Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador

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ABSTRACT

On November 4, 2023, a tailings dam failed at the Agroindustrial El Corazón gold mine in the province of Imbabura, northern Ecuador, releasing fine-grained tailings and cyanide-rich water into downstream waterways. A water sample collected by a local resident at the point of discharge showed a total cyanide concentration of 60.8 mg/L (over 600 times the maximum permissible limit of 0.1 mg/L). By contrast, water samples collected by Agroindustrial from the point of discharge to 884 meters downstream on November 4 and 6 ranged from 0.303 to 0.009 mg/L, while samples collected by the consulting company GRUNTEC on November 10 ranged from 0.009 mg/L to <0.001 mg/L. Since analyses by GRUNTEC measured only free cyanide, which can be as little as 1% of total cyanide, and Agroindustrial did not clarify what was measured, their measurements cannot show compliance with Ecuadorian standards. Moreover, the map, coordinates, and site descriptions are contradictory, so that the datasets by Agroindustrial and GRUNTEC should be regarded as entirely invalid. The proximal cause of the tailings dam failure was a tear in the geomembrane followed by internal erosion of the outer embankment. The root cause was inadequate design, including an excessively steep embankment, lack of a drainage system that would force water to exit at the toe of the dam, and the lack of destruction of the cyanide prior to deposition in the tailings pond. It should be assumed that future failures are likely because any additional tear in a geomembrane will have the same result, with the possibility of catastrophic impacts on fish, aquatic species, and livestock.

EXECUTIVE SUMMARY

On the early morning of November 4, 2023, a tailings dam failed at the Agroindustrial El Corazón gold mine in the province of Imbabura, northern Ecuador, releasing fine-grained tailings and cyanide-rich water into downstream waterways. The tailings and water were stored in 20 tailings ponds that are underlain by waterproof geomembranes and surrounded by earthen dams. The failure occurred from Pond No. 15, which is located less than 15 meters from Los Monos Creek, in violation of regulations that require a buffer of 30 meters from streams. Los Monos Creek flows into Verde Chico Creek and then the Verde River, before joining with the Guayllabamba River and then flowing to the Esmeraldas River and the Pacific Ocean. A grayish-green color was observed in the Manduriaco Chico River, a tributary of the Guayllabamba River, on the day of the tailings dam failure, although the hydraulic pathway from Pond No. 15 to the Manduriaco Chico River is unclear. The same grayish-green color had also appeared suddenly on

June 9, 2023. The death of 13 cattle in 2020 was believed by local residents to be a result of cyanide poisoning.

A local resident collected a water sample at the point of discharge from Pond No. 15 on the day of the tailings dam failure. Analysis of the sample showed a total cyanide concentration of 60.8 mg/L (over 600 times the Ecuadorian maximum permissible limit of 0.1 mg/L). Other exceedances included arsenic concentration of 0.750 mg/L, copper concentration of 1.88 mg/L, iron concentration of 136 mg/L, manganese concentration of 4.20 mg/L, and mercury concentration of 0.034 mg/L, which are 7.5 times, 1.88 times, 13.6 times. 2.1 times, and 6.8 times the respective Ecuadorian maximum permissible limits. By contrast, the mining company collected four water samples on each of November 4 and 6 at the point of discharge (PM1), 391 meters downstream (PM2), 581 meters downstream (PM3), and 884 meters downstream (PM4), and measured cyanide concentrations ranging from 0.303 mg/L at the point of discharge to 0.009 mg/L at the point farthest downstream. On November 10 the consulting company GRUNTEC collected a water sample 200 meters downstream from the point of discharge (P1) and at three additional points P2, P3, and P4, identical to PM2, PM3, and PM4, respectively. Analysis of the GRUNTEC samples showed free cyanide concentrations <0.001 mg/L at points P1 and P2, 0.012 mg/L at P3, and 0.009 mg/L at P4 with no exceedances of any maximum permissible limits, including arsenic, copper, iron, manganese, and mercury.

The objective of this report was to answer the following questions with regard to the tailings dam failure at the El Corazón mine:

1) Why are there discrepancies between the chemical analyses of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC?
2) Could the previous incident of cattle deaths have resulted from cyanide poisoning?
3) What is the cause of the grayish-green color in the Manduriaco Chico River?
4) Was heavy rainfall a contributing factor to the failure of the tailings dam?
5) What was the proximal cause of tailings dam failure?
6) What was the root cause of tailings dam failure?
7) Are the tailings dams at Pond No. 15 currently stable?
8) Has the possibility of further tailings dam failures been eliminated?

In order to facilitate reading by non-specialists, this report includes a tutorial on key aspects of gold ore processing, including the use of cyanide, the storage of gold tailings in tailings ponds, the industry guidance documents International Cyanide Code and Responsible Gold Mining Principles, the distinctions among free cyanide, WAD cyanide, and total cyanide, the mechanisms of failure of tailings dams, and the distinction between proximal and root causes of tailings dam failures.

The fundamental reason for the discrepancies between the cyanide concentrations of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC is that the community sample correctly analyzed for total cyanide, while GRUNTEC analyzed only for free cyanide. Free cyanide concentrations can be as little as 1% of total cyanide concentrations, so that free cyanide concentrations cannot be used to show compliance with Ecuadorian regulations that are based on total cyanide concentrations. Agroindustrial did not specify whether they analyzed free or total or some other measure of cyanide concentration. An additional consideration is that the locations of the sampling points by Agroindustrial and GRUNTEC are actually unknown. A sketch map by Agroindustrial was compared with Google Earth imagery to determine the coordinates of the sampling points. The measured coordinates did not correspond with the coordinates stated by Agroindustrial with mismatches of 18 meters, 392 meters, 206 meters, and 535 meters, for points P1, P2, P3, and P4, respectively. Moreover, distances as measured along the stream path were stated by Agroindustrial ultra-precisely as 678.45 meters from PM1 (point of discharge) to P2 (same as PM2), 1017.24 meters from PM1 to P3 (same as PM3), and 2767.85 meters from PM1 to P4 (same as PM4), which are far greater than the measured distances of 391 meters, 581 meters, and 884 meters, respectively. The numbering of the sample points is changed in various places in the report by Agroindustrial, but adjusting the numbering does not resolve any of the preceding contradictions. A final consideration is that water samples were collected by GRUNTEC six days after the tailings dam failure, which left ample time for the pulse of contaminated water to migrate farther downstream or for the cyanide to disappear from the water column by precipitation, oxidation, volatilization, photo dissociation or biodegradation. In summary, based on the measurement of the incorrect parameters at least by GRUNTEC, the lack of knowledge of the sampling locations on the part of both Agroindustrial and GRUNTEC, and the time elapsed until sample collection by GRUNTEC, the datasets by Agroindustrial and GRUNTEC should be regarded as totally invalid.

Given a typical cattle weight of 1000 kilograms, typical water consumption of 0.06 liters per kilogram per day, and the total cyanide concentration that was measured from the recent tailings dam failure (60 mg/L), the daily cyanide load for a cow drinking cyanide-contaminated water downstream from the El Corazón mine would be 3.6 mg/kg. Since the lethal dose for large ruminants is 2 mg/kg, it is possible that the recent cattle deaths resulted from cyanide poisoning. However, a definitive cause of death cannot be determined without further information. Since the Tortugo Unit, the geological unit that is the host for the ore body that is exploited by the El Corazón mine, has a grayish-green color, it is likely that the sudden appearance of a grayish-green color in the Manduriaco Chico River following the tailings dam failure on November 4, 2023, resulted from the introduction of fine-grained tailings into the river. It is also possible that earlier appearances of a grayish-green color in the Manduriaco Chico River resulted from undocumented tailings dam failures. There are many sources of coloration in streams, so that a definitive cause of sudden color changes cannot be determined without further information. A complicating factor is the lack of a clear hydraulic pathway between Pond No. 15 and the Manduriaco Chico River.

The possibility of heavy rainfall preceding the tailings dam failure at the El Corazón mine was examined based on precipitation data from the weather stations at La Concordia (69 kilometers to the southwest), Izobamba (73 kilometers to the south-southeast), San Gabriel (116 kilometers to the northeast), and San Luis in Colombia (141 kilometers to the northeast), which are the closest weather stations included in the (U.S.) National Climate Data Center (NCDC) database. There are 11 weather stations in the INAMHI (National Institute of Meteorology and Hydrology) database that are within 50 kilometers of the El Corazón mine, including Apuela (33.5 kilometers), Calacali (43.7 kilometers), Chontal Bajo (6.9 kilometers), Garcia Moreno (19.8 kilometers), Gualsaqui (44.2 kilometers), Inguincho (44.7 kilometers), Nanegalito (26.2 kilometers), Nono (45.6 kilometers), Pimampiro (20.5 kilometers), San Jose de Minas (46.9 kilometers), and Selva Alegre (25.2 kilometers). At the present time, data are not available from the preceding 11 weather stations after 2013. If INAMHI responds to a request for recent data from the 11 weather stations near the El Corazón mine, this report will be updated accordingly.

A great deal of information in the 2020-2022 Environmental Audit of the El Corazón mine by Agroindustrial is inconsistent with information available from other sources, with the meteorological information being only one example. The Environmental Audit states that there are five weather stations (Apuela, Chontal Bajo, Garcia Moreno, Inguincho, Selva Alegre) in the vicinity of the mine. However, weather stations at Calacali, Gualsaqui, Nanegalito, and Pimampiro are all closer than the weather station at Inguincho, and the weather station at Pimampiro is closer than the weather station at Selva Alegre. The Environmental Audit further states the locations of the weather stations at Chontal Bajo, Garcia Moreno and Selva Alegre incorrectly. The stated location of Chontal Bajo is 9.4 kilometers west-southwest of the correct location, while the stated location of Selva Alegre is 5.8 kilometers west-southwest of the correct location. Finally, the stated elevation of the weather station at Selva Alegre is 1950 meters above sea level, while the correct elevation is 1800 meters above sea level. No attempt was made in this report to document all information in the Environmental Audit that was inconsistent with information available in other sources.

The available precipitation data is inconclusive regarding whether heavy rainfall could have been a contributing factor to the tailings dam failure. September and October were unusually wet months at the La Concordia station, while the first days of November were unusually dry. September was unusually wet and October was unusually dry at the Izobamba station, while the opposite pattern was observed at the San Gabriel and San Luis stations. It is known that precipitation did not occur at the site of the El Corazón mine over the night of November 3-4. Despite the preceding lack of conclusive evidence, it should be noted that heavy rain cannot be a root cause of tailings dam failure because, according to Ecuadorian regulations, tailings dams are supposed to be designed to withstand heavy rains, except for the most rare and extreme precipitation events, such as a 1000-year storm.

The most likely proximal cause of the tailings dam failure was a tear in the geomembrane followed by internal erosion of the outer embankment, in which water flows so fast through the embankment that it entrains solid particles, which can result in the loss of structural integrity of the dam. The flow through the tailings dam for Pond No. 15 was measured at approximately 2.5 liters per second on November 4, with nearly the same flow rate measured on November 6 and 7. According to technicians with Agroindustrial, the same flow rate had persisted since August 2020 and the only change on November 4, 2023, was the appearance of solid particles in the water escaping from the tailings dam. The preceding observation is disturbing because it implies that the tailings dam had been in a state of continuous failure for over four years, meaning that toxic water was being released into downstream waterways without treatment. By the preceding account, internal erosion initiated over the night of November 3-4, which could have led to catastrophic failure of the dam and the release of much of the contents of the tailings pond if emergency action had not been taken to lower the water level in the pond.

The root cause of the tailings dam failure was improper design because a waterproof geomembrane should not be the sole line of defense against failure. The first element of improper design is that the slope of the outer embankment should have been much lower in order to lengthen the hydraulic pathway and decrease the speed of water flow through the embankment. Photos show the slopes of the embankments surrounding Pond No. 15 to be approximately 1V:1H (1 meter vertical for 1 meter horizontal) or 45° from the horizontal. By contrast, many guidance documents, such as those of the U.S. Army Corps of Engineers, recommend slopes no steeper than 1V:5H (11° from the horizontal) in order to avoid failure by internal erosion. In fact, a slope of 1V:1H is regarded as the maximum critical angle to avoid internal erosion, so that the tailings dams at the El Corazón mine have always been on the cusp of failure. A maximum slope of 1V:3H (18° from the horizontal) is also regarded as a maximum angle to ensure slope stability and to prevent surface erosion. The second element of improper design is that the outer embankment should include a combination of a vertical drain and a horizontal drain to force any seepage to exit at the toe of the dam. By contrast, the flow through the tailings dam on November 4 appeared high on the face of the embankment. Finally, in order to minimize the consequences of failure, no cyanide should be present in the tailings pond, meaning that all cyanide should be destroyed before the wet tailings are deposited in the tailings pond.

According to a post-failure inspection report by the Ministry of the Environment, Water and Ecological Transition (MAATE), the tailings dams surrounding Pond No. 15 are currently stable. However, this was only a visual assessment with no justification and no explanation of how the word "stable" was to be understood. Although Ecuadorian tailings dam regulations clarify that physical stability refers to the ability to operate under the design conditions with an acceptable factor of safety, no assessment was made of the factor of safety. In fact, Ecuadorian regulations describe in considerable detail the appropriate steps for assessing the factor of safety, as well as other aspects of tailings dam stability. It is disturbing that so little information is available concerning the tailings dams at the El Corazón mine, including such basic information as the construction material. In particular, the 432 pages of the 2020-2022 Environmental Audit do not even mention the existence of tailings ponds or tailings dams.

At the present time, no meaningful steps have been taken to prevent further tailings dam failures at the El Corazón mine. Based on the current design, any further tears in the geomembranes of any of the tailings ponds will most likely progress to internal erosion with the possibility of catastrophic failure and the release of most of the contents of a tailings pond. Although the volumes of tailings ponds are relatively small (for example, about 50,000 cubic meters for Pond No. 15) compared with the tailings ponds at the Mirador mine or the Fruta del Norte mine, the toxicity of the ponds must be taken into consideration in evaluating the possible consequences of catastrophic failure. For example, in 2000 a failure of the tailings dam at the Aurul gold mine near Baia Mare, Romania, released 100,000 cubic meters of cyanide-rich water (about twice the volume of a tailings pond at the El Corazón mine). The spill of cyanide-rich water flowed through the Somes and Tisza Rivers to the Danube River and all the way to the Black Sea, causing a massive fishkill and destruction of aquatic species. By analogy, a future catastrophic failure of a tailings dam at the El Corazón mine could have catastrophic impacts on fish, aquatic species, and livestock between the mine and the Pacific Ocean.

This report makes the following recommendations:

1) Complete dam safety audits should be carried out for all of the tailings dams at the El Corazón mine in accordance with Ecuadorian tailings dam regulations.
2) All tailings dams at the El Corazón mine that are not stable, as defined in Ecuadorian regulations, should be appropriately reinforced to achieve stability.
3) All tailings dams at the El Corazón mine that cannot be appropriately reinforced to achieve stability should be permanently and safely closed, which would probably involve the transfer of the gold tailings to a safe location.
4) All tailings dams at the El Corazón mine that violate the required buffer from a stream of 30 meters, including Pond No. 15, should be permanently and safely closed, which would probably involve the transfer of the gold tailings to a safe location.
5) Investigations should be carried out to determine the hydraulic connections between the tailings ponds and the local waterways, including high-precision Lidar surveys and the use of chemical tracers, including stable isotopes of water.
6) Further processing of ore and production of tailings should cease until the above steps have been completed.

7) Any future processing of ore and production of tailings should include the destruction of cyanide prior to the deposition of wet tailings in tailings ponds. In accordance with the requirements of the European Union, cyanide should be destroyed to the lowest possible level using best available techniques and no greater than 10 mg/L of WAD (Weak Acid Dissociable) cyanide.
8) Agroindustrial should be expected to become a signatory company of the International Cyanide Code.
9) Agroindustrial should be expected to comply with all requirements of the Responsible Gold Mining Principles, which were developed by the World Gold Council and which incorporate the International Cyanide Code.
10) Agroindustrial should be expected to fully comply with the requirements of the Global Industry Standard on Tailings Management at a minimum and, ideally, with the stricter requirements of Safety First: Guidelines for Responsible Mine Tailings Management.

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OVERVIEW

Failure of the Tailings Dam

On the early morning of November 4, 2023, a tailings dam failed at the Agroindustrial El Corazón underground gold mine in the province of Imbabura, northern Ecuador, releasing fine-grained tailings and cyanide-rich water into downstream waterways (Agencia de Prensa Minera [Mining Press Agency], 2023; Agroindustrial El Corazón S.A., 2023a-b; MAATE, 2023a-b; MEM, 2023); Municipio de Cotacachi [Municipality of Cotacachi], 2023a) (see Figs. 1-4). The gold tailings were stored in 20 tailings ponds that were underlain by waterproof geomembranes and surrounded by earthen dams (see Figs. 4-5) (Municipio de Cotacachi, 2023a). The failure occurred from Pond No. 15, which is located less than 15 meters from Los Monos Creek (see Fig. 4). Los Monos Creek flows into Verde Chico Creek and then the Verde River, before joining with the Guayllabamba River and then flowing to the Esmeraldas River and the Pacific Ocean (see Fig. 3).

The close proximity of Pond No. 15 to a downstream waterway has been a violation of the regulations of the canton of Cotacachi, in which the El Corazón mine is located (see Fig. 3). According to a Technical Report by the Municipio de Cotacachi (2023a), "*La piscina 15 ha sido construida a menos de 15 metros de la quebrada los monos, afluente de la Quebrada Verde Chico que desemboca en el Río Verde … Se evidenció que la piscina de relave minero número 15 está construida a pocos metros de la Quebrada Los Monos* [Pond 15 has been built less than 15 meters from Los Monos Creek, a tributary of Verde Chico, which flows into the Verde River … It was evident that mine tailings pond number 15 is built a few meters from the Los Monos Creek] (see Figs. 3-4). The Municipio de Cotacachi (2023a) continues, "*Conforme lo estipula la 'ORDENANZA SUSTITUTIVA QUE DELIMITA, REGULA, AUTORIZA Y CONTROLA EL USO DE RIBERAS Y LECHOS DE RÍOS, LAGOS Y LAGUNAS, QUEBRADAS, CURSOS DE AGUA, ACEQUÍAS Y SUS MÁRGENES DE PROTECCIÓN EN EL CANTÓN SANTA ANA DE COTACACHI', en su Art. 12, Inciso 5, donde se establece que: ' ...los márgenes de todos los ríos y quebradas del cantón, tendrán una zona de protección según establece el PDOT cantonal: para la Zona de Intag 30 metros para ríos" ... la empresa minera está incumpliendo con lo que establece la presente normativa ... por lo que deberá tomar acciones inmediatas, a fin de dar cumplimiento a la Ordenanza vigente*" [As stipulated in the "SUBSTITUTE ORDINANCE THAT DELIMITS, REGULATES, AUTHORIZES AND CONTROLS THE USE OF BANKS AND BEDS OF RIVERS, LAKES AND LAGOONS, STREAMS, WATERWAYS, CHANNELS AND THEIR PROTECTIVE MARGINS IN THE CANTON SANTA ANA DE COTACACHI," in its Art. 12, Section 5, which establishes that: "...the margins of all the rivers and streams of the canton will have a protection zone as established by the cantonal PDOT: for the Intag Zone 30 meters for rivers" … the mining company is failing to comply with what is established by this regulation ... so it must take immediate action in order to comply with the current Ordinance] (capitalization in the original). The Intag Zone that is mentioned in the ordinance is a mountainous area of the province of Imbabura. The entire parish of Garcia Moreno, in which the El Corazón mine is located, is included within the Intag Zone. An engineer with the Municipio de Cotacachi confirmed to the Defensoría del Pueblo del Ecuador [Ombudsman of Ecuador] (2024) that "*es común que en las concesiones mineras no consideren las ordenanzas que constituyen normativa local, en cuanto la distancia que deben conservar de quebradas, ríos o* *lagos*" [it is common that in the mining concessions they do not consider the ordinances that constitute local regulations, regarding the distance they must keep from creeks, rivers or lakes].

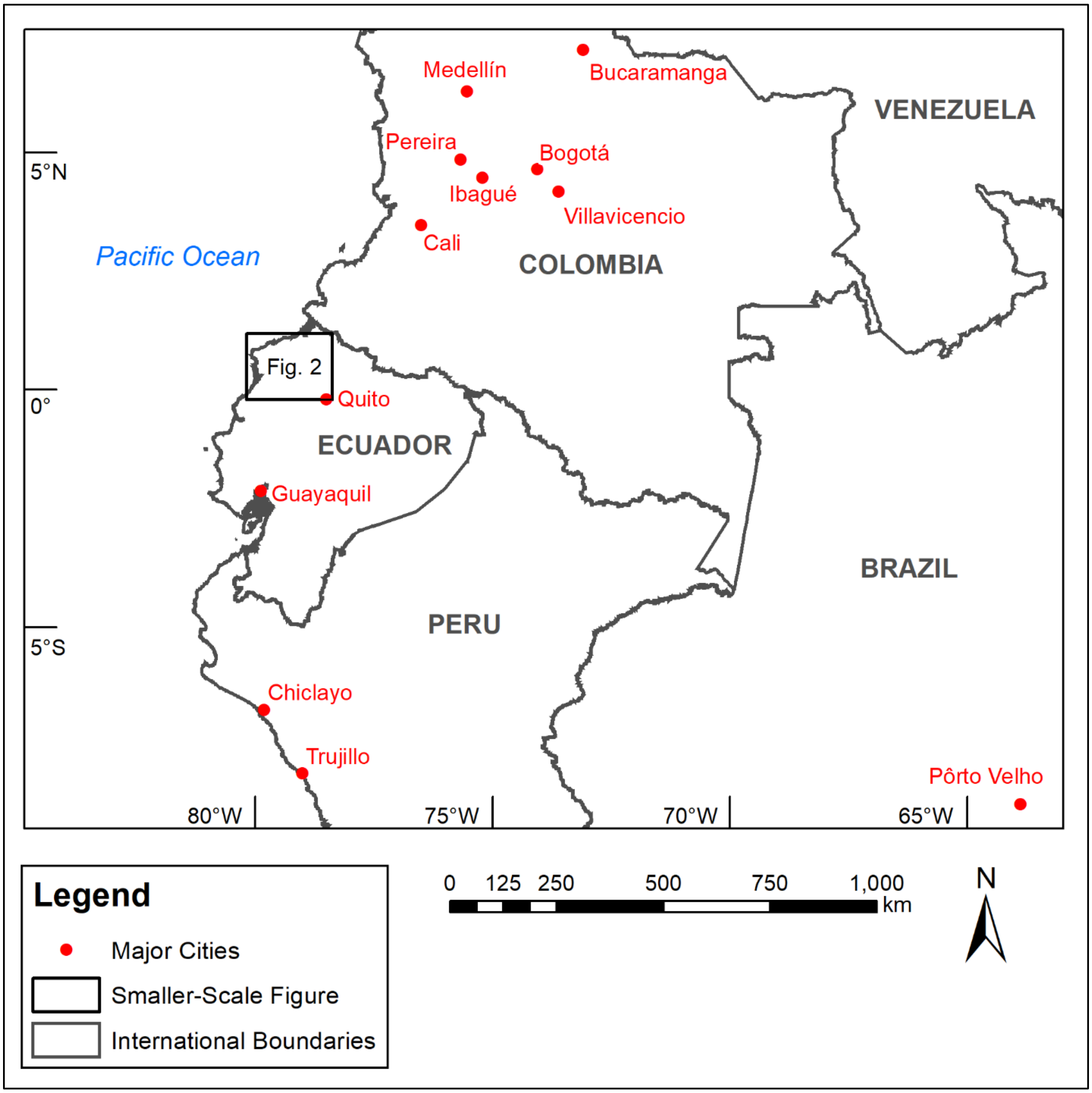


Figure 1. On November 4, 2023, a tailings dam failed at the Agroindustrial El Corazón gold mine in the province of Imbabura in northern Ecuador. See smaller-scale maps in Figs. 2-4.

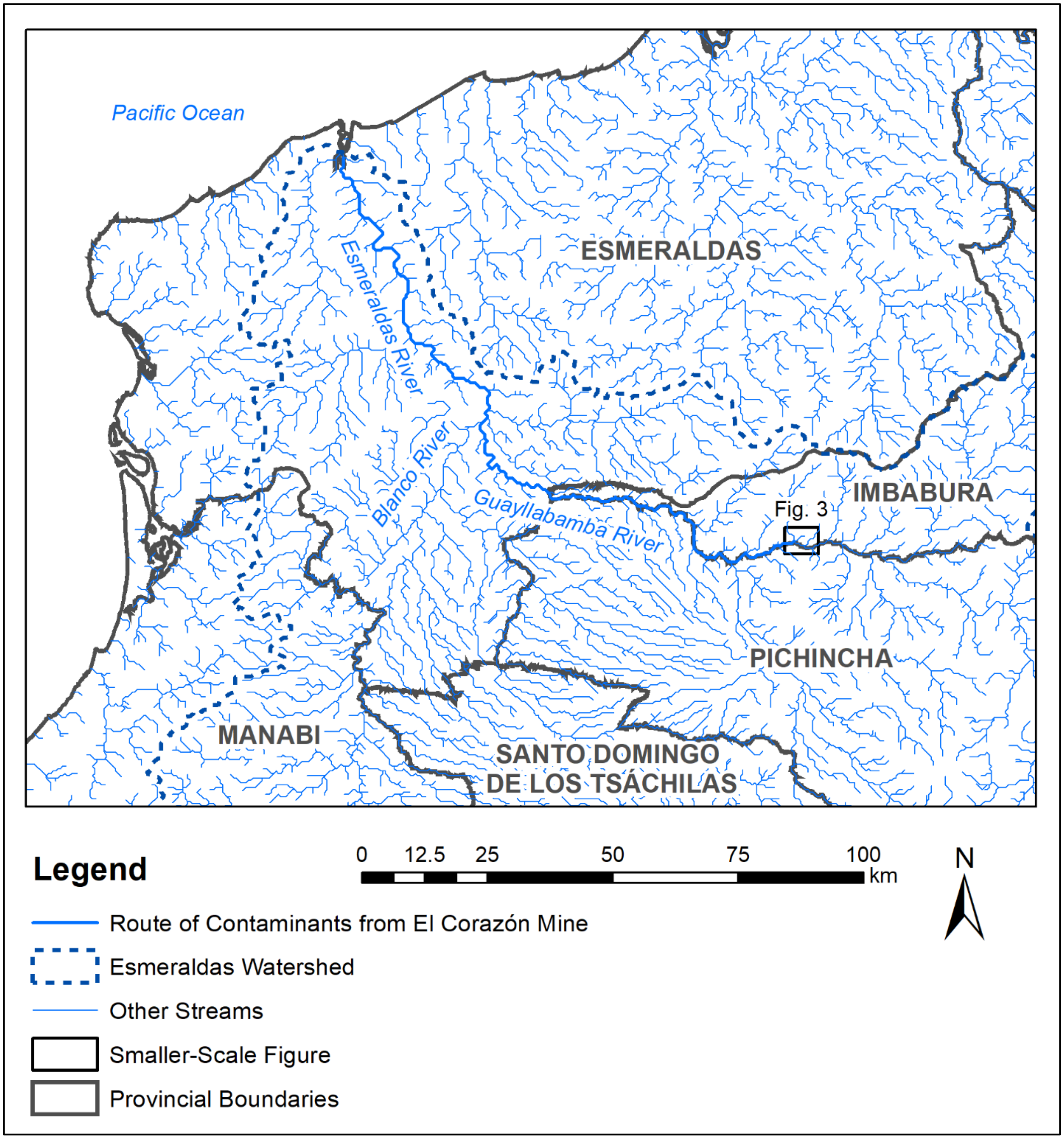


Figure 2. Contaminants released by the failure of a tailings dam at the El Corazón mine would ultimately flow into the Guayllabamba River, which forms the Esmeraldas River at the confluence with the Blanco River. The Esmeraldas River flows into the Pacific Ocean. See larger-scale map in Fig. 1 and smaller-scale maps in Figs. 3-4. Streams and Esmeraldas watershed from HydroSHEDS (2024).

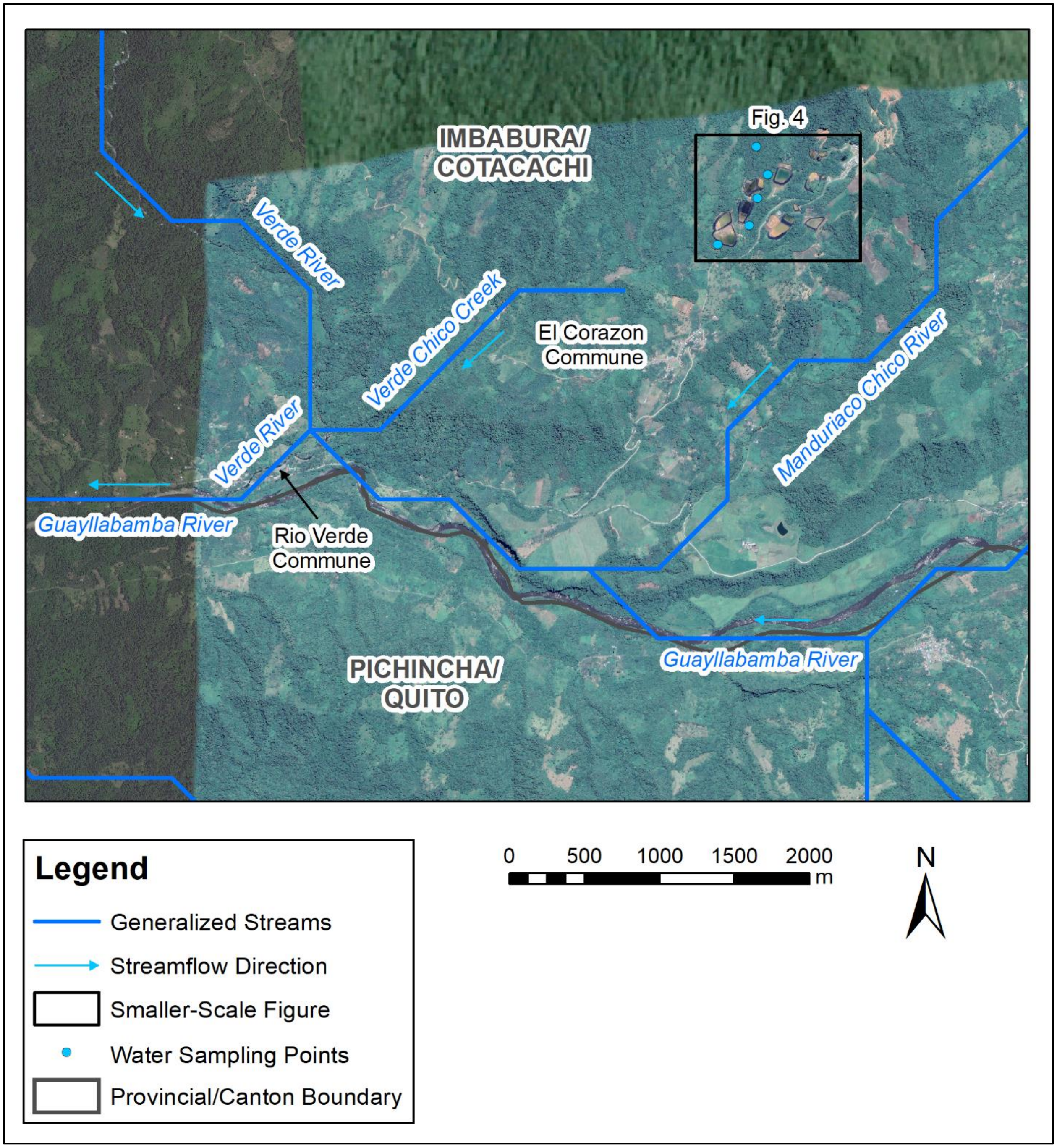


Figure 3. Contaminants released by the failure of Pond 15 at the El Corazón mine would flow into Verde Chico Creek, then into the Verde River, followed by flow into the Guayllabamba River (see Fig. 2). Contaminants from Pond 15 or other tailings ponds could potentially reach the Manduriaco Chico River and then flow into the Guayllabamba River, although the pathway from the mine site to the Manduriaco Chico River is not clear from the available stream maps, aerial photos, and satellite imagery. See larger-scale maps in Figs. 2-3 and smaller-scale map in Fig. 4. Background is Google Earth imagery from April 9, 2013, April 24, 2016, and June 27, 2019. Streams from HydroSHEDS (2024) are more generalized than can be seen in the Google Earth imagery. Water sampling points were determined by comparing the sketch map from Agroindustrial El Corazón (2023a) (see Fig. 19) with Google Earth imagery from June 27, 2019 (see Table 6).

