	100	1.328	114,120	1.335	0.3
Total Phosphorus	0.412	100	0.230	114,120	0.230	0.2
Sulfate	3,229.16	100	21.958	114,120	24.766	250
TDS	4,919.00	100	157.00	114,120	161.169	500
Nitrate	30.50	100	1.20	114,120	1.224	10

zones physical length: the mixing zone calculation confirms the in situ evaluation of the water electrical conductivity data, showing a quick parameter dilution in a small distance. With the calculations and analysis of the previous table, it was concluded that the Pará River establishes its original characteristics approximately 3 meters downstream the effluent discharge.

In this modeling the parameter sulfate was used in all the calculations. That way, to calculate the physical length of the mixing zone it was used a concentration of 22 mg/L, as suggested by the laboratory analysis of the superficial water of the Pará River.

In other words, a 3 meters long mixing zone is enough to reduce 3,229.16 mg/L of sulfate being discharged with a flow rate of 0.028 m^3/s (100 m^3/h) to 22 mg/L (upstream value) in the Pará River, therefore, making it possible to use this discharge alternative. This length is consistent with the electrical conductivity values obtained in the river at the time of the discharge, consequently validating the mathematical value calculated (Figure 1).

Therefore, as it was mentioned before, the mixing zone calculation is confirmed by the *in situ* evaluation at the discharge point, showing a quick recovery of the original river parameters after a small distance. At the discharge point, the river water electrical conductivity was slightly elevated (274 µs/cm), and about 3 meters downstream this value decreased to 92 µs/cm (upstream original value).

Conclusions

The study showed the results of an estimated and field measured mixing zone of a treated ETP effluent discharge into the Pará River. The procedure was made with the mass balance calculation and the mathematical modeling to estimate the physical length of the receiving body's mixing zone.

The mathematical modeling of the mixing

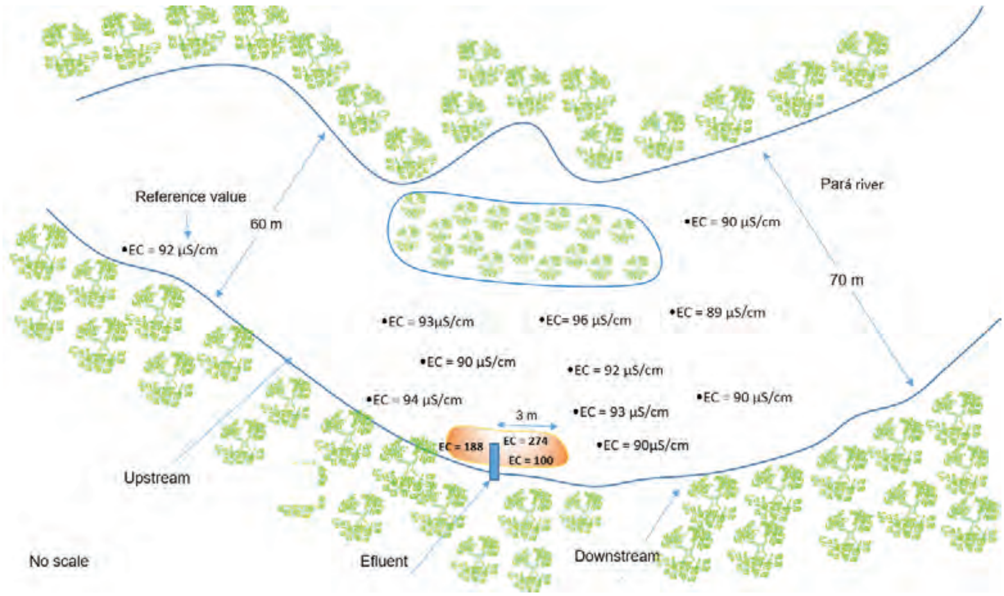

Figure 1 *Schematic drawing of the mixing zone.*

zone's length was made in agreement with the EPA norms, and an extension of 3 meters was found for it. In other words, the parameters concentration returns to the values collected upstream approximately 3 meters after the effluent launching point (the river reestablishes its original physical-chemical condition).

With all the calculations and analysis made it is safe to say that the discharge of the ETP effluent does not imply in consequences to the receiving body, since the parameters concentrations are quickly diluted due to the high flow rate of the receiving body.

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