Implications of the 2001 Baseline Study and the 2021-2023 Water Report for the Impact of the Rio Tinto QMM Ilmenite Mine on Downstream Water Quality, Southeastern Madagascar

Steven H. Emerman, Malach Consulting, 785 N 200 W, Spanish Fork, Utah 84660, USA,
E-mail: SHEmerman@gmail.com, Tel: 1-801-921-1228

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ABSTRACT

The Rio Tinto QMM ilmenite mine in southeastern Madagascar generates water enriched in radionuclides and lead, which it releases through intentional discharge into wetlands bordering a river and through accidental groundwater seepage and dam overspills. The QMM 2021-2023 Water Report and a newly available 2001 baseline study were evaluated to determine the impact of the mine on regional water quality. The 2021-2023 Water Report continues the practice of inconsistent detection limits in previous QMM mine reports. There are numerous contradictions between the graphs in the 2021-2023 Water Report and the accompanying spreadsheet data, so that it is impossible to determine which are the correct data. Combining the spreadsheet data with all of the existing surface water-quality data showed that the increases in the geometric means of the total uranium and lead concentrations from the upstream to the downstream side of the QMM mine by factors of 24 and 4.9, respectively, were statistically significant at better than the 99.999% confidence level for uranium and the 99.99% confidence level for lead, thus confirming the detrimental impact of the QMM mine on regional water quality. Further confirmation came through comparison of the baseline total uranium concentrations with all of the concentrations measured downstream of the QMM mine after the mine began operation, which showed that the increase in uranium concentration by a factor of 884 from before to after opening the mine was statistically significant at the 99.999999999% confidence level. The total lead concentrations clearly increased after opening of the mine, but the increase could not be evaluated quantitatively due to inconsistencies in the detection limits.

EXECUTIVE SUMMARY

The Rio Tinto QMM mine is located on the shores of the estuaries Lake Besaroy and Lake Ambavarano in Anosy region on the coastline of the southeastern tip of Madagascar. The QMM mine extracts ilmenite, monazite, and Zirsill (a blended mixture of zircon, sillimanite and quartz) from heavy mineral sands by creating shallow (5 to 15 meter-deep), unlined water-filled basins and then physically separating the economic minerals using a floating dredge plant. The arithmetic mean and maximum uranium concentrations in the water in the mining basins are 1.115 mg/L and 1.748 mg/L, respectively, so that the maximum is over 58 times the WHO drinking water guideline for uranium (0.03 mg/L). The hypothesis is that the process of dredging the heavy mineral sands and then returning the tailings to the mining basins causes the radionuclides uranium and thorium, as well as lead, which is the decay product of the radionuclides, to be transferred from sorption sites on the sands into the dissolved form in the mining basins. The possible release of radionuclides and lead into surface water and groundwater is a matter of great concern for public health, since there are 15,000 people living within a few kilometers of the QMM mine, of whom the majority obtain all of their drinking and culinary water from surface water.

There are numerous pathways for either intentional or accidental release of contaminants into the downstream lakes and waterways. Although Rio Tinto states that the mine uses 0% freshwater and has 100% water recirculation, diagrams from the company show the inputs of fresh groundwater, precipitation and surface runoff into the mining operation. The constant influx of groundwater from the highly permeable beach sands must eventually be released into the environment. The excess water has been discharged at three release points into wetlands that are adjacent to the Mandromondromotra River, only one of which (WMC603) was used during 2021-2023. Prior to 2022, the mine wastewater was discharged into the wetlands with no treatment except for settling ponds. A pilot water treatment plant was commissioned in July 2022 that uses crushed limestone to raise the pH and precipitate metals, followed by addition of an unknown polymer for further sorption of contaminants.

The mining basins are confined by dams constructed from tailings with a height of 4 meters. Accidental release of contaminants can occur due to spills of the water from the mining basins over the dams, which were reported in 2010, 2018, February 2022 and March 2022. Future overtopping events could potentially erode away the dam, thus releasing the entire contents of the mining basin. Smaller precipitation events could cause a rise in the water level in the mining basins above the water table, which would result in the seepage of water out of the basin and into the surrounding groundwater. Any monazite present in the tailings dam could be another unconfined source of radionuclides and lead. An inevitable source of accidental release of contaminants is the existence of the mining operation, especially the mining basins and their tailings dams, in the bed of Lake Besaroy. A previous report by the author used satellite imagery and elevation data to show that the mining operation had advanced 117 meters onto the bed of the estuary, in violation of the agreement between Rio Tinto and ONE (National Office of the Environment) that required a 50-meter buffer zone between any mining activities and the estuary. Rio Tinto has admitted the encroachment, but claims that the mine has advanced only 90 meters into the buffer zone, or 40 meters onto the bed of the estuary. The intentional release of water from the mining basins into groundwater is also required by the mining operation, which involves raising the water elevation to 2 meters above sea level for three-week periods in order to float the dredge and concentrator over a rocky basal ridge.

Previous water-quality data for the region around the QMM mine have been released by Rio Tinto on three occasions as part of an independent radioactivity study in 2019, as a report to Rio Tinto by the consulting company JBS&G in 2020, and as a QMM water report in 2021. The fundamental problem with the succession of data releases is that each set of water-quality data is reported and interpreted independently with no reference to or integration with previous datasets. By contrast, a sequence of three previous reports by the author have integrated all existing water-quality data to demonstrate the detrimental impact of the QMM mine on regional water quality. The first report by the author included water samples that had been collected by the community and analyzed at the University of Utah. The third report by the author, which was an evaluation of all existing data through the 2021 QMM water report, confirmed the detrimental impact of the QMM mine by showing that the increases in the geometric means of the total uranium and lead concentrations in surface water from the upstream to the downstream side of the mine by factors of 9.7 and 5.75, respectively, were statistically significant at better than the 99% confidence level for uranium and better than the 99.9% confidence level for lead. Maximum downstream uranium and lead concentrations were 52 and 40 times the WHO drinking water guidelines, respectively, for water analyses reported by Rio Tinto. The maximum uranium concentration measured in a downstream waterway (52 times the WHO guideline) was only slightly less than the maximum concentration measured in the QMM mining basin (58 times the WHO guideline).

The QMM 2021-2023 Water Report was released by Rio Tinto in December 2023 and continues the practice of reporting and interpreting only the new water-quality data from April 2021 through December 2023 with no reference to or integration with previous datasets. Although not included with the publicly available 2021-2023 Water Report, an accompanying spreadsheet was provided to Andrew Lees Trust, which was then shared with the author. The 2021-2023 Water Report compares surface water-quality data for 10 elements, including lead, with Malagasy decree limits, in addition to data for uranium, for which there is no Malagasy decree limit. Although elsewhere Rio Tinto claims to abide by international water-quality standards, the Malagasy decree limits are considerably weaker than international standards. For example, the Malagasy decree limit for lead is 0.2 mg/L, while the WHO drinking water guideline is 0.01 mg/L and the US EPA aquatic life criterion is 0.0025 mg/L. Since the wastewater from the QMM mine is discharged into waterways that are both aquatic habitat and the source of water for human consumption, the wastewater ought to comply with both drinking water and aquatic standards.

Since the third report by the author on water quality near the QMM mine in 2021, a 2001 baseline study by CDN Water Management Consultants has become available. The baseline study by CDN Water Management Consultants measured surface water quality for six elements, including uranium and lead, at three sites upstream and two sites downstream of the current mine location. Although the 2001 baseline study is certainly useful, it cannot be regarded as completely adequate. In order to capture the seasonal and annual variations in surface water quality, it is typical to collect baseline water samples monthly for three years. By contrast, the 2001 baseline study collected water samples only once in December 1999 and once in February-March 2000, both sampling times occurring during the rainy season.

The objective of this report was to answer the following questions:

1) Does the QMM 2021-2023 Water Report include consistent and credible data?
2) Is the monitoring program described in the QMM 2021-2023 Water Report adequate for the detection of downstream contamination?
3) When the new data in the QMM 2021-2023 Water Report are integrated with all of the existing surface water-quality data, do aqueous concentrations of radionuclides and lead increase from the upstream to the downstream side of the mine?
4) When the newly available data in the 2001 baseline study are compared with all of the existing surface water-quality data downstream of the mine, do aqueous concentrations of radionuclides and lead increase from before to after the opening of the mine?

Two methodological issues were the highly variable frequencies of sample collection and the inconsistent detection limits. For example, according to the 2021-2023 Water Report, samples were collected for measurement of lead at stations S46 (upstream) and S41 (downstream) on 10 occasions from March 9-18, 2022, including twice on March 16, 2022. By contrast, the next sample collection for measurement of lead took place on June 20, 2022, while the previous collections took place on April 8, 2021, and July 30, 2021. As a second example, sample collections in the Méandre River and Lake Ambavarano have not taken place since December 2, 2019, and no sample has been collected from Lake Besaroy since April 18, 2018. In order to avoid biasing the results toward periods with greater frequency of sample collection, statistics were carried out on monthly arithmetic means of each parameter at each sampling site.

Inconsistent detection limits involved multiple detection limits for a single parameter without explanation, reported measurements with values that were lower than the stated detection limits, and unreasonably high detection limits. In the case of the surface water-quality data included in a 2019 independent radioactivity study, the detection limits were so inconsistent that it was assumed that the technicians did not understand the meaning of a detection limit and measurements reported as less than a detection limit were excluded from the statistics. The 2001 baseline study included similar inconsistent detection limits for cadmium, lead and zinc, but not for aluminum, iron, and uranium. For the elements in the baseline study with inconsistent detection limits, only qualitative comparisons were made with downstream concentrations after the opening of the mine. For the elements in the baseline study with consistent detection limits, quantitative comparisons were made with the concentrations below the detection limit set to half the detection limit. For all other measurements below the detection limit in the data released prior to the QMM 2021-2023 Water Report, statistics were carried out on concentrations set at half the detection limit. The practice of inconsistent detection limits was continued in the 2021-2023 Water Report, but only for aluminum, for which measurements below the detection limit were reported as either <0.05 mg/L or <0.5 mg/L. It was assumed that the expression <0.5 mg/L was a typographical error and those measurements were set to 0.025 mg/L, along with all measurements reported as <0.05 mg/L. For all other measurements below a detection limit in the 2021-2023 Water Report, statistics were carried out on concentrations set at half the detection limit.

The greatest concern with the consistency and credibility of the data in the QMM 2021-2023 Water Report was that there were numerous contradictions between the graphs in the report and the data in the accompanying spreadsheet. It was not possible to assign values to all of the data points on the graphs, but it was relatively easy to compare the maximum values for each parameter at each sample site between the spreadsheet and the graphs. No attempt was made in this report to document every contradiction between the spreadsheet and the graphs. It was impossible to determine whether the graphs or the spreadsheet had the correct data and it was not clear as to why there were two versions of the same dataset. Due to the difficulty in assigning values to data points on the graphs, the spreadsheet data was used for the statistical comparisons in this report.

The current surface water monitoring program is designed to detect only intentional releases of contaminants into the wetlands bordering the Mandromondromotra River. The QMM 2021-2023 Water Report includes water-quality data only from the discharge point WMC603 and sites S46 and S41, which are 1487 meters upstream and 916 meters downstream, respectively, from the probable point of entry of contaminants into the Mandromondromotra River. In a similar manner, the previous 2021 QMM water report included water-quality data only from the discharge points and sites WS0501 and WS0502, which are farther upstream and downstream, respectively, from the points of entry into the Mandromondromotra River. Thus, the current monitoring program is incapable of detecting accidental releases of contaminants into the Méandre River, Lake Besaroy or Lake Ambavarano. The monitoring program is also incapable of detecting intentional releases of contaminants into groundwater (which could emerge into the Méandre River, Lake Besaroy or Lake Ambavarano) during the three-week periods when the water level is raised above sea level for floating the dredge and concentrator. It has already been pointed out that no water samples have been analyzed from the Méandre River or Lake Ambavarano since 2019, and no samples has been analyzed from Lake Besaroy since 2018.