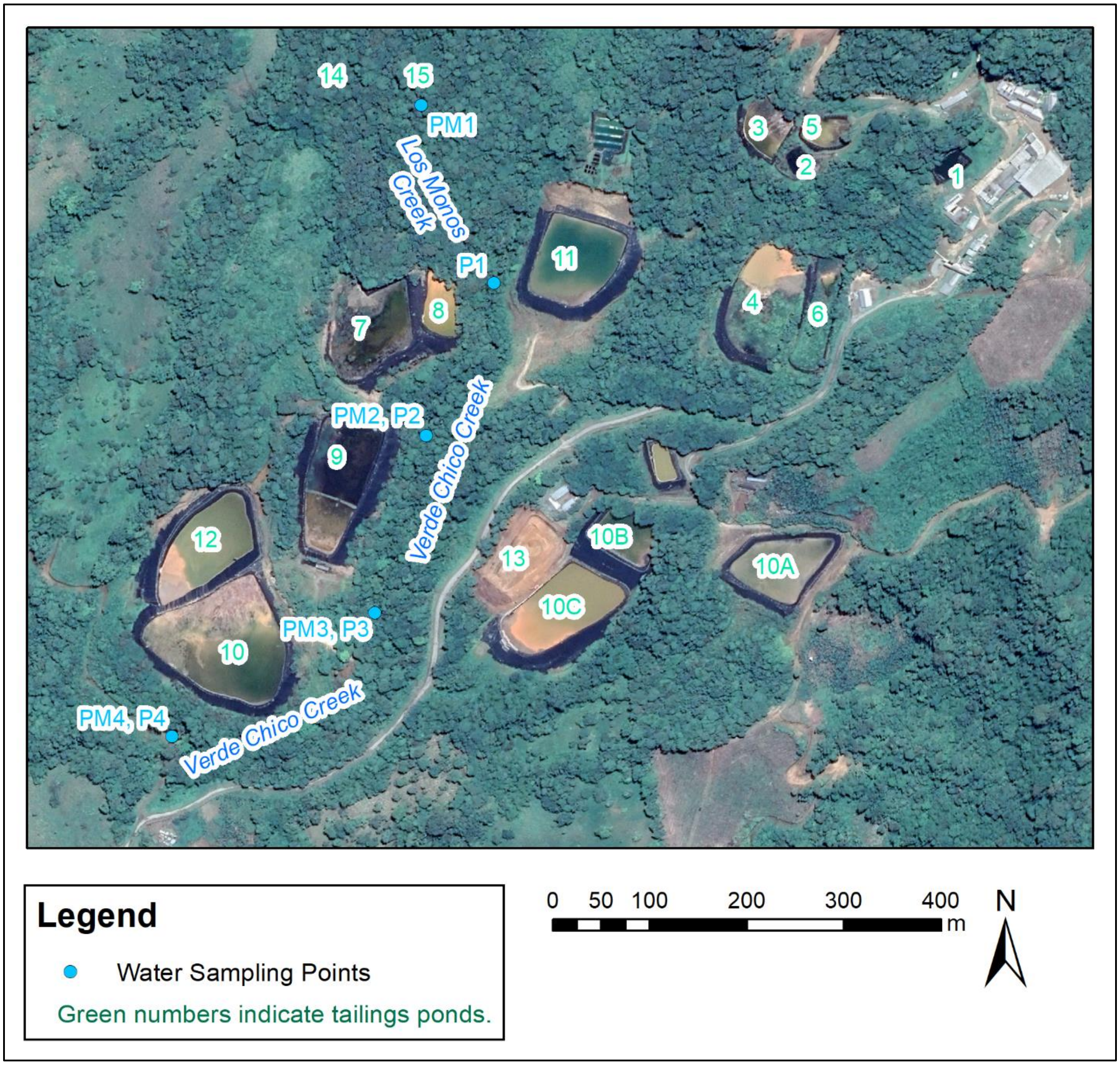


Figure 4. Water samples were collected by the mining company at points PM1, PM2, PM3 and PM4 and by the consulting company GRUNTEC at points P1, P2, P3, and P4. Point PM1 is also the point of discharge from Pond 15. Water sampling points were determined by comparing the sketch map from Agroindustrial El Corazón (2023a) (see Fig. 19) with Google Earth imagery from June 27, 2019 (see Table 6). The coordinates of the sampling points stated in Agroindustrial El Corazón (2023a) (see Fig. 20) do not correspond to the measured coordinates (compare Table 6 with Fig. 20). The tailings ponds were labeled by comparison with the sketch map (see Fig. 19). Background is Google Earth imagery from June 27, 2019. Note that Ponds 14 and 15 were constructed between 2020 and 2021, so that they are absent from the background imagery.

Figure 5. The wet tailings remaining from the processing of gold ore using cyanide at the El Corazón mine are stored in a succession of tailings ponds (see Fig. 4). There is no indication that the cyanide is destroyed (oxidized) prior to deposition in the tailings ponds, so that it should be assumed that the water in the tailings ponds is enriched in cyanide. Photo from Agencia de Prensa Minera (2023).

According to the report in Agencia de Prensa Minera (2023), the tailings pond "*explotó*" [exploded]. Agroindustrial El Corazón S.A. (2023c) described the story in Agencia de Prensa Minera (2023) as "*sensacionalista*" [sensationalist] and the word "*fuga*" [leak] was preferred in reports by Agroindustrial El Corazón S.A. (2023a), as well as by MAATE (2023a-b) and MEM (2023b). The Municipio de Cotacachi (2023, 2024) preferred the term "*filtración*" [seepage], which was also occasionally used in the reports by Agroindustrial El Corazón S.A. (2023a), MAATE (2023a-b) and MEM (2023). Although leaks and seepages did occur, the technical term in the dam safety literature for the incident is "failure," and the November 4 incident will be referred to as a "tailings dam failure" throughout the rest of this report.

The failure of a tailings dam does not necessarily refer to a catastrophic failure, which would constitute a collapse of the dam and the release of much or all of the contents of the tailings pond. Failure refers to the inability to meet the performance objectives, of which the most important is the containment of water and tailings. Thus, any unintentional loss of containment literally constitutes failure. For example, according to the (U.S.) Federal Emergency Management Agency, "Any malfunction or abnormality outside the design assumptions and parameters which adversely affect a dam's primary function of impounding water is properly considered a failure. Such lesser degrees of failure can progressively lead to or heighten the risk of a catastrophic failure. They are, however, normally amenable to corrective action" (FEMA, 2004). Although FEMA (2004) primarily deals with water-retention dams, the same document clarifies that "In addition to conventional structures, this definition of 'dam' specifically includes 'tailings dams,' embankments built by waste products disposal and retaining a disposal pond." ANCOLD (2012, 2019) defines "failure" as "the occurrence of an event outside the expectation of the design or facility licence conditions, that could range from the uncontrolled release of water including seepage, to a major instability of an embankment leading to loss of tailings and/or water.” Finally, according to Canadian Dam Association (2021), “a tailings dam failure can generally be defined as the inability of the dam to meet its design intent, whether in terms of management, operational, structural, or environmental function, resulting in potential loss of life, loss to the stakeholders, or adverse environmental effects.”

Water Sampling by the Community, the Mining Company, and their Consultants

On the morning of November 4, 2023, a local resident collected a sample from the water and tailings that were flowing through the failed dam (see Fig. 6). The sample was delivered to Laboratorio Anncy for analysis on November 22 and the analysis was complete on December 4 (Laboratorio Anncy, 2023). The analysis showed a total cyanide concentration of 60.8 mg/L, which is over 600 times the maximum permissible limit for freshwater bodies in Ecuador of 0.1 mg/L (see Table 1). Other exceedances included arsenic concentration of 0.750 mg/L, copper concentration of 1.88 mg/L, iron concentration of 136 mg/L, manganese concentration of 4.20 mg/L, and mercury concentration of 0.034 mg/L, which are 7.5 times, 1.88 times, 13.6 times. 2.1 times, and 6.8 times the respective Ecuadorian maximum permissible limits (see Table 1).

It should be noted that freshwater environmental standards in Ecuador are much less strict than in many other countries (see comparison with Brazil, Spain and USA in Table 2). In comparison to the freshwater environmental standards in Brazil, the maximum concentrations in Ecuador are 10 times higher for arsenic, 20 times higher for cadmium, over 111 times higher for copper, over 33 times higher for iron, 20 times higher for lead, 20 times higher for manganese, 25 times higher for mercury, 80 times higher for nickel, 10 times higher for selenium, 10 times higher for silver, and nearly 28 times higher for zinc (see Table 2). In comparison to the freshwater environmental standards in Spain, the maximum concentrations in Ecuador are nearly 28 times higher for lead, over 71 times higher for mercury, and 100 times higher for selenium (see Table 2). In comparison to the freshwater environmental standards in the USA, the maximum concentrations in Ecuador are 80 times higher for lead and over 41 times higher for zinc (see Table 2). Thus, in addition to the exceedances mentioned above, the water sample collected by the local resident would have exceeded maximum permissible limits for chromium, lead, nickel, selenium, silver and zinc in Brazil (compare Tables 1 and 2). International standards for cyanide will be compared after an explanation of the distinctions among free cyanide, WAD cyanide and total cyanide in the section “Tutorial on Gold Ore Processing.”

The mining company also collected water samples on November 4, although the time of day has not been stated (Agroindustrial El Corazón S.A., 2023a) (see Figs. 4 and 7). Water samples were collected at PM1 (the point of discharge from Pond No. 15), PM2 (391 meters downstream from the point of discharge), PM3 (581 meters downstream from the point of discharge), and PM4 (884 meters downstream from the point of discharge) (see Figs. 4 and 7). The discrepancy between the distances stated above and those stated in Fig. 7 will be discussed in the subsection “The Cyanide Data of the Company and their Consultants are Invalid.” Water sampling from the same four sites was repeated on November 6 (see Fig. 7). Cyanide concentrations for the samples collected by Agroindustrial ranged from 0.303 mg/L at the point of discharge on both sampling dates to 0.009 mg/L at the point farthest downstream (PM4) on November 6 (see Fig. 7).

Figure 6. On the day of the tailings dam failure (November 4, 2023), a local resident struggles to gain footing on the steep embankment to collect a water sample from the leaking dam (see results of water analysis by Laboratorio Anncy (2023) in Table 1). The steepness of the embankment is further indicated by the steepness of the pipe, the exposed plant roots, and the near vertical fall of contaminated water from the tailings pond. Still photo at 0:04 of video provided by Asociación de Propietarios de Tierras Rurales del Norte and Frente Antiminero (labeled Video 1 by author). Another still photo from the same video is available in Municipio de Cotacachi (2023a).

Table 1. Comparison of community sample with GRUNTEC samples[1]

Parameter	Community Sample[2] (mg/L)	GRUNTEC Samples[3] (mg/L)				Permissible Limit[4] (mg/L)
		P1	**P2**	**P3**	**P4**	
Cyanide	60.8[5]	<0.001[6]	<0.001[6]	0.012[6]	0.009[6]	0.1[5]
Arsenic	0.750	0.025	<0.001	0.001	0.0018	0.1
Cadmium	<0.010	<0.0002	<0.0002	0.0004	0.0006	0.02
Chromium	0.284	0.0096	0.0024	0.0005	<0.0002	N/A
Copper	1.88	0.02	0.05	0.55	0.75	1.0
Iron	136	4.3	0.12	0.30	0.15	10.0
Lead	0.182	0.005	<0.001	<0.001	<0.0005	0.2
Manganese	4.20	0.17	0.057	0.38	0.45	2.0
Mercury	0.034	0.0009	<0.0002	0.0004	0.0002	0.005
Molybdenum	<0.050	0.0010	0.0006	0.0021	0.0019	N/A
Nickel	0.063	0.002	<0.002	0.006	0.012	2.0
Selenium	0.015	<0.002	<0.002	<0.002	0.001	0.1
Silver	0.033	0.0004	0.0009	0.0065	0.0073	0.1
Zinc	0.323	0.01	<0.01	<0.02	<0.033	5.0

[1] Values in red exceed maximum permissible limits for discharge into freshwater bodies in Ecuador.

[2] See sample point PM1 in Figs. 4 and 19 and Table 6. Sample was collected on November 4, 2023.

[3] See sample points in Figs. 4 and 19 and Table 6. Note that the various versions of the locations of the sample points are contradictory. Samples were collected on November 10, 2023.

[4] Ministerio del Ambiente [Ministry of the Environment] (2003, 2015)

[5] Total cyanide

[6] Free cyanide

Table 2. Comparison of selected freshwater environmental standards[1]

	Ecuador[2]	**Brazil**[3]	**Spain**[4]	**USA**[5,6]
Cyanide (µg/L)	100[7]	5[8]	40[7]	5.2[8]
Arsenic (µg/L)	100	10	50	150
Cadmium (µg/L)	20	1	0.08-0.25[9]	complex[10]
Chromium (µg/L)	N/A	50	50	85
Copper (µg/L)	1000	9	5-120[9]	complex[10]
Iron (µg/L)	10,000	300	N/A	1000
Lead (µg/L)	200	10	7.2	2.5
Manganese (µg/L)	2000	100	N/A	N/A
Mercury (µg/L)	5	0.2	0.07	0.77
Molybdenum (µg/L)	N/A	N/A	N/A	N/A
Nickel (µg/L)	2000	25	20	52
Selenium (µg/L)	100	10	1	complex[10]
Silver (µg/L)	100	10	N/A	complex[10]
Zinc (µg/L)	5000	180	30-500[9]	120

[1] Note that 1000 µg/L = 1 mg/L (compare with Table 1)

[2] Ministerio del Ambiente [Ministry of the Environment] (2003, 2015)

[3] CONAMA (2005)

[4] Boletín Oficial del Estado [Official State Bulletin] (2015)

[5] EPA (2024)

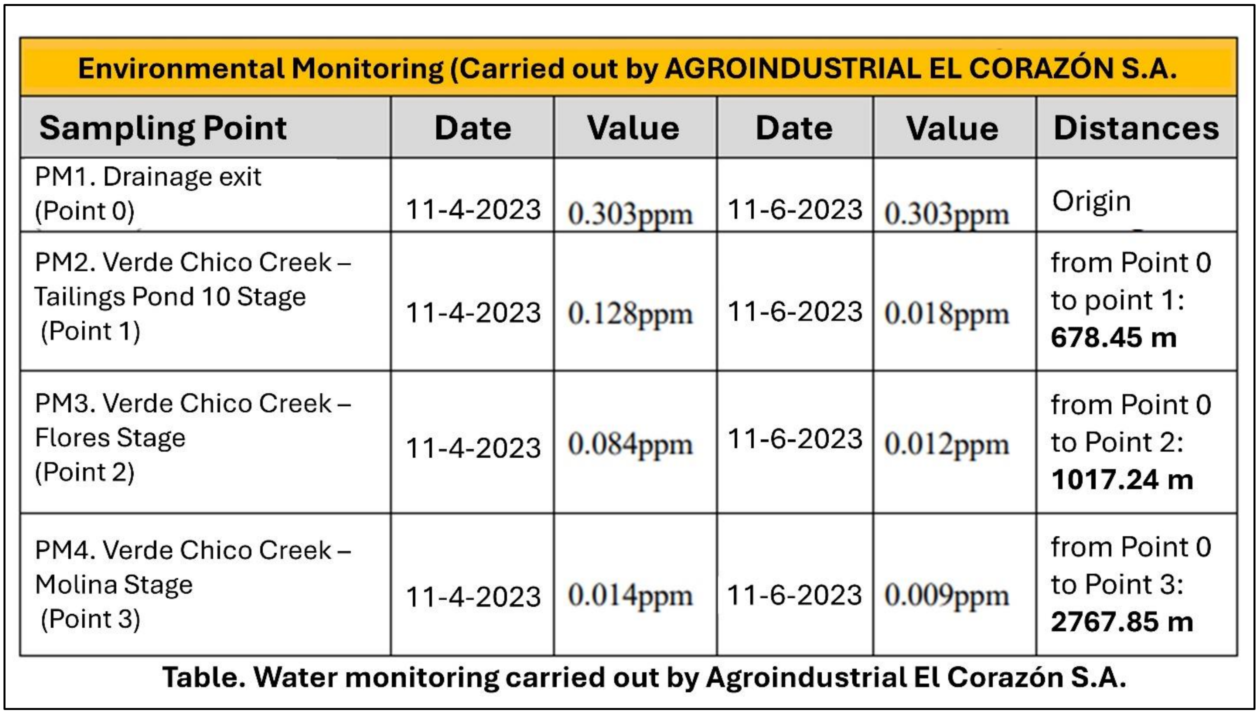
[6] Maximum value for chronic exposure of organisms in freshwater

[7] Total cyanide

[8] Free cyanide

[9] Value depends upon hardness.

[10] Value is under review or depends upon water chemistry.



Environmental Monitoring (Carried out by AGROINDUSTRIAL EL CORAZÓN S.A.

Sampling Point	Date	Value	Date	Value	Distances
PM1. Drainage exit (Point 0)	11-4-2023	0.303ppm	11-6-2023	0.303ppm	Origin
PM2. Verde Chico Creek – Tailings Pond 10 Stage (Point 1)	11-4-2023	0.128ppm	11-6-2023	0.018ppm	from Point 0 to point 1: **678.45 m**
PM3. Verde Chico Creek – Flores Stage (Point 2)	11-4-2023	0.084ppm	11-6-2023	0.012ppm	from Point 0 to Point 2: **1017.24 m**
PM4. Verde Chico Creek – Molina Stage (Point 3)	11-4-2023	0.014ppm	11-6-2023	0.009ppm	from Point 0 to Point 3: **2767.85 m**

Table. Water monitoring carried out by Agroindustrial El Corazón S.A.

Figure 7. Agroindustrial El Corazón collected water samples at PM1, PM2, PM3, and PM4, while the consulting company GRUNTEC collected samples at P1, P2, P3 and P4 (see Fig. 4). Based on the sketch map (see Fig. 19) and the descriptions (see Fig. 20) in Agroindustrial El Corazón S.A. (2023a), sampling point PM1 (the point from discharge from Pond 15) is north of P1, while sites PM2, PM3, and PM4 are identical to sites P2, P3, and P4, respectively. The sketch map (see Fig. 19) was compared with Google Earth imagery from June 27, 2019 (see Fig. 4) to determine the coordinates of the sampling points (see Table 6). The distances were presumably measured along the stream paths and are not straight-line distances. However, based upon the Google Earth imagery (see Fig. 4), the distances should be 391 meters from Point 0 (the same as PM1) to PM2, 581 meters from Point 0 to PM3, and 884 meters from Point 0 to PM4. Thus, the distances stated in the above table are far too large. The "value" in the table refers to cyanide, although Agroindustrial El Corazón S.A. (2023a) did not clarify whether the mining company measured free cyanide or total cyanide. Figure from Agroindustrial El Corazón S.A. (2023a) with overlay of English labels.

The consulting company GRUNTEC was hired by Agroindustrial to collect water samples from four sites on November 10. Site P1 was 200 meters downstream from the point of discharge (PM1), while sites P1, P2, and P3 were identical to sites PM2, PM3, and PM4, respectively (see Fig. 4). The water samples collected by GRUNTEC were analyzed for 58 chemical parameters, of which 14 are shown in Table 1. No exceedances of maximum permissible limits in Ecuador were found for any chemical parameters (see Table 1). However, it should be noted that the lack of exceedances is partly due to the less strict freshwater environmental standards in Ecuador. For example, the samples collected by GRUNTEC would have exceeded the Brazilian standards for arsenic, copper, iron at site P1, the Brazilian standard for manganese at sites P1, P3, and P4, and the freshwater standard in the USA for lead at site P1 (compare Tables 1 and 2).

In summary, the analysis of the sample collected by the community showed far higher concentrations for every parameter than the analyses of the samples collected by Agroindustrial and GRUNTEC (see Table 1 and Fig. 7). The discrepancy in measured cyanide concentrations is of particular interest, first, because cyanide is used in the processing of the gold ore and thus is present in the gold tailings, and because Agroindustrial used the low measured cyanide concentrations to argue for the insignificant impact of the tailings dam failure. With regard to its own analyses from samples collected on November 4, Agroindustrial El Corazón S.A. (2023a) stated, "*De acuerdo a los resultados del monitoreo realizados por la empresa el 4 de noviembre, y luego de compararlos con los valores establecidos en la normativa ambiental vigente (0.1 mg/l) ... se puede deducir que la afectación por CN no alcanzó el segundo punto de monitoreo"* [According to the results of the monitoring carried out by the company on November 4, and after comparing them with the values established in the current environmental regulations (0.1 mg/l) ... it can be deduced that the impact by CN [cyanide] did not reach the second point of monitoring]. With regard to its own analyses from samples collected on November 6, Agroindustrial El Corazón S.A. (2023a) stated, "*De acuerdo a los resultados del monitoreo realizados por la empresa el 6 de noviembre, y luego de compararlos con los valores establecidos en la normativa ambiental vigente (0.1 mg/l) ... se puede deducir que la afectación por CN pudo ser controlada y que los valores de CN en todos los puntos monitoreados se encontraron dentro de los límites permisibles establecidos en la normativa ambiental vigente*" [According to the results of the monitoring carried out by the company on November 6, and after comparing them with the values established in the current environmental regulations (0.1 mg/l) ... it can be deduced that the impact by CN could be controlled and that the CN values at all monitored points were within the permissible limits established in current environmental regulations." The preceding statement regarding "*todos los puntos monitoreados"* [all the monitoring points] is confusing because the cyanide concentration (0.303 mg/L) at the point of discharge (PM1) did not change between November 4 and 6 and still exceeded what Agroindustrial stated as the Ecuadorian standard (0.1 mg/L) on November 6 (see Fig. 7). With regard to the analyses of the samples collected by GRUNTEC on November 10, Agroindustrial El Corazón S.A. (2023a) stated, "*Los resultados obtenidos demuestran que los valores de CN y metales pesados al momento del monitoreo realizado por GRUNTEC, se encuentran dentro de los límites permisibles establecidos en la normativa ambiental vigente*" [The results obtained demonstrate that the values of CN and heavy metals at the time of monitoring carried out by GRUNTEC are within the permissible limits established in current environmental regulations].

Preliminary Objectives

The preliminary objectives of this report were to answer the following questions with regard to the El Corazón mine:

1) Why are there discrepancies between the chemical analyses of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC?
2) What was the cause of the tailings dam failure?
3) Has the possibility of further tailings dam failures been eliminated?

The questions will be further refined in the "Methodology" section. Before addressing the methodology and the more detailed questions, in order to facilitate reading by non-specialists, this report includes a tutorial on key aspects of gold ore processing, including the use of cyanide, the storage of gold tailings in tailings ponds, the industry guidance documents International Cyanide Code and Responsible Gold Mining Principles, the distinctions among free cyanide, WAD cyanide, and total cyanide, the mechanisms of failure of tailings dams, and the distinction between proximal and root causes of tailings dam failures. The tutorial will be followed by summaries of the tailings ponds at the El Corazón mine and a detailed description of the failure on November 4, 2023, and its antecedents.

TUTORIAL ON GOLD ORE PROCESSING

Use of Cyanide for Processing Gold Ore

Cyanide was first used as an extractant for gold in 1889 at the Crown mine in New Zealand (Johnson, 2015). Cyanide is such an effective extractant (also called a lixiviant) that it can extract microscopic quantities of gold from a large body of gold ore, on the order of fractions of a gram of gold per metric ton of ore (fractions of a part per million). In this way, the gold mining industry has continued to be profitable, even while the grades of the remaining gold deposits have declined from 50 grams per metric ton in the mid-19th century to around 1 gram per metric ton at the present time (Mudd, 2010). According to Laitos (2013), "Nonetheless, by the 21st century, over 90% of gold extracted worldwide is the result of cyanide leaching techniques. Prior to the introduction of cyanide leaching operations, most low-grade ore deposits could not be profitably removed using traditional placer or lode mining techniques; to that end, the low capital costs associated with cyanide heap leaching have made profitability on low-grade ores a reality. By utilizing cyanide mineral leaching techniques in large-tonnage mine projects, operators were able to extract small, sometimes microscopic flecks of gold and other precious minerals from low-grade ore with 90% to 95% efficiency. As a result of the efficiency of heap leaching, mountains full of low-grade ore have been transformed into profitable mineral extraction operations."

Cyanide is highly toxic and can be lethal to birds, wildlife, aquatic organisms, livestock, and humans if it is accidentally released into the environment. The lethal effect of cyanide results from its tendency to attach to red blood cells, so that the blood cells can no longer release oxygen to tissues and organs, resulting in suffocation. Because of its high toxicity, alternatives to cyanide have been sought for over a century, or almost since the use of cyanide in gold ore processing was first introduced. Any alternative lixiviant to cyanide should have some combination of the following characteristics (Laitos, 2013):

1) It should be relatively inexpensive.
2) It should be relatively recyclable, meaning that after extracting gold from gold ore, the lixiviant can be recovered, so that it can be applied to more gold ore.
3) It should be selective, meaning that it preferentially extracts gold and not every other metal.
4) It should be relatively non-toxic.
5) It should be possible to destroy or recover the lixiviant from any water or waste that might be released into the environment.

After over a century of research, no lixiviant has emerged that satisfies a reasonable number of the above characteristics. Mercury is just as effective at extracting gold as cyanide, but it is much more toxic and is highly persistent in the environment. On that basis, the World Gold Council (2019a) does not recommend the use of mercury for gold processing under any circumstances. Thiosulfate is an effective lixiviant and less toxic than cyanide, but it is too expensive due to its high consumption rate during gold ore processing. Coal-gold agglomeration (CGA) is far less toxic than cyanide, but is effective only for extracting free gold particles (such as may be found in river or beach deposits), not in extracting gold from hardrock (Laitos, 2013). In summary, despite its toxicity, the modern gold mining industry could not exist without the use of cyanide.

The process of gold ore processing using cyanide involves dissolving a cyanide salt (such as sodium cyanide) in water, so that it dissociates to form the cyanide ion (CN^-) and hydrogen cyanide (HCN). The gold ore is crushed and is either placed onto a heap leach pad, where cyanide solution is poured over it, or mixed with the cyanide solution in a vat. The cyanide ion extracts the gold from the ore to form a dissolved gold-cyanide complex. The solution with the gold-cyanide complex is called the pregnant solution. The pregnant solution is then mixed with or passed over activated carbon, so that the gold-cyanide complex leaves the solution and attaches to the activated carbon, after which the solution is referred to as the barren solution. Further steps (called stripping or elution) remove the gold from the activated carbon and restore the cyanide to the barren solution. Any lost cyanide is replaced in the barren solution and the solution is then recycled to extract additional gold from more gold ore. Botz (2024) is an excellent reference on the use of cyanide for gold extraction.

A considerable portion of the environmental toxicity that is a consequence of the use of cyanide in gold ore processing is not the cyanide itself, but the by-products of the use of cyanide. Cyanide is equally effective in extracting mercury from crushed ore, so that any mercury present in the gold ore also appears as a dissolved mercury-cyanide complex within the pregnant solution. There is a mercury-cyanide complex that could attach to activated carbon along with the gold-cyanide complex, but not the particular mercury-cyanide complex that forms under the alkaline conditions that are necessary for processing with cyanide. Some of the hydrogen cyanide that develops when sodium cyanide is dissolved to form the cyanide solution remains in the dissolved form, but most of it volatilizes to escape as hydrogen cyanide gas. Hydrogen cyanide gas would be lethal to the mineworkers and would be economically undesirable, even if it could be ventilated, because it represents a loss of cyanide from the processing circuit. In order to minimize the production of hydrogen cyanide and maximize the production of the cyanide ion, the cyanide solution is maintained in a very alkaline state, in the pH range of 10-11 (Botz, 2024). In such a high pH range, the mercury-cyanide complex remains in the barren solution. Thus, every passage of the cyanide solution through the processing circuit causes the solution to encounter more ore that may contain additional mercury. As a consequence, the cyanide solution becomes increasingly enriched in mercury, which can be far more toxic to the environment than cyanide.

Other contaminants can be mobilized into the cyanide solution solely as a result of the high pH. These contaminants include elements that form oxyanions (negatively-charged ions that include oxygen) in the dissolved form. Examples of such elements are arsenic, antimony, molybdenum, selenium, and uranium. As with mercury, since none of the preceding oxyanions will attach to activated carbon, they will remain in the barren solution. Thus, every passage of the cyanide solution through the processing circuit will cause the solution to become increasingly enriched in arsenic, antimony, molybdenum, selenium, and uranium, if those elements are present in the gold ore. The co-occurrence of arsenic and gold in ore bodies is very common. In fact, Rivera-Parra et al. (2021) wrote with regard to the El Corazón deposit, “This deposit also has very high concentrations of arsenic, chrome, copper, lead, mercury, molybdenum, nickel, silver, vanadium, zinc and antimony.” The connection between the use of cyanide in gold ore processing and the occurrence of cyanide (as well as the other elements that are mobilized as a by-product of cyanide processing) in the tailings pond is discussed in the next subsection.

Gold Tailings and Tailings Ponds

The management or storage or disposal of mine waste is a critical component of any modern, large-scale mining project. Waste rock and tailings comprise the vast majority of mine waste. Waste rock is the rock that must be removed to reach the ore body. Whether a particular body of rock is regarded as ore or waste rock can vary as the cut-off grade varies, in which the cut-off grade is the minimum gold concentration for which a particular rock body can be processed at a profit under particular social, economic and technical circumstances. The tailings are the wet and crushed rock particles that remain after the commodity of value, such as gold, has been extracted. Thus, the crushed ore particles that remain after interaction with cyanide solution at a cyanide processing facility constitute the gold tailings.

On a global basis, for gold mining, 2.86 metric tons of waste rock are removed for every metric ton of gold ore. Considering a typical ore grade of 0.00008% (0.8 grams of gold per metric ton of ore) and typical concentrator and smelter/refinery recovery rates, 3,046,349 metric tons of mine waste (both tailings and waste rock) are generated for every metric ton of refined gold, which is the largest waste-to-metal ratio for any common mined commodity (Nassar et al., 2022a-b). The grade of the ore deposit at the El Corazón mine is 2.5-3.0 grams of gold per metric ton of ore (MEM, 2023), so that the waste-to-metal ratio is somewhat lower than the global average. However, it cannot be emphasized too many times that the chief product of a modern hardrock mine, especially a gold mine, is waste, which is an unusual outcome for a modern industrial process.

Because of the typical size of the blocks, waste rock can often be deposited as a free-standing waste rock dump. By contrast, because they are wet and fine-grained, tailings require confinement behind a dam. In conventional tailings management, the wet tailings are piped to a tailings disposal facility with no dewatering, so that water contents are in the range 150-400%, where the water content is the ratio of the mass of water to the mass of dry solid particles. Typically, the tailings will settle out of suspension, leaving an overlying layer of supernatant water that can be reclaimed and pumped back into the mining operation. The supernatant water may include very fine-grained tailings that may take a long time to settle or may remain in suspension indefinitely.