Combining the spreadsheet data with all of the existing surface water-quality data showed that the increases in the geometric means of the total uranium and lead concentrations from the upstream to the downstream side of the QMM mine by factors of 24 and 4.9, respectively, were statistically significant at better than the 99.999% confidence level for uranium and the 99.99% confidence level for lead, thus confirming the detrimental impact of the QMM mine on regional water quality. The geometric mean of the total uranium concentration on the downstream side of the mine was 0.0495 mg/L or 1.65 times the WHO drinking water guideline (0.03 mg/L). The increases in the geometric means of the total cadmium and zinc concentrations from the upstream to the downstream side of the QMM mine by factors of 1.5, and 1.75, respectively, were not statistically significant at the 95% confidence level. The lack of change in cadmium and zinc concentrations from the upstream to the downstream side of the mine is not surprising, since there is no apparent reason as to why the ore processing should result in enrichment of the mine process water in those elements, so that cadmium and zinc concentrations in surface water are probably naturally occurring.

A surprising result was that the increase in the geometric mean of the total aluminum concentration from the upstream to the downstream side of the QMM mine by a factor of 1.9 was statistically significant at the 95% confidence level. Moreover, the decrease in the geometric mean of the total iron concentration from the upstream to the downstream side of the mine by a factor of 3.1 was highly statistically significant ($P = 8 \times 10^{-10}$). Although Rio Tinto relates the enrichment in aluminum to the acidification of the mining basin water during dredging of the heavy mineral sands, it is not at all obvious why this would happen. A possible explanation for the depletion in iron is that some chemical species in the mine wastewater is causing the precipitation of iron in the Mandromondromotra River. There has been insufficient disclosure of the ore processing technology and the chemistry of the mineral sands to identify the relevant chemical species or to understand the acidification of the mining basin.

A comparison of the baseline total uranium concentrations with all of the total uranium concentrations measured downstream of the QMM mine after the mine began operation showed that the increase in uranium concentration by a factor of 884 from before to after opening the mine is statistically significant at the 99.999999999% confidence level, thus further confirming the detrimental impact of the QMM mine on regional water quality. The increase in aluminum concentration by a factor of 2.1 from before to after opening the mine is statistically significant at better than the 95% confidence level. The decrease in iron concentration from before to after opening the mine is not statistically significant at the 95% confidence level. A quantitative comparison of the baseline total lead concentrations with all of the total lead concentrations measured downstream of the QMM mine after the mine began operation was not possible. However, a qualitative comparison of baseline total lead concentrations of <0.001 mg/L (eight times), <0.005 mg/L (one time) and <0.01 mg/L (two times) with the geometric mean of the total lead concentration of 0.0064 mg/L downstream of the QMM mine after the mine began operation clearly showed the detrimental impact of the QMM mine on regional water quality.

The addition of limestone to mine wastewater in order to raise the pH in the pilot water treatment plant can cause the precipitation of dissolved metals, but typically only of cations (positively charged ions), such as aluminum. However, raising the pH can mobilize elements that occur in the dissolved form as oxyanions (negatively-charged ions that include oxygen), such as arsenic, selenium, and uranium. In that way, raising the pH can increase the concentrations of arsenic, selenium, and uranium in wastewater. The specific polymer that is added in the pilot water treatment process is not stated in the QMM 2021-2023 Water Report, nor are there any publicly available test results that would demonstrate the ability of the water treatment process to adequately treat the wastewater from the QMM mine, especially in terms of uranium, thorium, and lead. The 2021-2023 Water Report refers to a “polishing pond” as the final step before the wastewater is discharged into the wetlands that border the Mandromondromotra River. “Polishing” normally refers to improving water quality from a relatively pure state to an “ultrapure” state and the discharge of treated wastewater into a settling pond is not normally referred to as “polishing.”

This report makes the following recommendations:

1) Rio Tinto must provide consistent and credible data on surface water quality in the vicinity of the QMM mine.
2) Rio Tinto must monitor surface water quality in the Méandre River, Lake Ambavarano and Lake Besaroy.
3) Rio Tinto must provide evidence that the water treatment plant can adequately treat the wastewater from the QMM mine, especially in terms of uranium, thorium, and lead.
4) Rio Tinto must provide safe drinking water to the 15,000 people who live in the vicinity of the QMM mine.

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OVERVIEW

The QMM mine is located on the shores of the estuaries Lake Besaroy and Lake Ambavarano in Anosy region on the coastline of the southeastern tip of Madagascar (see Figs. 1 and 2). The mine is owned by QIT Madagascar Minerals S.A. (QMM), which is a subsidiary of Rio Tinto that is owned 80% by Rio Tinto and 20% by the Government of Madagascar. The QMM mine extracts ilmenite and Zirsill (a blended mixture of the minerals zircon, sillimanite and quartz) from heavy mineral sands by creating shallow (5 to 15 meter-deep), unlined water-filled basins and then physically separating the economic minerals using a floating dredge plant (see Fig. 3) (QIT Madagascar Minerals, 2015; Randriantseheno et al., 2015; Rio Tinto, 2023a). The quartz grains that are not incorporated into Zirsill are returned to the mining basin (see Fig. 3). Prior to 2018, monazite was also returned to the mining basin. However, since 2018, monazite has been extracted from the mineral sands and exported for extraction of rare earth elements (Rio Tinto, 2020a, 2021a). The ilmenite is exported for the production of titanium dioxide, an industrial product that is used to produce ultra-white pigments for paints, papers, cosmetics, toothpaste and food.

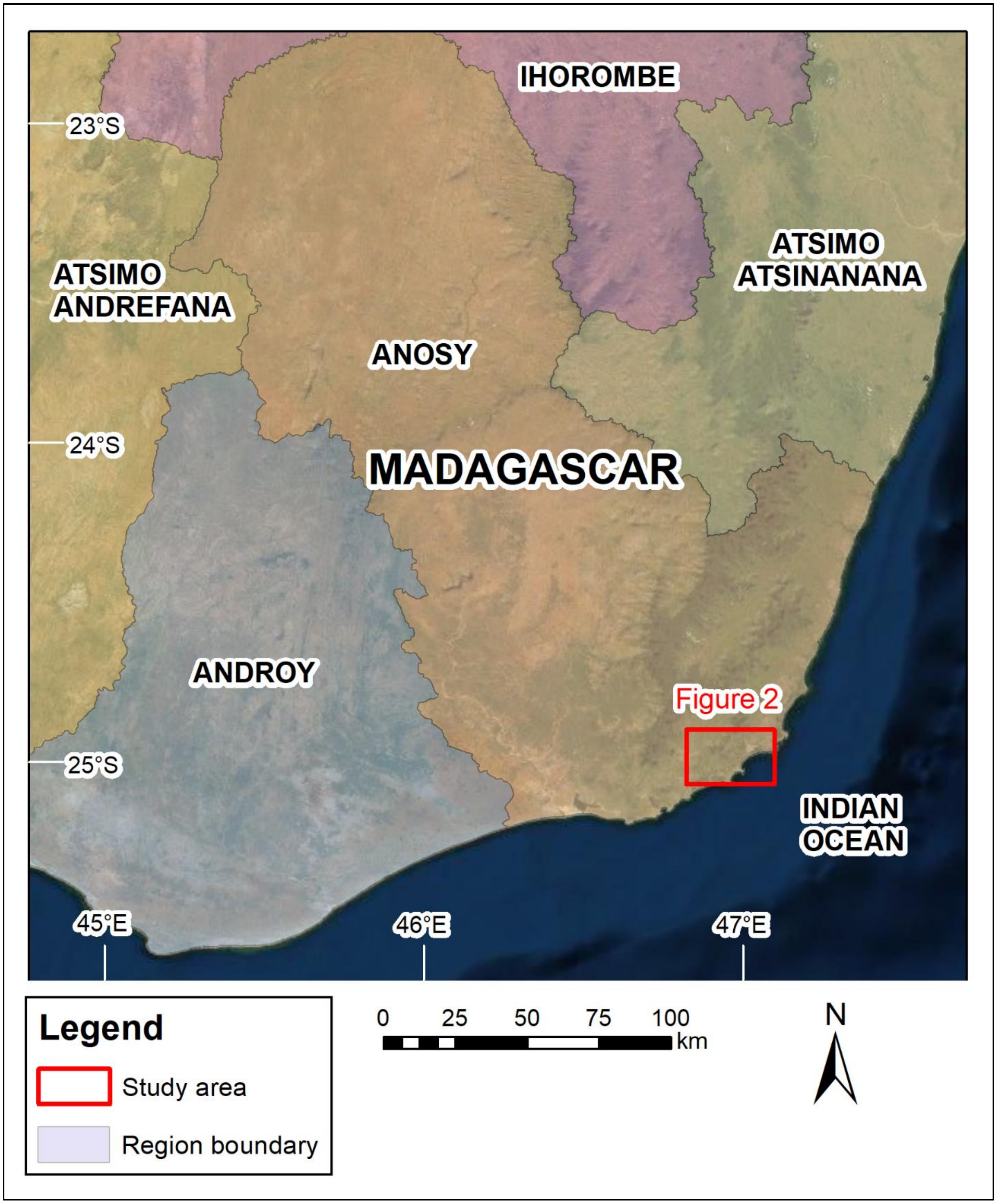


Figure 1. Five studies (Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) have reported measurements of surface water quality upstream and downstream of the QMM mine, which is located within Anosy region on the southeastern tip of Madagascar.