The deposited body of water and tailings is referred to as the "tailings pond." Sometimes the entire facility, including the confining dam, is referred to as a "tailings pond," and sometimes the phrase "tailings dam" is used to refer to the entire facility. In any event, the failure of the tailings dam would constitute a failure of the tailings pond, so that often the phrases "tailings pond" and "tailings dam" are used interchangeably. It is noteworthy that all of the reports regarding the tailings dam failure at the El Corazón mine by either the company (Agroindustrial El Corazón S.A., 2023a) or governmental regulatory agencies (MAATE, 2023a-b; MEM, 2023a) exclusively use the word "pond" [*piscina*] and never use the word "dam" [*represa*] or "embankment" [*terraplén*], except to refer to the dam that was constructed out of nylon bags to block the flow of water and tailings after failure of the tailings dam. It should be cautioned that the lack of use of the phrase "tailings dam" could be stylistic, but could also be an attempt to avoid compliance with Ecuadorian regulations and international standards regarding tailings dams.

At a gold processing operation that uses cyanide, the water that is exported to the tailings pond along with the tailings is simply the barren cyanide solution that stayed with the tailings, such as the cyanide solution within the pore spaces between the tailings or the cyanide solution that could not be separated from the tailings. Not only will this water retain some cyanide, but it could also include whatever mercury, arsenic, antimony, molybdenum, selenium or uranium that was mobilized from the ore body by the cyanide processing. The consequences of failure of a tailings pond at a cyanide processing facility and the means of reducing those consequences will be discussed in the following subsection.

International Cyanide Code and Responsible Gold Mining Principles

In January 2000 a tailings dam failed at the Aurul S.A. gold mine near Baia Mare, Romania. The tailings dam failure released 100,000 cubic meters of cyanide-rich water into the Somes and Tisza Rivers, which then flowed into the Danube River and finally into the Black Sea, a distance of over 2000 kilometers. The cyanide spill resulted in massive fishkill and the destruction of aquatic species (ICOLD and UNEP, 2001). An earlier failure of the tailings dam at the Omai gold mine in Guyana in 1995 released 4.2 million cubic meters of cyanide-contaminated water into the Omai River, fortunately, with only minor fishkill (ICOLD and UNEP, 2001). The public and governmental response led to a concern in the gold mining industry that governments would begin banning the use of cyanide, which would effectively put an end to the gold mining industry in those jurisdictions.

In fact, following the tailings dam failure at Baia Mare, the use of cyanide in ore processing was banned in Costa Rica, Czech Republic, Germany, and Hungary (Laitos, 2013). Turkey had already banned the use of cyanide in 1997 (Laitos, 2012). In 2010 the European Parliament called for a ban on the use of cyanide in mineral processing throughout the European Union, stating that a ban "is the only safe way to protect our water resources and ecosystems against cyanide pollution from mining activities" (Environment and Natural Resources Law & Policy Program, 2010). In the United States, the state of Montana had already banned the use of cyanide at open-pit mines in 1998 (Laitos, 2013). The states of Wisconsin and Virginia banned the use of cyanide in 2001 and 2024, respectively (Wisconsin State Legislature, 2001; Virginia's Legislative Information System, 2024). Eight provinces of Argentina have prohibited the use of cyanide in mineral processing, although there is no nationwide prohibition (Laitos, 2013). Some countries (for example, Burkina Faso, Cameroon, Ghana, Kenya, Mongolia, South Africa, Tanzania) prohibit the use of cyanide by artisanal and small-scale gold miners, that is, by gold mining operations that lack the capital and technical capacity to carry out cyanide processing safely (IGF, 2024).

In an effort to forestall such governmental bans and their existential threat to the industry, the gold mining industry created the International Cyanide Management Code for the Manufacture, Transport, and Use of Cyanide in the Production of Gold (called the International Cyanide Code in this report) (The Cyanide Code, 2024). The International Cyanide Code is a voluntary commitment that includes third-party audits for full certification. Thus far, over 200 companies are signatory to the International Cyanide Code, including mining companies, cyanide producers, and cyanide transporters. The two signatory companies in Ecuador are Transportes Noroccidental Cia. Ltda. and Ciateite S.A., both of which are cyanide transporters (The Cyanide Code, 2024). Agroindustrial is not a signatory company to the International Cyanide Code. The Responsible Gold Mining Principles, which were developed by the World Gold Council are even broader than the International Cyanide Code because they incorporate the International Cyanide Code, in addition to other requirements. According to the Responsible Gold Mining Principles, "Where our operations use cyanide, we will ensure that our arrangements for the transport, storage, use and disposal of cyanide are in line with the standards of practice set out in the International Cyanide Management Code" (World Gold Council, 2019a).

This review of the International Cyanide Code and Responsible Gold Mining Principles will focus on the aspects of gold ore processing most relevant to this report, which are the use of tailings ponds for the storage or disposal of cyanide, the proper construction and operation of tailings ponds, and the requirements for public disclosure of information concerning the use of cyanide. International requirements for public disclosure regarding tailings ponds will be discussed further in the section "Summary of Tailings Ponds at El Corazón Gold Mine." It should be kept in mind that the International Cyanide Code, as well as Responsible Gold Mining Principles, were developed almost entirely by the mining industry with little to no input by other stakeholders, such as civil society organizations or mining-affected communities. In other words, the industry guidance documents should be regarded as guidelines that balance protecting the environment with guaranteeing the profits of gold mining companies, not as guidelines that are intended to maximize the protection of the environment and downstream communities. In the following review, some examples will be given as to how the International Cyanide Code and Responsible Gold Mining Principles might have been stricter if they had been intended to maximize protection of the environment. It should be noted that Agroindustrial has not committed to even the minimal requirements of the International Cyanide Code and Responsible Gold Mining Principles.

The International Cyanide Code is made up of nine Mining Principles, five Production Principles, and three Transportation Principles, each of which is subdivided into multiple Standards of Practice. Mining Principle 4 (Operations) includes Mining Standard of Practice 4.2, which states, "Introduce management and operating systems to minimize cyanide use, thereby limiting concentrations of cyanide in mill tailings" (International Cyanide Management Institute, 2021a). Two related Mining Standards of Practice are 4.4 and 4.5, which state "Implement measures to protect birds, other wildlife and livestock from adverse effects of cyanide process solutions" and "Implement measures to protect fish and wildlife from direct and indirect discharges of cyanide process solutions to surface water," respectively (International Cyanide Management Institute, 2021a).

Because some amount of cyanide will be retained within the water that is mixed with the tailings and, thus, deposited within the tailings pond, the tailings pond constitutes a "cyanide facility." According to the International Cyanide Management Institute (2021b), "Since the Code defines Process Solution as any solution with a concentration of 0.5 mg/l WAD cyanide or greater, the following would likely be cyanide facilities at most operations: … Tailings storage facilities." The precise meaning of WAD (Weak Acid Dissociable) cyanide will be explained in the following subsection "Free Cyanide, WAD Cyanide, and Total Cyanide." The intention of the International Cyanide Code is to minimize the impact on birds, wildlife, and livestock by minimizing the concentration of cyanide in the tailings pond. The minimization of cyanide in the tailings pond minimizes the impact both on animals that interact directly with the tailings pond and on animals that could interact with water that is intentionally or accidentally released from tailings ponds. According to the International Cyanide Management Institute (2021b), "Lower cyanide concentrations reduce risks to wildlife from exposures to tailings and to water quality from potential seepage." The cyanide concentration in the tailings pond is minimized by minimizing the use of cyanide in processing of the gold ore and by destroying the cyanide in the water that is mixed with the tailings prior to deposition of water and tailings in the tailings pond. A variety of processes could be used to destroy cyanide prior to deposition, such as ultraviolet light or the addition of oxidizing reagents.

The International Cyanide Code sets quantitative limits for cyanide concentrations in the within the tailings pond (50 mg/L WAD cyanide), in seepage from the tailings pond (0.5 mg/L WAD cyanide), and in waterways downstream from the tailings pond (0.022 mg/L WAD cyanide). Thus, the audit of Mining Standard of Practice 4.4 asks the question "Can the operation demonstrate that the cyanide concentration in open water in Tailings Storage Facilities, leach facilities and ponds does not exceed 50 mg/l WAD cyanide?" (International Cyanide Management Institute, 2021c). The audit of Mining Standard of Practice 4.5 asks the question "Does the operation have a direct discharge to surface water and if so, is it no greater than 0.5 mg/l WAD cyanide" (International Cyanide Management Institute, 2021c). The protection of downstream waterways applies to both the direct discharge from the tailings pond into surface water and the indirect discharge, which could involve seepage of cyanide-enriched water into groundwater with subsequent emergence into a waterway. Thus, the audit of Mining Standard of Practice 4.5 also includes the questions "Does the operation monitor for cyanide in surface water downgradient of the site and can the operation demonstrate that direct discharges to surface water do not cause the concentration of free cyanide in the receiving water to exceed 0.022 mg/l downstream of any established mixing zone?" and "Can the mine demonstrate that indirect discharges to surface water do not cause the instream concentration of free cyanide to exceed 0.022 mg/l downstream of any established mixing zone?" (International Cyanide Management Institute, 2021b). The distinction between WAD cyanide and free cyanide will also be explained in the following subsection "Free Cyanide, WAD Cyanide, and Total Cyanide," although it should be noted that the WAD cyanide concentration always exceeds the free cyanide concentration.

It is somewhat surprising that the International Cyanide Code allows the cyanide concentration in the tailings pond to be 100 times greater than in seepage from the tailings pond. In practice, unless the water in the tailings pond passes through a water treatment system prior to seepage, the cyanide concentration in seepage from the tailings pond should be expected to be roughly identical to the cyanide concentration within the tailings pond. Since seepage could be accidental and could bypass a water treatment system, even if it existed, the more conservative standard (more protective of the environment) would be to require a maximum concentration of 0.5 mg/L WAD cyanide within the tailings pond, the same as in seepage from the tailings pond. Along the same lines, the International Cyanide Code allows the WAD cyanide concentration in seepage from the tailings pond to be nearly 23 times greater than the concentration of free cyanide in downstream waterways with the caveat that downstream waterways begin at the end of the "mixing zone." The International Cyanide Code clarifies that "the Code does not establish mixing zones but recognizes that some political jurisdictions have established them. Without such a mixing zone, the 0.022 mg/l free cyanide concentration must be achieved at the point of discharge, effectively applying this value to the discharge itself" (International Cyanide Management Institute, 2021b). Thus, even without a "mixing zone" (which is a space that is defined by regulation), the International Cyanide Code allows a WAD cyanide concentration within the tailings pond that could be nearly 2300 times greater than the free cyanide concentration in the seepage from the tailings pond. As above, a more conservative standard would acknowledge the possibility of accidental seepage with a cyanide concentration equal to the concentration within the tailings pond and would require a maximum free cyanide concentration of 0.022 mg/L within the tailings pond.

The regulations within the European Union for the disposal of cyanide into tailings ponds actually are more stringent than what is found in the International Cyanide Code. Article 13(6) of

Adopted Directive 2006/21/EC requires that "the concentration of weak acid dissociable cyanide in the pond [be] reduced to the lowest possible level using best available techniques" (Laitos, 2012). The Directive states further that mines started after May 1, 2008, may not deposit tailings containing more than 10 mg/L of WAD cyanide, while mines built or permitted before that date were allowed no more than 50 mg/L initially, falling to 25 mg/L in 2013 and 10 mg/L by 2018. It should be noted that the European Union has declined to ban the use of cyanide, although such a ban has been repeatedly urged by the European Parliament.

Mining Principle 9 of the International Cyanide Code deals with the need for "Dialogue and Disclosure" with stakeholders and affected communities (International Cyanide Management Institute, 2021a). Mining Standard of Practice 9.1 requires that signatory companies "Promote dialogue with stakeholders regarding cyanide management and responsibly address identified concerns," while Mining Standard of Practice 9.2 requires that companies "Make appropriate operational and environmental information regarding cyanide available to stakeholders" (International Cyanide Management Institute, 2021a). Questions for audits of Mining Standard of Practice 9.2 include: "Has the operation developed written descriptions of how their activities are conducted and how cyanide is managed? Are these descriptions available to communities and other stakeholders? Has the operation disseminated information on cyanide in verbal form where a significant percentage of the local population is illiterate?" (International Cyanide Management Institute, 2021c).

In addition to the requirement that gold mining companies commit to the entirety of the International Cyanide Code, the Responsible Gold Mining Principles require adherence to best practices in the design and operation of tailings ponds and tailings dams. Principle 8 of Responsible Gold Mining Principles is entitled "Environmental stewardship: we will ensure that environmental responsibility is at the core of how we work" (World Gold Council, 2019a). Requirement 8.2 then states, "We will design, build, manage and decommission tailings storage and heap-leaching facilities and large-scale water infrastructure using ongoing management and governance practices in line with widely supported good practice guidelines" (World Gold Council, 2019a). The World Gold Council (2019b) then clarifies that Requirement 8.2 means that gold mining companies should "Ensure management and governance practices are in place for existing facilities, and provide evidence of how these align with good practice guidance … For new facilities, develop design, build and management specifications with explicit references to widely recognised good practice guidelines … Discuss and review how widely recognised good practice guidelines have been taken into account in the design, build and management of facilities."

Although not stated in Responsible Gold Mining Principles, current best practice guidelines include the Global Industry Standard for Tailings Management (GISTM) (ICMM-UNEP-PRI, 2020) and Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2022). One way in which Responsible Gold Mining Principles is more protective of the environment than the GISTM is that Responsible Gold Mining Principles prohibits the direct deposition of tailings into rivers or shallow submarine environments for new mines (World Gold Council (2019a-b), which is not prohibited in the GISTM (ICMM-UNEP-PRI, 2020), but which is prohibited for all mines in Safety First (Morrill et al., 2022). According to the World Gold Council (2019a), "We will not develop a new mine that would involve the use of riverine or shallow submarine tailings."

Free Cyanide, WAD Cyanide and Total Cyanide

Environmental standards for cyanide may refer either to free cyanide or total cyanide, and sometimes to WAD (Weak Acid Dissociable) cyanide (see Table 2). Free cyanide refers to cyanide in the form of the cyanide ion plus hydrogen cyanide. Total cyanide refers to all forms of cyanide including free cyanide and a wide variety of metal-cyanide complexes. WAD cyanide refers to free cyanide plus those metal-cyanide complexes that will dissociate into free cyanide upon application of a weak acid, including complexes of cyanide with cadmium, chromium, copper, manganese, mercury, nickel, silver, and zinc. WAD cyanide does not include the strong metal-cyanide complexes, such as gold cyanide, cobalt cyanide or iron cyanide that require the application of strong acids for the dissociation of the metal-cyanide complexes into free cyanide (Johnson, 2015; Botz, 2024). Thus, total cyanide is always equal to or greater then WAD cyanide, which is always greater than or equal to free cyanide.

The environmental significance of the three measures of cyanide relate to their different levels of toxicity. Thus, free cyanide has high toxicity, the weak metal-cyanide complexes have intermediate toxicity, and the strong metal-cyanide complexes have low toxicity (Johnson, 2015). Because free cyanide is the highly toxic form of cyanide, only free cyanide is regulated in some countries, such as Brazil and the USA (see Table 2). However, because the weak acids in animal and human stomachs will convert weak metal-cyanide complexes into free cyanide (Laitos, 2013), some regulations and guidance documents are based on WAD cyanide. It has been mentioned that the International Cyanide Code sets standards for WAD cyanide in tailings ponds and in seepage from tailings ponds, but standards for free cyanide in downstream waterways, although the same standard for free cyanide applies to the seepage from tailings ponds in jurisdictions that do not define a "mixing zone" (International Cyanide Management Institute, 2021b). Finally, because all forms of cyanide, including the strong metal-cyanide complexes, can be converted into free cyanide under certain circumstances, such as exposure to sunlight (Johnson et al., 2001, 2002, 2008), only total cyanide is regulated in some countries, such as Ecuador and Spain (see Table 2).

It is critical that concentrations of free cyanide, WAD cyanide and total cyanide not be used interchangeably in comparing measured concentrations with regulatory limits, in particular because total cyanide can be far greater than free cyanide. For example, Ecuador and Spain, which regulate total cyanide, have maximum permissible limits of 0.1 mg/L and 0.04 mg/L, respectively (see Table 2). On the other hand, Brazil and the USA, which regulate free cyanide, have maximum permissible limits of 0.005 mg/L and 0.0052 mg/L, respectively (see Table 2), which suggests that a total cyanide concentration could be 8-20 times higher than a free cyanide concentration. There are many examples of data throughout the geochemical literature in which total cyanide in mine wastewater was 10-100 times greater than either WAD cyanide or free cyanide (Smith and Mudder, 1999; Johnson et al., 2000, 2001, 2002, 2008; Johnson, 2015). Such results should be expected because free cyanide will much more readily be attenuated in surface water, by processes such as volatilization or biodegradation, than the more resistant forms of cyanide.

An additional factor that minimizes the free cyanide concentration in the wastewater from a gold mine is that the cyanide processing operation is designed in such a way as to minimize the appearance of free cyanide (cyanide ion plus hydrogen cyanide) in the pregnant solution. The intention of a cyanide operation is to maximize the conversion of the cyanide salt (which would have dissociated into the cyanide ion and hydrogen cyanide) into a gold-cyanide complex. Thus, any cyanide ion or hydrogen cyanide remaining in the pregnant solution represents cyanide that did not extract gold and which could potentially be lost from the processing circuit. The hydrogen cyanide could be lost by volatilization, while any remaining free cyanide could convert to hydrogen cyanide and then be lost.

Mechanisms of Failure of Tailings Dams

The principal mechanisms of failure of tailings dams are, in no particular order (ICOLD and UNEP, 2001):

1) overtopping
2) slope instability
3) seismic liquefaction
4) static liquefaction
5) foundation failure
6) internal erosion

The preceding mechanisms will be reviewed in this subsection, with particular attention to internal erosion (also called piping).

Overtopping occurs when a tailings pond contains an excessive amount of water, so that additional precipitation or flow of surface water into the pond causes water to flow over the face of the outer embankment. To reduce costs, tailings dams are nearly always constructed out of material that is locally available on the mine site, as opposed to concrete or to material that is purchased from quarries. The locally available material could be rock or soil or it could be the waste that is generated by the mining operation, such as waste rock or the coarser fraction of the tailings themselves. Any water flowing over an earthen embankment will tend to erode away the embankment, and the resulting gullies could progress to the breach of the embankment or its complete disappearance. Whether an overtopping event will progress to catastrophic failure depends upon the rate and duration of flow and whether the embankment has any protective layer, such as a layer of rock armor. The sliding or slumping of a slope can have the same effect and could progress to the breach or the complete disappearance of an embankment once water starts to flow over the slump. Slope instability can be promoted by an increase in pore water pressure within the dam or by a rise in the water table.

Seismic activity could lead to liquefaction of either the tailings or the dam material. The tailings in the tailings pond are deposited without compaction and could not be compacted because they are too wet. The dam material could be compacted during dam construction, but the compaction could have been inadequate. In either case, seismic shaking or other disturbances, such as drilling or vehicular activity, could promote a sudden consolidation of the tailings or dam material. If the materials are saturated with water and if the disturbance is so sudden that water cannot escape from the pores between the solid particles, then the particles will be unable to consolidate, so that the disturbing stress will cause an increase in the pressure of the pore water. This increase in water pressure breaks the contacts between the particles. Since water is now carrying the entire weight of the tailings or the dam, the mass of particles and water behaves as a liquid with almost no strength, a phenomenon known as liquefaction. Liquefaction typically proceeds to catastrophic failure of the tailings facility.

If the liquefaction is not initiated by cyclic motion, such as in an earthquake, the failure mechanism is called static liquefaction. Static liquefaction can be initiated by any non-cyclic event that can promote a sudden attempt at consolidation of the solid particles without an opportunity for water to escape. Examples of non-cyclic events could be any sudden increases of stress on the uncompacted solid particles, such as heavy rainfall or adding new tailings so fast that the tailings cannot settle out of water and consolidate. Failure of the foundation beneath a tailings dam or tailings pond can also be a type of static liquefaction.

Internal erosion is the phenomenon in which the seepage of water through the dam or its foundation is fast enough to entrain fine particles, which can lead to a loss of structural integrity, followed by a breach of the dam (see Figs. 8-9). There are three principal ways of preventing internal erosion of earthen or tailings dams through the proper design of the dam. The first method is the installation of a combination of a vertical drain and a horizontal drain in order to force seepage to exit at the toe of the embankment, as opposed to exiting along the face of the embankment (see Figs. 10-11 and compare with Fig. 9). Drains are preferential pathways for the flow of water through a dam because they are constructed out of materials with higher hydraulic conductivity than the rest of the dam, such as gravel or crushed rock. The second method is the installation of an appropriate filter on the upstream side of the drainage system to catch fine particles and prevent their entrainment with the seepage through the dam (see Fig. 11).

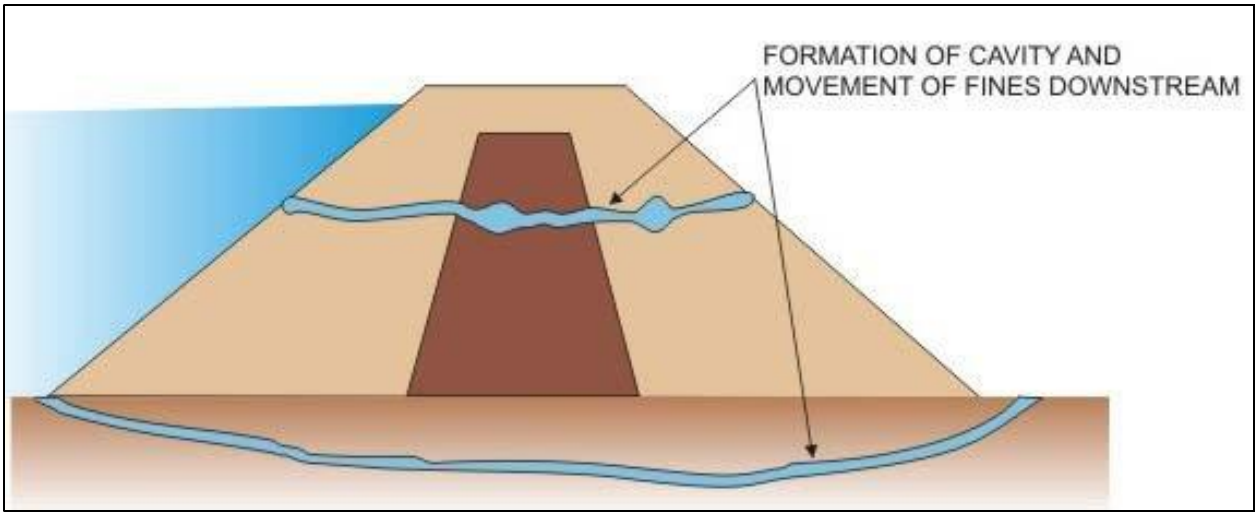


Figure 8. Internal erosion (also called piping) is a common mechanism of tailings dam failure. Internal erosion occurs when the seepage of water through the dam or its foundation is fast enough to entrain fine particles, which can lead to a loss of structural integrity, followed by a breach of the dam. Figure from Bentaher (2012).

The third method of designing dams so as to prevent internal erosion is to reduce the rate of water flowing through the dam as much as possible. The flow rate of water is proportional to the hydraulic gradient, which is the difference between the water levels on the upstream and downstream sides divided by the length of the hydraulic pathway (see Fig. 12). The hydraulic gradient can be reduced by lowering the water level on the upstream side of the tailings dam (see Fig. 12), which would also reduce the likelihood of overtopping of the dam. Another approach to reducing the hydraulic gradient is lengthening the hydraulic pathway, for example, by decreasing the slope of the outer embankment. From a theoretical standpoint, the maximum critical angle to avoid internal erosion is 1V:1H (1 meter vertical for 1 meter horizontal) (Holtz et al., 2011). Such a steep embankment would leave no margin for error and is not recommended.

Figure 9. Internal erosion (also called piping) is a common mechanism of tailings dam failure. Internal erosion occurs when the seepage of water through the dam or its foundation is fast enough to entrain fine particles, which can lead to a loss of structural integrity, followed by a breach of the dam. The photos show the failure by internal erosion of the Tunbridge dam in Tasmania, Australia, in 2005. Figure from Fisher et al. (2017).

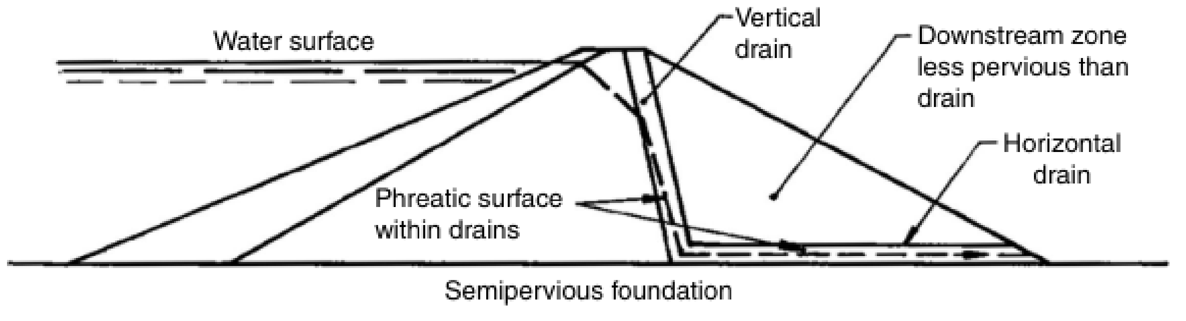


Figure 10.20 Earth dam with internal drain designed to prevent the phreatic surface from rising above the top of the drain.

Figure 10. There are three principal methods for preventing internal erosion of earthen or tailings dams. The first method is the installation of a combination of a vertical drain and a horizontal drain in order to force seepage to exit at the toe of the embankment, as opposed to exiting along the face of the embankment (compare with Figs. 8-9). Figure from Fell et al. (2015).

The U.S. Army Corps of Engineers recommends that slopes be no steeper than 1V:5H (11° from the horizontal) to avoid internal erosion. According to USACE (2000), “For sand levees, a 1V on 5H landside slope is considered flat enough to prevent damage from seepage exiting on the landside slope.” <u>Safety First</u> concurs in writing, “The slope of the outer embankment of the tailings dam must be low enough to keep the annual probability of failure due to piping (also called internal erosion) below an acceptable level. New outer embankments must be constructed with slopes 1V:5H or less, and additional fill must be added to existing outer embankments with a slope steeper than 1V:5H in order to reduce the slope to 1V:5H, as per guidance from the USACE. A proposal to construct or maintain an outer embankment steeper than 1V:5H must be justified in writing to both regulators and the public. The justification cannot be based solely on economic considerations, but must demonstrate that, for a particular design, failure by internal erosion is still sufficiently unlikely even with a steeper slope" (Morrill et al., 2022).

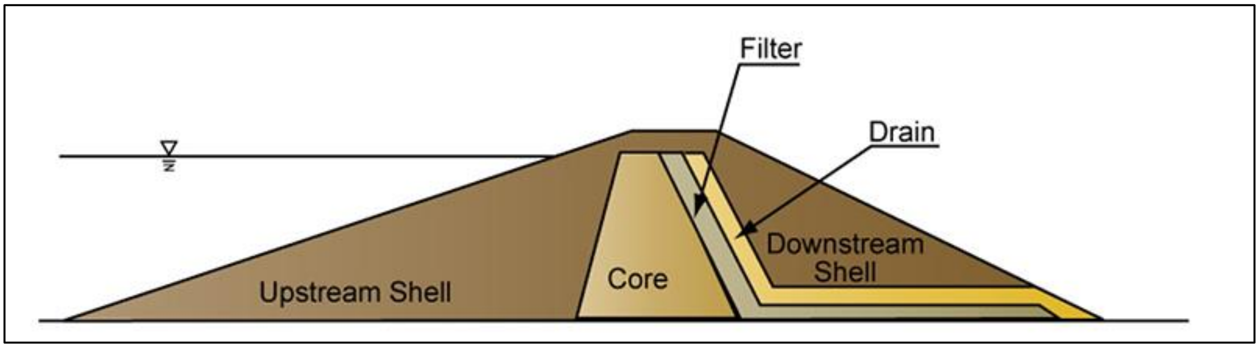


Figure 11. There are three principal methods for preventing internal erosion of earthen or tailings dams. The second method is the installation of an appropriate filter to catch fine particles and prevent their entrainment with the seepage through the dam. The diagram also shows the combination of a vertical drain and a horizontal drain that forces seepage to exit at the toe of the embankment, as opposed to exiting along the face of the embankment (see Fig. 9). Figure from ASDSO (2024).

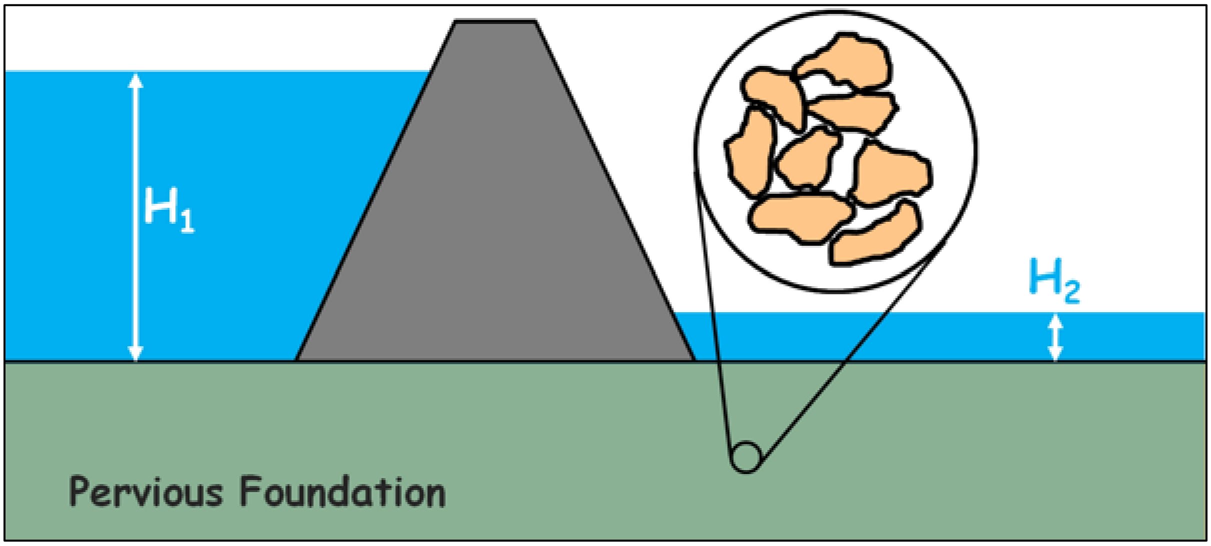


Figure 12. There are three principal methods for preventing internal erosion of earthen or tailings dams. The third method is reducing the slope of the outer embankment, so as to lengthen the pathway for seepage through the embankment. Lengthening the pathway reduces the hydraulic gradient (ratio of the head difference ($H_1 - H_2$) to the length of the pathway), thus reducing the speed of seepage through the dam. The U.S. Army Corps of Engineers requires slope angles no greater than 1V:5H (11° from the horizontal) to avoid failure by internal erosion (USACE, 2000). Figure from Elementary Engineering Library (2024).