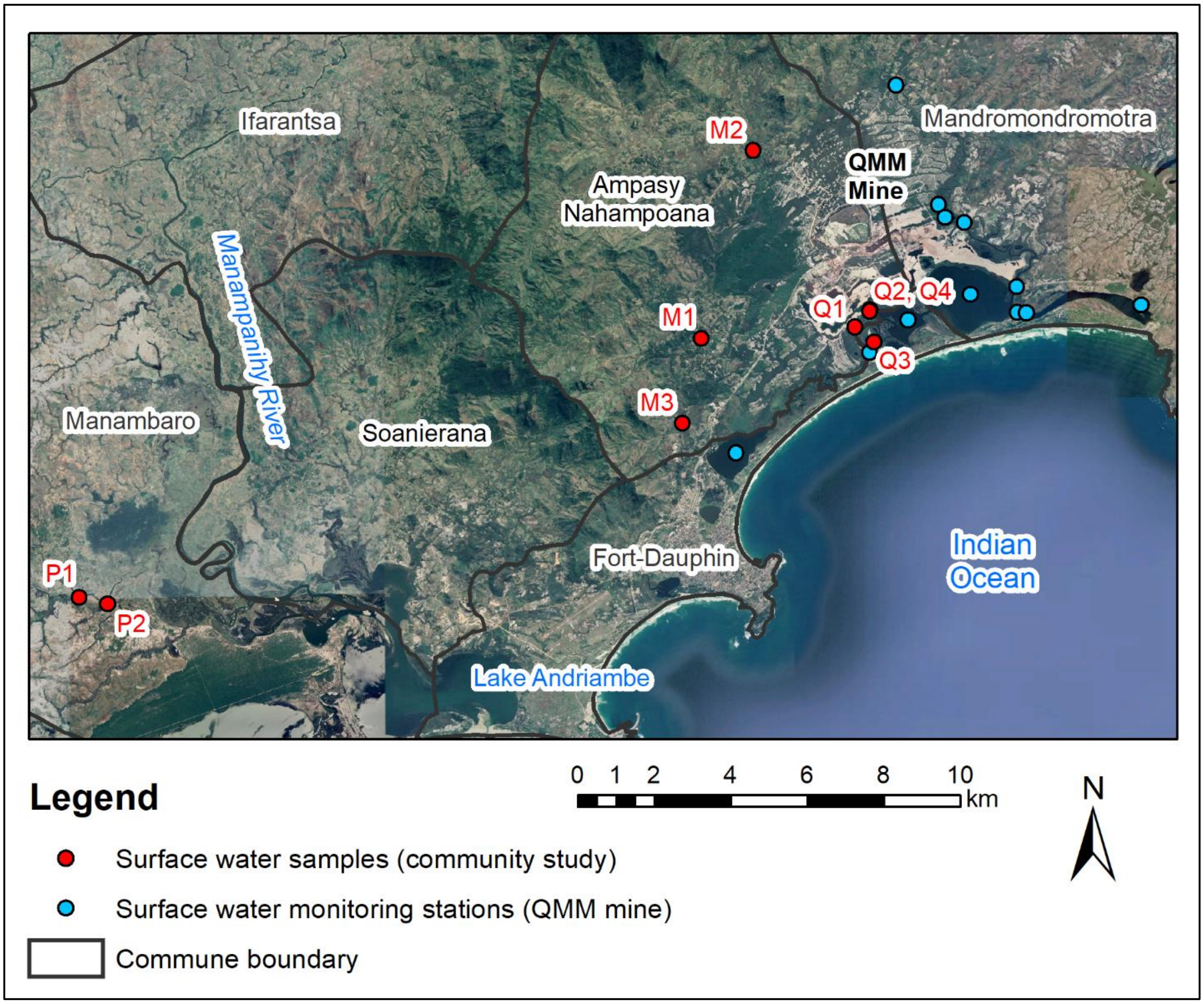


Figure 2. Prior to 2021, the Rio Tinto QMM mine had monitored surface water quality at 12 stations, two of which were upstream from the mine and 10 of which were downstream (Swanson, 2019b-c). Emerman (2019) reported water-quality analyses of samples collected by local residents from nine additional sites, three of which are upstream from the mine (M1, M2, M3), and four of which are downstream from the mine (Q1, Q2, Q3, Q4). Two other sample sites (P1, P2) are outside of the watershed of the mine, but could be indicative of background water quality, since they are not downstream from mineral sands mining. Background is composite of Google Earth images from October 13, 2018, and August 24, 2020. See larger-scale map in Fig. 1.

Using data provided by the QMM mine, Swanson (2019a) reported an arithmetic mean uranium concentration of 1.115 mg/L and maximum uranium concentration of 1.748 mg/L, based upon 99 samples of water collected from mining basins, so that the maximum is over 58 times the World Health Organization (WHO) drinking water guideline for uranium (0.03 mg/L) (WHO, 2022). The radionuclide uranium tends to be associated with other radionuclides, such as thorium, as well as lead, which is the decay product of both uranium and thorium. In this case, the common co-occurrence of lead with radionuclides would result not from radioactive decay within the water of the mining basin, but from long-term (over geologic time) radioactive decay in whatever source is providing radionuclides to the mining basin. According to Swanson (2019a), "The QMM mine definitely releases more uranium into water on the site, thus creating an enhanced source of uranium to the Mandromondromotra River and Lac Ambavarano" (see

Figs. 4a-c). The possible release of radionuclides and lead into surface water and groundwater is a matter of great concern for public health, since there are 15,000 people living within a few kilometers of the QMM mine, of whom the majority obtain all of their drinking and culinary water from surface water, as well as fish and other natural products (Swanson, 2019b-c).

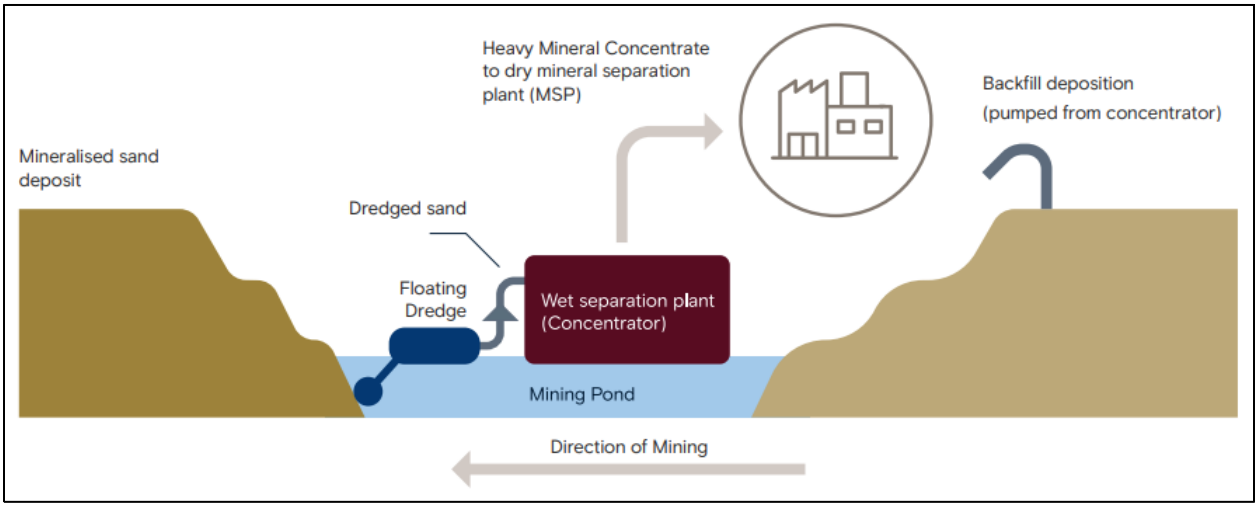


Figure 3. The heavy mineral sands are mined by constructed unlined water-filled basins with depths 5 to 15 meters and then excavating the sands using floating dredges. The mixing of the sands with water during dredging results in the transfer of radionuclides and lead from their sorbed (attachment) sites on sand grains into the dissolved form within the mining basin, so that the mining basin becomes progressively enriched in radionuclides and lead. Figure from Rio Tinto (2023a).

Previous surface water-quality data for the region around the QMM mine have been released by Rio Tinto on three occasions as part of an independent radioactivity study (Swanson, 2019b-c), as a report to Rio Tinto by the consulting company JBS&G that was a companion report to another radioactivity study (JBS&G, 2020a-b), and as a QMM water report entitled “QMM Water Discharge Monitoring Data—March 2021” (Rio Tinto, 2021b). The fundamental problem with the succession of data releases is that each new set of water-quality data has been reported and interpreted independently with no reference to or integration with previous datasets.

By contrast, a sequence of three previous reports by the author (Emerman, 2019, 2020, 2021) have integrated all surface water-quality data existing at the time of report release to demonstrate the detrimental impact of the QMM mine on regional water quality. The first report by the author (Emerman, 2019) included water samples that had been collected by the community and analyzed at the University of Utah. The third report by the author (Emerman, 2021), which was an evaluation of all existing data through the 2021 QMM water report (Rio Tinto, 2021b), confirmed the detrimental impact of the QMM mine by showing that the increases in the geometric means of the total uranium and lead concentrations in surface water from the upstream to the downstream side of the mine by factors of 9.7 and 5.75, respectively, were statistically significant at better than the 99% confidence level for uranium and better than the 99.9% confidence level for lead. Maximum downstream uranium and lead concentrations were 52 and 40 times the WHO drinking water guidelines, respectively, for water analyses reported by Rio Tinto and included in the independent radioactivity study by Swanson (2019b-c). The maximum uranium concentration measured in a downstream waterway (52 times the WHO guideline) was only slightly less than the maximum concentration measured in a mining basin (58 times the WHO guideline) (Swanson, 2019a).

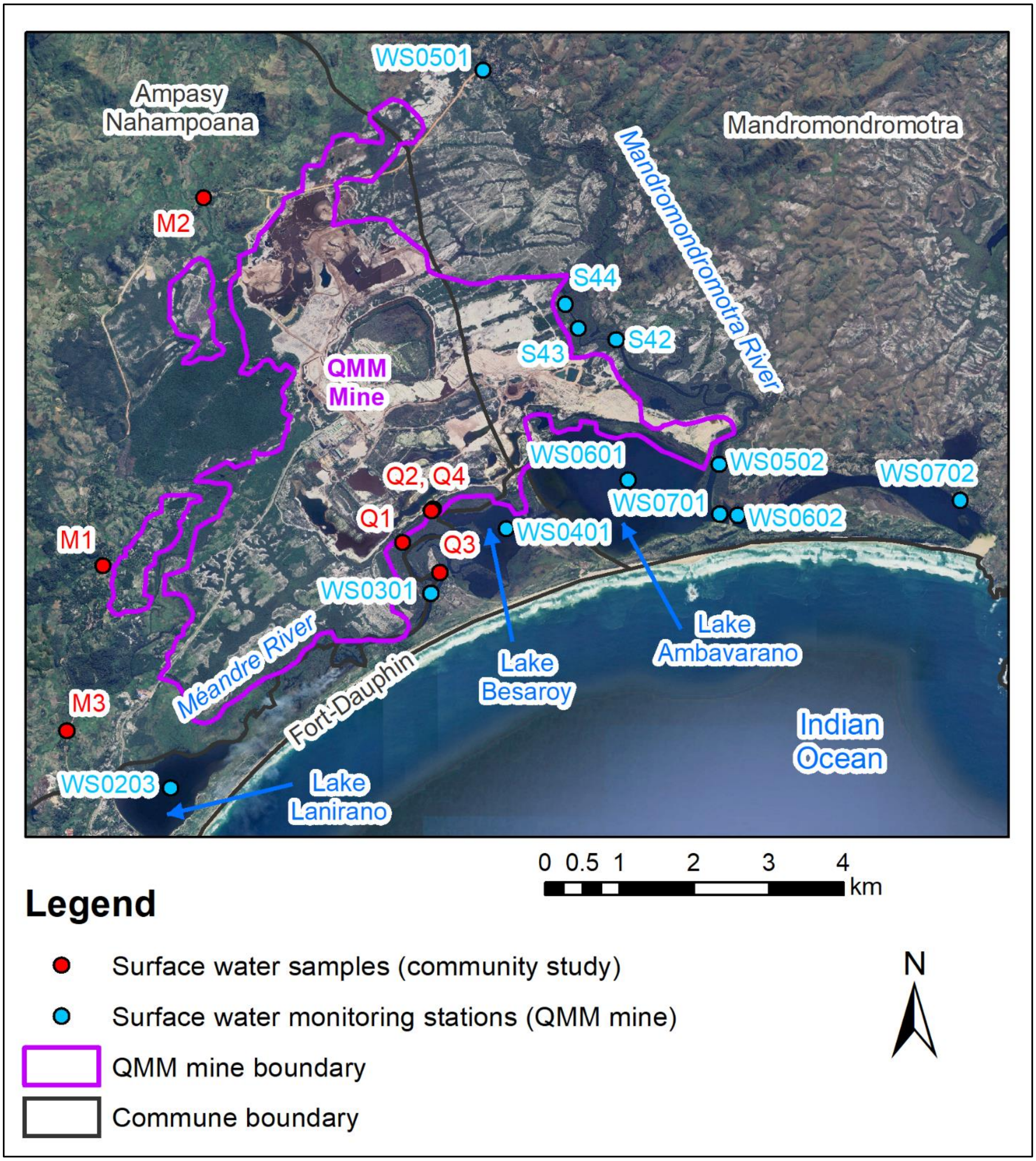


Figure 4a. QMM surface water monitoring stations WS0501 and WS0203 are upstream of the mine, while the other stations are downstream. QMM water-monitoring stations S42, S43, and S44 on the Mandromondromotra River are downstream sites because they are adjacent to the points where mine wastewater enters the river after being discharged into the wetlands to the southwest of the river. Emerman (2019) questioned the validity of the data collected by the QMM mine, based upon the high and ambiguous detection limits for lead and uranium. However, based upon a comparison of measurements of community-collected samples at Q3 and QMM-collected samples at WS0301, the QMM dataset was accepted as valid. QMM mine boundary traced from JBS&G (2020b). Background is Google Earth imagery from May 4 and June 25, 2023. See larger-scale map in Fig. 2.