Gentle slopes can also prevent failure by seismic activity or slope instability. Moreover, a gentle embankment slope could reduce the likelihood of foundation failure by distributing the weight of the dam over a greater area. According to the textbook Geotechnical Engineering for Mine Waste Storage Facilities, "Considering the requirement that the storage capacity for tailings solids of a given site must be maximized, together with the requirements for overall shear stability and the requirement to limit rates of surface erosion, as well as the practical advantage of a slope that can be worked mechanically, an acceptable slope angle for tailings slopes appears to lie in the range of 15-20°. A round figure of 1 vertical on 3 horizontal or 18° appears to be a good compromise" (Blight, 2010). It should be emphasized that the maximum slope of 1V:3H was not intended to maximize the protection of the environment, but to strike a balance between a need to protect the environment and a need to store the maximum volume of tailings (which might entail reducing the space occupied by the dam in order to create more space for storage behind the dam). The Ministry of Energy and Mines (British Columbia) (2016) specifies a downstream slope no steeper than 1V:2H (26.5° from the horizontal). In line with the regulations in British Columbia, the above quote from Safety First continues, "In all instances, a dam slope must not be steeper than 1V:2H" (Morrill et al., 2022).

The appearance of muddy water emerging from a tailings dam (see Fig. 9) is a dangerous sign because it indicates that internal erosion has progressed to the point where the seepage is entraining small particles, which could be fine-grained tailings or the dam construction material or both. Thus, the appearance of muddy seepage could indicate a last chance to take corrective action, which could mean immediate lowering of the water level behind the dam or the emergency construction of a buttress at the toe of the dam to increase the length of the hydraulic pathway, both of which could reduce the flow rate of seepage. If the dam is in the process of losing its structural integrity, for example, if the crack through which seepage emerges is expanding in the upward direction, then it may be necessary to take measures to protect the downstream community, such as evacuations (see Fig. 9). The significance of corrective actions in the chain of events that lead to tailings dam failure is discussed further in the following subsection.

An additional factor related to design, which would apply to internal erosion, as well as all other mechanisms of failure, is that the tailings pond must be designed in such a way as to minimize the consequences of failure. By contrast, the storage of toxic materials in a tailings pond would maximize the consequences of failure. For this reason, the International Cyanide Code, the Responsible Gold Mining Principles (which incorporate the International Cyanide Code, and the European Union all require the destruction of cyanide before gold tailings are deposited into tailings ponds. The only distinction is that the International Cyanide Code requires cyanide destruction down to 50 mg/L of WAD cyanide (International Cyanide Management Institute, 2021c), while the European Union requires cyanide destruction "to the lowest possible level using best available techniques" and no greater than 10 mg/L of WAD cyanide under any circumstances (Laitos, 2012).

Proximal and Root Causes of Tailings Dam Failures

It is important to note that the preceding list of mechanisms of tailings dam failure (overtopping, slope instability, seismic liquefaction, static liquefaction, foundation failure, internal erosion) are all proximal or ultimate causes, that is, the causes that occurred more or less immediately before dam failure. However, dams fail because of a chain of events or causes, of which the proximal cause is only the final event or the trigger. The first step in the chain, which starts the events in motion, is the root cause. The root cause could also be an ongoing event that, if it had been removed, would have prevented the dam failure. The proximal cause is nearly always a physical event, such as water overtopping and eroding away a dam. The root causes, as well as many of the intervening causes, are always the actions of human beings. In this way, a dam is an anthropogenic construct, not simply a physical landform.

The following possible chain of events, which could apply to the tailings dam at the El Corazón mine, is presented at this point only to illustrate the distinction between root and proximal causes:

1) A tailings pond is designed for a gold mine in which the embankment is excessively steep. Moreover, the dam does not include a drainage system that would force seepage to emerge at the toe of the dam and does not include filters for trapping fine particles. Finally, there is no plan for destruction of cyanide before the tailings and cyanide-enriched water are deposited into the tailings pond.
2) Either the design of the tailings pond is not reviewed or the review is inadequate, so that no attention is called to deficiencies in the design.
3) The tailings pond is constructed as designed.
4) Either dam safety inspections or reviews do not occur or they are inadequate, so that no attention is called to deficiencies in the design.
5) Seepage (cyanide-enriched water) appears high on the face of the dam. The seepage is clear and not muddy.
6) Either no one notices the seepage or no one understands its significance.
7) The seepage turns muddy (indicating that internal erosion is in progress) and the mud and cyanide-enriched water appear in downstream waterways.

By Step #7, the dam has failed, but it has not yet undergone catastrophic failure. In fact, the dam had already failed by Step #5 because the dam was not fulfilling its function of preventing cyanide-enriched water from entering into downstream waterways. The important point is that, although the final event (the entrainment of fine particles into the seepage) was purely physical, the root cause was the inadequate design of the tailings pond, which reflected the actions or lack of actions of human beings. In a similar way, the intermediate causes (repeated failures to carry out inspections or reviews or to understand the significance of observations) reflected the actions or lack of actions of human beings. If at any point in the chain of events, the root cause or the intermediate causes had been reversed (either the facility had been adequately designed or someone had drawn attention to the inadequacy of the design), the chain of events would have been broken and failure would not have occurred. The question as to whether the preceding hypothetical chain of events is relevant to the tailings dam failure at the El Corazón mine will be discussed in the “Responses” section.

SUMMARY OF TAILINGS PONDS AT EL CORAZÓN GOLD MINE

Despite the dangers that tailings ponds pose to the downstream environment and downstream communities, there is surprisingly little publicly available information about the tailings ponds at the El Corazón mine. It is especially surprising that the 423 pages of the 2020-2022 Environmental Audit (Agroindustrial El Corazón S.A., 2023b) do not even mention the existence of the tailings ponds or provide any information as to what happens with the mine tailings. The 2020-2022 Environmental Audit mentions the existence of waste rock, but not that the vast majority of the ore body is converted into tailings, and that something must be done with the tailings. It has already been mentioned that the grade of the ore body is 2.5-3.0 grams of gold per metric ton of ore (MEM, 2023), so that 99.99970-99.99975% of the ore body is converted into tailings. According to the 2020-2022 Environmental Audit, "*El método de explotación subterráneo empleado por Agroindustrial El Corazón S.A., permite el arranque selectivo de mineral, por lo que la mayor parte de material extraído en la mina es enviada a la planta de beneficio*" [The underground exploitation method used by Agroindustrial El Corazón S.A. allows the selective extraction of ore, so most of the material extracted in the mine is sent to the processing plant] (Agroindustrial El Corazón S.A., 2023b). It is equally surprising that the 2020-2022 Environmental Audit does not mention that cyanide is used in the processing of the gold ore or provide any information as to how cyanide is stored and managed in a safe manner. Besides the preoccupation of the company that cyanide might have been released into downstream waterways (Agroindustrial El Corazón S.A., 2023a), the only explicit information that cyanide is used for the processing of gold ore at the El Corazón mine is the statement in Defensoría del Pueblo del Ecuador (2024) that "*La compañía explicó que el agua que se ocupa en la actividad industrial recircula, esta agua contiene cianuro*" [The company explained that the water used in industrial activity recirculates, this water contains cyanide].

Such an extreme lack of transparency is not standard in the mining industry. The Global Industry Standard on Tailings Management (GISTM) was released by the International Council on Mining & Metals (ICMM), United Nations Environment Programme (UNEP), and Principles for Responsible Investment (PRI) in August 2020 (ICMM-UNEP-PRI, 2020). Principle 15 of the GISTM calls on mining companies to "publicly disclose and provide access to information about the tailings facility to support public accountability" (ICMM-UNEP-PRI, 2020). Requirement 15.1 clarifies that companies should "publish and regularly update information on the Operator's commitment to safe tailings facility management, implementation of its tailings governance framework, its organisation-wide policies, standards or approaches to the design, construction, monitoring and closure of tailings facilities" (ICMM-UNEP-PRI, 2020). Requirement 15.2 is even broader in that it requires that companies "respond in a systematic and timely manner to requests from interested and affected stakeholders for additional information material to the public safety and integrity of a tailings facility." Finally, Requirement 15.3 calls on companies to "commit to cooperate in credible global transparency initiatives to create standardised, independent, industry-wide and publicly accessible databases, inventories or other information repositories about the safety and integrity of tailings facilities" (ICMM-UNEP-PRI, 2020). An example of Requirement 15.3 would be the Global Tailings Portal (GRID-Arendal et al., 2024), which has received no information about the tailings dams at the El Corazón mine.

Company Members of ICMM were obligated to fully comply with the GISTM by August 5, 2023 (ICMM, 2021). Just as Agroindustrial is not a signatory of the International Cyanide Code, it is not a Company Member of ICMM, nor has it made its own commitment to comply with the GISTM. However, it is noteworthy that Association Members of ICMM include the Cámara de Minería del Ecuador (CME) [Ecuador Chamber of Mining], the Asociación Colombiana de Minería (ACM) [Colombian Mining Association], the Instituto Brasileiro de Mineração (IBRAM) [Brazilian Mining Institute], the Instituto de Ingenieros de Minas del Peru (IIMP) [Institute of Mining Engineers of Peru], the Peruvian organization Instituto de Seguridad Minera (ISEM) [Institute of Mine Safety], and the World Gold Council (ICMM, 2024). Thus, the expectation for public disclosure regarding tailings facilities is well-established nationally, regionally, and globally.

In terms of transparency regarding tailings facilities, the GISTM should be regarded as a minimum standard because, by and large, it requires public disclosures only in summary form.

For example, Requirement 15.1 elaborates that companies should provide "A summary of risk assessment findings relevant to the tailings facility … A summary of impact assessments and of human exposure and vulnerability to tailings facility credible flow failure scenarios … A summary of material findings of annual performance reviews and DSR [Dam Safety Reviews], including implementation of mitigation measures to reduce risk to ALARP [As Low As Reasonably Practicable] … A summary of material findings of the environmental and social monitoring programme including implementation of mitigation measures … A summary version of the tailings facility EPRP [Emergency Preparedness and Response Plan] for facilities that have a credible failure mode(s) that could lead to a flow failure event" (ICMM-UNEP-PRI, 2020). By contrast, the guidance document Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2022) is much more broad-ranging in terms of the information that must be disclosed to the public and is not restricted to providing information only in summary form. According to Safety First, "Operating companies must make all information relevant to the safety and stability of tailings facilities publicly available … Operating companies and regulators must respond to all stakeholder requests for information regarding the tailings facility to the fullest extent possible in formats and languages that are understandable to all stakeholders" (Morrill et al., 2022). However, it should be noted that Requirement 15.2 of GISTM, which was quoted above, calls for companies to respond to "requests from interested and affected stakeholders for additional information" (ICMM-UNEP-PRI, 2020) and does not state that it would be acceptable to provide this information only in summary form. Additional ways in which Safety First is more protective of the environment and mining-affected communities than is the GISTM was provided in the subsection "Mechanisms of Failure of Tailings Dams."

Some information about Pond No. 15 is available in the various reports on the tailings dam failure, but it is not clear as to what extent this information applies to the 19 other tailings ponds. Even so, the information regarding Pond No. 15 is not always clear or consistent. According to Agroindustrial El Corazón S.A. (2023a), "*La piscina Nro. 15 se encuentra en el sector de coordenadas: 743.895; 10.028.835 (en el punto de descarga de la fuga de relave por fisuramiento de la geomembrana de la piscina 15), cuyo volumen de relaves almacenados alcanza los 51000* m^3" [Pool No. 15 is located in the sector with coordinates: 743,895; 10,028,835 (at the discharge point of the tailings leak due to cracking of the geomembrane of pool 15), whose volume of tailings stored reaches 51,000 m^3]. On the other hand, according to the Municipio de Cotacachi (2023a), "*En el caso de piscina número 15, señalaron que tenía una capacidad aproxima de 55 mil metros cúbicos, es decir capacidad para 55 millones de litros de agua*" [In the case of pool number 15, they [representatives of Agroindustrial] indicated that it had a capacity of approximately 55 thousand cubic meters, that is, capacity for 55 million liters of water].

Thus, it is not clear as to whether Pond No. 15 was storing less than its full capacity at the time of failure or whether the stated volumes refer to the volume of tailings or the combined volume of tailings and supernatant water. All photos of Pond No. 15 have shown water covering the tailings (see Fig. 13), but the depth of water is not known. The Municipio de Cotacachi (2023a) continues, "*Técnicos de la empresa manifestaron que en la piscina sedimentada hay aproximadamente un 40% de metales pesados*" [Company technicians stated that there are approximately 40% heavy metals in the sedimented pool]. The preceding statement may be using the phrase "*metales pesados*" [heavy metals] as synonymous with "solid tailings" (which would be incorrect) and may mean that that 40% of Pond No. 15 was filled with a mixture of water and tailings, while 60% of the pond volume was a water cover on top of the tailings. Since water will fill the pore spaces between the tailings, it is difficult to talk about separate volumes for water and tailings. With regard to the capacity of Pond No. 15, representatives of Agroindustrial informed the Defensoría del Pueblo del Ecuador (2024) that Pond No. 15 was not only full, but at an emergency capacity at the time of failure. According to the Defensoría del Pueblo del Ecuador (2024), "*Adicional señalan que desde octubre de 2023 la piscina estuvo suspendida, encontrándose 1 mes suspendida, se dio la fisura de la geomembrana, encontrándose la piscina de relave nro. 15 inactiva ... Debido a que su contenido llegó al punto de emergencia, teniendo en cuenta que cada piscina cuenta con una línea de seguridad y un punto de emergencia frente al cual la recomendación técnica es su suspensión*" [Additionally, they [the representatives of Agroindustrial] point out that since October 2023 the pond [No. 15] was suspended, being suspended for 1 month when the geomembrane crack occurred, leaving tailings pond no. 15 inactive ... Because its contents reached the emergency point, taking into account that each pool has a safety line and an emergency point against which the technical recommendation is its suspension].

Figure 13. Pond No. 15 at the El Corazón mine contained about 50,000 cubic meters of water and tailings prior to the failure of the tailings dam on November 4, 2023. Photo from Municipio de Cotacachi (2023a).

The water and tailings in Pond No. 15 were deposited on top of a waterproof geomembrane with a thickness of 0.7 millimeters (see Fig. 14). The waterproof geomembrane was placed on top of a drainage system that was constructed to prevent rainwater from ponding underneath the geomembrane. According to Agroindustrial El Corazón S.A. (2023a), "*La misma cuenta con drenajes artificiales de hasta 3 m. de profundidad, construidos con piedra, grava y arena y cubiertos con Geomembrana de 0,7 mm color negra, termo unida por el proveedor del material; los drenes son construidos para captar filtraciones de aguas lluvia bajo geomembrana de la piscina*" [It has artificial drainages of up to 3 meters deep, constructed with stone, gravel and sand and covered with 0.7 mm black Geomembrane, thermo-joined by the material supplier; the drains are constructed to capture rainwater seepage under the pool's geomembrane]. During the construction of Ponds No. 14 and 15, springs were discovered, so that the drains beneath the geomembrane have the additional task of preventing groundwater from ponding beneath the geomembrane. According to the Municipio de Cotacachi (2023a), "*Señalaron que durante la construcción de estas 2 piscinas se encontraron vertientes de agua, mismos que han realizado obras para drenar el agua subterránea encontrada en la base de la piscina y luego de eso se ha colocado la geo-membrana que cubre toda la dimensión de las piscina*" [They [the representatives of Agroindustrial] pointed out that during the construction of these 2 ponds [Nos. 14 and 15], water springs were found, so that works have been carried out to drain the groundwater found at the base of the pond and after that the geomembrane has been placed that covers the entire dimension of the ponds]. There is no information as to whether springs exist beneath any of the other tailings ponds.

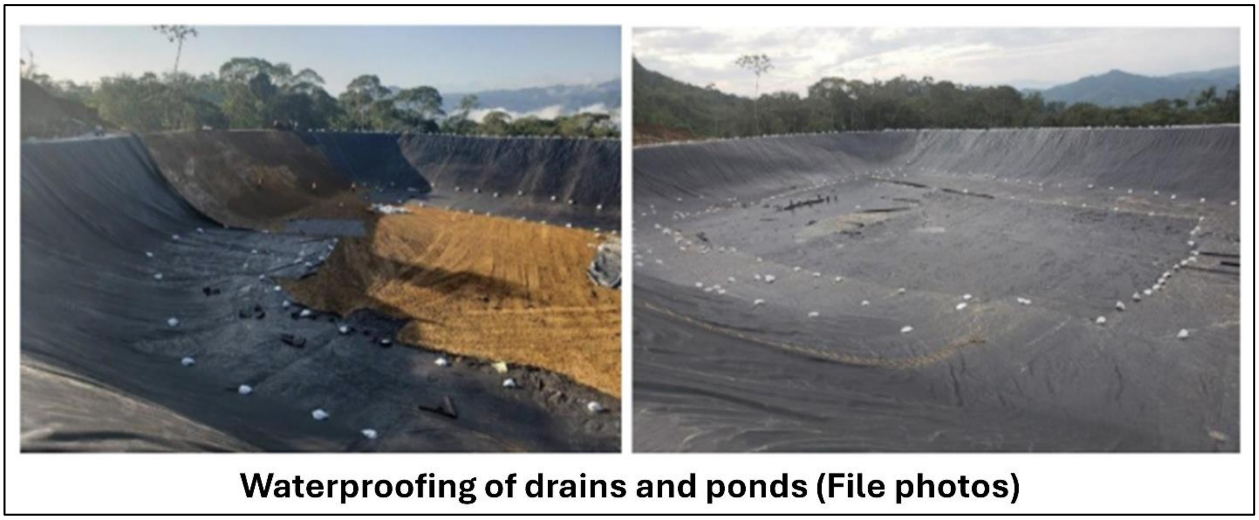


Figure 14. Wet gold tailings from the El Corazón mine are deposited onto a waterproof geomembrane. The fundamental problem with the design is that a geomembrane should not be the sole mechanism of defense against failure of the tailings pond. Based on the current design, any tear in the geomembrane will lead to the release of tailings and water laden with cyanide. Photo from Agroindustrial El Corazón S.A. (2023a) with overlay of English label.

During the inspection by the Municipio de Cotacachi (2023a) on November 6-7, 2023, it was discovered that water from the underground mine was discharging directly to the Manduriaco Chico River (sometimes written as Manduriacu Chico) (see Fig. 3). According to the Municipio de Cotacachi (2023a), "*De dos bocaminas se encontró que existe descarga de aguas subterráneas, sin tratamiento, al río Manduriaco Chico*" [From two mine openings it was found that there is a discharge of groundwater, without treatment, to the Manduriaco Chico River]. The representatives of Agroindustrial even identified the untreated flow of mine water as the source of the coloration in the Manduriaco Chico River. According to the Municipio de

Cotacachi (2023a), "*Señalan que en esta galería se encuentra una arcilla denominada Sericita y que ella sería la causante de la coloración verdosa del agua y que toma esta coloración más fuerte cuando al interior de los túneles hay movimientos*" [they [the representatives of Agroindustrial] point out that in this gallery there is a clay called Sericite and that it would be the cause of the greenish coloration of the water and that it takes on this coloration stronger when there are movements inside the tunnels]. The Municipio de Cotacachi (2023a) concluded, "*Se recomienda realizar el tratamiento de aguas subterráneas antes de realizar descargas por la salida de los túneles: Florencia y túnel 110 del nivel 3, que son afluentes del río Manduriaco Chico, para lo cual deberá tener medios de verificación*" [The treatment of groundwater is recommended before discharging through the exit of the tunnels: Florencia and tunnel 110 of level 3, which are tributaries of the Manduriaco Chico river, for which there must be means of verification]. The significance of the coloration of the waterways downstream from the El Corazón mine will be discussed further in the following section. Some further information about the tailings dams at the El Corazón mine will be provided in the "Responses" section.

SUMMARY OF TAILINGS DAM FAILURE ON NOVEMBER 4, 2023

Changes in Stream Coloration and Previous Cattle Deaths

The failure of the tailings dam at the El Corazón mine occurred at 2:00 am on Saturday, November 4, 2023 (Agroindustrial El Corazón S.A., 2023a; MAATE, 2023b; MEM, 2023). Six hours later, residents of the El Corazón and Rio Verde communes noticed pronounced changes in the color and turbidity of the Manduriaco Chico River, Verde Chico Creek, and Verde River (see Fig. 3). According to the Municipio de Cotacachi (2023a), "*Mediante llamada telefónica y videos enviados por la aplicación WhatsApp de pobladores de las comunidades de Río Verde y El Corazón el 06 de noviembre de 2023, ponen en conocimiento de la municipalidad una presunta contaminación al río Manduriaco Chico y al río Verde Chico, esto ya que visualmente se nota un cambio en la coloración del agua (turbidez) ... Habitantes de la comuna de Río Verde señalan que ellos se dieron cuenta del cambio de coloración del Río Verde el día sábado 4 de noviembre de 2023, aproximadamente a las 8h00 am, hora en la cual turistas y visitantes iban a visitar el río*" [Through a telephone call and videos sent by the WhatsApp application from residents of the communities of Rio Verde and El Corazón on November 6, 2023, the municipality was informed of an alleged contamination of the Manduriaco Chico River and the Verde Chico River, this since visually a change in the color of the water (turbidity) was evident … Inhabitants of the Rio Verde commune point out that they noticed the change in color of the Verde River on Saturday, November 4, 2023, at approximately 8:00 am, the time at which tourists and visitors were going to visit the river]. It is not clear how to reconcile the claim by Agroindustrial El Corazón S.A. (2023a) that "*la afectación por CN no alcanzó el segundo punto de monitoreo"* [the impact by CN did not reach the second point of monitoring] (391 meters downstream from the point of discharge from Pond No. 15) when turbidity (presumably, fine-grained tailings) was observed in the Verde River, more than 4 kilometers downstream from the point of discharge (see Fig. 3), unless the mining company is simply claiming that the cyanide-rich water released from Pond No. 15 had been sufficiently diluted by other river water.

Figure 15a. On June 11, 2023, a grayish-green color was observed in the Manduriaco Chico river (see Fig. 3), which had appeared suddenly two days previously. Grayish colors are typically associated with fine particulate matter, such as fine-grained tailings. Based on available stream maps, aerial photos and satellite images, the pathway from one of the tailings ponds to the Manduriaco Chico river is not clear (see Figs. 3-4). Photos from Municipio de Cotacachi (2023b).

Figure 15b. On June 11, 2023, a grayish-green color was observed in the Manduriaco Chico river (see Fig. 3), which had appeared suddenly two days previously. Grayish colors are typically associated with fine particulate matter, such as fine-grained tailings. Based on available stream maps, aerial photos and satellite images, the pathway from one of the tailings ponds to the Manduriaco Chico river is not clear (see Figs. 3-4). Photos from Municipio de Cotacachi (2023b).

Figure 16. On November 4, 2023, the same grayish-green color appeared in the Manduriaco Chico river (compare with Figs. 16a-b) following the failure of the tailings dam at the El Corazón mine. Grayish colors are typically associated with fine particulate matter, such as fine-grained tailings. Based on available stream maps, aerial photos and satellite images, the pathway from Pond 15 to the Manduriaco Chico river is not clear (see Figs. 3-4). Still photo at 0:30 of video provided by Asociación de Propietarios de Tierras Rurales del Norte and Frente Antiminero (labeled Video 3 by author).

Figure 17. A death of 13 cattle occurred downstream from the El Corazón mine in 2020. It is believed that the cattle died from cyanide poisoning following a tailings dam failure. Photo provided by Asociación de Propietarios de Tierras Rurales del Norte and Frente Antiminero. A lower-resolution version of the photo is also available in Asamblea de Unidad—Cantonal de Cotacachi [Assembly of Unity—Canton of Cotacachi] (2023).

The characteristic change in coloration of the waterways downstream from the El Corazón mine has a history in this area, which suggests that there have been undocumented tailings dam failures. For example, there was a sudden appearance of a grayish-green color in the Manduriaco Chico River on June 9, 2023 (see Figs. 15a-b). According to the Municipio de Cotacachi (2023b), "*En este lugar, el Sr. Landi Wilson, señala que él día viernes 09 de junio de 2023, a los 8h00 am bajo a observar el río, porque el día sábado 10 de junio de 2023 tenía un grupo de turista y les gusta visitar el río, en este recorrido se encontró con la novedad de que este río estaba totalmente de un color plomo … Señala que los turistas, por las condiciones que estaba el río, el día sábado 10 de junio de 2023, ya no pudieron meterse a bañar, que en lo que va de este año es la segunda vez que ocurre este cambio repentino de coloración de este río*" [In this place, Mr. Landi Wilson points out that on Friday, June 9, 2023, at 8:00 am he went down to observe the river, because on Saturday, June 10, 2023, he had a group of tourists and they like to visit the river, on this trip he met with the news that this river was completely lead-colored … He points out that the tourists, due to the conditions of the river, on Saturday, June 10, 2023, could no longer go swimming, which so far this year is the second time this sudden change in color has occurred]. After carrying out an inspection on June 11, 2023, the Municipio de Cotacachi (2023b) observed that "*El agua del Río Manduriaco Chico, aunque ha pasado tres días desde que se ha visibilizado el cambio repentino de color, aún permanece de una tonalidad ploma-verdosa*" [The water of the Manduriaco Chico River, although three days have passed since the sudden change in color has been visible, still remains a lead-greenish hue]. The description of the color as "lead," probably refers to the characteristic light gray color of the mineral galena (lead sulfide).

The grayish-green color that was observed in the Manduriaco Chico River by the Municipio de Cotacachi (2023b) on June 11, 2023 (see Figs. 15a-b) appears quite similar to the grayish-green color that appeared in the same river on November 4, 2023 (see Fig. 16). According to the Municipio de Cotacachi (2023a), with regard to the changes in color of the Manduriaco Chico River and Verde River, local residents "*manifiestan que por varias ocasiones ha pasado eso y que en la parte alta se encuentra la empresa minera El Corazón, que puede ser la causante de* esto" [state that this has happened on several occasions and that in the upper part is the El Corazón mining company, which may be the cause of this]. The dissatisfaction with periodic stream discolorations was expressed quite strongly by Junta Administradora de Agua Potable [Drinking Water Administrative Board] (JAAP) "Río Manduriacu Chico" (2023) in complaining on November 12, 2023, about "*las varias ocasiones que los Río Manduriacu Chico y Verde; así como, las Quebradas Los Monos y Verde Chico, Cuenca del Río Guayllabamba, Demarcación geográfica del Río Esmeraldas, fuentes importantísimas de agua segura y de calidad, han sufrido varios procesos de decoloración ploma-verdosa-lodosa arcillosa*" [the various occasions that the Manduriacu Chico and Verde Rivers; as well as, the Los Monos and Verde Chico Creeks, Guayllabamba River Basin, geographical demarcation of the Esmeraldas River, very important sources of safe and quality water, have suffered several leaden-greenish-muddy clay discoloration processes]. It has been claimed that the grayish-green coloration of the rivers has been both uninvestigated and under-reported. According to the Defensoría del Pueblo del Ecuador (2023), "*Hasta la presente fecha el MAATE no ha realizado inspección sobre la repentina coloración ploma verdosa del río Manduriacu Chico para determinar las causas, afectaciones y responsables de las constantes presuntas contaminaciones de los Ríos Verde y Manduriacu y otros afluentes , así como para establecer medidas de mitigación, prevención y cese de vulneración de derechos constitucionales … Señala que la coloración del agua en ploma* *verdosa se ha dado durante varias ocasiones, no obstante no ha sido denunciada por la comunidad pues esta es víctima de hostigamiento*" [To date, MAATE has not carried out an inspection on the sudden greenish lead color of the Manduriacu Chico River to determine the causes, effects and those responsible for the constant alleged contamination of the Verde and Manduriacu Rivers and other tributaries, as well as to establish mitigation measures, prevention and cessation of violation of constitutional rights … He [the petitioner] points out that the greenish color of the water has occurred on several occasions, however it has not been reported by the community because it is a victim of harassment].

A related issue is that 13 head of cattle suddenly died in the area in 2020 (see Fig. 17). It is believed by local residents that the cattle died from drinking river water that was enriched in cyanide, although the cause of death has never been formally investigated. According to Asamblea de Unidad—Cantonal de Cotacachi (2023), "*Recordamos lo sucedido en el año 2020 cuando en el mismo sector murieron 13 cabezas de ganado al beber agua contaminada con cianuro químico de uso común en la extracción de oro"* [We remember what happened in 2020 when 13 head of cattle died in the same sector after drinking water contaminated with the chemical cyanide commonly used in gold extraction]. According to the Defensoría del Pueblo del Ecuador (2023), "*Indica que son varias ocasiones en la que han sido vertidas aguas residuales, lodos y otras sustancias en el Río Verde y Río Manduriacu debido a que las concesiones mineras el Corazón y los Manduriacus se desarrollan de forma inconsulta y sin seguir debida diligencia en el control, seguimiento y monitoreo por parte de autoridades competentes de ambiente y minería metálica, lo descrito ocasionó que ya en el 2020 haya muerte de animales vacunos provocados por derrames tóxicos en la Mina el Corazón"* [He [the petitioner] indicates that there are several occasions in which wastewater, sludge and other substances have been discharged into the Rio Verde and Rio Manduriacu due to the fact that the Corazón and Manduriacus mining concessions are developed without consultation and without following due diligence in control, tracking and monitoring by competent environmental and metallic mining authorities, what is described resulted in the death of cattle in 2020 caused by toxic spills at the El Corazón mine].

Containment of the Failure and Attempted Repair of the Failed Dam

By 10 am on November 4, 2023, eight hours after the initiation of the tailings dam failure, the failure had been contained in that the discharge from Pond No. 15 was being collected in a metal container and then channeled by pipe to Pond No. 9 (see Figs. 4 and 18). Agroindustrial decided that the failure had been caused by a tear in the geomembrane and began a procedure of lowering the water level in Pond No. 15 in order to locate and repair the tear. According to Agroindustrial El Corazón S.A. (2023a), "*Para detectar el lugar donde se encuentra la fisura en la geomembrana de la piscina 15, se inició la evacuación del agua de la piscina 15, conduciéndola a la piscina 7 a través de 3 mangueras de 2" y a la piscina 17 con otra manguera también de 2*" [To detect the place where the crack is located in the geomembrane of pool 15, the evacuation of water from pool 15 began, leading it to pool 7 through 3 2" hoses and to pool 17 with another hose also of 2"] (see Fig. 4). The intention of the company was to repair the geomembrane "*por termosellado y posteriores pruebas de impermeabilización*" [by heat sealing and subsequent waterproofing tests]. The report by MAATE on November 8 concurred that the failure had been caused by a tear in the geomembrane. According to MAATE (2023b), "*Se estima que el evento ambiental estaría dada por una fisura a nivel de la* *geomembrana de la piscina 15 de la relavera*" [It is estimated that the environmental event would be caused by a crack at the level of the geomembrane of pool 15 of the tailings pond].

Figure 18. The water and tailings that were discharged from Pond No. 15 were collected in a metal container and then transferred to Pond No. 9 (see Fig. 4). Photo from Municipio de Cotacachi (2023a).

By the time the report by Agroindustrial El Corazón S.A. (2023a) was written, a tear in the geomembrane had still not been located, so that the report described a plan for further steps for locating the tear. The further steps involved the progressive removal of solid tailings from Pond No. 15 together with the need to construct new ponds to store the tailings from Pond No. 15. According to Agroindustrial El Corazón S.A. (2023a), "*Debido que hasta el momento no se ha podido detectar la fisura por donde fuga el relave de la piscina 15. Se hace necesario construir una instalación (piscina de contingencia) para almacenar los sólidos que se vayan evacuando de la piscina 15, hasta ubicar la fisura en la geomembrana ... Como medida de carácter emergente … al sur de la piscina 9, se encuentra construyendo una piscina de contingencias de pequeñas dimensiones con capacidad para almacenar aproximadamente 4.500 m^3, que será debidamente impermeabilizada con geomembrana para almacenar una pequeña parte de los relaves que se evacúen de la piscina 15 cuyo volumen de relaves almacenados alcanza los 51000 m^3* [Because so far it has not been possible to detect the crack through which the tailings leak from pond 15, it is necessary to construct a facility (contingency pond) to store the solids that are evacuated from pond 15, until the crack in the geomembrane is located … As an emergency measure … to the south of pond 9, a small contingency pond is being constructed with the capacity to store approximately 4,500 m^3, which will be duly waterproofed with a geomembrane to store a small part of the tailings that are evacuated from pond 15, for which the volume of stored tailings reaches 51,000 m^3].