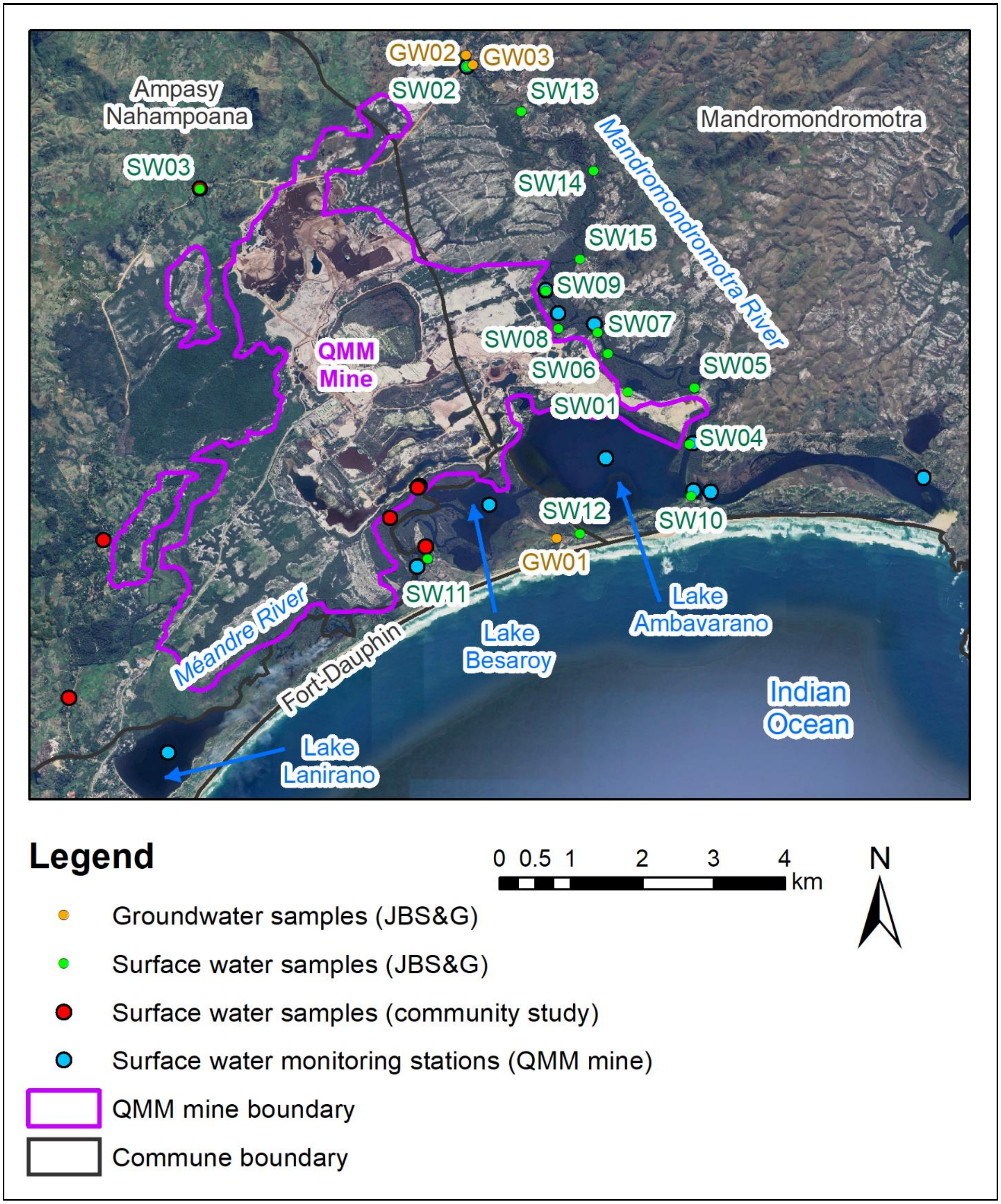


Figure 4b. JBS&G (2020b) reported analyses of groundwater samples from two upstream sites (GW02, GW03) and one downstream site (GW01), as well as surface water samples from four upstream sites (SW02, SW03, SW13, SW14) and ten downstream sites (SW04-SW12, SW15). The analysis of downstream site SW01 was withheld because it was "not considered a potential POU [Point of Use] drinking water sample". Sites SW07-SW09 and SW15 on the Mandromondromotra River are downstream sites because they are adjacent to the points where mine wastewater enters the river after being discharged into the wetlands to the southwest of the river. QMM mine boundary traced from JBS&G (2020b). Background is Google Earth imagery from May 4 and June 25, 2023

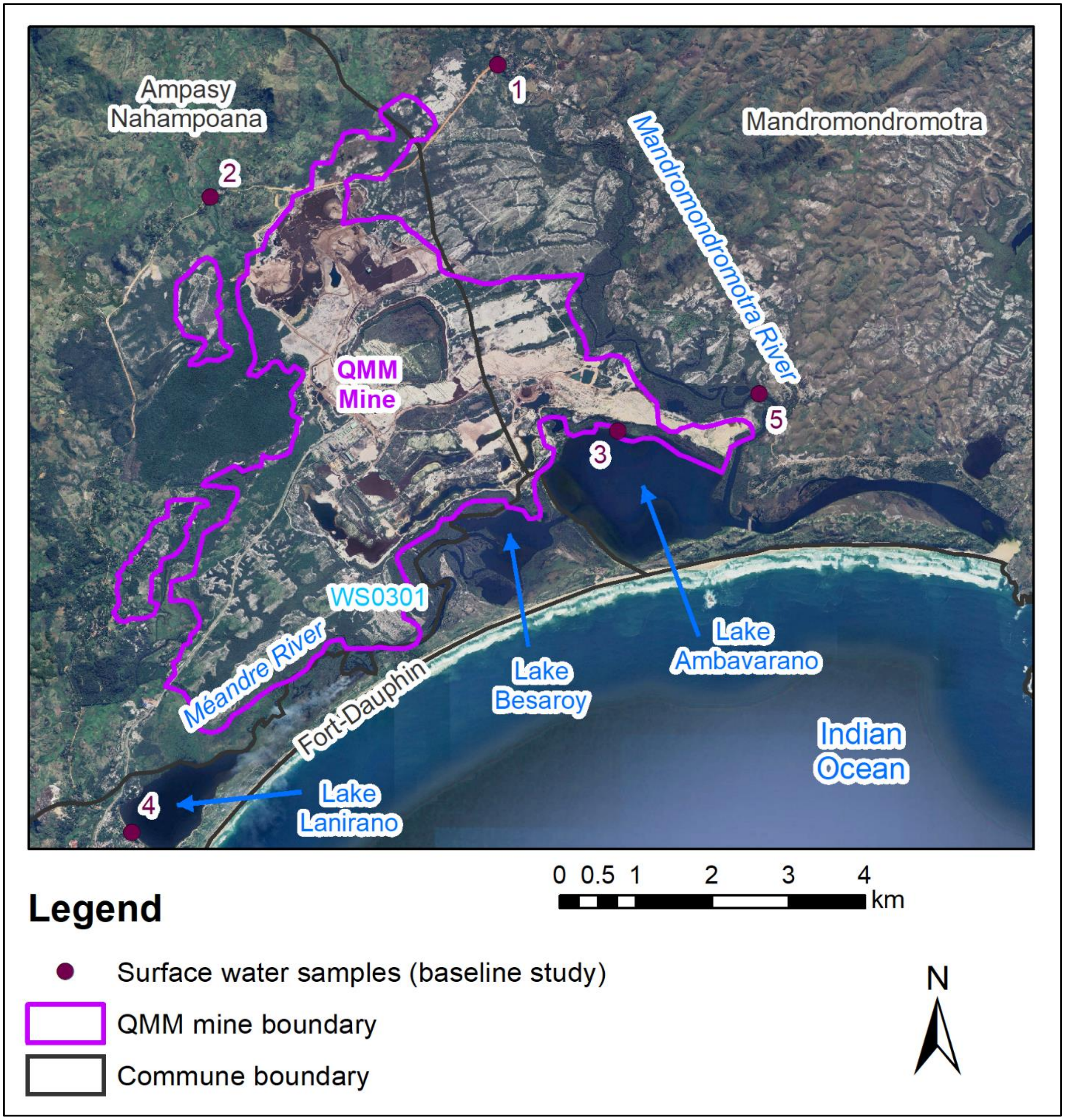


Figure 4c. CDN Water Management Consultants (2001a-b) carried out a baseline study of surface water quality at five sites before the QMM mine was constructed (see Table 2). Samples were collected in December 1999 and February-March 2020 and analyzed for total concentrations of aluminum, cadmium, iron, lead, uranium, and zinc (see Tables 3a-b). Background is Google Earth imagery from May 4 and June 25, 2023.

The QMM 2021-2023 Water Report was released by Rio Tinto (2023a) in December 2023 and continues the practice of reporting and interpreting only the new surface water-quality data from April 2021 through December 2023 with no reference to or integration with previous datasets. Although not included with the publicly available 2021-2023 Water Report, an accompanying spreadsheet was provided to Andrew Lees Trust by Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto), which was then shared with the author. Since the third report by the author on water quality near the QMM mine in Emerman (2021), a baseline study carried out by CDN Water Management Consultants (2001a-b) before the QMM mine opened in 2009 has become available, although not to the general public. A second baseline study by SENES Consultants (2001) is referenced in Swanson (2019b). The second baseline study is still not available to the author nor to the general public and it is not clear why Rio Tinto commissioned two baseline studies by two different consulting firms in the same year.

The objective of this report was to answer the following questions:

1) Does the QMM 2021-2023 Water Report include consistent and credible data?
2) Is the monitoring program described in the QMM 2021-2023 Water Report adequate for the detection of downstream contamination?
3) When the new data in the QMM 2021-2023 Water Report are integrated with all of the existing surface water-quality data, do aqueous concentrations of radionuclides and lead increase from the upstream to the downstream side of the mine?
4) When the newly available data in the 2001 baseline study are compared with all of the existing surface water-quality data downstream of the mine, do aqueous concentrations of radionuclides and lead increase from before to after the opening of the mine?

Before addressing the methodology for answering the above questions, this report includes a review of water contamination by the QMM mine, including the mechanisms for enrichment of the mining basins with radionuclides and lead, the pathways for release of radionuclides and lead from the QMM mine, and the previous water-quality studies. The review of the QMM mine is followed by summaries of the relevant aspects of the QMM 2021-2023 Water Report (Rio Tinto, 2023a) and the 2001 baseline study (CDN Water Management Consultants, 2001a-b).

Key statistical concepts in this report are the geometric mean and statistical significance. Since Emerman (2020) includes a tutorial on statistical significance and Emerman (2021) includes an appendix on the concept of the geometric mean, those statistical concepts are not reviewed in detail in this report. Briefly, the geometric mean is a statistical measure of the expected value of a set of measurements. The average (or arithmetic mean) is another type of measure of the expected value. The geometric mean avoids giving excessive weight to very large values and is commonly used when measured values range over several orders of magnitude. Statistical significance is a measure of the extent to which differences in sets of measurements (such as the difference between a set of measurements upstream of a mine and downstream of a mine) are real, as opposed to artifacts of the variability within each set of measurements. The common practice is to disregard differences that are not statistically significant at better than the 95% confidence level. The statistical measure P is the probability that two sets of measurements are statistically indistinguishable, so that $P = 0.05$ corresponds to 95% confidence level with smaller values of P indicating greater confidence that two sets of measurements are statistically distinguishable.