If the tear was not located even after removing 4500 cubic meters of solid tailings, then the plan was to construct another pond so that more tailings could be removed from Pond No. 15. According to Agroindustrial El Corazón S.A. (2023a), "*Para el caso que la medida antes indicada sea insuficiente para detectar la fisura en la geomembrana y se deba proseguir con la evacuación de adicional de relaves de la piscina 15, se deberá construir otra instalación (piscina emergente proyectada con capacidad para almacenar aproximadamente 20.000 m3) para poder seguir evacuando los restantes relaves de la piscina 15 hasta poder detectar la fisura en la geomembrana*" [In the event that the aforementioned measure is insufficient to detect the crack in the geomembrane and the evacuation of additional tailings from pond 15 must continue, another facility must be constructed (emergency pond designed with capacity to store approximately 20,000 m^3) to continue evacuating the remaining tailings from pond 15 until the crack in the geomembrane can be detected]. If the tear in the geomembrane had still not been located even after filling the second contingency pond, the plan was to pass the remaining tailings through a filter press in order to reduce the water content sufficiently so that the tailings could be compacted and stacked on the surface without placement into a constructed pond. According to Agroindustrial El Corazón S.A. (2023a), "*En el sistema de tratamiento de relaves las colas serán conducidas a un sistema de filtrado para obtener un relave filtrado con un contenido de humedad de hasta un 20%, para posteriormente ser transportado a la relavera para su compactación*" [In the tailings treatment system, the tailings will be taken to a filtering system to obtain filtered tailings with a moisture content of up to 20%, to later be transported to the tailings facility for compaction]. It should be noted that the construction of a filtered tailings stack would still require construction of a dam for confinement of the tailings (also called a structural zone) (Klohn Crippen Berger, 2017; Morrill et al., 2022), which is not mentioned in the plan described in Agroindustrial El Corazón (2023a).

The report by Agroindustrial was not dated, but it described steps that would be initiated on November 11, 2023 (Agroindustrial El Corazón S.A., 2023a). Since that time, there have been no publicly available progress reports on the attempts to locate and repair the tear in the geomembrane of Pond No. 15. However, it is known that, as of an inspection that was carried out on January 26, 2024, and reported in March 2024, the tear had still not been located. According to the Defensoría del Pueblo del Ecuador (2024), "*En el lugar el ing. Alex Ayala explicó que el día de los hechos 4 de noviembre de 2023, se suspendió el bombeo del relave y procedieron a enviar a la piscina nro 9, 7000m^3 … con el objeto de verificar el lugar donde se dio la fisura. Realizada esta actividad no se encontró el lugar de la fisura , motivo por el cual se mantiene la hipótesis de que la fisura se pudo haber sellado por la misma arcilla*" [At the site, the engineer Alex Ayala [a representative of Agroindustrial] explained that on the day of the events, November 4, 2023, the pumping of the tailings was suspended and they proceeded to send 7,000 m^3 to pond number 9 … in order to verify the place where the crack occurred. Once this activity was carried out, the location of the crack was not found, which is why the hypothesis is maintained that the crack could have been sealed by the clay itself]. Any self-sealing of the tear by filling with clay (fine-grained tailings) would, of course, be very temporary and very different from the anticipated heat sealing and waterproofing tests that were described in the November

2023 report by Agroindustrial El Corazón S.A. (2023a). Further information about the events of the tailings dam failure will be provided in the "Responses" section.

METHODOLOGY

Based upon the preceding sections, the preliminary objectives of this report can be refined into the following questions with regard to the tailings dam failure at the El Corazón mine:

1) Why are there discrepancies between the chemical analyses of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC?
2) Could the previous incident of cattle deaths have resulted from cyanide poisoning?
3) What is the cause of the grayish-green color in the Manduriaco Chico River?
4) Was heavy rainfall a contributing factor to the failure of the tailings dam?
5) What was the proximal cause of tailings dam failure?
6) What was the root cause of tailings dam failure?
7) Are the tailings dams at Pond No. 15 currently stable?
8) Has the possibility of further tailings dam failures been eliminated?

The first question regarding the discrepancies between the community water analysis and the water analyses carried out by the mining company and its consultants was addressed by considering whether the same chemical parameter was measured by the different parties and by considering the locations of the water samples. The coordinates of the samples collected by the mining company and its consultants were determined by comparing the sketch map provided in Agroindustrial El Corazón S.A. (2023a) (see Fig. 19) with the latest Google Earth imagery, which is dated June 27, 2019 (see Fig. 4). The map in Fig. 19 is referred to as a "sketch map" because it lacks a scale bar and it is not clear that it was intended to be drawn to scale. However, by comparison with Google Earth imagery, the sketch map does seem to show the correct stream channels and the correct spatial relationships between the stream channels and the tailings ponds. The tailings ponds in Fig. 4 were labeled by comparison with the sketch map (see Fig. 19), which was consistent with the labeling on another map in MEM (2023). Note that Ponds No. 14 and 15 were constructed between 2020 and 2021 (Municipio de Cotacachi, 2023) and are, thus, not visible in Google Earth imagery from 2019 (see Fig. 4). The point of discharge from Pond No. 15 (PM1) was located using the Zone 17S UTM coordinates of 743,895 m E and 10,028,835 m N that were stated in Agroindustrial El Corazón S.A. (2023a). MEM (2023) described the same location as Zone 17N UTM of coordinates 743,893 m E and 28,832 m N, or only 2 meters farther west and 3 meters farther south. The UTM coordinates obtained from Google Earth and the measured distances between sampling points were compared with the UTM coordinates and distances between sampling points stated in Agroindustrial El Corazón S.A. (2023a) (see Figs. 7 and 20). All maps in this report were created using ESRI ArcMap v. 10.8.2.

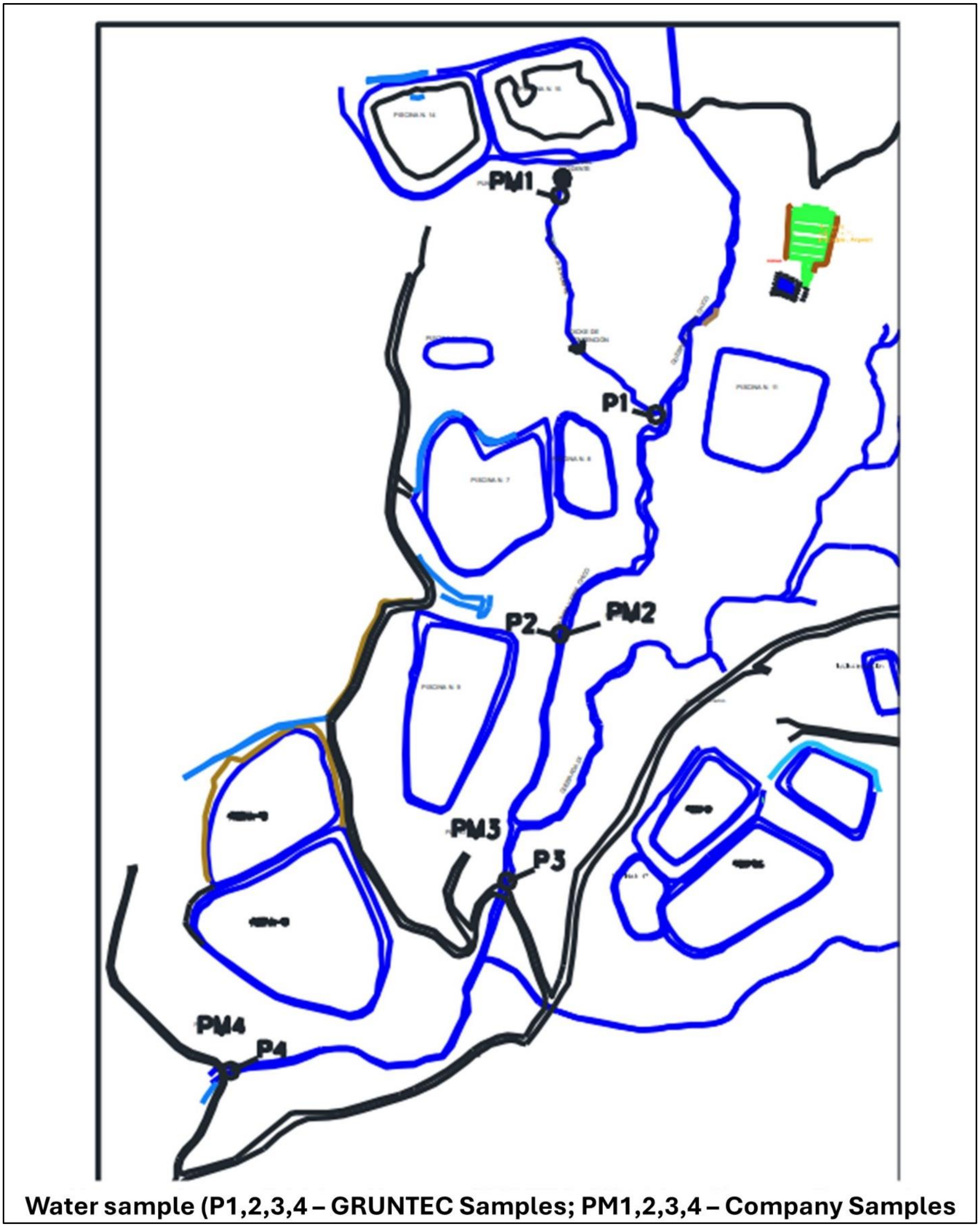
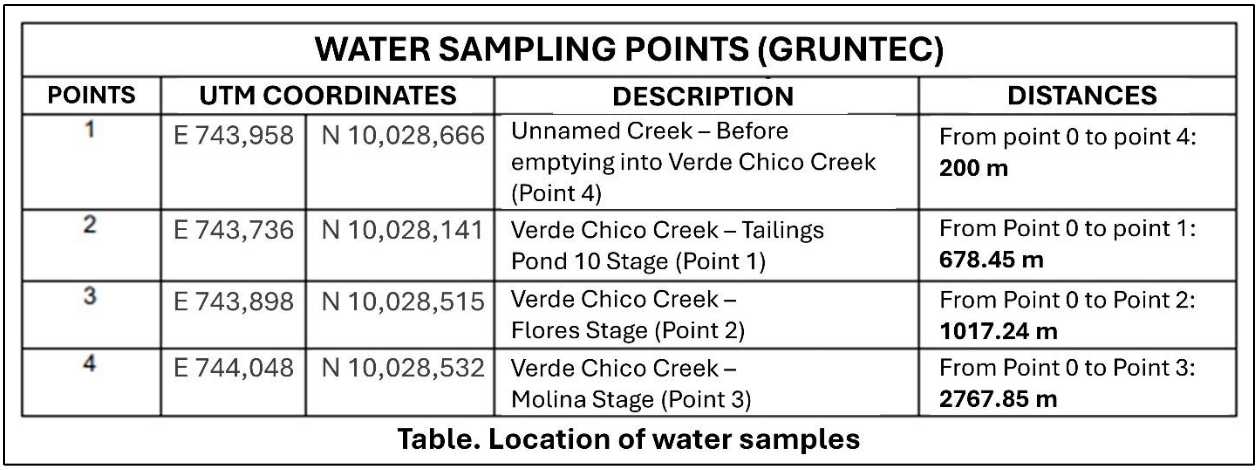


Figure 19. The above sketch map was compared with Google Earth imagery from June 27, 2019, to determine coordinates for the points of water sampling by the company and its consultants (see Table 6 and Fig. 4). The measured coordinates do not correspond to the coordinates stated in Agroindustrial El Corazón S.A. (2023a). The misfit for points P1, P2, P3 and P4 are 18 meters, 392 meters, 206 meters, and 535 meters, respectively (compare Table 6 with Fig. 20). Figure from Agroindustrial El Corazón S.A. (2023a) with overlay of English label.



WATER SAMPLING POINTS (GRUNTEC)

POINTS	UTM COORDINATES		DESCRIPTION	DISTANCES
1	E 743,958	N 10,028,666	Unnamed Creek – Before emptying into Verde Chico Creek (Point 4)	From point 0 to point 4: **200 m**
2	E 743,736	N 10,028,141	Verde Chico Creek – Tailings Pond 10 Stage (Point 1)	From Point 0 to point 1: **678.45 m**
3	E 743,898	N 10,028,515	Verde Chico Creek – Flores Stage (Point 2)	From Point 0 to Point 2: **1017.24 m**
4	E 744,048	N 10,028,532	Verde Chico Creek – Molina Stage (Point 3)	From Point 0 to Point 3: **2767.85 m**

Table. Location of water samples

Figure 20. The coordinates stated in the above table do not correspond to the coordinates determined by comparing the sketch map in Agroindustrial El Corazón S.A. (2023a) (see Fig. 19) with Google Earth imagery from June 27, 2019 (see Fig. 4). The misfit for points P1, P2, P3 and P4 are 18 meters, 392 meters, 206 meters, and 535 meters, respectively (compare Table 6 with the above table). From Points 1 to 4, both the northing and easting coordinates should decrease (see Fig. 19), which is not seen in the above table. It is not clear why the points are re-numbered in the second column from the right, but changing the numbering of the coordinates does not resolve the above contradiction. The distances were presumably measured along the stream paths and are not straight-line distances. However, based upon the Google Earth imagery (see Fig. 4), the distances should be 391 meters from Point 0 (presumably, the same as PM1) to P2 (Point 2), 581 meters from Point 0 to P3 (Point 3), and 884 meters from Point 0 to P4 (Point 4) (points numbered as in the left-hand column). Thus, the corresponding distances stated in the above table of 678.45 meters, 1017.24 meters, and 2767.85 meters are far too large. Figure from Agroindustrial El Corazón S.A. (2023a) with overlay of English labels.

The second question regarding the possible cause of the previous incident of cattle deaths was addressed by comparing the typical cattle weight, the typical daily water consumption by cattle, and the total cyanide concentration that was measured from the recent tailings dam failure in the sample collected by the community with the lethal cyanide dose for large ruminants. There are many possible causes of cattle deaths and a definitive cause cannot be determined without further information. The third question regarding the possible cause of the grayish-green color in the Manduriaco Chico River was addressed by comparing the stream color with the color of the ore body. As above, there are many possible causes of stream coloration and a definitive cause cannot be determined without further information.

With regard to the fourth question as to whether heavy rainfall was a contributing factor to the failure of the tailings dam, it has been mentioned that the water level in Pond No. 15 was already at the emergency level since sometime in October 2023 (Defensoría del Pueblo del Ecuador, 2024), so that additional rainfall could potentially have caused an overflow of the tailings pond. On the other hand, it is also known that there was no rain at the mine site over the night of November 3-4. According to the Municipio de Cotacachi (2023a), "*Habitantes de la comuna de Río Verde señalan que ellos se dieron cuenta del cambio de coloración del Río Verde el día sábado 4 de noviembre de 2023, aproximadamente a las 8h00 am … no había llovido y el cambio de color repentino del río era extraño*" [Inhabitants of the Río Verde commune point out that they noticed the change in color of the Río Verde on Saturday, November 4, 2023, at approximately 8:00 am ... it had not rained and the sudden change in color of the river was strange]. At the present time, no information is available regarding the precipitation history at the mine site or even when the most recent rainfall had occurred prior to the failure.

Thus, the fourth question could be restated in the following way: Were September 2023, October 2023 or November 1-4, 2023, unusually wet time periods in comparison with the historical record in the region of the El Corazón mine? The question was addressed by considering the historic precipitation data from four weather stations in the vicinity of the El Corazón mine in the database of the (U.S.) National Climatic Data Center (NCDC), including La Concordia (69 kilometers to the southwest), Izobamba (73 kilometers to the south-southeast), San Gabriel (116 kilometers to the northeast), and San Luis in Colombia (141 kilometers to the northeast) (see Tables 3a-b and 4a-b and Fig. 21) (NOAA, 2024). The distance from the El Corazón mine was measured based on the center of the El Corazón mining concession, as stated in Agroindustrial El Corazón S.A. (2023a).

The central problem with the use of the above weather stations, besides the distance from the mine site and the differences in elevation, is the number of days with missing data in the NCDC database. In particular, the coverage is 41% at Las Concordia, 39% at Izobamba, 50% at San Gabriel, and 46% at San Luis (see Tables 3b and 4b). The problem was partially resolved by weighting precipitation amounts by the numbers of days with precipitation data. The weighted rainfall for each time period of interest for each year was calculated as the total rainfall divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4. The mean rainfall for each time period of interest was calculated as the total rainfall over the entire historical record prior to 2023 divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4. The maximum and minimum rainfalls for September and October were calculated based only upon years with at least 33% coverage (10 days of precipitation data).

There are actually 11 weather stations in the INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]) database within only 50 kilometers of the El Corazón mine, with the closest weather station being Chontal Bajo, 6.9 kilometers to the southeast (see Table 5 and Fig. 22). The precipitation data from these weather stations are publicly available only as monthly summaries from 1994 to 2013 (INAMHI, 1996, 1997, 2000a-b, 2001, 2002, 2006a-f, 2008, 2010a-b, 2012a-b, 2014, 2015, 2017). Thus, for example, although the mean monthly precipitation at Chontal Bajo is known for October, there is no available precipitation for October 2023 for comparison with the mean. This aspect of the report will be updated, if and when INAMHI complies with a request for more recent precipitation data.

At this point it is appropriate to note that a great deal of information from the 2020-2022 Environmental Audit by Agroindustrial El Corazón S.A. (2023b) can be compared with the same data available in other sources and that much of the data in the 2020-2022 Environmental Audit are inconsistent with data in other sources. The meteorological data are used as an example. Agroindustrial El Corazón S.A. (2023b) states that the source of the meteorological data is INAMHI, so that the data taken directly from INAMHI publications should be regarded as the correct information. No attempt was made in this report to document all contradictions between the 2020-2022 Environmental Audit and other sources of information.

Table 3a. Ecuador weather stations in NCDC database: Location and elevation[1,2]

Station	Latitude (°N)[3]	Longitude (°E)[3]	Elevation (m)
Canar	-2.55	-78.933	3083
Galapagos Island NF	-0.43333	-90.28333	23.2
Isabel Maria	-1.83	-79.56	4
Izobamba	-0.35	-78.55	3058
La Concordia	0.017	-79.367	360
Loja La Argelia	-4.033	-79.2	2160
Macara Aeropuerto	-4.367	-79.933	430
Nuevo Rocafuerte	-0.917	-75.417	265
Pichilingue	-1.1	-79.467	73
Portoviejo	-1.033	-80.45	60
Puerto Ila	-0.49	-79.36	260
Puyo	-1.5	-77.9	960
San Cristobal	-0.917	-89.617	18.9
San Gabriel	0.6	-77.817	2860
San Juan La Mana	-0.92	-79.22	223

[1] NOAA (2024)
[2] Stations in red were used in the analysis of this report.
[3] WGS 84

Table 3b. Ecuador weather stations in NCDC database: Date ranges and coverage[1,2]

Station	Start Date[3]	End Date[3]	Coverage (%)
Canar	1/1/1973	5/31/2024	16
Galapagos Island	4/1/1945	3/29/1946	73
Isabel Maria	1/1/1961	12/31/1986	95
Izobamba	9/20/2005	5/31/2024	39
La Concordia	9/20/2005	6/3/2024	41
Loja La Argelia	10/23/2001	5/31/2024	26
Macara Aeropuerto	10/3/1977	2/2/1984	68
Nuevo Rocafuerte	9/20/2005	5/31/2024	30
Pichilingue	1/1/1964	5/17/2022	58
Portoviejo	10/23/2001	5/31/2024	24
Puerto Ila	1/1/1965	12/31/1994	98
Puyo	7/4/2011	5/31/2024	39
San Cristobal	4/18/1985	6/3/2024	32
San Gabriel	7/16/2011	5/31/2024	50
San Juan La Mana	4/1/1964	12/31/1992	93

[1] NOAA (2024)
[2] Stations in red were used in the analysis of this report.
[3] month/day/year

Table 4a. Colombia weather stations in NCDC database: Location and elevation[1,2]

Station	Latitude (°N)[3]	Longitude (°E)[3]	Elevation (m)
Alfonso Lopez Pumarejo	10.435	-73.25	147.2
Alfredo Vasquez Cobo	-4.193	-69.943	84.4
Almirante Padilla	11.526	-72.926	13.1
Antonio Roldan Betancourt	7.812	-76.716	14
Benito Salas	2.95	-75.294	446.2
Bogota Eldorado	4.701	-74.15	2548
Cali Alfonoso Bonill	3.55	-76.383	969
Camilo Daza	7.928	-72.512	334.1
El Carano	5.691	-76.641	62.2
El Eden	4.453	-75.766	1216.2
El Embrujo	13.357	-81.358	3
Ernesto Cortissoz	10.89	-74.781	29.9
Jose Maria Cordova	6.165	-75.423	2142.1
Las Gaviotas	4.55	-70.917	167
Los Garzones	8.824	-75.826	11
Matecana	4.813	-75.74	1346
Olaya Herrera	6.22	-75.591	1505.7
Palonegro	7.127	-73.185	1187.8
Pasto Antonio Narino	1.417	-77.267	1836
Perales	4.422	-75.133	949.1
Puerto Carreno A.Gu	6.167	-67.5	55
Rafael Nunez	10.442	-75.513	1.2
San Andres Isla S	12.583	-81.717	6
San Luis	0.862	-77.672	2976.4
Santa Rosa Amanadona	1.45	-66.92	667
Santiago Perez	7.069	-70.737	128
Simon Bolivar	11.12	-74.231	6.7
Vanguardia	4.168	-73.614	424.9
Yariguies	7.024	-73.807	125.6

[1] NOAA (2024)

[2] Stations in red were used in the analysis of this report.

[3] WGS 84

Table 4b. Colombia weather stations in NCDC database: Date ranges and coverage[1,2]

Station	Start Date[3]	End Date[3]	Coverage (%)
Alfonso Lopez Pumarejo	8/20/1969	6/3/2024	41
Alfredo Vasquez Cobo	8/23/1967	6/3/2024	90
Almirante Padilla	1/3/1973	6/3/2024	42
Antonio Roldan Betancourt	12/29/1984	6/3/2024	40
Benito Salas	9/17/1964	6/3/2024	61
Bogota Eldorado	3/2/1941	6/3/2024	79
Cali Alfonoso Bonilla	1/1/1961	6/3/2024	94
Camilo Daza	9/16/1964	6/3/2024	69
El Carano	1/21/1963	6/3/2024	42
El Eden	9/17/1964	6/3/2024	45
El Embrujo	4/23/1979	6/3/2024	32
Ernesto Cortissoz	5/2/1941	6/3/2024	79
Jose Maria Cordova	12/1/1985	6/3/2024	96
Las Gaviotas	8/1/1967	5/2/2002	86
Los Garzones	9/17/1964	6/3/2024	36
Matecana	3/22/1963	6/3/2024	84
Olaya Herrera	1/2/1958	6/3/2024	65
Palonegro	4/5/1974	6/3/2024	86
Pasto Antonio Narin	1/1/1957	6/3/2024	77
Perales	1/1/1973	6/3/2024	54
Puerto Carreno A.Gu	3/14/1968	6/3/2024	57
Rafael Nunez	11/25/1963	6/3/2024	90
San Andres Isla S	1/1/1962	6/3/2024	88
San Luis	9/16/1964	6/3/2024	46
Santa Rosa Amanadona	11/28/1969	1/31/1992	98
Santiago Perez	9/17/1964	6/3/2024	46
Simon Bolivar	6/16/1964	6/3/2024	75
Vanguardia	9/17/1964	6/3/2024	53
Yariguies	9/16/1964	6/3/2024	58

[1] NOAA (2024)

[2] Stations in red were used in the analysis of this report.

[3] month/day/year

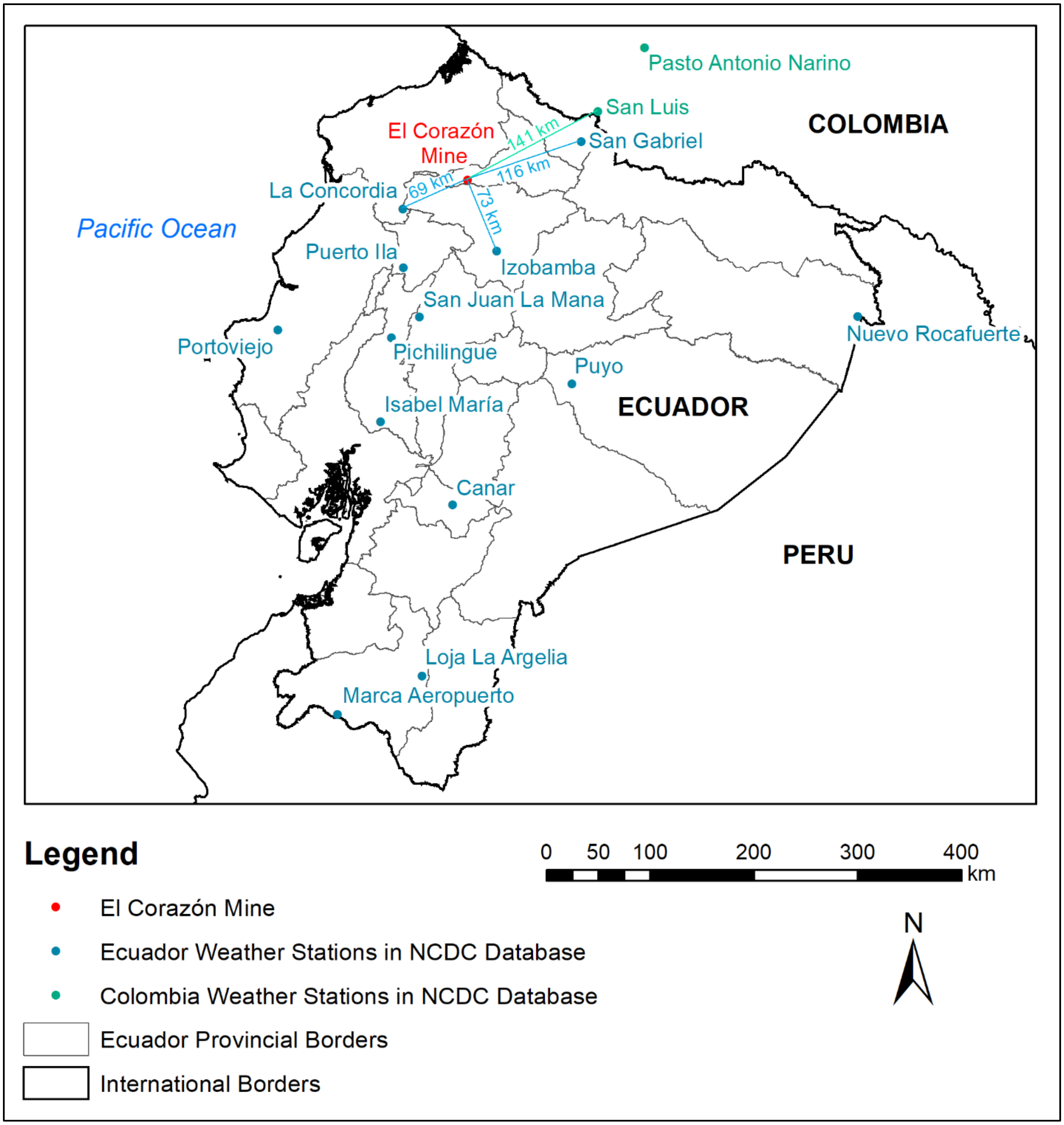


Figure 21. The closest weather stations to the El Corazón mine in the National Climate Data Center (NCDC) database are La Concordia to the southwest (distance of 69 kilometers), Izobamba to the south-southeast (distance of 73 kilometers), San Gabriel to the northeast (distance of 116 kilometers), and San Luis in Colombia to the northeast (distance of 141 kilometers) (see Tables 3a-b and 4a-b). The El Corazón mine is mapped as the center of the mining concession as stated in Agroindustrial El Corazón S.A. (2023b). Weather station locations from NOAA (2024).

Table 5. Weather stations in INAMHI database within 50 kilometers of El Corazón mine[1]

Station	Code	Latitude[2,3]	Longitude[2,3]	Elevation (m)	Distance[4] (km)
Apuela	M0318	0º 21’ 18” N 0.35500ºN	78º 30’ 49” W 78.51361ºW	1620	33.5
Calacali	M0358	0º 0’ 5” N 0.00139ºN	78º 30’ 45” W 78.51250ºW	2810	43.7
Chontal Bajo	M0327	0º 14’ 14" N 0.2372ºN	78º 44’57” W 78.74917ºW	675	6.9
Garcia Moreno	M0325	0º 14’ 5” N 0.23472ºN	78º 37’ 38” W 78.62722ºW	1950	19.8
Gualsaqui	M0909	0 º 19’ 15” N 0.32083ºN	78º 24’ 30” W 78.40833ºW	2710	44.2
Inguincho	M001	0º 15’ 30” N 0.25833ºN	78º 24’ 3” W 78.40083ºW	3140	44.7
Nanegalito	M0339	0º 4’ 0” N 0.06667ºN	78º 40’ 35” W 78.67639ºW	1580	26.2
Nono	M0361	0º 4’ 24” S 0.07333ºS	78º 34’ 22” W 78.57278ºW	2710	45.6
Pimampiro	M0315	0º 23’ 23” N 0.38972ºN	78º 56’ 28” W 78.94111ºW	2090	20.5
San Jose de Minas	M0337	0 º 10’ 8” N 0.16889ºN	78 º 23’ 35” 78.39306ºW	2440	46.9
Selva Alegre	M0326	0º 14’ 47” N 0.24639ºN	78º 34’ 37” W 78.57694ºW	1800	25.2

[1] Data from INAMHI (2015) except for distance to El Corazón mine

[2] Upper line is degrees minutes seconds. Lower line is decimal degrees.

[3] WGS 84

[4] Distance measured from weather station to center of El Corazón mining concession as stated in Agroindustrial El Corazón S.A. (2023b).