A key concept in water chemistry is the distinction between dissolved and total concentrations, which is reviewed in an appendix in Emerman (2021). Briefly, dissolved concentrations are determined by filtering the water sample before digestion and instrumental analysis, so that any contaminants that are sorbed (attached) to small particles are not measured. Total concentrations are determined without filtering the water sample before digestion and instrumental analysis, so that the measurement is a sum of both dissolved contaminants and contaminants that are sorbed to small particles. For the analysis of drinking water, the standard practice is to measure total concentrations as a measure of the total load of contaminants that is experienced by the water consumer. This point is emphasized by Saar (1997), “If direct ingestion from a drinking water source is involved, whole, unfiltered samples … are needed.” Therefore, since the concern with regard to the QMM mine is the release of contaminants into sources of drinking water, total concentrations are most relevant in this case. Further information about this subject is available in Emerman (2021) and in the section “Summary of QMM 2021-2023 Water Report” in this report.

REVIEW OF WATER CONTAMINATION BY QMM MINE

Mechanisms for Enrichment of Mining Basins with Radionuclides and Lead

The generation of water that is enriched in radionuclides and lead is a common environmental consequence of the mining of heavy mineral sands. The heavy minerals monazite and zircon tend to include uranium and thorium in the crustal structures. According to Rio Tinto (2020a), “Zircon may have traces of thorium and uranium, whilst monazite contains thorium.” In fact, in the case of the QMM mine, even after mixing the zircon with non-radioactive sillimanite and quartz, the Zirsill still contains 463 ppm of uranium and thorium (Elmer, 2013). For comparison, most countries, including the U.S., Japan, and the European Union, do not allow the import of zircon concentrates containing more than 500 ppm of uranium and thorium (Elmer, 2013; World Nuclear Association, 2014). As already mentioned, since the radionuclides uranium and thorium are present within the heavy mineral sands, lead must also be present due to radioactive decay. Rio Tinto has not released any chemical analysis of any of the minerals contained within the heavy mineral sands.

Some enrichment of the mining basin water with radionuclides and lead occurs as a result of the concentration of the radioactive minerals in the heavy mineral sands after the non-radioactive minerals have been removed. However, for the QMM mine, there is insufficient concentration of radioactive minerals to account for the level of uranium within the mining basins. The most recent analysis of upstream uranium concentrations prior to this report documented a geometric mean uranium concentration of 0.008 mg/L for total uranium (Emerman, 2021), so that a comparison with the mean uranium concentration (1.115 mg/L) reported in the mining basins (Swanson, 2019a) would imply a mineral concentration factor of 139. Such a high degree of concentration of radioactive minerals within the heavy mineral sands is not plausible, especially since, according to Rio Tinto (2020a), “Approximately 95 percent of the sand excavated is returned to the pond.” An additional factor arguing against the importance of concentration of radioactive minerals within the mining basins is that the radioactive monazite has not been returned to the mining basins since 2018 (Rio Tinto, 2020a, 2021a).

The explanation for the documented high uranium concentrations within the mining basin water must be sought within the processes of creating a mining basin, dredging the heavy mineral sands from the mining basins and then returning the mine tailings to the same basin. Even in the absence of mining, the slow dissolution of zircon and monazite will release uranium, thorium and lead from sites in the crystal structures. In the absence of a mining basin that could accept the released contaminants in dissolved form, these elements will attach to sorption sites on the heavy mineral sand grains. The creation of a mining basin then allows the transfer of sorbed radionuclides and lead into the mining basin water as dissolved elements. Without dredging, a boundary layer of water would form on top of the heavy mineral sands. This boundary layer would contain a concentration of dissolved contaminants that was in equilibrium with the sorbed contaminants, which would inhibit any further transfer of contaminants into the dissolved phase. The process of dredging would bring heavy mineral sand grains into contact with relatively fresh mining basin water, which would promote further transfer of radionuclides and lead into the dissolved phase. The suspension of sand grains would further promote the transfer of contaminants into the dissolved phase simply by increasing the surface area of sand grains in contact with water. The return of the mine tailings would cause additional suspension of sand grains with even more transfer of radionuclides and lead into the mining basin water in the dissolved phase.

The preceding mechanism for enrichment of the mining basins with radionuclides and lead should be regarded as a hypothesis that cannot yet be confirmed either experimentally or computationally without detailed information regarding the chemistry and mineralogy of the heavy mineral sands. However, it should be emphasized that only the mechanism of enrichment in uranium is in doubt. The existence of elevated uranium within the mining basins has already been documented by Swanson (2019a) using data provided by the QMM mine. At the time that Swanson (2019a) wrote her report, it could have been supposed that the elevated uranium in the mining basins was simply the naturally occurring background uranium in the surface water of this region. In fact, in their response that was included as an addendum to Swanson (2019b), Rio Tinto wrote, "QMM acknowledges that the region has a high natural background radiation level that existed prior to the commencement of mining, and that fully understanding the impacts of mining is scientifically challenging … As was determined before the commencement of mining the area surrounding QMM has naturally elevated levels of radiation. This is a result of the surrounding geological conditions and this leads to naturally enhanced levels of uranium in drinking water. This is not a QMM related impact and is an aspect of the water used by local communities before the commencement of construction or operations at QMM" (Swanson, 2019b). However, subsequent data collected by both the local residents and external consultants hired by Rio Tinto have established the low background level of uranium in both surface water and groundwater upstream from the QMM mine (Emerman, 2019, 2020; JBS&G, 2020b). These subsequent data will be further discussed in the subsection on "Previous Water-Quality Studies."

A final point will be made regarding the reference to the heavy mineral sands that are returned to the mining basin after removal of the commodity of value (see Fig. 3) as "tailings." At the 2022 Annual General Meeting (AGM) of Rio Tinto, Simon Thompson, Chair of the Board of Directors, stated, "There are no tailings at QMM. And we take mine tailings management extremely seriously." It is, of course, a matter of great concern that the senior management at Rio Tinto does not understand the meaning of "tailings," although the company claims to take the matter "extremely seriously." According to the SME (Society for Mining, Metallurgy and Exploration) Surface Mining Handbook, "Tailings are fine-grained mineral waste that remains after processing and recovery of the minerals of economic interest, along with process water and chemical reagents added during the milling or beneficiation stages" (Snow and Morrison, 2023), so that the sands that are returned to the mining basin are exactly what is meant by "tailings." In their formal response to an earlier report by Emerman (2018a), Rio Tinto (2019) did not hesitate to refer to the sands that are returned to the mining basins as "tailings." According to Rio Tinto (2019), "Within the mining industry, rock or materials not retained for their economic value during the refining process are referred to as 'tailings.' This term can refer broadly to a number of different types of discarded rock or materials, and in the case of QMM it is sometimes used to refer to the ordinary sand that is returned to the pond after separating the ilmenite." In a similar way, the 2001 baseline study stated, "The orebody contains between 4 and 12% total heavy minerals … The balance of the orebody consists of between 88 to 95% quartz (silica) sand and 1 to 2% finely divided clays. The majority of this material will be rejected as tailings during the separation process at the mine" (CDN Water Management Consultants, 2001a-b). The significance of the current refusal by Rio Tinto to use the word "tailings" will be addressed in the following subsection.

Pathways for Release of Radionuclides and Lead from the QMM Mine

Due to the elevated levels of radionuclides and lead within the mining basins, the intentional or accidental release of the water from the mining basins into either surface water or groundwater could pose a significant threat to human and aquatic life. The release of water from the mining basins to surface water is actually required by the operation of the QMM mine. In order to prevent seepage of water out of the mining basins and into groundwater, the water level is maintained 1-2 meters below the level of the neighboring water bodies (QIT Madagascar Minerals, 2015). On that basis, there must be a constant influx of groundwater into the mining basins through the highly-permeable beach sands, which must eventually be released into the environment.

Although the QMM 2021-2023 Water Report states that the mine uses 0% freshwater and has 100% water recirculation, a diagram in the same report shows the input of freshwater through groundwater, precipitation, and surface runoff (see Fig. 5). The 2001 baseline study confirmed that fresh groundwater would flow into the mining basins, that freshwater would be required by the mining operation, and that a weir at the outlet of Lake Ambavarano would be required to guarantee that fresh groundwater would flow into the mining basins. According to CDN Water Management Consultants (2021a), "A fresh water lens is present overlying salt water under the coastal dunes … From the ocean shore, a salt-water wedge extends inland under a freshwater lens … Construction of a gated salinity control structure [weir] at the outlet of Lac Ambavarano will provide a freshwater environment upstream while maintaining the fluctuation of lake levels similar to natural conditions." The weir was actually constructed in 2007 prior to opening the mine in 2009 (Publiez Ce Que Vous Payez [Publish What You Pay] Madagascar, 2022). Although not stated in any available document from the mining company, it should be assumed that the entrance of saline groundwater into the mining basins would result in the precipitation of salts onto all components of the ore processing plant and the rest of the mining operation. According to Vyawahare (2023), "QMM built this dam [weir] at the edge of Lake Ambavarano to prevent saltwater intrusions, turning it and the area's other brackish estuarine lakes into freshwater bodies so the water would be compatible with mine's machinery." Finally, it is not at all clear what is meant by "100% water recirculation" (see Fig. 5).

According to Swanson (2019b-c) and Rio Tinto (2021b), this excess water has been discharged at several release points into wetlands that are adjacent to the Mandromondromotra River (see Fig. 6). Only release point WMC603 was used during the period 2021-2023 (Rio Tinto, 2023a). The total volumes of water released during 2022 and 2023 were 3.25 and 2.98 million cubic meters, respectively, corresponding to average discharge rates of 103 L/s and 94 L/s (Rio Tinto, 2023a). Based on the average streamflow of the Mandromondromotra River of 1910 L/s (CDN Water Management Consultants, 2001a), the discharges of mine wastewater were 5.4% and 4.9% of the flow of the Mandromondromotra River in 2022 and 2023, respectively. The total release volume for 2023 is probably an underestimate, since the QMM 2021-2023 Water Report (Rio Tinto, 2023a) was released before the year had ended.

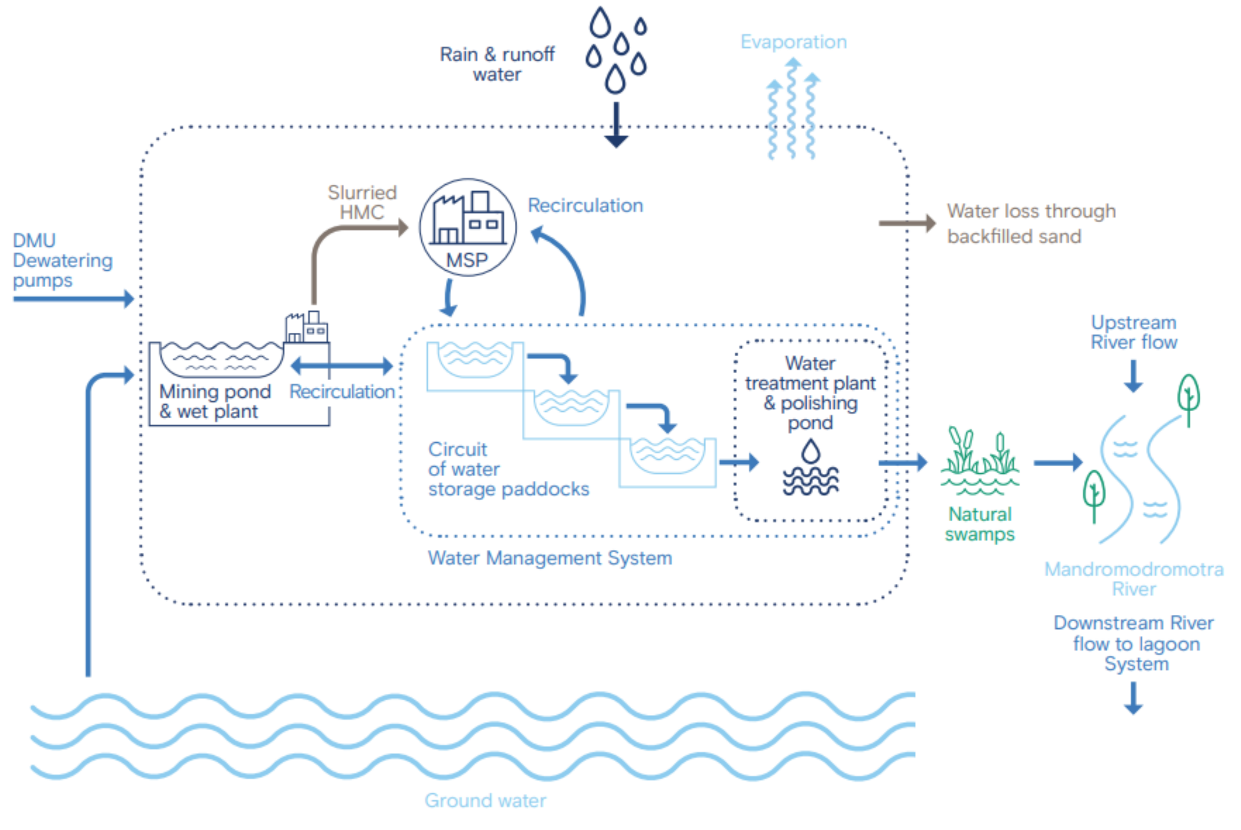


Figure 4: QMM simplified water flow diagram

Figure 5. Although Rio Tinto (2023a) states that the QMM mine uses 0% freshwater and has 100% water recirculation, the diagram above shows the input of freshwater through groundwater, precipitation, and surface runoff. Figure from Rio Tinto (2023a).

Prior to 2022, the only treatment of the mine effluent water was a "biodiversity control pond" or "settling pond" (Swanson, 2019b) that was intended to remove suspended solids and any heavy metals that will sorb onto the solid particles. The passage of the mine wastewater through the wetlands resulted in further removal of suspended particles and sorption of metals, so that the wetlands were acting as a kind of natural settling pond. From the wetlands, any contaminants could travel to the Mandromondromotra River and downstream the river to the Indian Ocean (see Figs. 4a-c). However, because the water bodies along the shoreline constitute an estuary system in which water can also flow upstream as tidal currents, contaminants could travel upstream through Lakes Ambavarano and Besaroy and possibly as far as Lake Lanirano (Swanson, 2019b). According to Rio Tinto (2019), the construction of a weir at the inlet/outlet between Lake Ambavarano and the Indian Ocean (see Figs. 4a-c) eliminated the effect of tidal currents.

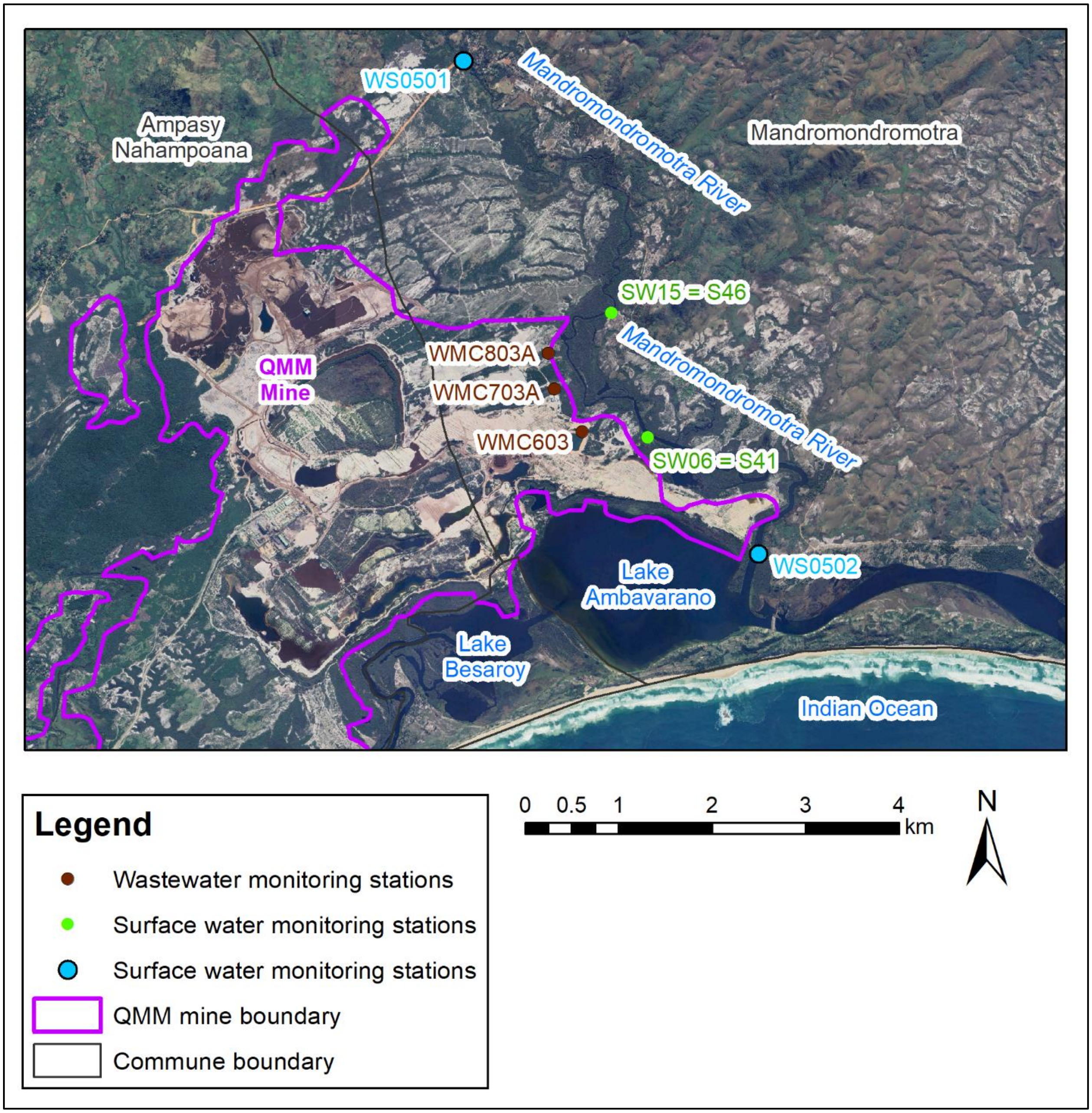


Figure 6. Wastewater from the QMM mine is released at stations WMC803A, WMC703A, and WMC603, but only WMC603 was used during the period covered by the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The 2021 water report (Rio Tinto, 2021b) relied on WS0501 and WS0502 as upstream and downstream stations, respectively, to monitor the impact of mine wastewater discharge on the Mandromondromotra River. By contrast, the 2021-2023 Water Report relied on stations S46 (identical to SW15; see Fig. 4b) and S41 (identical to SW06; see Fig. 4b) as upstream and downstream stations, respectively. The choice to report only surface water quality from stations S41 and S46 meant that downstream contamination could be detected only if it occurred due to intentional release of mine wastewater at discharge point WMC603 (the only discharge point in use during 2021-2023). In particular, the monitoring program made it impossible to detect unintentional release of contaminants into Lake Besaroy, Lake Ambavarano, or the Méandre River, which flows into Lake Besaroy (see Figs. 4a-c). Background is Google Earth imagery from May 4 and June 25, 2023.

A pilot water treatment plant was commissioned in July 2022 that uses crushed limestone to raise the pH and precipitate metals, followed by addition of an unknown polymer for further sorption of contaminants, prior to discharge of the mine wastewater into the wetlands. However, not all of the mine wastewater passes through the water treatment plant. The QMM 2021-2023 Water Report distinguishes between "normal operations" in which there is a "controlled release of water through the water treatment plant and polishing pond at the approved release point WMC603" and "emergency release of additional volume at the approved release point WMC603" (Rio Tinto, 2023a). The "emergency release" presumably occurs with no treatment other than the passage through the wetlands. In 2022, 1.26 million cubic meters of mine wastewater (72% of all mine wastewater) underwent "emergency release," while 1.72 million cubic meters of mine wastewater (38% of all mine wastewater) underwent emergency release in 2023 (Rio Tinto, 2023a).

Accidental release of the mining basin water into the environment is also possible. The mining basins are confined by 4-meter high dams (6-8 meters above the water level in the mining basin) to prevent overtopping of the basins due to heavy precipitation (QIT Madagascar Minerals, 2015; Emerman, 2018b). An even smaller precipitation event could cause a 1-2 meter rise in the water level, which would result in the seepage of water out of the basin and into the surrounding groundwater. Based upon the topography and the precipitation history, Emerman (2018b) calculated the annual probabilities of seepage from the basins and overtopping of the dams between the basins and the lakes to be 0.18-2.08% and 0.17-0.31%, respectively. Since, according to Rio Tinto (2019), the dams are constructed out of the mine tailings, an overtopping of the dam could destroy the dam completely because water flowing over the downstream embankment could erode away the unconsolidated tailings. Moreover, any monazite present in the tailings dam could be another unconfined source of radionuclides and lead. Finally, Swanson (2019b) noted that the predominant winds from the east to northeast could transport radionuclides as dust into the Méandre River, from where it could flow downstream into Lakes Besaroy and Ambavarano or upstream toward Lake Lanirano (see Figs. 4a-c).

In fact, spills of water from the mining basin over the dams have occurred on at least four occasions, in 2010, December 2018, February 2022, and March 2022 with significant fish kills on each occasion (Orengo, 2022a-c, 2023a-b; Rio Tinto, 2022a-b; Andrew Lees Trust and Publiez Ce Que Vous Payez Madagascar, 2023; Morrill, 2023; Rafitoson, 2023; Vyawahare, 2023). On March 8, 2022, the QMM mine initiated a release of 1 million cubic meters of mine wastewater over a period of seven weeks in order to prevent a catastrophic collapse of the tailings dam with the possibility of the release of the entire contents of the mining basin (Orengo, 2022a). Based on average mining basin area of 16 hectares (Emerman, 2018b) and a typical depth range 5-15 meters (QIT Madagascar Minerals, 2015), the capacity of a typical mining basin filled to the brim would be 0.8-2.4 million cubic meters, so that the release of 1 million cubic meters was 42-127% of the total capacity of a single mining basin. According to Morrill (2023), "One additional incident was reported by the local community in April of 2022 but was denied by QMM." Based on a minimum of four overspill events over the 14 years from the opening of the QMM mine in 2009 through 2023, the annual probability of overtopping has been 28.6% or 92-168 times higher than the annual probability of 0.17-0.31% that was estimated by Emerman (2018b). By analogy, since both overtopping and seepage result from precipitation and surface runoff into the mining basins, the annual probability of seepage from the mining basins would be in the range 30.3% to 349.6% (indicating that three to four seepage events per year are likely). In other words, overtopping of the tailings dams and seepage of water from the mining basins into groundwater are expected events and not at all unusual.