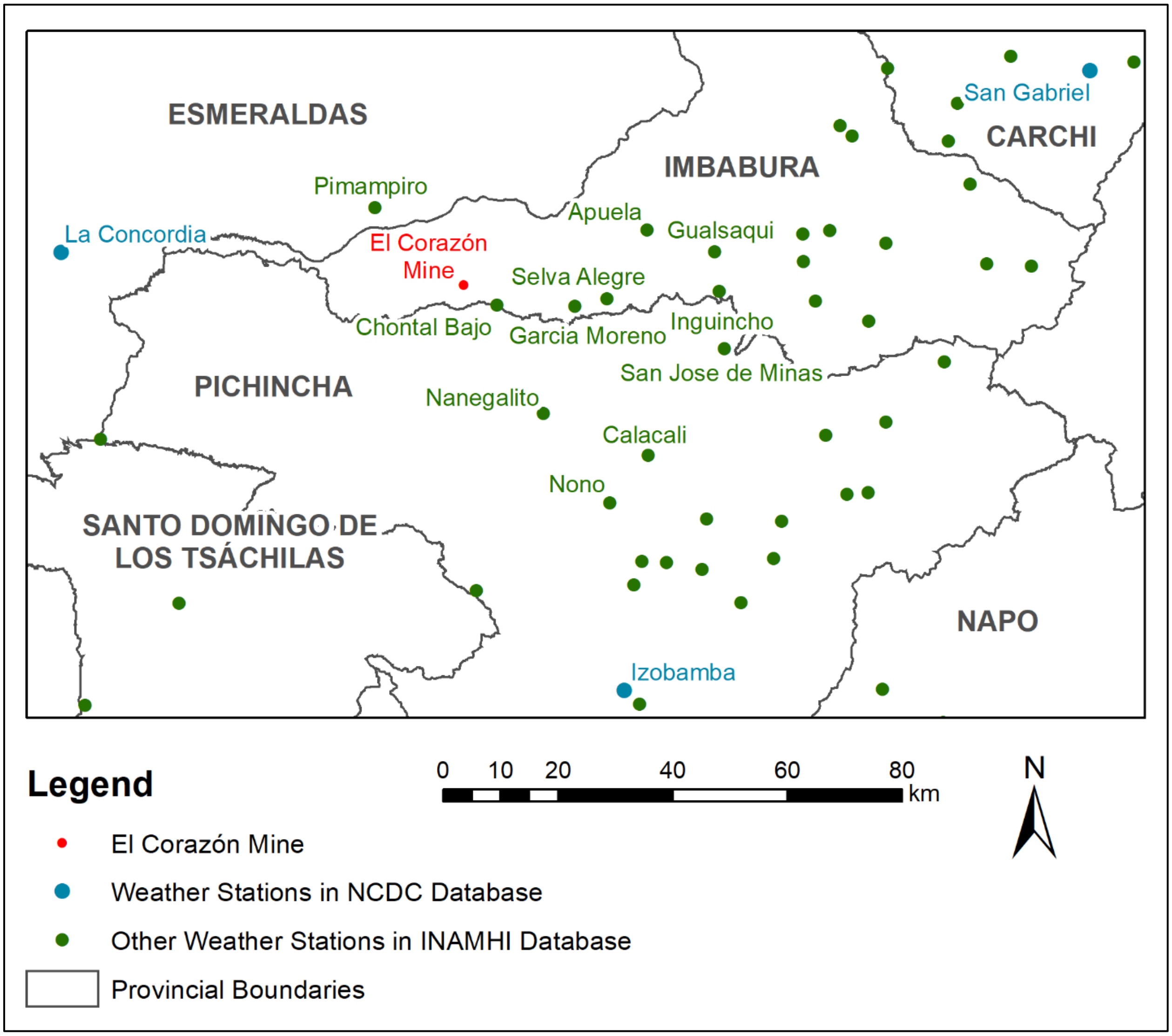
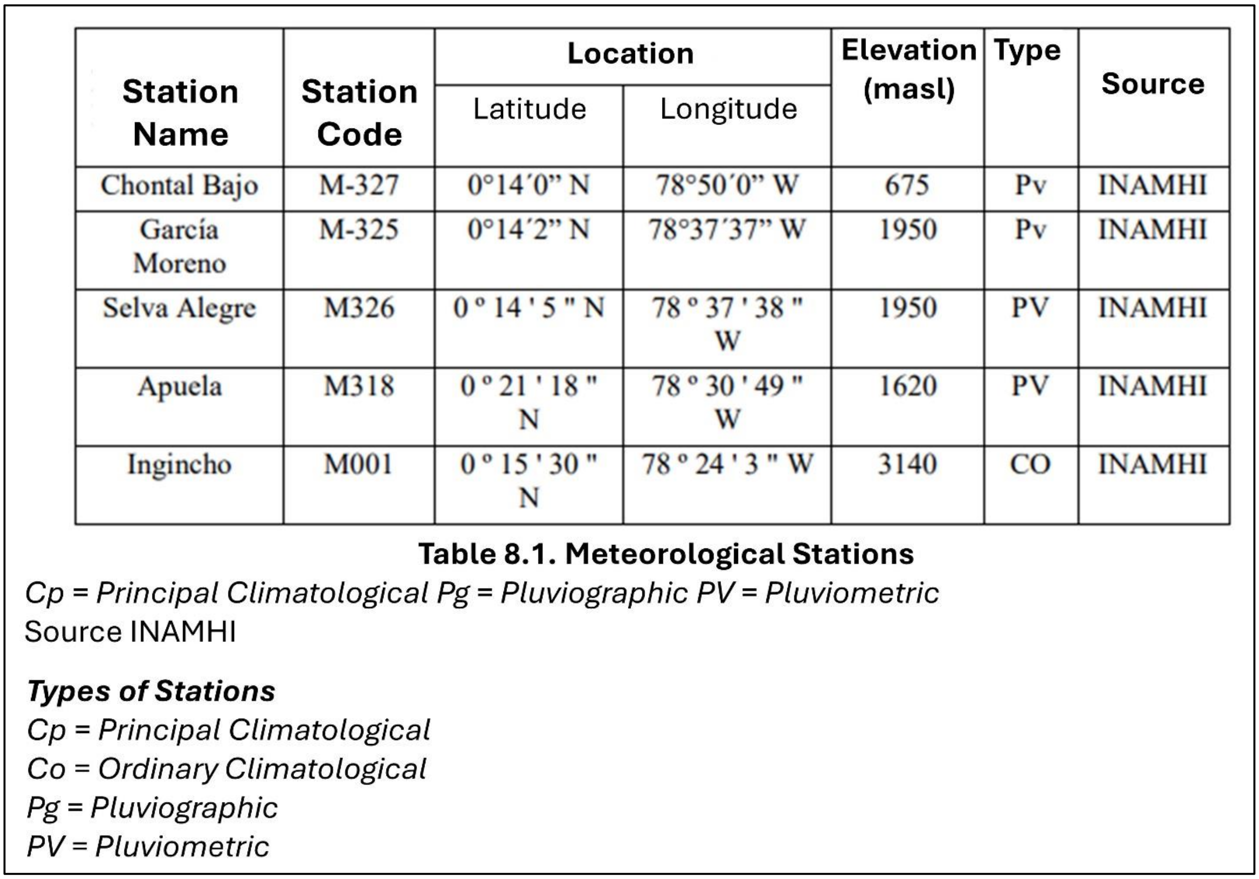


Figure 22. There are 11 weather stations in the INAMHI database within 50 kilometers of the El Corazón mine. The closest weather station is Chontal Bajo, 6.9 kilometers to the southeast (see Table 5). The El Corazón mine is mapped as the center of the mining concession as stated in Agroindustrial El Corazón S.A. (2023b). Weather station locations from INAMHI (2015).

The site descriptions of weather stations listed in the 2020-2022 Environmental Audit can be compared with the same information in INAMHI (2015). Agroindustrial El Corazón S.A. (2023b) states that there are five weather stations close to the El Corazón mine. However, weather stations at Calacali, Gualsaqui, Nanegalito, and Pimampiro are all closer than the weather station at Inguincho, and the weather station at Pimampiro is closer than the weather station at Selva Alegre (compare Fig. 23 with Table 5 and Figs. 22). In addition, the locations of weather stations at Chontal Bajo, Garcia Moreno and Selva Alegre are stated incorrectly in the 2020-2022 Environmental Audit (see Fig. 23). The stated location of Chontal Bajo is 9.4 kilometers west-southwest of the correct location, while the stated location of Selva Alegre is 5.8 kilometers west-southwest of the correct location (compare Fig. 23 with Table 5). Finally, the stated elevation of the weather station at Selva Alegre is 1950 meters above sea level, while the correct elevation is 1800 meters above sea level (compare Fig. 23 with Table 5).



Station Name	Station Code	Location		Elevation (masl)	Type	Source
		Latitude	Longitude			
Chontal Bajo	M-327	0°14´0” N	78°50´0” W	675	Pv	INAMHI
García Moreno	M-325	0°14´2” N	78°37´37” W	1950	Pv	INAMHI
Selva Alegre	M326	0 º 14 ' 5 " N	78 º 37 ' 38 " W	1950	PV	INAMHI
Apuela	M318	0 º 21 ' 18 " N	78 º 30 ' 49 " W	1620	PV	INAMHI
Ingincho	M001	0 º 15 ' 30 " N	78 º 24 ' 3 " W	3140	CO	INAMHI

Table 8.1. Meteorological Stations

Cp = Principal Climatological Pg = Pluviographic PV = Pluviometric

Source INAMHI

Types of Stations

Cp = Principal Climatological

Co = Ordinary Climatological

Pg = Pluviographic

PV = Pluviometric

Figure 23. Agroindustrial El Corazón S.A. (2023b) states that there are five weather stations close to the El Corazón mine. However, weather stations at Calacali, Gualsaqui, Nanegalito, and Pimampiro are all closer than the weather station at Inguincho, and the weather station at Pimampiro is closer than the weather station at Selva Alegre (see Table 5 and Fig. 22). The locations of weather stations at Chontal Bajo, Garcia Moreno and Selva Alegre are stated incorrectly in the above table. The stated location of Chontal Bajo is 9.4 kilometers west-southwest of the correct location, while the stated location of Selva Alegre is 5.8 kilometers west-southwest of the correct location (compare with Table 5). The stated elevation of the weather station at Selva Alegre is 1950 meters above sea level, while the correct elevation is 1800 meters above sea level (compare with Table 5). Table from Agroindustrial El Corazón S.A. (2023b) with overlay of English labels.

The fifth and sixth questions regarding the proximal and root causes of the tailings dam failure were addressed by comparing the description of the tailings dam failure at the El Corazón mine provided in previous sections with current knowledge about the causes of tailings dam failures and their means of prevention. The seventh question regarding the current stability of the tailings dams was addressed by comparing assertions made in reports by Agroindustrial El Corazón S.A. (2023a) and MEM (2023) with Ecuadorian tailings dam regulations. The eighth question regarding whether the possibility of further tailings dam failures has been eliminated is sufficiently important that the "Discussion" section is devoted to answering this question. The final question was addressed largely by a synthesis of the answers to the fifth, sixth and seventh questions about proximal and root causes and the current state of stability.

RESPONSES

The Cyanide Data of the Company and their Consultants are Invalid

The fundamental reason for the discrepancies between the cyanide concentrations of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC is that the community sample correctly analyzed for total cyanide, while GRUNTEC analyzed only for free cyanide (see Table 1). It has already been mentioned that free cyanide concentrations can be as low as 1% of total cyanide concentrations, so that there is absolutely no justification for using free cyanide concentrations to show compliance with Ecuadorian regulations that are based on total cyanide concentrations (see Table 2). Therefore, the statement by Agroindustrial El Corazón S.A. (2023a) that "*Los resultados obtenidos demuestran que los valores de CN ... al momento del monitoreo realizado por GRUNTEC, se encuentran dentro de los límites permisibles establecidos en la normativa ambiental vigente*" [The results obtained demonstrate that the values of CN … at the time of monitoring carried out by GRUNTEC are within the permissible limits established in current environmental regulations] is simply false because free cyanide concentrations cannot be compared with total cyanide concentrations. It is disturbing that Agroindustrial El Corazón S.A. (2023a) did not clarify whether total cyanide or free cyanide was measured in the water samples collected by the company, which is a critical missing piece of information (see Fig. 7). Although Fig. 7 states only "*Valor*" [Value] and not what chemical parameter was measured, the text clarifies that some form of cyanide was measured. For example, Agroindustrial El Corazón S.A. (2023a) states, "*Los resultados de los análisis de laboratorio realizados por la empresa los días 04 y 06 de noviembre, demuestran que el relave que fugó por la fisura de la geomembrana de la piscina 15 en el punto del incidente tenía un contenido de 0.303 ppm de CN (0.303 mg/l)"* [The results of the laboratory analyses carried out by the company on November 4 and 6 demonstrate that the tailings that leaked through the crack in the geomembrane of pool 15 at the point of the incident had a content of 0.303 ppm of CN (0.303 mg/l)] (compare with Fig. 7). Agroindustrial El Corazón S.A. (2023a) does not clarify why they decided to measure only some unspecified form of cyanide and no other parameter. An additional consideration is that water samples were collected by GRUNTEC six days after the tailings dam failure, which left ample time for the pulse of contaminated water to migrate farther downstream or for the cyanide to disappear from the water column by precipitation, oxidation, volatilization, photo dissociation, or biodegradation.

Besides the discrepancies in chemical parameters and sampling dates, the datasets of the mining company and GRUNTEC can be dismissed completely because the sampling locations are unknown. The UTM coordinates that were stated by Agroindustrial El Corazón S.A. (2023a) as the GRUNTEC sampling points (Fig. 20) were compared with the UTM coordinates that were measured from Google Earth after comparing the sketch map in Agroindustrial El Corazón S.A. (2023a) (see Fig. 19) with Google Earth imagery (see Fig. 4). The measured coordinates did not correspond with the coordinates stated by Agroindustrial El Corazón S.A. (2023a) with mismatches of 18 meters, 392 meters, 206 meters, and 535 meters, for points P1, P2, P3, and P4, respectively (see Table 6). The UTM coordinates stated by Agroindustrial El Corazón S.A. (2023a) (see Fig. 20) cannot be correct since they do not show a progression toward the south and west from P1 to P2 to P3 to P4 as the sketch map shows (see Fig. 19). It is quite confusing the way that the points are re-numbered from the column "*Puntos*" [Points] to the column "*Descripción*" [Description] in Fig. 20 taken from Agroindustrial El Corazón S.A. (2023a). In particular, the sampling points P1, P2, P3, and P4 in the "Points" column become Point 4, Point 1, Point 2, and Point 3, respectively, in the "Description" column (see Fig. 20). Attempts to adjust the numbering of the points and correct possible typographical errors in the stated coordinates (see Fig. 20) were unsuccessful at resolving the discrepancies between the measured and stated coordinates for the GRUNTEC sampling points (see Table 6).

Table 6. Coordinates of water sampling points based on comparison of sketch map in Agroindustrial El Corazón S.A. (2023b) with Google Earth

	Geographic Coordinates (WGS 84)		**Projected Coordinates (UTM Zone 17S WGS 84)**	
	Latitude (°N)	**Longitude (°W)**	**Easting (m)**	**Northing (m)**
Sampling by Agroindustrial El Corazón				
PM1	0.260687	78.808693	743,894	10,028,834
PM2	0.257627	78.808650	743,900	10,028,497
PM3	0.25598	78.809127	743,847	10,028,315
PM4	0.254837	78.811004	743,638	10,028,188
Sampling by GRUNTEC				
P1	0.259039	78.808022	743,970	10,028,653
P2	0.257627	78.808650	743,900	10,028,497
P3	0.255986	78.809127	743,847	10,028,315
P4	0.254837	78.811004	743,638	10,028,188

A comparison between the "*Distancias*" [Distances] columns in Fig. 7 and Fig. 20, as well as Fig. 19, show that the sampling points PM2, PM3, and PM4 of Agroindustrial are identical to the sampling points P2, P3, and P4 of GRUNTEC. The comparison also shows that the "*Origen*" [Origin] in Fig. 7 (the same as PM1) is the same as Point 0 in Fig. 20. Thus, the locations of the sampling points PM2, PM3, and PM4 of Agroindustrial are as equally unknown as the locations of sampling points P2, P3, and P4 of GRUNTEC. The stated distances between each sampling point and PM1 (see Figs. 7 and 20) are presumably measured along stream paths and are not straight-line distances. It is perplexing as to how these distances could have been measured with the ultraprecision of 1 centimeter (see Figs. 7 and 20) and why the distance from Point 0 (PM1) to P1 is stated simply as 200 meters (see Fig. 20) with an implied precision of 1 meter or greater.

The distances between sampling points stated in Figs. 7 and 20 are also not correct. Based upon a comparison of the sketch map (see Fig. 19) with the Google Earth imagery (see Fig. 4), the distances should be 391 meters from Point 0 (the same as PM1) to PM2 (the same as P2), 581 meters from Point 0 to PM3 (the same as P3), and 884 meters from Point 0 to PM4 (the same as P4). In other words, the distances between points stated in Figs. 7 and 20 are far too large. If the distances stated in Figs. 7 and 20 are meant to be straight-line distances, then the discrepancies between the stated distances and the distances measured from Google Earth (see Fig. 4) would be even greater.

In summary, the datasets of Agroindustrial and GRUNTEC should be regarded as completely invalid for the following reasons:

1) GRUNTEC measured only free cyanide, which cannot be compared with the Ecuadorian regulations that are based on total cyanide.
2) Agroindustrial did not specify whether free cyanide or total cyanide or some other form of cyanide (such as WAD cyanide) was measured.
3) The water samples were collected by GRUNTEC six days after the tailings dam failure.
4) The sampling locations on the sketch map do not correspond to the stated UTM coordinates.
5) The stated distances between the sampling locations are much greater than the distances that can be measured by comparing the sketch map with Google Earth imagery.

The last two points can be summarized by stating that water analyses with unknown or contradictory sample locations cannot be regarded as reliable.

Cattle Deaths could have Resulted from Cyanide Poisoning

Given a typical cattle weight of 1000 kilograms, typical water consumption of 0.06 liters per kilogram per day (University of Nebraska-Lincoln, 2015), and the total cyanide concentration that was measured from the recent tailings dam failure (60 mg/L), the daily cyanide load for a cow drinking cyanide-contaminated water downstream from the El Corazón mine would be 3.6 mg/kg. Since the lethal dose for large ruminants is 2 mg/kg (Cope, 2021), it is possible that the recent cattle deaths resulted from cyanide poisoning. However, a definitive cause of death cannot be determined without further information. In this case, a critical missing piece of information is the exact location of the cattle deaths.

The Color of Affected Streams Results from Fine-Grained Tailings

The color of the Manduriaco Chico River has been described as "*totalmente de un color plomo"* [completely lead-colored] on June 9, 2023 (Municipio de Cotacachi, 2023b), as "*una tonalidad ploma-verdosa"* [a lead-greenish hue] on June 11, 2023 (Municipio de Cotacachi (2023b), and as "*ploma verdosa"* [greenish lead] (Defensoría del Pueblo del Ecuador, 2023) and "*ploma-verdosa-lodosa"* [muddy-greenish-lead] (Junta Administradora de Agua Potable (JAAP) "Río Manduriacu Chico," 2023) on multiple occasions. The colors of the Manduriaco Chico River can be compared with those of the Tortugo Unit, which is the host rock for the ore body that is exploited by the El Corazón mine. According to Agroindustrial El Corazón S.A. (2023b), the Tortugo Unit "*definida por Boland et al. (2000), consiste en secuencias de sedimentos color gris-verdoso, silicificados, ricos en feldespatos, augitas, anfíboles y líticos de lavas riolíticas con textura bandeada*" [defined by Boland et al. (2000), consists of sequences of grayish-green, silicified sediments, rich in feldspars, augites, amphiboles and lithics of rhyolitic lavas with a banded texture]. Agroindustrial El Corazón S.A. (2023b) further noted that "*rocas verdes de grano fino con alteración hidrotermal pertenecientes a la Unidad Tortugo se encuentran sobre-yacidas por cherts de la Unidad La Cubera*" [fine-grained green rocks with hydrothermal alteration belonging to the Tortugo Unit are overlain by cherts from the La Cubera Unit]. In other words, the color of the river seems to have the same description as the color of the ore body, which implies that the river color could result from the release of fine-grained tailings into the river.

The missing link in the above connection between the color of the Manduriaco Chico River and the color of the ore body is that the Google Earth imagery (see Figs. 3-4) and the sketch map (see Fig. 19) do not show any obvious hydraulic pathway between Pond No. 15 and the Manduriaco Chico River. In fact, based on the available information, Pond No. 15 seems to be in the watershed of Verde Chico Creek, not the Manduriaco Chico River (see Figs. 3-4). This point cannot be pursued any further without detailed knowledge of the topography. Such knowledge could be obtained simply by walking the land downstream from Pond No. 15. However, the ideal basis for determining whether there is a hydraulic connection would be a high-precision Lidar survey of the area. A hydraulic connection between Pond No. 15 (or other tailings ponds) and the Manduriaco Chico River could also be assessed using a variety of chemical tracers. For example, the water in a tailings pond should show the stable-isotopic signature of an extended period of evaporation and it might be possible to find that same stable-isotopic signature in water samples from the Manduriaco Chico River. Detailed discussion of the use of stable isotopes of water to identify connections between tailings ponds and downstream waterways in the context of gold mining can be found in Emerman (2024) (available from the author in English and Portuguese). It should be noted that a grayish-green discoloration has also been observed in the Verde River and in Verde Chico Creek (Municipio de Cotacachi, 2023a; Defensoría del Pueblo del Ecuador, 2023, Junta Administradora de Agua Potable "Río Manduriacu Chico", 2023) and that the hydraulic connection between these streams and Pond No. 15 is sufficiently clear from the Google Earth imagery (see Figs. 3-4) and the sketch map (see Fig. 19).

It was mentioned earlier that the representatives of Agroindustrial have identified the untreated flow of water from the underground galleries as the source of the coloration in the Manduriaco Chico River. According to the Municipio de Cotacachi (2023a), "*Señalan que en esta galería se encuentra una arcilla denominada Sericita y que ella sería la causante de la coloración verdosa del agua y que toma esta coloración más fuerte cuando al interior de los túneles hay movimientos*" [they [the representatives of Agroindustrial] point out that in this gallery there is a clay called Sericite and that it would be the cause of the greenish coloration of the water and that it takes on this coloration stronger when there are movements inside the tunnels]. The preceding quote presumes a hydraulic connection between the underground mine workings and the Manduriaco Chico River, not between the tailings ponds and the Manduriaco Chico River. It is possible that a connection between Pond No. 15 and the Manduriaco Chico River occurs through the groundwater system, since groundwater pathways do not always follow surface water pathways. However, more investigation would be required to establish such a connection.

The Tailings Dam Failure was not Preceded by Heavy Rainfall

It is known that the tailings dam failure on the early morning of November 4, 2023, was not immediately preceded by heavy rainfall at the mine site. According to the Municipio de Cotacachi (2023a), "*Habitantes de la comuna de Río Verde señalan que ellos se dieron cuenta del cambio de coloración del Río Verde el día sábado 4 de noviembre de 2023, aproximadamente a las 8h00 am ... no había llovido y el cambio de color repentino del río era extraño*" [Inhabitants of the Río Verde commune point out that they noticed the change in color of the Río Verde on Saturday, November 4, 2023, at approximately 8:00 am ... it had not rained and the sudden change in color of the river was strange]. The preceding quote also confirms that the discoloration was observed in the Verde River and not only in the Manduriaco Chico River. Unfortunately, there is no information regarding whether rainfall occurred at the mine site during the three days preceding the failure.

The record for rainfall during the first four days of November 2023 is mixed at the four nearby weather stations in the NCDC database (see Fig. 21). The total rainfall at La Concordia for November 1-4, 2023, was 2.0 mm, which was well below the mean of 30.2 mm (see Table 7a). Unfortunately, all precipitation data for November 1-4, 2023, are missing for the weather stations at Izobamba and San Gabriel (see Tables 7b-c). By contrast, the total rainfall at San Luis (Columbia) for November 1-4, 2023, was 40.4 mm, which was well above the mean of 10.2 mm and even greater than the maximum precipitation for that period of 39.6 mm, which was recorded in 1993 (see Table 7d). In summary, because of the lack of consistency in the neighboring weather stations, there is certainly no persuasive evidence that the tailings dam failure was preceded by heavy rainfall over the preceding three days.

The rainfall record for the two months preceding the tailings dam failure is also mixed for the four nearby weather stations in the NCDC database (see Fig. 21). At the La Concordia weather station, the total precipitation amounts for September 2023 and October 2023 were 131.5 mm and 293.9 mm, respectively (see Table 7a). By comparison with data in the NCDC database (2005-2022), the September 2023 rainfall was far above both the mean of 49.9 mm and the maximum of 85.1 mm, which was recorded in 2015 (see Table 7a). By comparison with data in the INAMHI database (1994-2013), the September 2023 rainfall at La Concordia was still above the mean of 89.2 mm, but not even close to the maximum of 849.6 mm of rainfall that was recorded in 1997 (see Table 8). By comparison with data in the NCDC database (2005-2022), the October 2023 rainfall was far above the mean of 141.4 mm, but not the maximum of 459.9 mm, which was recorded in 2015 (see Table 7a). By comparison with data in the INAMHI database (1994-2013), the October 2023 rainfall at La Concordia was far above the mean of 84.8 mm, but not the maximum of 757.2 mm that was again recorded in 1997 (see Table 8). Thus, La Concordia was unusually wet during both September and October of 2023.

At the Izobamba weather station, the total precipitation amounts for September 2023 and October 2023 were 178.5 mm and 99.2 mm, respectively (see Table 7b). By comparison with data in the NCDC database (2011-2022), the September 2023 rainfall was above both the mean of 153.0 mm and the maximum of 149.7 mm, which was recorded in 2014 (see Table 7b). Note that, in this case, the maximum is greater than the mean because the mean is calculated using all of the data, while the maximum was calculated using only years with at least 10 days of precipitation data in the month of interest (only 2011, 2013, 2014, 2016, 2021, and 2022; see Table 7b). By comparison with data in the INAMHI database (1994-2013), the September 2023 rainfall at Izobamba was above both the mean of 70.6 mm and the maximum of 167.7 mm of rainfall that was recorded in 2000 (see Table 8). By comparison with data in the NCDC database (2011-2022), the October 2023 rainfall was far less than the mean of 193.6 mm and only slightly greater than the minimum of 97.4 mm, which was recorded in 2015 (see Table 7b). By comparison with data in the INAMHI database (1994-2013), the October 2023 rainfall at Izobamba was less than the mean of 129.7 mm, but far above the minimum of 7.9 mm that was recorded in 2001 (see Table 8). Thus, Izobamba was unusually wet during September 2023 and unusually dry during October 2023.

Table 7a. Historical precipitation compared with 2023 in NCDC database: La Concordia (Ecuador)[1]

Year	September		October		November 1-4	
	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)
2005	—	—	1	31.0	—	—
2011	12	43.8	13	129.5	2	38.2
2012	17	10.1	17	92.3	3	30.8
2013	19	10.9	12	14.2	2	0.0
2014	12	31.8	9	301.0	—	—
2015	22	85.1	22	459.9	—	—
2016	11	28.1	10	38.8	—	—
2017	1	123.0	5	14.3	1	1.2
2018	3	43.0	5	1.9	—	—
2020	1	1257	2	0.0	—	—
2021	24	74.6	23	97.6	3	92.1
2022	18	12.5	18	20.8	4	1.5
Mean[3]		49.9		141.4		30.2
Maximum[4]		85.1		459.9		92.1
Minimum[4]		10.1		14.2		0.0
2023	19	131.5	26	293.9	2	2.0

[1] Data from NOAA (2024)

[2] The weighted rainfall for each year was calculated as the total rainfall divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4.

[3] The mean rainfall was calculated as the total rainfall over the entire historical record prior to 2023 divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4.

[4] The maximum and minimum rainfalls for September and October were calculated based only upon years with at least 33% coverage (10 days of precipitation data).

Table 7b. Historical precipitation compared with 2023 in NCDC database: Izobamba (Ecuador)[1]

Year	September		October		November 1-4	
	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)
2011	12	134.3	20	289.5	3	13.6
2012	8	72.4	17	164.5	4	7.1
2013	10	67.8	17	222.5	2	12.2
2014	10	149.7	8	201.9	—	—
2015	6	9.0	22	97.4	2	12.2
2016	10	114.0	14	176.5	2	14.2
2017	2	391.5	4	94.6	1	16.4
2018	1	90.0	8	68.6	2	62.0
2019	—	—	9	201.5	1	3.2
2020	—	—	1	9.3	—	—
2021	19	147.0	22	267.9	1	4.0
2022	17	132.2	19	206.6	3	13.6
Mean[3]		153.0		193.6		15.9
Maximum[4]		149.7		289.5		62.0
Minimum[4]		67.8		97.4		3.2
2023	4	178.5	11	99.2	—	—

[1] Data from NOAA (2024)

[2] The weighted rainfall for each year was calculated as the total rainfall divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4.

[3] The mean rainfall was calculated as the total rainfall over the entire historical record prior to 2023 divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4

[4] The maximum and minimum rainfalls for September and October were calculated based only upon years with at least 33% coverage (10 days of precipitation data).

Table 7c. Historical precipitation compared with 2023 in NCDC database: San Gabriel (Ecuador)[1]

Year	September		October		November 1-4	
	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)
2011	14	66.4	20	125.1	—	—
2012	15	52.6	15	108.1	—	—
2013	24	25.1	13	128.5	2	2.0
2014	12	30.3	14	126.7	—	—
2015	12	39.8	22	59.6	4	1.4
2016	5	16.8	6	108.0	1	24.4
2017	—	—	—	—	—	—
2018	6	53.5	8	103.9	—	—
2019	1	30.0	7	193.5	—	—
2020	—	—	1	158.1	—	—
2021	7	69.9	14	95.2	2	15.8
2022	8	136.1	8	203.8	—	—
Mean[3]		49.8		114.7		7.3
Maximum[4]		66.4		128.5		24.4
Minimum[4]		25.1		59.6		1.4
2023	7	23.6	3	136.4	—	—

[1] Data from NOAA (2024)

[2] The weighted rainfall for each year was calculated as the total rainfall divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4.

[3] The mean rainfall was calculated as the total rainfall over the entire historical record prior to 2023 divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4

[4] The maximum and minimum rainfalls for September and October were calculated based only upon years with at least 33% coverage (10 days of precipitation data).

Table 7d. Historical precipitation compared with 2023 in NCDC database: San Luis (Colombia)[1]

Year	September		October		November 1-4	
	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)	Data Days	Weighted Rainfall[2] (mm)
1973	9	120.0	9	24.1	1	16.4
1974	8	46.9	14	99.0	3	3.3
1976	9	173.3	22	110.5	4	15.2
1977	29	115.6	30	53.5	4	6.0
1978	23	38.7	26	11.7	4	0.0
1979	21	55.6	28	69.8	3	9.5
1980	17	36.5	19	186.2	3	0.0
1981	10	10.5	19	25.6	—	—
1990	2	19.5	2	169.0	—	—
1993	9	11.0	4	38.8	1	39.6
1994	4	81.8	1	62.0	4	1.0
1995	—	—	3	0.0	—	—
1996	3	25.0	1	9.3	—	—
1997	6	211.5	4	171.3	—	—
1998	5	98.4	3	31.0	—	—
1999	2	118.5	2	217.0	2	2.0
2000	14	96.6	10	50.2	1	8.0
2001	10	15.6	2	12.4	1	12.0
2002	6	19.0	8	202.7	2	16.4
2003	12	58.5	13	95.6	—	—
2004	4	285.8	16	102.5	3	1.5
2005	12	17.5	18	105.2	4	5.6
2006	2	60.0	1	24.8	—	—
2007	1	30.0	3	148.8	—	—
2010	18	55.3	25	94.9	3	20.4
2011	11	48.3	13	99.4	1	24.4
2012	14	25.5	17	106.7	1	8.0
2013	23	23.5	17	122.0	1	0.0
2014	24	50.0	31	74.2	4	28.0
2015	22	21.8	30	43.2	4	18.8
2016	29	99.1	30	48.1	4	10.4
2017	29	21.1	30	73.3	4	12.1
2018	27	45.2	31	53.8	4	1.8
2019	28	19.9	31	108.3	4	18.0
2020	20	6.6	—	—	—	—
2022	15	24.8	24	127.7	—	—
Mean[3]		53.1		81.9		10.2
Maximum[4]		115.6		186.2		39.6
Minimum[4]		6.6		11.7		0.0
2023	4	7.5	4	232.5	3	40.4

[1] Data from NOAA (2024)
[2] The weighted rainfall for each year was calculated as the total rainfall divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4.
[3] The mean rainfall was calculated as the total rainfall over the entire historical record prior to 2023 divided by the number of days with precipitation data and then multiplied by 30 for September, 31 for October, and 4 for November 1-4
[4] The maximum and minimum rainfalls for September and October were calculated based only upon years with at least 33% coverage (10 days of precipitation data).