It is now appropriate to return to the significance of the current refusal by Rio Tinto to use the word "tailings." During the same AGM, Simon Thompson, Chair of the Board of Directors of Rio Tinto, stated, "There is no tailings dam at QMM. The berm you refer to is an embankment made of sand which separates the mine from the external environment" (Andrew Lees Trust, 2022). By contrast, the Australian National Committee on Large Dams (ANCOLD) defines a tailings dam as "a structure or embankment that is built to retain tailings and/or to manage water associated with the storage of tailings, and includes the contents of the structure" (ANCOLD, 2012, 2019). According to the Canadian Dam Association (2021), "Tailings dams are containment structures constructed to impound by-products of mining, often with a co-purpose to store supernatant water that is recycled to the process plant …" This type of tailings dam is clearly shown in Fig. 7, which is taken from QIT Madagascar Minerals (2015).

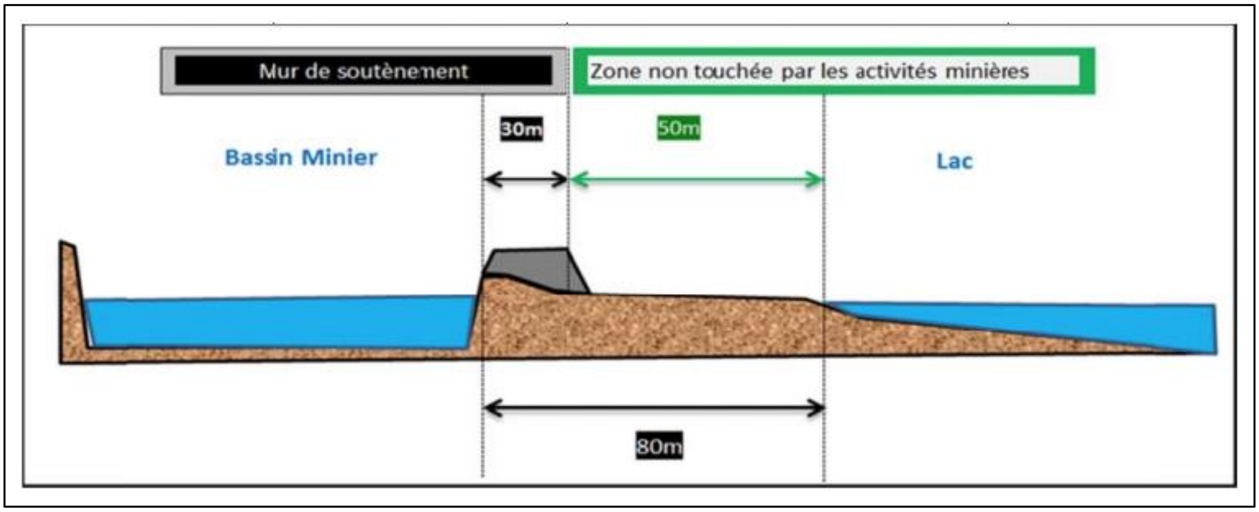


Figure 7. The mining basins are confined by a dam with a height of 4 meters. The dam is constructed out of tailings, that is, the heavy mineral sands that are returned to the mining basins after the commodities of value have been removed (see Fig. 3). Any spill from the mining basin over the dam would be an unintentional pathway for radionuclides and lead to enter downstream lakes and waterways. Reported overspills have occurred in 2010, 2018, February 2022 and March 2022. Emerman (2018a) documented that the mining operation had encroached onto the 50-meter buffer zone by 167 meters, so that the mining operation had advanced 117 meters onto the bed of Lake Besaroy. Translation: Mur de soutènement = retaining wall, Bassin Minier = Mining Basin, Lac = Lake, Zone non touchée par les activités minières = Area not affected by mining activities. Figure from QIT Madagascar Minerals (2015).

The varying uses of "dam," "berm," and "embankment" are not simply a matter of semantics. The refusal to use the expression "tailings dam" does not relieve Rio Tinto of their obligation to conform to tailings dam safety standards. The document Safety First: Guidelines for Responsible Mine Tailings Management explicitly warned against the use of alternative vocabulary to avoid compliance with tailings dam safety requirements. According to Morrill et al. (2022), "Operating companies may avoid using the word 'dam' in an attempt to skirt tailings dam safety requirements. However, it is important to note that these guidelines apply to any engineered structure that contains mine tailings, regardless of the terminology used by the operating company to describe the engineered structure." As a Company Member of the International Council on Mining & Metals (ICMM), Rio Tinto is obligated to fully comply with the Global Industry Standard on Tailings Management (GISTM) (ICMM-UNEP-PRI, 2020; ICMM, 2021, 2024). In fact, Rio Tinto (2024) states, "QMM is scheduled to comply with

GISTM by August 2025," which would make no sense if the QMM mine did not store mine tailings.

The flood design standards for a tailings dam depend upon the consequences of catastrophic failure. According to the GISTM, some characteristics of High consequences include "process water moderately toxic … Potential area of impact 10 km^2 – 20 km^2 … 500-1,000 people affected by disruption of business, services or social dislocation … Potential for short term human health effects. High economic losses affecting infrastructure, public transportation, and commercial facilities, or employment" (ICMM-UNEP-PRI, 2020). The most recent overspill in March 2022 was followed by a massive fish kill and a ban on fishing that lasted for three months (Vyawahare, 2023). According to Orengo (2023a), "A total of 8778 affected villagers submitted complaints after the fishing ban destroyed their livelihoods, compounding ten years of losses and health issues that they attribute to water quality degradation caused by QMM operations." Thus, based upon the toxicity of the water in the mining basins, the number of affected people, and the high economic losses, based upon the GISTM, the tailings dams at the QMM mine should be in the High consequence category at a minimum (more severe consequence categories are Very High and Extreme). These types of tailings dams should be designed to withstand floods with return periods of 2475 years (annual probability of exceedance equal to 0.04%) (ICMM-UNEP-PRI, 2020).

In contrast to the above analysis, Rio Tinto (2024) places the tailings dams at the QMM mine into the Significant consequence category. According to the GISTM, some characteristics of Significant consequences include "No significant loss or deterioration of habitat. Potential contamination of livestock/fauna water supply with no health effects. Process water low potential toxicity … Low likelihood of loss of regional heritage, recreation, community, or cultural assets. Low likelihood of health effects. Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes" (ICMM-UNEP-PRI, 2020). The preceding list is difficult to reconcile with the description by Vyawahare (2023) that "A few days later [following March 5, 2022] … Thousands of dead fish were floating on Lake Ambavarano … In December 2018, following fierce downpours, foul water from the mine flowed into the lakes, several residents told Mongabay. Then, too, the lake waters belched dead fish … The governor of Anosy region, under whose jurisdiction Fort Dauphin falls, told the communities not to eat or sell the fish … The fishing embargo hit meager incomes and made food scarcer … When the fish died, the stench hung over the hamlets for days … Villagers did not want their children, who spend most of their day by the lakeshore, to accidentally eat the fish and fall ill."

Rio Tinto has not released any analysis that explains how it arrived at the Significant consequence category, although it claims that such an analysis was carried out in December 2021 (Rio Tinto, 2023b). Rio Tinto (2023b) lists tailings dams for two facilities at the QMM mine, described as the "Feedprep Pond" and the "Settling Pond." The settling pond includes the additional description "Predominantly a Water Storage Facility. Minerals carried from the Mineral Separation Plant [see Fig. 3] are periodically recovered and re-processed" (Rio Tinto, 2023b), so that the settling pond is clearly different from the mining basin or mining pond (see Figs. 3 and 5). Rio Tinto (2023a) does not explain the meaning of "feedprep pond," but Fig. 2 in Tio Tinto (2023a) shows the "feed prep pond" as a feature that is different from the "mining pond." On that basis, Rio Tinto might not have established any consequence category for the catastrophic failure of the tailings dams for the mining basins, which would be consistent with the claim by the Chair of Rio Tinto that "There is no tailings dam at QMM … There are no tailings at QMM" (Andrew Lees Trust, 2022), but not with the statement by Rio Tinto (2024) that the QMM mine will comply with the GISTM by 2025.

From another perspective, the failure consequence categories of the GISTM relate only to catastrophic failures. The overtopping events in 2010, December 2018, February 2022, March 2022, and possibly in April 2022, were certainly tailings dam failures, but they did not rise to the level of catastrophic failures. 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."

In other words, an actual catastrophic failure of a tailings dam at the QMM mine, with the release of all or nearly all of the contents of a mining basin, could potentially have impacts far greater than the massive fish kills and loss of food and livelihood that were consequences of the recent non-catastrophic tailings dam failures. By contrast, a memorandum from Rio Tinto dated October 3, 2017, referred to the tailings dam shown in Fig. 7 as a "berm" and stated, "Berm Design Criteria specified as a Factor of Safety of 1.3 at the 1 in 50 year flood event lake level" (Rio Tinto, 2017a). It should be clear that design for a 50-year flood is woefully inadequate for a dam that is supposed to prevent the entrance of water enriched in radionuclides and lead into downstream lakes and waterways that are sources of culinary water, as well as fish habitat. According to Emerman (2018a), "The safety criterion used by Rio Tinto is similar to the criterion that would be used for the design of storm drains at a shopping mall parking lot." This criterion can literally be found in Nathanson and Schneider (2014). Even so, the design for a 50-year flood (annual exceedance probability of 2%) is not even close to accurate, since at least four overtopping events have occurred over 14 years.

An inevitable source of accidental release of contaminants into the environment is the existence of the mining operation, especially the tailings dams, in the bed of Lake Besaroy. Emerman (2018a) used satellite imagery and elevation data to show that the mining operation had advanced 117 meters onto the bed of the estuary, in violation of the agreement between Rio Tinto and ONE (National Office of the Environment) that required a 50-meter buffer zone between any mining activities and the estuary (see Fig. 7). Rio Tinto contracted a study from Ozius Spatial (2018) that used Lidar data provided by Rio Tinto to show that the mining operation had encroached 52 meters onto the bed of the estuary. After numerous denials by Rio Tinto (2017a, 2018b) that they had encroached onto the buffer zone at all, Rio Tinto (2019) admitted that the QMM mine had advanced 90 meters into the buffer zone, or 40 meters onto the bed of the estuary. This encroachment onto the estuary is categorized as a source of accidental release of contaminants since Rio Tinto (2019) described the breach of the buffer zone as "an unintended occurrence." The significance of the encroachment of the mining basins and tailings dams onto the bed of Lake Besaroy is the very short pathway required for contaminants to reach the water of the estuary after seepage from the basins into groundwater.

In addition to the possible accidental release of water from the mining basin into groundwater, the intentional release into groundwater is also required by the mining operation. In the first place, the water level that is maintained in the mining basins varies from document to document. According to Rio Tinto (2017a), the Ordinary High Water Mark (OHWM) of Lake Ambavarano, Lake Besaroy and Méandre River is 0.6 meters above sea level, while the mining basin elevation is maintained at 1 meter below sea level for a water-level difference of 1.6 meters. (The elevation of the OHWM was disputed by Emerman (2018a), but is not relevant for this discussion). According to Rio Tinto (2017b), the current objective was to raise the water in the mining basin to between 0-1 meters below sea level for a water-level difference of 0.6-1.6 meters. According to Rio Tinto (2018a, 2019), the water level is maintained 0.5-1.5 meters below sea level for a water-level difference of 1.1-2.1 meters. According to Rio Tinto (2018c), the "typical level" is 0-5 meters below sea level, for a water-level difference of 0.6-5.6 meters. However, Rio Tinto (2018b) committed only that "the dredge pond [mining basin] is *generally* operated at an elevation below the neighboring lakes and below the natural topography" (emphasis added). It is most important that Rio Tinto (2019) eventually asserted that "the pond elevation must be raised to 2 meters above sea level for approximately three weeks in order to float the dredge and concentrator over a rocky basal ridge." In other words, the release of water enriched in radionuclides and lead is deliberate (because the water level in the mining basin is 1.4 meters higher than in the surrounding lakes) for three-week periods (the frequency of the three-week periods was never specified).