Table 8. Historical monthly precipitation (mm) in INAMHI database[1]

Year	La Concordia		Izobamba		San Gabriel	
	September	October	September	October	September	October
1994	25.3	39.1	86.8	75.2	38.3	62.3
1995	9.6	99.7	50.7	137.1	19.6	78.2
1996	12.3	19.8	45.6	163.6	40.5	84.2
1997	849.6	757.2	71.1	150.5	81.0	73.0
1998	82.6	13.9	57.4	192.5	44.3	309.1
1999	124.8	65.2	157.2	104.2	82.4	45.2
2000	64.4	79.1	167.7	49.9	45.9	54.4
2001	33.9	4.8	91.4	7.9	16.9	4.3
2002	108.0	86.1	22.9	129.6	3.7	138.8
2003	3.0	130.6	101.3	153.2	41.0	102.6
2004	81.7	99.0	98.7	136.3	61.9	63.3
2005	24.3	33.4	84.1	83.7	47.6	130.9
2006	48.9	25.1	51.6	76.5	50.7	72.3
2007	33.6	17.2	16.4	201.9	39.2	198.7
2008	152.0	55.4	103.1	199.5	45.1	211.0
2009	6.8	8.1	9.7	86.4	16.5	47.1
2010	45.2	13.2	79.5	89.7	78.7	134.0
2011	65.0	48.3	56.9	197.6	40.7	96.1
2012	4.9	73.7	20.5	167.0	25.9	77.0
2013	7.1	26.6	38.9	191.5	19.7	80.3
Mean	89.2	84.8	70.6	129.7	42.0	103.1
Max	849.6	757.2	167.7	201.9	82.4	309.1
Min	3.0	4.8	9.7	7.9	3.7	4.3

[1] Data from INAMHI (1996, 1997, 2000a-b, 2001, 2002, 2006a-f, 2008, 2010a-b, 2012a-b, 2014, 2015, 2017).

The opposite pattern was observed at the San Gabriel weather station (see Tables 7c and 8). The total precipitation amounts for September 2023 and October 2023 were 23.6 mm and 136.4 mm, respectively (see Table 7c). By comparison with data in the NCDC database (2011-2022), the September 2023 rainfall was well below the mean of 49.8 mm and even below the minimum of 25.1 mm, which was recorded in 2013 (see Table 7c). By comparison with data in the INAMHI database (1994-2013), the September 2023 rainfall at San Gabriel was well below the mean of 42.0 mm, but still greater than the minimum of 3.7 mm that was recorded in 2002 (see Table 8). By comparison with data in the NCDC database (2011-2022), the October 2023 rainfall was greater than the mean of 114.7 mm and the maximum of 128.5 mm, which was recorded in 2013 (see Table 7c). By comparison with data in the INAMHI database (1994-2013), the October 2023 rainfall at San Gabriel was greater than the mean of 103.1 mm, but far less than the maximum of 309.1 mm that was recorded in 1998 (see Table 8). Thus, San Gabriel was unusually dry during September 2023 and unusually wet during October 2023.

For the weather station at San Luis (Colombia), the total precipitation amounts for September 2023 and October 2023 were 7.5 mm and 232.5 mm, respectively (see Table 7d). By comparison with data in the NCDC database (1973-2022), the September 2023 rainfall was far below the mean of 53.1 mm and only slightly greater than the minimum of 6.6 mm, which was observed in 2020 (see Table 7d). By comparison with the same dataset, the October 2023 rainfall was greater than both the mean of 81.9 mm and the maximum of 186.2 mm, which was observed in 1980 (see Table 7d). Thus, San Luis (Colombia) followed the pattern of San Gabriel in being unusually dry during September 2023 and unusually wet during October 2023.

In summary, based on the lack of consistency in neighboring weather stations and the knowledge that it did not rain at the mine site over the night of November 3-4, there is no evidence that heavy rainfall preceded the tailings dam failure neither for the night preceding the failure, nor for the three days preceding the failure, nor for the two months preceding the failure. It was previously noted that Pond No. 15 was at an emergency water level at the time of failure (Defensoría del Pueblo del Ecuador, 2024), but the excessive water could have resulted only from the water that was mixed with the tailings as the tailings arrived from the processing plant, and was not necessarily connected with rainfall. Having said the above, it should be noted that heavy rainfall can form a part of the chain of events leading to failure, but heavy rainfall can never be the cause of failure. In Imbabura province, heavy rainfall is simply a fact of life. According to data in Agroindustrial El Corazón S.A. (2023b), the mean annual precipitation amounts at Apuela, Chontal Bajo, Garcia Moreno, Inguincho, and Selva Alegre (see Fig. 22) are 1414.2 mm, 1590.0 mm, 1569 mm, 1210.8 mm, and 1730.2 mm, respectively, while the maximum annual precipitation at Garcia Moreno was 3293 mm for the period 2000-2016.

The Ecuadorian tailings dam regulations specify that a tailings dam is supposed to be designed to withstand a particular precipitation event, depending upon the consequences of catastrophic failure on a five-level scale (MERNNR, 2020a-c). For example, the Ecuadorian regulations define a catastrophic failure as "*Significativo*" [Significant] if catastrophic failure will result in "*pérdida no significativa o deterioro del habitat silvestre o acuático*" [insignificant loss or deterioration of fish or wildlife habitat] with "*sólo pérdida marginal del habitat*" [only marginal loss of habitat] (MERNNR, 2020b). The regulations define catastrophic failure as "*Alta*" [High] if catastrophic failure will result in "*pérdida significativa o deterioro importante del habitat silvestre o acuático*" [significant loss or deterioration of important fish or wildlife habitat] (MERNNR, 2020b). The regulations then state that a tailings dam for which the consequences of catastrophic failure will be Significant should be designed to withstand a precipitation event with a return period of between 100 and 1000 years. A tailings dam for which the consequences of catastrophic failure will be High should be designed to withstand a precipitation event one-third of the way between a precipitation event with a return period of 1000 years and the Probable Maximum Flood (PMF) (MERNNR, 2020b). Therefore, tailings dams in Imbabura province are supposed to be designed to withstand both the typical and extreme heavy rainfall of the province, so that causes of failure should be sought in the actions or lack of actions of human beings, not in meteorological phenomena. The probable causes of the failure of the tailings dam at the El Corazón mine will be addressed in the next two subsections.

The Proximal Cause of Tailings Dam Failure was Internal Erosion

For the determination of the proximal cause of failure, the key information is Fig. 6, which is a still image from a 46-second video. The still image, as well as the entire video, clearly shows muddy water emerging from the face of the embankment (see Fig. 6 and compare with Fig. 9). Thus, the proximal cause of failure was not overtopping, which would have resulted in water flowing over the top of the embankment. The proximal cause was also not foundation failure, since the settling of the tailings pond into the foundation would also have resulted in water flowing over the top of the embankment. Seismic activity can be dismissed because there are no records of earthquakes within 1000 kilometers of the mine site during the 24 hours preceding the tailings dam failure (USGS, 2024). Static liquefaction and slope instability can be dismissed because there is no evidence of flow behavior or sliding (see Fig. 6).

In fact, the emergence of muddy water from the face of an embankment is the characteristic feature of internal erosion (compare Fig. 6 with Fig. 9). It has already been mentioned that seepage of muddy water (as opposed to clear water) is a dangerous sign because it means that the seepage is entraining either tailings or the dam construction material, or both, which could eventually lead to the loss of structural integrity of the tailings pond. Based upon information provided by a representative of Agroindustrial, the Municipio de Cotacachi (2023a) reported that the flow rate from the dam was 2.57 liters per second at 4:50 pm on Monday, November 6 (two and a half days after the tailings dam failure) with the nearly identical flow rate (2.48 liters per second) measured at 10:00 am on Tuesday, November 7. The Municipio de Cotacachi (2023a) then reported the shocking information that "*En la visita los técnicos de la empresa manifestaron que el caudal viene siendo similar desde aproximadamente agosto del año 2020, lo que ha variado es la turbidez*" [During the visit, the company's technicians stated that the flow has been similar since approximately August 2020, what has changed is the turbidity]. In other words, based on the fact that Pond. No 15 was constructed between 2020 and 2021 (Municipio de Cotacachi, 2023a), the company technicians were reporting that Pond No. 15 had been releasing cyanide-enriched water from the tailings pond ever since the pond was constructed with no apparent action being taken by the mining company. The tailings pond failure only came to the attention of the downstream community when fine-grained tailings were observed in the Verde River (Municipio de Cotacachi, 2023a). From another perspective, since the purpose of the dam was to prevent the flow of cyanide-enriched water into downstream waterways, the tailings dam had been in a continuous state of failure ever since it was constructed. What changed on the early morning of November 4 was that the seepage began to entrain solid particles, so that the continuous failure began the progression to catastrophic failure, which was fortunately interrupted when the mining company finally took action.

The Root Cause of Tailings Dam Failure was Improper Design

Both the mining company and the responsible governmental agency stated the cause of the tailings dam failure as a tear in the geomembrane. According to Agroindustrial El Corazón S.A. (2023a), "*La fuga de relave de la piscina 15 se produjo debido a un fisuramiento en la geomembrana de la piscina 15*" [The tailings leak from Pool 15 occurred due to a crack in the geomembrane of Pool 15]. According to MAATE (2023b), "*Se estima que el evento ambiental estaría dado por una fisura a nivel de la geomembrana de la piscina 15 de la relavera*" [It is estimated that the environmental event would be caused by a crack at the level of the geomembrane of pool 15 of the tailings pond]. Of course, a tear in the geomembrane is a necessary step in the chain of events that ends in the internal erosion of the tailings dam. It is clear that no water can leave the tailings pond without a tear in the geomembrane, unless water flows over the top of the embankment, which does not appear to have occurred (see Fig. 6). However, a geomembrane should not be the sole line of defense against tailings dam failure. Thus, it is necessary to consider whether water ought to flowing out of the face of the embankment just because there is a tear in the geomembrane. The claims by company technicians that the same flow rate had been observed since Pond No. 15 was constructed (Municipio de Cotacachi, 2023a) should also be noted. The claims imply that the geomembrane was torn when it was first installed and that the only change on November 4 was that the flow began to entrain solid particles.

Photograph 1.
Pond No. 15 surface view looking northwest, stable slopes.

Photograph 2.
Pond No. 15 surface view looking southwest, stable slopes.

Photograph 3.
Pond No. 15 surface view looking southeast, stable slope.

Photograph 4.
Pond No. 15 surface view looking southeast, stable slope.

Figure 24. MAATE (2023b) states that the slopes of Pond No. 15 are stable without giving any evidence or explaining how the word "stable" is to be understood. The photos (especially the upper right) clarify that the embankments are very steep and on the order of 1V:1H (45°), which is the maximum critical angle necessary to avoid failure by internal erosion. By contrast, the U.S. Army Corps of Engineers requires slope angles no greater than 1V:5H (11° from the horizontal) to avoid failure by internal erosion (USACE, 2000). Since there are two views to the southeast and no view to the northeast, the directions might be mislabeled. Figure from MAATE (2023b) with overlay of English labels.

An earthen dam ought to be able to prevent the flow of water even if there is a tear in the geomembrane and even if there is no geomembrane at all. The earlier subsection "Mechanisms of Failure of Tailings Dams" described three principal means of preventing tailings dam failure by internal erosion, none of which include geomembranes. First, the embankment needs a gentle slope in order to reduce the hydraulic gradient and, thus, reduce the flow rate of water through the embankment. The U.S. Army Corps of Engineers (USACE, 2000) recommends that the embankment be no steeper than 1V:5H (11° from the horizontal). By contrast, the photos in MAATE (2023b) clarify that the slopes of the embankments are about 1V:1H (45°), which is far too steep (see Fig. 24). In fact, a slope of 1V:1H is regarded as the maximum critical angle for the prevention of internal erosion (Holtz et al., 2000), which implies that the embankments of Pond No. 15 have always existed on the cusp of failure. Therefore, once the geomembrane tore, the water from the tailings pond was flowing so fast through the tear and then across the embankment that it was able to entrain solid particles. The steepness of the embankment is also evident in the way that the local resident struggled to gain footing to collect a water sample from the leaking tailings dam (see Fig. 6). The steepness of the embankment is further indicated by the steepness of the pipe, the exposed plant roots, and the near vertical fall of contaminated water from the tailings pond (see Fig. 6).

Figure 25. Drains were constructed in the foundations of the tailings ponds underneath the geomembrane. However, there are no drains that would force water and tailings that escape from the geomembrane and flow against the tailings dam to exit the tailings dam at the toe (compare with Figs. 10-11). Photo from Agroindustrial El Corazón S.A. (2023a) with overlay of English label.

The second means of preventing tailings dam failure by internal erosion is the installation of a drainage system that would force seepage to exit at the toe of the dam, rather than along the face of the dam (see Fig. 10). However, the only drains that are discussed in the mining company documents are the drains that were constructed in the foundations of the tailings ponds underneath the geomembrane (see Fig. 25). That is, there is no mention of drains that could control the flow of water after the water emerged from a tear in the geomembrane. The fact that the seepage appeared high on the face of the dam (see Fig. 6), rather than at the toe of the dam, certainly counts as evidence either that an appropriate drainage system had never been installed or that it was completely ineffective. The third means of prevention is the installation of filters in order to trap fine particles and prevent their entrainment in the seepage (see Fig. 11). In the same way, there is no mention of filters within the embankments of the tailings ponds at the El Corazón mine. Although the excessively steepness of the embankments is visually apparent (see

Fig. 24), some caution is needed regarding the lack of drains and filters, simply due to the general lack of information that was reviewed in the section "Summary of Tailings Ponds at El Corazón Gold Mine."

In summary, while the proximal cause of tailings dam failure was internal erosion, the root cause was an inadequate design that allowed a tear in the geomembrane to progress to internal erosion. The tailings dam failure did not involve only the release of water into downstream waterways, but the release of water that was enriched in cyanide. Thus, an additional aspect of inadequate design was the failure to destroy the cyanide before tailings and water are discharged into a tailings pond. In other words, the failure to destroy cyanide turned a relatively minor accident into a much more serious accident.

The possible chain of events that was listed in the subsection "Proximal and Root Causes of Tailings Dam Failures" can now be revisited:

1) A tailings pond is designed for a gold mine in which the embankment is excessively steep. Moreover, the dam does not include a drainage system that would force seepage to emerge at the toe of the dam and does not include filters for trapping fine particles. Finally, there is no plan for destruction of cyanide before the tailings and cyanide-enriched water are deposited into the tailings pond.
2) Either the design of the tailings pond is not reviewed or the review is inadequate, so that no attention is called to deficiencies in the design.
3) The tailings pond is constructed as designed.
4) Either dam safety inspections or reviews do not occur or they are inadequate, so that no attention is called to deficiencies in the design.
5) Seepage (cyanide-enriched water) appears high on the face of the dam. The seepage is clear and not muddy.
6) Either no one notices the seepage or no one understands its significance.
7) The seepage turns muddy (indicating that internal erosion is in progress) and the mud and cyanide-enriched water appear in downstream waterways.

It cannot be definitively established that the above sequence of events occurred, but the sequence is consistent with this subsection and the previous subsection, in which four aspects of inadequate design constitute the root cause (Step #1), while internal erosion is the proximal cause (Step #7). The tear in the geomembrane could have been present when the geomembrane was first installed (Step #3) or it could have occurred just prior to the appearance of seepage (Step #5). In this respect, it should be recalled, that according to mining company technicians, seepage from the dam began as soon as the tailings pond was constructed (Municipio de Cotacachi, 2023a), which would compress Steps #3, #4, and #5 into a single event. It is not clear what caused the seepage to turn muddy in the early morning of November 4, 2023. It could be that nothing changed from November 3 to November 4, except that sufficient time was required so that the flow through the embankment could loosen the solid particles and turn the seepage muddy. It should be clear by this point that excessive concern about the proximal cause can be counterproductive and that attention needs to focus on root causes and the prevention of further failures.

There is no Indication that the Existing Tailings Dams are Stable

Immediately after the tailings dam failure, both the mining company and the responsible governmental agency certified the stability of the existing tailings dams at the El Corazón mine.

According to Agroindustrial El Corazón S.A. (2023a), "*En el transcurso del día el personal técnico de la empresa realiza la verificación de las condiciones de estabilidad de los taludes de la relavera, sin encontrarse anomalías*" [During the day [November 4], the technical staff of the company verified the stability conditions of the tailings dam slopes, without finding any anomalies]. In turn, in their report of the inspection that was carried out on November 7, MAATE (2023b) labeled each of four views of Pond No. 15 as "taludes estables" [stable slopes] (see Fig. 24), but without any commentary. Considering the speed with which these inspections were carried out and in the absence of any supporting data, it should be assumed that the certifications of stability were based solely on the visual appearance of the tailings dams.

In contrast to the rudimentary certifications of stability that were carried out by Agroindustrial El Corazón S.A. (2023a) and MAATE (2023b), the Ecuadorian tailings dam regulations provide detailed information regarding the meaning of "stability" and the proper methods for determining whether a tailings dam is stable. According to MERNNR (2020a), "*estabilidad física*" [physical stability] is defined as the "*condición a la cual se encuentra sometida una estructura, bajo cargas estáticas, hidráulicas y sísmicas y que es capaz de cumplir con los criterios de aceptabilidad o factores de seguridad (estática, seudoestática, dinámico, post sísmico) frente a una condición de inestabilidad*" [condition to which a structure is subjected, under static, hydraulic and seismic loads and that is capable of meeting the criteria of acceptability or factors of safety (static, pseudostatic, dynamic, post-seismic) against a condition of instability]. The factor of safety against instability is the ratio of the shear strength of a dam to the shear stress acting on a dam. A dam with a factor of safety equal to 1.0 is at the cusp of failure with higher factors of safety indicating greater stability. For static (non-seismic) loading, MERNNR (2020b) specifies minimum factors of safety of 1.3 during or at the end of dam construction and 1.5 during dam operation. MERNNR (2020b) further specifies minimum factors of safety of 1.0 during the design earthquake and 1.2 after the deformation resulting from the design earthquake. Since there is no discussion of the factor of safety in either Agroindustrial El Corazón S.A. (2023a) and MAATE (2023b), there can be no verification of physical stability.

MERNNR (2020a) provides further general information regarding the range and depth of knowledge that is required to demonstrate stability. Article 12 states that the mining company "*facilitará información generada del sistema de monitoreo en tiempo real para evaluar la estabilidad física*" [will provide information generated from the real-time monitoring system to evaluate physical stability] (MERNNR (2020a). Article 15 states that "*la distancia entre la poza y la presa debe estar técnicamente justificada mediante un análisis hidráulico (nivel de aguas máximas extraordinarias) y geotécnico (estabilidad de la presa)*" [the distance between the pond and the dam must be technically justified through a hydraulic analysis (extraordinary maximum water level) and geotechnical analysis (stability of the dam)] (MERNNR (2020a). Article 21 states that "*El titular deberá realizar auditorías internas y externas de manera anual ... Para el caso de la inspección evaluación de la estabilidad física, la auditoría debe considerar criterios mínimos como revisión de documentos de aseguramiento y control de la calidad de construcción, operación y mantenimiento del depósito, gestión del manejo de agua, manejo e interpretación del sistema de monitoreo de la instrumentación geotécnica, así como la aplicación de alguna de las guías de Revisión de Seguridad de Presas enunciadas en los estándares señalados en el Artículo 4 de este instructive* [The owner must carry out internal and external audits annually ... In the case of the inspection and evaluation of physical stability, the audit must consider minimum criteria such as review of quality assurance and quality control documents regarding the construction, operation and maintenance of the tailings deposit, the management of water, the management and interpretation of the geotechnical instrumentation monitoring system, as well as the application of any of the Dam Safety Review guidelines set forth in the standards indicated in Article 4 of this guidance document] (MERNNR, 2020a). In summary, physical stability is not evaluated visually, but through the analysis of monitoring data, geotechnical analysis, and the review of all documents related to the construction and operation of the tailings pond. It should be clear that the requirements outlined in MERNNR (2020a) far exceed the visual inspections by Agroindustrial El Corazón S.A. (2023a) and MAATE (2023b).

In addition to the general guidelines in MERNNR (2020a), MERNNR (2020b-c) are highly detailed in terms of the appropriate steps that must be carried out to establish physical stability of a tailings dam, especially in terms of the proper calculation of the factor of safety. In fact, the methodology for the assessment of stability is the entire subject of Section 9 entitled "*Análisis de Estabilidad Física*" [Analysis of Physical Stability] and much of Section 10 entitled "*Análisis y Gestión de Riesgos*" [Analysis and Management of Risks] of MERNNR (2020b). For example, with regard to calculating the factor of safety, MERNNR (2020b) states, "*Se debe emplear métodos de análisis de estabilidad basados en métodos de equilibrio límite ... Complementariamente se deben realizar modelaciones numéricas con base en técnicas de elementos finitos (MEF) o diferencias finitas (MDF) a fin de estimar las deformaciones y presiones de poro. Se debe considerar la condición de carga según la condición física o un escenario que requiere ser analizado con diferentes parámetros de resistencia, incluso para el mismo material. Las siguientes condiciones de carga deben ser analizadas: 1. Condiciones drenadas: Representa la estabilidad a largo plazo de una presa o muro de contención de los relaves bajo condiciones de flujo permanente. Sin cambios rápidos en la superficie del nivel freático … 2. Condiciones no drenadas: La condición de carga no drenada o parcialmente drenada representa la estabilidad de una presa, muro o dique de contención donde la carga y/o falla ocurre lo suficientemente rápido como para que no haya suficiente tiempo para el drenaje del exceso inducido de poro presiones de agua, o donde se desarrollan presiones de poro debido a la naturaleza contractiva de los relaves y/o presa y materiales de cimentación* [Stability analysis methods based on limit equilibrium methods must be used ... In addition, numerical modeling must be carried out based on finite element (FEM) or finite difference (FDM) techniques in order to estimate deformations and pore pressures. The loading condition must be considered in terms of the physical condition or scenario that requires analysis with different strength parameters, even for the same material. The following loading conditions should be analyzed: 1. Drained conditions: Represents the long-term stability of a tailings dam or retaining wall under permanent flow conditions. Without rapid changes in the surface of the water table … 2. Undrained conditions: The undrained or partially drained loading condition represents the stability of a dam, wall or retaining dike where loading and/or failure occurs quickly enough that there is not enough time for the drainage of the excess induced by pore water pressures, or where pore pressures develop due to the contractive nature of the tailings and/or dam and foundation materials]. With regard to the input data for the calculation of the factor of safety, MERNNR (2020b) states, "*El Titular debe seleccionar adecuadamente los parámetros de la resistencia al corte del material que constituirá el relleno de la presa, dique o muro de contención, considerando que tanto las investigaciones de campo como de laboratorio para caracterizar la misma deben ser compatibles con el análisis asociado y debe tomar en cuenta que la resistencia al corte de los materiales de origen geológico ya sea en condiciones drenadas o no drenadas está en función de los esfuerzos efectivos*" [The Owner must properly select the shear strength parameters of the material that will constitute the fill of the dam, dike or retaining wall, considering that both field and laboratory investigations for their characterization must be compatible with the associated analysis and it must be taken into account that the shear strength of materials of geological origin, whether in drained or undrained conditions, is a function of the effective stresses].

MERNNR (2020b) is especially detailed with regard to the methodology for establishing that a tailings dam will be able to withstand the design earthquake. It should be noted that the definition of physical stability in MERNNR (2020a) includes the ability to withstand the design earthquake. For example, MERNNR (2020b) states, "*Para los análisis de estabilidad física, la determinación del coeficiente sísmico debe ajustarse a las características sísmicas del área y debe ser adoptado en forma criteriosa. La aceleración máxima de campo libre (PGA) debe obtenerse de un estudio de peligro sísmico según el Requisito 4.7.1. Como referencia puede consultarse la zonificación sísmica según la Norma Ecuatoriana de la Construcción (NEC) en su versión más actualizada. La magnitud del coeficiente sísmico debe simular la naturaleza del evento que depende de la intensidad o aceleración del sismo, duración del movimiento y frecuencia*" [For physical stability analyses, the determination of the seismic coefficient must be adjusted to the seismic characteristics of the area and must be adopted judiciously. The peak ground acceleration (PGA) must be obtained from a seismic hazard study according to Requirement 4.7.1. As a reference, the seismic zoning according to the Ecuadorian Construction Standard (NEC) in its most updated version can be consulted. The magnitude of the seismic coefficient must simulate the nature of the event, which depends on the intensity or acceleration of the earthquake, duration of the movement and frequency]. As a final example, with regard to the assessment of slope instability, MERNNR (2020b) states, "*Se deben realizar el o los análisis de estabilidad de taludes por métodos de equilibrio límite o numéricos y cálculos volumétricos que permitan predecir los escenarios de riesgo para las distintas situaciones en que puede producirse la desestabilización de las laderas situadas en el límite del vaso del depósito y de la presa para relaves. La metodología utilizada para la realización de este requisito debe complementarse con un análisis geológico-geomorfológico de la zona de la presa, muro o dique de contención, centrado en los aspectos referentes a la posible inestabilidad de las laderas, contando para ello con un estudio topográfico a detalle*" [The slope stability analyses must be carried out by limit equilibrium or numerical methods and volumetric calculations that allow predicting the risk scenarios for the different situations in which destabilization of the slopes located at the limit of the basin of the tailings pond and tailings dam may occur. The methodology used to carry out this requirement must be complemented with a geological-geomorphological analysis of the region of the dam, wall or retaining dike, focused on aspects related to the possible instability of the slopes, relying on a detailed topographic study for this purpose].

At this point, it should be clear that Agroindustrial El Corazón S.A. (2023a) and MAATE (2023b) did not actually carry out a stability analysis in accordance with Ecuadorian regulations, but merely expressed an opinion, probably based solely upon the visual appearance of the tailings dams. As a consequence, there is no reason for the downstream communities to believe that the tailings dams at the El Corazón mine are stable. In particular, there is no publicly available document that states the factor of safety, explains how the factor of safety was calculated, reviews the input data for the calculation of the factor of safety, states the magnitudes of the design earthquake and the design flood, or assesses the regional slope stability. According to the mining company and the responsible government agencies, the tailings dam failure occurred due to a tear in a geomembrane and the solution has been to try to locate the tear in the geomembrane of Pond No. 15. Whether the actions of the mining company and the government are sufficient to prevent future tailings dam failures at the El Corazón mine is the subject of the next section.

DISCUSSION: FURTHER TAILINGS DAM FAILURES ARE LIKELY

In the absence of further information, it should be assumed that each of the 20 tailings ponds at the El Corazón mine shares the following characteristics in common with Pond No. 15:

1) A geomembrane is the only line of defense against the loss of water and fine-grained tailings.
2) While there may be a drainage system under the geomembrane, there is no drainage system that would force water that leaks from the geomembrane to exit from the foot of the embankment.
3) There is no filter inside the embankment to prevent the entrainment of fine particles by the leakage.
4) The slope of the embankment is 1V:1H, which is regarded as the cusp of failure by internal erosion.
5) There is no destruction of cyanide before the tailings and water are discharged into the tailings pond.
6) The physical stability of the tailings dam has not been evaluated in terms of the definition of physical stability and the procedures for evaluating physical stability in the Ecuadorian tailings dam regulations.

Based upon the above characteristics, further tailings dam failures from any of the other tailings ponds should be regarded as likely because any tear in a geomembrane will begin the progression to internal erosion. It is even possible that the geomembranes of other tailings ponds are already torn. It was very disturbing to learn that the Municipio de Cotacachi (2023a) had been informed by technicians at Agroindustrial that Pond No. 15 had been leaking ever since it was constructed. It would have been worthwhile for the team from the municipality to ask whether other tailings ponds were currently leaking.

It has already been explained that the root causes of tailings dam failures are never purely physical phenomena, such as heavy rainfall, but the actions or lack of actions of human beings. Thus, in the case of the El Corazón mine, it is most important to fully consider the human factors that are promoting the likelihood of future tailings dam failures. In this respect, a very informative document is the two-page cover letter that Agroindustrial El Corazón S.A. (2024) sent to the Defensoría del Pueblo del Ecuador [Office of the Ombudsman of Ecuador] on April 23, 2024. The cover letter included four other documents, which were the governmental approval of the biotic component of the environmental remediation program (MAATE, 2024a), a set of governmental observations regarding the biotic component of the environmental remediation program (MAATE, 2024b), an undated study of aquatic fauna (Ojeda, n.d.), and the action plan that was submitted by the mining company in November 2023 (Agroindustrial El Corazón S.A., 2023a).

According to the cover letter, "*Dejamos constancia que a petición del ciudadano norteamericano Nicholas Peter Shear, director ejecutivo de APT Norte se han realizado 11 inspecciones al Proyecto Minero el Corazón por parte de distintas entidades administrativas, -a ninguna de ellas ha asistido- (desgastando la unidad procesal administrativa), nos ha acusado de varios delitos entre ellos de hostigamiento a miembros de la Comunidad El Corazón -no ha* *presentado una sola prueba-, haciendo tabla rasa de los principios de participación y buena fe establecidos en el Código Orgánico Administrativo, gestando una conducta abusiva y premeditada con la intención de causarnos daño, generando una perturbación social hacia mi representado y violentando el interés general establecido en la Constitución de la República*" [We record that at the request of the North American citizen Nicholas Peter Shear, executive director of APT Norte, 11 inspections have been carried out at the El Corazón Mining Project by different administrative entities, -he has attended none of them- (wearing down the administrative procedural unit), he has accused us of several crimes, including harassment of members of the El Corazón Community -he has not presented a single piece of evidence-, making a clean slate of the principles of participation and good faith established in the Organic Administrative Code, carrying out abusive and premeditated conduct with the intention of causing us harm, generating a social disturbance towards my client and violating the general interest established in the Constitution of the Republic] (Agroindustrial El Corazón S.A., 2024). The ire of the mining company has been directed not only against the Asociación de Propietarios de Tierras Rurales del Norte [Northern Rural Landowners Association] (APT Norte), but also against the pro-mining press. It should be recalled that Agroindustrial El Corazón S.A. (2023c) also accused the Agencia de Prensa Minera [Mining Press Agency] of "*sensacionalista*" [sensationalist] conduct.

The following observations can be made regarding the above statement by Agroindustrial El Corazón S.A. (2024):

1) The author is aware of only six inspections that have been related to the causes and consequences of the tailings dam failure on November 4, 2023 (Agroindustrial El Corazón S.A., 2023a; MAATE, 2023b; MEM, 2023; Municipio de Cotacachi, 2023a; Defensoría del Pueblo del Ecuador, 2024; Armijos Ojeda, n.d.), one of which was carried out by the mining company.
2) Two of the inspections (Municipio de Cotacachi, 2023a; Defensoría del Pueblo del Ecuador, 2024) certainly did not grant a "clean bill of health" to the tailings dams at the El Corazón mine. In particular, the Municipio de Cotacachi (2023a) reported the damaging findings that Pond No. 15 violated the required 30-meter buffer between tailings ponds and streams, that untreated mine water from the underground galleries was being discharged directly into rivers, and that Pond No. 15 had been leaking ever since it was constructed.
3) None of the inspections have addressed the physical stability of the tailings dams in terms of the definition of physical stability and the procedures for evaluating physical stability in the Ecuadorian tailings dam regulations.
4) None of the inspections have addressed the compliance of the mining company with the International Cyanide Code or with the World Gold Council Responsible Gold Mining Principles.
5) The defensive responses from the mining company, which involve personal attacks on anyone who expresses concerns, whether they are an association of rural landowners or a pro-mining news source, have hindered the ability of the mining company to learn from the previous tailings dam failure and to prevent future tailings dam failures. This refusal to learn from either their own experience or the experiences of others is an important human factor that increases the likelihood of future tailings dam failures.

Since future tailings dam failures are likely, it is worthwhile to consider the potential consequences of future failures. Fortunately, the failure on November 4, 2023, did not progress to catastrophic failure. If a future failure did progress to catastrophic failure, it could involve the release of about 50,000 cubic meters of tailings and cyanide-enriched water. The preceding volume is relatively small compared to the volumes of tailings and water stored at the mega-mines, such as Mirador or Fruta del Norte. However, the storage of cyanide-enriched water in the tailings ponds at the El Corazón mine is a critical factor. The failure of the tailings dam near Baia Mare, Romania, in 2000, which resulted in a massive fishkill and destruction of aquatic species along 2000 kilometers of the Danube River before reaching the Black Sea, released only 100,000 cubic meters of cyanide-enriched water, or about twice as much as is contained in a tailings pond at the El Corazón mine. Thus, a future catastrophic failure of a tailings pond at the El Corazón mine could potentially release cyanide-enriched water that could travel down the Verde River to the Guayllabamba River to the Esmeraldas River before reaching the Pacific Ocean (see Fig. 2) with catastrophic impacts on fish, aquatic species, and livestock between the mine and the Pacific Ocean.

SUMMARY CONCLUSIONS

The eight questions posed in the "Methodology" section are repeated below, followed by very brief responses. More complete responses can be found in the "Responses" and "Discussion" section.

1) Why are there discrepancies between the chemical analyses of the water sample collected by a local resident and the samples collected by Agroindustrial and GRUNTEC?

Discrepancies occurred because, although Ecuadorian standards are based on total cyanide concentrations, GRUNTEC measured free cyanide concentrations, which can be as little as 1% of total cyanide concentrations. The sample collected by the local resident was correctly analyzed for total cyanide, while Agroindustrial did not specify what type of cyanide concentration was measured. In addition, because of the numerous contradictions among the map, the stated coordinates, and the stated descriptions of the sampling sites, the datasets by Agroindustrial and GRUNTEC should be rejected as totally invalid.

2) Could the previous incident of cattle deaths have resulted from cyanide poisoning?

Based on typical cattle weight, typical water consumption by cattle, the total cyanide concentration that was measured from the recent tailings dam failure, and the lethal dose of cyanide for large ruminants, it is possible that the recent cattle deaths resulted from cyanide poisoning. However, a definitive cause of death cannot be determined without further information.

3) What is the cause of the grayish-green color in the Manduriaco Chico River?

Since the Tortugo Unit that is exploited by the El Corazón mine has a grayish-green color, it is likely that the sudden appearance of a grayish-green color in the Manduriaco Chico River following the tailings dam failure resulted from the introduction of fine-grained tailings into the river. There are many sources of coloration in streams, so that a definitive cause of sudden color changes cannot be determined without further information. A complicating factor is the lack of a clear hydraulic pathway between Pond No. 15 and the Manduriaco Chico River.

4) Was heavy rainfall a contributing factor to the failure of the tailings dam?

The available meteorological data are inconclusive regarding whether unusually heavy rainfall occurred during the months and days prior to the failure of the tailings dam at the El Corazón mine. However, it is known that rainfall did not occur at the mine site during the night preceding the failure.

5) What was the proximal cause of tailings dam failure?

The most likely proximal cause was a tear in the geomembrane followed by internal erosion of the outer embankment.

6) What was the root cause of tailings dam failure?

The most likely root cause was improper design, including excessively steep outer embankments, the lack of a drainage system that would force seepage to exit at the toe of the embankment, and the lack of destruction of cyanide prior to the deposition of wet tailings in tailings ponds.

7) Are the tailings dams at Pond No. 15 currently stable?

There is no indication that the tailings dams at Pond No. 15 are currently stable. The post-failure inspection was purely visual and did not follow the procedures that are described in Ecuadorian tailings dam regulations.

8) Has the possibility of further tailings dam failures been eliminated?

The possibility of further tailings dam failures has not been eliminated because any future tears in a geomembrane will likely progress to internal erosion, with the possibility of catastrophic failure of a tailings dam and the release of most of the contents of the tailings pond.

RECOMMENDATIONS

This report makes the following recommendations:

1) Complete dam safety audits should be carried out for all of the tailings dams at the El Corazón mine in accordance with Ecuadorian tailings dam regulations.
2) All tailings dams at the El Corazón mine that are not stable, as defined in Ecuadorian regulations, should be appropriately reinforced to achieve stability.
3) All tailings dams at the El Corazón mine that cannot be appropriately reinforced to achieve stability should be permanently and safely closed, which would probably involve the transfer of the gold tailings to a safe location.
4) All tailings dams at the El Corazón mine that violate the required buffer from a stream of 30 meters, including Pond No. 15, should be permanently and safely closed, which would probably involve the transfer of the gold tailings to a safe location.
5) Investigations should be carried out to determine the hydraulic connections between the tailings ponds and the local waterways, including high-precision Lidar surveys and the use of chemical tracers, including stable isotopes of water.

6) Further processing of ore and production of tailings should cease until the above steps have been completed.
7) Any future processing of ore and production of tailings should include the destruction of cyanide prior to the deposition of wet tailings in tailings ponds. In accordance with the requirements of the European Union, cyanide should be destroyed to the lowest possible level using best available techniques and no greater than 10 mg/L of WAD (Weak Acid Dissociable) cyanide.
8) Agroindustrial should be expected to become a signatory company of the International Cyanide Code.
9) Agroindustrial should be expected to comply with all requirements of the Responsible Gold Mining Principles, which were developed by the World Gold Council and which incorporate the International Cyanide Code.
10) Agroindustrial should be expected to fully comply with the requirements of the Global Industry Standard on Tailings Management at a minimum and, ideally, with the stricter requirements of Safety First: Guidelines for Responsible Mine Tailings Management.

ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has over 70 peer-reviewed publications in these areas. Since 2018 Dr. Emerman has been the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and nongovernmental organizations. Dr. Emerman has evaluated proposed and existing tailings storage facilities in North America, South America, Europe, Africa, Asia and Oceania, and has testified on tailings storage facilities before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States, the European Parliament, the United Nations Permanent Forum on Indigenous Issues, the United Nations Environment Assembly, the Permanent Commission on Human Rights of the Chamber of Deputies of the Dominican Republic, and the Minnesota Senate Environment, Climate and Legacy Committee. Dr. Emerman is the former Chair of the Body of Knowledge Subcommittee of the U.S. Society on Dams and one of the authors of Safety First: Guidelines for Responsible Mine Tailings Management.

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REFERENCES

Agencia de Prensa Minera [Mining Press Agency], 2023. Relavera rompió El Corazón—Explota relavera de la mina de El Corazón, ubicada en la parroquia García Moreno, sector El Corazón, cantón Cotacachi de la provincia de Imbabura [El Corazón tailings dam ruptured—Tailings dam explodes at the El Corazón mine, located in the García Moreno parish, El Corazón sector, Cotacachi canton of the province of Imbabura]: November 6, 2023. Available online at: https://prensaminera.org/relaver-rompio-el-corazon/

Agroindustrial El Corazón S.A., 2023a. Plan de acción para remediar afectaciones por fuga de relaves de Piscina 15. Concesión Minera: El Corazón (Cód. 401133) [Plan of action to remedy damages caused by tailings leak from Pond 15. Mining Concession: El Corazón (Code 401133)], 58 p.

Agroindustrial El Corazón S.A., 2023b. Auditoría Ambiental de Cumplimiento [Environmental Compliance Audit]—Concesión Minera [Mining Concession]—El Corazón—Periodo—Diciembre/2020 - Diciembre/2022 [Period—December 2020 – December 2022], 423 p.

Agroindustrial El Corazón S.A., 2023c. A la opinión pública [To the public opinion]: Press release, November 6, 2023, 1 p.

Agroindustrial El Corazón S.A., 2024. Letter from J. Escobar Cisneros (Gerente General [General Manager]) to F.P. Calle Arias (Delegado Provincial Imbabura, Defensoría del Pueblo del Ecuador [Imbabura Provincial Delegate, Office of the Ombudsman of Ecuador]), Expediente [Proceedings] 3549-2023, April 23, 2024, 2 p.

ANCOLD (Australian National Committee on Large Dams), 2012. Guidelines on tailings dams—Planning, design, construction, operation and closure, 84 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/references/ancold-2012.pdf

ANCOLD (Australian National Committee on Large Dams), 2019. Guidelines on tailings dams—Planning, design, construction, operation and closure—Addendum—July 2019, 11 p. Available online at: https://www.ancold.org.au/wp-content/uploads/2019/07/Tailings-Guideline-Addendum-July-2019.pdf

Armijos Ojeda, D., n.d. Estudio de Fauna Acuática [Study of Aquatic Fauna]—Proyecto Minero [Mining Project] "Agroindustrial El Corazón", 42 p.

Asamblea de Unidad—Cantonal de Cotacachi [Assembly of Unity—Canton of Cotacachi], 2023. Urgente—!Moratoria Minera Ya! [Urgent—Mining Moratorium Now!: Facebook post on November 11, 2023. Available online at: https://www.facebook.com/100064691468864/posts/pfbid02vkyu78QZRDMYsKpWmbNrMi9NjUZajTXPwFW5kdesHxDx4Sir5LBrVn4rtJRBMUkVl/?mibextid=WC7FNe

ASDSO (Association of State Dam Safety Officials), 2024. Lessons Learned—High and significant hazard embankment dams should have internal filter and seepage collection systems. Available online at: https://damfailures.org/lessons-learned/internal-filter-and-seepage-collection-systems/

Bentaher, L., 2012. Prediction of peak breach outflow, and breach parameters for embankment dams using fuzzy logic and artificial neural network techniques: M.S. Thesis, Faculty of Irrigation and Hydraulics Engineering, Cairo University, 152 p. Available online at: https://www.researchgate.net/publication/330113598_Prediction_of_Peak_Breach_Outflow_and_Breach_Parameters_for_Embankment_Dams_Using_Fuzzy_Logic_and_Artificial_Neural_Network_Techniques

Blight, G.F., 2010. Geotechnical engineering for mine waste storage facilities: CRC Press/Balkema, AK Leiden, The Netherlands, 634 p.

Boland, M.P., W.J. McCourt, and B. Beate, 2000. Mapa geológico de la Cordillera Occidental del Ecuador entre 0°-1°N, escala 1/200.000 [Geological map of the Western Cordillera of Ecuador between 0°-1°N, scale 1:200,000]: Ministerio de Energía y Minas [Ministry of Energy and Mines] and British Geological Survey.

Boletín Oficial del Estado [Official State Bulletin], 2015. Real Decreto 817/2015, de 11 de septiembre, por el que se establecen los criterios de seguimiento y evaluación del estado de las aguas superficiales y las normas de calidad ambiental [Royal Decree 817/2015, of September 11, which establishes the criteria for monitoring and evaluating the state of surface waters and environmental quality standards], 96 p. Available online at: https://www.boe.es/boe/dias/2015/09/12/pdfs/BOE-A-2015-9806.pdf

Botz, M.M., 2024. Basic cyanide chemistry—An essential guide for gold and silver leaching: Society for Mining, Metallurgy and Exploration, Englewood, Colorado, 112 p.

Canadian Dam Association, 2021. Technical Bulletin—Tailings dam breach analysis, 68 p.

CONAMA (Conselho Nacional do Meio Ambiente [National Council on the Enviroment]), 2005. Resolução CONAMA N° 357, de 17 de março de 2005 [CONAMA Resolution No. 357 of March 17, 2005], 36 p. Available online at: https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Resolucao/2005/res_conama_357_2005_classificacao_corpos_agua_rtfcda_altrd_res_393_2007_397_2008_410_2009_430_2011.pdf

Cope, R.B., 2021. Cyanide Poisoning in Animals: Merck Veterinary Manual. Available online at: https://www.merckvetmanual.com/toxicology/cyanide-poisoning/cyanide-poisoning-in-animals

Defensoría del Pueblo del Ecuador [Office of the Ombudsman of Ecuador], 2023. Providencia Admisibilidad [Providence of Admissibility]: CASO-DPE-1001-100101-204-2023-3549-MG, November 27, 2023, 6 p.

Defensoría del Pueblo del Ecuador [Office of the Ombudsman of Ecuador], 2024. Informe de visita in situ compañía Agroindustrial El Corazón [Report of Agroindustrial El Corazón on-site company visit]: March 2024, 11 p.

Elementary Engineering Library, 2024. Piping Failure in Hydraulic Structures. Available online at : https://www.elementaryengineeringlibrary.com/civil-engineering/soil-mechanics/piping-failure-in-hydraulic-structures#google_vignette

Emerman, S.H., 2024. The sustainability of a proposed dam on the Santa Isabel river in the context of water consumption and surface water and groundwater contamination by the Kinross Gold Morro do Ouro mine, Minas Gerais, Brazil: Report prepared at the request of Fundação Acangaú, 116 p.

Environment and Natural Resources Law & Policy Program, 2010. European Parliament Calls for "Complete Ban on Use of Cyanide Mining Technologies" in European Union and for EU States to Oppose Cyanide Use Elsewhere: Environment & Natural Resources in the 21st Century—Environment21, University of Denver—Sturm College of Law, June 25, 2010. Available online at: https://enrlgp.blogspot.com/2010/06/european-parliament-calls-for-complete.html

Fell, R., P. MacGregor, D. Stapledon, G. Bell, and M. Foster, 2015. Geotechnical engineering of dams, 2nd ed.: CRC Press, 1348 p.

FEMA ((U.S.) Federal Emergency Management Agency), 2004. Federal guidelines for dam safety: April 2004, 63 p. Available online at: https://www.fema.gov/sites/default/files/2020-08/fema_dam-safety_P-93.pdf

Fisher, W., T. Camp, and V. Krzhizhanovskaya, 2017. Anomaly detection in earth dam and levee passive seismic data using support vector machines and automatic feature selection: Journal of Computational Science, vol. 20, pp. 143-153. Available online at: https://www.researchgate.net/publication/311357951_Anomaly_Detection_in_Earth_Dam_and_Levee_Passive_Seismic_Data_Using_Support_Vector_Machines_and_Automatic_Feature_Selection

GRID-Arendal, UNEP (United Nations Environment Programme), COE (The Church of England), and CESNPF (Council on Ethics—Swedish National Pension Funds), 2024. Global Tailings Portal. Available online at: https://tailing.grida.no/

Holtz, R.D., W.D. Kovacs, and T.C. Sheahan, 2011. An introduction to geotechnical engineering, 2nd ed.: Pearson, 863 p.

HydroSHEDS, 2024. Seamless hydrographic data for global and regional applications. Available online at: https://www.hydrosheds.org/

ICMM (International Council on Mining & Metals), 2021. Conformance Protocols—Global Industry Standard on Tailings Management, 110 p. Available online at: https://www.icmm.com/website/publications/pdfs/environmental-stewardship/2021/tailings_conformance-protocols.pdf?cb=21097

ICMM (International Council on Mining & Metals), 2024. Our Members. Available online at: https://www.icmm.com/en-gb/our-story/our-members

ICMM-UNEP-PRI (International Council on Mining & Metals-United Nations Environment Programme-Principles for Responsible Investment), 2020. Global industry standard on tailings management—August 2020, 40 p, Available online at: https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard-on-tailings-management.pdf

ICOLD (International Commission on Large Dams) and UNEP (United Nations Environment Programme (UNEP), 2001. Tailings dams—risk of dangerous occurrences—Lessons learnt from practical experiences: Bullletin 121, 146 p. Available online at: https://ussdams.wildapricot.org/resources/Documents/ICOLD%202001%20Bulletin%20121.pdf

IGF (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development), 2024. ASGM tailings management and reprocessing governance—Global trends: The International Institute for Sustainable Development, 152 p. Available online at: https://www.iisd.org/system/files/2024-05/igf-asgm-tailings-management-reprocessing-governance.pdf

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 1996. Anuario Meteorológico [Meteorological Yearbook]—1994: No. 34, Edición Especial [Special Edition], Quito – Ecuador, 100 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 1997. Anuario Meteorológico [Meteorological Yearbook]—1995: No. 35, Quito – Ecuador, 168 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2000a. Anuario Meteorológico [Meteorological Yearbook]—1996: No. 36, Quito – Ecuador, 160 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2000b. Anuario Meteorológico [Meteorological Yearbook]—1997: No. 37, Quito – Ecuador, 160 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2001. Anuario Meteorológico [Meteorological Yearbook]—1998: No. 38, Quito – Ecuador, 156 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2002. Anuario Meteorológico [Meteorological Yearbook]—1999: No. 39, Quito – Ecuador, 158 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006a. Anuario Meteorológico [Meteorological Yearbook]—2000: No. 40, Quito – Ecuador, 212 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006b. Anuario Meteorológico [Meteorological Yearbook]—2001: No. 41, Edición Especial [Special Edition], Quito – Ecuador, 192 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006c. Anuario Meteorológico [Meteorological Yearbook]—2002: No. 42, Quito – Ecuador, 200 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006d. Anuario Meteorológico [Meteorological Yearbook]—2003: No. 43, Quito – Ecuador, 202 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006e. Anuario Meteorológico [Meteorological Yearbook]—2004: No. 44, Quito – Ecuador, 196 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2006f. Anuario Meteorológico [Meteorological Yearbook]—2005: No. 45, Quito – Ecuador, 200 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2008. Anuario Meteorológico [Meteorological Yearbook]—2006: No. 46, Edición Especial [Special Edition], Quito – Ecuador, 121 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2010a. Anuario Meteorológico [Meteorological Yearbook]—2007: No.

47, Versión Preliminar [Preliminary Version], Quito – Ecuador, 121 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2010b. Anuario Meteorológico [Meteorological Yearbook]—2008: No. 48, Versión Preliminar [Preliminary Version], Quito – Ecuador, 123 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2012a. Anuario Meteorológico [Meteorological Yearbook]—2009: No. 49, Quito – Ecuador, 102 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2012b. Anuario Meteorológico [Meteorological Yearbook]—2010: No. 50, Versión Preliminar [Preliminary Version], Quito – Ecuador, 139 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2014. Anuario Meteorológico [Meteorological Yearbook]: No. 51-2011, Quito – Ecuador, 149 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2015. Anuario Meteorológico [Meteorological Yearbook]: No. 52-2012, Quito – Ecuador, 153 p. Available online at: https://inamhi.website/anuarios-metereologicos/

INAMHI (Instituto Nacional de Meteorologia e Hidrologia [National Institute of Meteorology and Hydrology]), 2017. Anuario Meteorológico [Meteorological Yearbook]: No. 53-2013, Quito – Ecuador, 165 p. Available online at: https://inamhi.website/anuarios-metereologicos/

International Cyanide Management Institute, 2021a. The International Cyanide Management Code: June 2021, 14 p. Available online at: https://cyanidecode.org/wp-content/uploads/2021/06/01-The-Cyanide-Code-JUNE-2021.pdf

International Cyanide Management Institute, 2021b. Guidance for use of the Mining Operations Verification Protocol: June 2021, 93 p. Available online at: https://cyanidecode.org/wp-content/uploads/2021/06/15-Mining-Guidance-JUNE-2021.pdf

International Cyanide Management Institute, 2021c. Mining Operations Verification Protocol: June 2021, 22 p. Available online at: https://cyanidecode.org/wp-content/uploads/2021/06/14-Mining-Verification-Protocol-JUNE-2021.pdf

Johnson, C.A., D.J. Grimes, and R.O. Rye, 2000. Fate of process solution cyanide and nitrate at three Nevada gold mines inferred from stable carbon and nitrogen isotope measurements: Transactions of the Institution of Mining and Metallurgy, Section C, vol. 109, pp. C68-78.

Johnson, C.A., D.J. Grimes, R.W. Leinz, G.N. Breit, and R.O. Rye, 2001. The critical importance of strong cyanocomplexes in the remediation and decommissioning of cyanidation heap leach operations: In C. Young (Ed.), Cyanide—Social, Industrial and Economic Aspects (pp. 35-49), The Minerals, Metals & Materials Society, Warrendale, Pennsylvania, 582 p.

Johnson, C.A., R.W. Leinz, D.J. Grimes, and R.O. Rye, 2002. Photochemical changes in cyanide speciation in drainage from a precious metal ore heap: Environmental Science and Technology, vol. 36, pp. 840-845.

Johnson, C.A., D.J. Grimes, R.W. Leinz, and R.O. Rye, 2008. Cyanide speciation at four gold leach operations undergoing remediation: Environmental Science and Technology, vol. 42, pp. 1038-1044.

Johnson, C.A., 2015. The fate of cyanide in leach wastes—An environmental perspective: Applied Geochemistry, vol. 57, pp. 194-205.

Junta Administradora de Agua Potable [Drinking Water Administrative Board] (JAAP) "Río Manduriacu Chico", 2023. Acta de la Primera Asamblea Extraordinaria [Minutes of the First Extraordinary Assembly]: García Moreno, November 12, 2023, 3 p.

Klohn Crippen Berger, 2017. Study of tailings management technologies: Report to Mine Environment Neutral Drainage (MEND) Program, MEND Report 2.50.1, 164 p. Available online at: http://mend-nedem.org/wp-content/uploads/2.50.1Tailings_Management_TechnologiesL.pdf

Laboratorio [Laboratory] Anncy, 2023. Informe de Ensayos [Test Report] No. 29576-01: Report to Asociación de Propietarios de Tierras Rurales del Norte del EC, December 5, 2023, 1 p.

Laitos, J.G., 2012. The current status of cyanide regulations: Engineering and Mining Journal, February 2012. Available online at: https://www.e-mj.com/features/the-current-status-of-cyanide-regulations/

Laitos, J.G., 2013. Cyanide, mining, and the environment: Pace Environmental Law Review, vol. 30, pp. 869-949. Available online at: https://digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1728&context=pelr

MAATE (Ministerio del Ambiente, Agua y Transición Ecológica [Ministry of the Environment, Water and Ecological Transition]), 2023a. Asunto—Minería-DCA—Notificación a la concesión minera El Corazón (Cód. 401133), ubicada en la provincia de Imbabura [Subject—Mining-DCA—Notification to the El Corazón mining concession (Code 401133), located in the province of Imbabura]: Memorandum to J.E. Cisneros (Gerente General [General Manager], Agroindustrial El Corazón S.A.), Oficio Nro. [Job No.] MAATE-SCA-2023-4410-O, November 8, 2023, 4 p.

MAATE (Ministerio del Ambiente, Agua y Transición Ecológica [Ministry of the Environment, Water and Ecological Transition]), 2023b. Informe Técnico de la Inspección de Control y Seguimiento a la Concesión Minera El Corazón Cód. (401133), ubicada en la provincia de Imbabura [Technical Report of the control and monitoring inspection of the El Corazón mining concession Code (401133), located in the province of Imbabura]: Informe Técnico [Technical Report]—MAATE-DCA-INF-2023-3999, November 8, 2023, 24 p.

MAATE (Ministerio del Ambiente, Agua y Transición Ecológica [Ministry of the Environment, Water and Ecological Transition]), 2024a. Asunto—Minería—Pronunciamiento a las observaciones del plan de acción y programa de remediación ambiental del evento ambiental ocurrido el 04 de noviembre de 2023, en la concesión minera El Corazón (Cód. 401133), provincia de Imbabura (Aprobado) [Subject—Mining—Statement on the observations on the plan of action and environmental remediation program for the environmental event that occurred on November 4, 2023, in the El Corazón mining concession (Code 401133), province of Imbabura (Approved)]: Letter from N.F. Sarrade Gastelu (Subsecretaria de Calidad Ambiental [Undersecretary of Environmental Quality]) to J. Escobar Cisneros (Gerente General [General Manager], Agroindustrial El Corazón S.A.), Oficio [Job] Nro. MAATE-SCA-2024-0935-O, April 5, 2024, 3 p.

MAATE (Ministerio del Ambiente, Agua y Transición Ecológica [Ministry of the Environment, Water and Ecological Transition]), 2024b. Análisis a las observaciones del componente biótico al estudio de la fauna acuática del plan de acción y programa de remediación ambiental en la concesión minera "El Corazón" Código 401133 [Analysis of the observations of the biotic component to the study of aquatic fauna of the action plan and environmental remediation program in the "El Corazón" mining concession Code 401133]: Informe Técnico [Technical Report]—MAATE-DCA-INF-2024-245, April 1, 2024, 12 p.

MEM (Ministerio de Energía y Minas [Ministry of Energy and Mines]), 2023. Informe Técnico de inspección técnica de control y seguimiento al incidente referente a la descarga de efluentes de la Relavera Nro. 15 en la Concesión Minera "El Corazón" Código 491133 [Technical Report of technical inspection of control and monitoring of the incident regarding the discharge of effluents from Tailings Pond No. 15 in the "El Corazón" Mining Concession Code 491133]: Informe [Report] No. ARCERNNR-CZI-FSV-2023-0136-ME, Coordinación Zonal de Imbabura [Imbabura Zonal Coordination], November 2023, 9 p.

MERNNR (Ministerio de Energía y Recursos Naturales No Renovables [Ministry of Energy and Non-Renewable Resources]), 2020a. Acuerdo [Agreement] Nro. MERNNR-MERNNR-2020-0043-AM, 27 p. Available online at: https://www.recursosyenergia.gob.ec/wp-content/uploads/2020/07/MERNNR-MERNNR-2020-0043-AM-Instructivo-aprobacion-proyectos-relaves-mineria-FIRMADO.pdf

MERNNR (Ministerio de Energía y Recursos Naturales No Renovables [Ministry of Energy and Non-Renewable Resources]), 2020b. Anexo II—Guía técnica para la presentación de proyectos de diseño de los depósitos de relaves [Appendix II—Technical guide for the presentation of tailings deposit design projects], 25 p. Available online at: https://www.recursosyenergia.gob.ec/wp-content/uploads/2020/08/ANEXO-II_GUIA-TECNICA-PROYECTOS-DE-DISE%C3%91O.pdf

MERNNR (Ministerio de Energía y Recursos Naturales No Renovables [Ministry of Energy and Non-Renewable Resources]), 2020c. Anexo III— Términos de referencia para la presentación del informe semestral de los depósitos de relaves [Appendix III— Terms of reference for the presentation of the semiannual report on tailings deposits], 4 p. Available online at: https://www.recursosyenergia.gob.ec/wp-content/uploads/2020/08/ANEXO-III_TDR-INFORMES-SEMESTRALES.pdf

Ministerio del Ambiente [Ministry of the Environment], 2015a. Reforma Texto Unificado Legislación Secundaria, Medio Ambiente, Libro VI, Decreto Ejecutivo 3516, Registro Oficial Suplemento 2, 31/03/2003 [Reform Unified Text Secondary Legislation, Environment, Book VI, Executive Decree 3516, Official Registry Supplement 2, 03/31/2003]: Acuerdo Ministerial 97, Registro Oficial Edición Especial 387 de 04-nov.-2015, Estado—Vigente [Ministerial Agreement 97, Official Registry Special Edition 387 of 04-Nov-2015, Status—Current], 75 p. Available online at: https://www.ambiente.gob.ec/wp-content/uploads/downloads/2018/05/Acuerdo-097.pdf

Ministerio del Ambiente [Ministry of the Environment], 2015b. Acuerdo Ministerial 097-A mediante el cual se expiden los Anexos del Texto Unificado del Ministerio del Ambiente [Ministerial Agreement 097-A through which the Annexes are issued of the Unified Text of the Ministry of the Environment], November 4, 2015, 184 p. Available online at: https://www.gob.ec/regulaciones/2156/informacion

Ministry of Energy and Mines (British Columbia), 2016. Guidance document— Health, safety and reclamation code for mines in British Columbia, Version 1.0: Victoria, British Columbia, updated July 2016, 37 p. Available online at: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/mineral-exploration-mining/documents/health-and-safety/part_10_guidance_doc_10_20july_2016.pdf

Morrill, J., D. Chambers, S. Emerman, R. Harkinson, J. Kneen. U. Lapointe, A. Maest, B. Milanez, P. Personius, P. Sampat, and R. Turgeon, 2022. Safety first—Guidelines for responsible mine tailings management: Earthworks, MiningWatch Canada, and London Mining Network: Version 2.0, May 2022, 55 p. Available online at: https://earthworks.org/resources/safety-first/

Mudd, G.M., 2010. The environmental sustainability of mining in Australia—Key mega-trends and looming constraints: Resources Policy, vol. 35, pp. 98-115.

Municipio de Cotacachi [Municipality of Cotacachi], 2023a. Atención a denuncia ciudadana sobre presunta contaminación por parte de la empresa minera El Corazón hacia la quebrada Los Monos y río Manduriaco Chico [Attention to citizen complaint about alleged contamination by the El Corazón mining company towards the Los Monos Creek and the Manduriaco Chico River]: Dirección de Ambiente [Environmental Management], Informe Técnico [Technical Report] Nro. 005-GADMSAC-DBTA-2023, November 23, 2023, 26 p.

Municipio de Cotacachi [Municipality of Cotacachi], 2023b. Informe de inspección al río Manduriaco Chico— Informe de visita in situ para verificar cambio de color repentino de las aguas del Río Manduriaco Chico [Inspection report on the Manduriaco Chico river—Report of on-site visit to verify sudden change in color of the waters of the Manduriaco Chico river]: Prepared by Ángel Paul Gualotuña Pastrano (Director de Desarrollo de la Zona Subtropical-Municipio de Cotacachi [Director of Development of the Subtropical Zone-Municipality of Cotacachi), June 11, 2023, 6 p.

Municipio de Cotacachi [Municipality of Cotacachi], 2024. Proceso Administrativo Sancionador [Administrative Sanctioning Process] Nro. GADMSAC-DA-002-2024: February 19, 2024, 40 p.

Nassar, N.T., G.W. Lederer, J.L. Brainard, A.J. Padilla, and J.D. Lessard, 2022a. Rock-to-metal ratio—A foundational metric for understanding mine wastes: Environmental Science & Technology, vol. 56, pp. 6710-6721. Available online at: https://pubs.acs.org/doi/epdf/10.1021/acs.est.1c07875

Nassar, N.T., G.W. Lederer, J.L. Brainard, A.J. Padilla, and J.D. Lessard, 2022b. Supporting information for Rock-to-metal ratio—A foundational metric for understanding mine wastes: Environmental Science & Technology, vol. 56, pp. 6710-6721. Available online at: https://pubs.acs.org/doi/epdf/10.1021/acs.est.1c07875

NOAA (National Oceanic and Atmospheric Administration), 2024. Climate Data Online: National Centers for Environmental Information. Available online at: https://www.ncei.noaa.gov/cdo-web/

Rivera-Parra, J.L, B. Beate, X. Diaz, and M.B. Ochoa, 2021. Artisanal and small gold mining and petroleum production as potential sources of heavy metal contamination in Ecuador—A call to action: International Journal of Environmental Research and Public Health, vol. 18, 15 p. Available online at: https://www.mdpi.com/1660-4601/18/6/2794

Smith, A.C.S. and T.I. Mudder, 1999. Chapter 11—The environmental geochemistry of cyanide: In Plumlee, G.S. and M.J. Logsdon (Eds.), The environmental geochemistry of mineral deposits—Part A—Processes, techniques, and health issues (pp. 229-248), Reviews in Economic Geology, vol. 6, Part A, 571 p.

The Cyanide Code, 2024. About the Cyanide Code. Available online at: https://cyanidecode.org/about-cyanide-code/

University of Nebraska-Lincoln, 2015. Water Requirements for Beef Cattle. Available online at : https://beef.unl.edu/water-requirements-for-beef-cattle

USACE (U.S. Army Corps of Engineers), 2000. Design and construction of levees: Manual No. 1110-2-1913, 164 p. Available online at: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1913.pdf

USEPA, 2024. National Recommended Water Quality Criteria - Aquatic Life Criteria Table. Available online at: https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table

USGS (U.S. Geological Survey), 2024. Search Earthquake Catalog. Available online at: https://earthquake.usgs.gov/earthquakes/search/

Virginia's Legislative Information System, 2024. HB 85 Mineral mining and processing; use of cyanide or a cyanide compound prohibited. Available online at: https://lis.virginia.gov/cgi-bin/legp604.exe?ses=241&typ=bil&val=Hb85

Wisconsin State Legislature, 2001. 2001 Assembly Bill 95. Available online at: https://docs.legis.wisconsin.gov/2001/related/proposals/ab95

World Gold Council, 2019a. Responsible Gold Mining Principles: September 2019, 19 p. Available online at: https://www.gold.org/industry-standards/responsible-gold-mining

World Gold Council, 2019b. Guidance on implementing and assuring the RGMPs—Supplement to the Assurance Framework: September 2019, 36 p. Available online at: https://www.gold.org/industry-standards/responsible-gold-mining