Previous Water-Quality Studies

Prior to 2021, in order to monitor the impact of the mine on the regional water quality, the QMM mine collected and analyzed water from 12 surface water sites (see Fig. 4a; Swanson, 2019b). As part of an assessment of the release of radioactive material from the mine, Swanson (2019b) compiled all water-quality data that had been provided to her by Rio Tinto as of August 2018, which included analyses of iron, lead, titanium, thorium, uranium, pH, electrical conductivity, dissolved oxygen, salinity, total dissolved solids, and total suspended solids. According to Swanson (2019b), a total of 60 sets of measurements (a set consists of a site and a sampling date) had been made since June 2015. Not every parameter was measured during every set of measurements. It was not specified whether elemental concentrations were measured from filtered samples (dissolved concentrations) or unfiltered samples (total concentrations).

It is important to note that Swanson (2019b) evaluated almost entirely the chemical concentrations of the radionuclides uranium and thorium, as opposed to the radiation levels. According to Swanson (2019b), "All radionuclide levels in river and lake water samples were well below World Health Organization drinking water guidelines for radiation exposure. However, these measurements were from one sampling event only. Therefore, there is no way of knowing whether these results represent typical conditions. Furthermore, there are several anomalies in the data which indicate that there may be significant problems with the laboratory analysis results. Because the radionuclide data for water were so limited (and questionable), results of analysis of uranium and thorium as heavy metals were evaluated."

Out of 54 measurements of uranium, 20 (37%) were above a detection limit (minimum measurable concentration), all of which exceeded the WHO (2022) drinking-water guideline for uranium (0.03 mg/L). The maximum measured uranium concentration in a downstream waterway was 1.574 mg/L, or over 52 times the WHO (2022) guideline, which was only slightly less than the maximum uranium concentration in a mining basin (58 times the WHO guideline) (Swanson, 2019a). Out of 54 measurements of lead, 27 exceeded a detection limit and 23 (43%) exceeded the WHO (2022) drinking-water guideline for lead (0.01 mg/L). In addition, 27 (50%) measurements of lead exceeded the US EPA (2024a) aquatic standard for lead (0.0025 mg/L), based upon chronic exposure by freshwater organisms. The maximum measured lead concentration was 0.398 mg/L, or almost 40 times the WHO (2022) drinking-water guideline and over 159 times the US EPA (2024a) aquatic standard. WHO (2022) does not have drinking-water guidelines for iron, thorium or titanium. However, the US EPA (2024b) has a secondary drinking-water standard for iron (0.3 mg/L), which is based upon taste, color and odor (which affects the willingness of people, especially children and the elderly, to drink water), rather than health effects. This secondary standard was exceeded in 11 (20%) out of 54 measurements.

Although the water-quality results were alarming, especially for uranium and lead, the lack of water samples collected upstream of the QMM mine made it difficult to assess the impact of the mine based upon the data compiled in Swanson (2019b). Only two out of the 12 QMM water-monitoring stations are located upstream of the mine, which are WS0501 on the Mandromondromotra River and WS0203 on Lake Lanirano (see Fig. 4a). QMM water-monitoring stations S42, S43, and S44 on the Mandromondromotra River are downstream sites because they are adjacent to the points where mine wastewater enters the river after being discharged into the wetlands to the southwest of the river (see Fig. 4a). According to Swanson (2019a), "The primary question is whether the water released from the QMM site causes an increase in uranium in river or lake water; unfortunately, this question cannot definitively be answered because there are no uranium monitoring data for sites which are truly upstream of the QMM site."

In response to the relative lack of upstream samples in the existing dataset, in August 2019 local residents collected surface water samples from nine additional sites, including three upstream sites, five downstream sites, and two sites that were outside of the watershed of the QMM mine (see Figs. 2 and 4a-b; Emerman, 2019). These samples were analyzed at the University of Utah ICP-MS (Inductively-Coupled Plasma – Mass Spectrometry) Metals Lab for both dissolved and total concentrations of 46 elements and isotopes. For comparison of upstream and downstream concentrations, the two sample sites (P1, P2) outside of the watershed were included as upstream samples, since they are not downstream from any heavy mineral sands mining (see Fig. 2). By combining the analyses of the community-collected samples with the analyses from the QMM mine (Swanson, 2019b), Emerman (2019) showed that, from the upstream to the downstream side of the mine, the geometric means of the total concentrations increased from 0.00014 mg/L to 0.049 mg/L, from 0.00011 mg/L to 0.016 mg/L, and from 0.0026 mg/L to 0.0256 mg/L, for uranium, thorium, and lead, respectively. From the upstream to the downstream side of the mine, the geometric means of the dissolved concentrations increased from 0.00008 mg/L to 0.042 mg/L, from 0.00016 mg/L to 0.014 mg/L, and from 0.0018 mg/L to 0.0224 mg/L, for uranium, thorium, and lead, respectively. Since it is not known whether the QMM mine has been measuring dissolved or total concentrations, the reported values (Swanson, 2019b) were used for both the dissolved and the total concentrations, the choice of which had little effect on the results. On the downstream side of the mine, the geometric means of the total concentrations of uranium and lead were 1.63 times and 2.56 times the WHO (2022) drinking-water guidelines (which typically refer to total concentrations). The maximum measured uranium and lead concentrations, which were found downstream of the mine, were still 1.574 mg/L (over 52 times the WHO guideline) and 0.398 mg/L (almost 40 times the WHO drinking-water guideline and over 159 times the US EPA aquatic standard), respectively, as reported by Swanson (2019b).

In April 2020, JBS&G, consultants for Rio Tinto, released two reports, the first being a radioactivity study (JBS&G, 2020a) in the vicinity of the QMM mine in response to the recommendations of Swanson (2019b), and the second entitled "QMM Mandena Mine Madagascar – Incidental water quality sampling report" (JBS&G, 2020b). Nothing in the second report explained the sense in which the report was "incidental." JBS&G (2020b) collected samples from 15 surface water sites and three groundwater sites on December 2, 2019 (see Fig. 4b). Out of the three groundwater sites, two were upstream and one was downstream from the QMM mine (see Fig. 4b). Out of the 14 surface water sites, four were upstream and 10 were downstream from the QMM mine (see Fig. 4b). Sites SW07-SW09 and SW15 on the Mandromondromotra River are regarded as downstream sites because they are adjacent to the points where mine wastewater enters the river after being discharged into the wetlands to the southwest of the river (see Fig. 4b).

JBS&G (2020b) reported concentrations of arsenic, barium, copper, lead, manganese, mercury, titanium, uranium and zinc. JBS&G (2020b) obtained only total concentrations, meaning that they did not filter the samples after collection, so as to remove any solid particles and obtain the dissolved concentrations. According to JBS&G (2020b), "It should be noted that groundwater samples were not filtered prior to sample collection such to be representative of the point of use application (i.e. filtering of water by villagers does not occur prior to consumption)." It is noteworthy that JBS&G (2020b) withheld the analysis of SW01, although it is a downstream site (see Fig. 4b). According to JBS&G (2020b), "SW01 is not considered a potential POU [Point of Use] drinking water sample as it was collected from a mining rehabilitation water pond and therefore the analytical results have not been included in assessment discussed in this report." Without further information, it should be assumed that elevated uranium and lead were measured at site SW01. No other document from Rio Tinto or JBS&G has clarified the meaning of "mining rehabilitation water pond."

In their transmittal of the reports by JBS&G (2020a-b) to Andrew Lees Trust, Rio Tinto (2020b) stated that "all results for community drinking water supply samples were within the relevant WHO guidelines for drinking water quality." In the same way, JBS&G (2020b) summarized the results by stating that "the incidental water quality sampling program did not detect concentrations of selected heavy metals above the WHO (2017) GDWQ [Guidelines for Drinking-Water Quality] guidelines in any of the samples collected as representative POU [Point of Use] samples from locations that are (or may be) accessed by communities surrounding the Site. Further, concentrations of heavy metals were not detected above the WHO (2017) GDWQ guidelines in any of the samples collected from the MMM [Mandromondromotra] River adjacent to mine surface water discharge points, or in any of the sample collected downstream of these discharge points (noting these areas may also be accessed by the community for potable water supply)." Neither the summary by JBS&G (2020b) nor the cover letter by Rio Tinto (2020b) mentioned the existence of any other water-quality data, even though the majority of the existing data had been collected by Rio Tinto (Swanson, 2019b).

In his evaluation of the report by JBS&G (2020b), Emerman (2020) pointed out that the additional data should not be interpreted in the absence of all of the other existing data, which, at that time, included the water-quality data provided by the QMM mine (Swanson, 2019b-c) and the samples collected by the local community (Emerman, 2019). In fact, the integration of the new data from JBS&G (2020b) with the existing data (Swanson, 2019a-b; Emerman, 2019) strengthened the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on regional water quality. In particular, the statistical significance of the increase in the geometric means of total uranium concentrations from the upstream to the downstream sides strengthened from $P = 0.008$ (Emerman, 2019) to $P = 0.003$. The geometric mean of the downstream total uranium concentration decreased to 0.03823 mg/L, but it was still 1.27 times the WHO (2022) guideline for uranium in drinking water. In the same way, the statistical significance of the increase in the geometric means of total lead concentrations from the upstream to the downstream sides strengthened from $P = 0.003$ (Emerman, 2019) to $P = 0.0004$. The geometric mean of the downstream total lead concentration decreased to 0.0141 mg/L, but it was still 1.41 times the WHO guideline for lead in drinking water.

In March 2021 Rio Tinto released a report entitled "QMM Water Discharge Monitoring Data" (Rio Tinto, 2021b), which included water-quality data from 2015 through 2020 from five mine wastewater discharge sites (WMC803, WMC803A, WMC703, WMC703A, and WMC603), as well as stations WS0501 and WS0502 on the Mandromondromotra River, upstream and downstream, respectively, from the discharge sites (see Fig. 6). Discharge sites WMC803 and WMC703 are within the wetlands upstream (southwest) of sites WMC803A and WMC703A, respectively (see Fig. 6). The measured parameters included aluminum, cadmium, lead, uranium, zinc, pH, total dissolved solids, and total suspended solids. In the same manner as the report by JBS&G (2020b), the 2021 QMM water report (Rio Tinto, 2021b) did not include any mention of the existing water-quality data available in Swanson (2019b-c) and JBS&G (2020b), nor the analyses of community water samples and the compilations and interpretations of existing data available in Emerman (2019, 2020). In fact, Emerman (2021) documented numerous contradictions between the uranium concentrations at discharge sites reported in Rio Tinto (2021b) and the uranium in wastewater data reported in Swanson (2019a), although Swanson (2019a) is only an interpretation and compilation of data provided to her by the QMM mine.

There was a partial overlap between the surface water-quality data in Rio Tinto (2021b) and Swanson (2019b). Rio Tinto (2021b) reported the analyses of samples that were collected between June 2015 and December 2020 on 20 dates at WS0501 and 21 dates at WS0502 (see Fig. 6). At WS0501, eight measurements each of lead and uranium repeated data that were available in Swanson (2019b), while at WS0502, three measurements each of lead and uranium repeated data available in Swanson (2019b). In addition to data collected after August 2018 (when all water-quality data were supposed to be provided to Swanson (2019b-c)), Rio Tinto (2021b) included at WS0501 four measurements of lead and three measurements of uranium made prior to August 2018, and at WS0502 eight measurements each of lead and uranium made prior to August 2018 that were not made available to Swanson (2019b-c). There is no indication in Swanson (2019b-c) that the QMM mine was also monitoring aluminum, cadmium and zinc, as was reported in Rio Tinto (2021b). Finally, Rio Tinto (2021b) included no data on iron, titanium or thorium, as was reported in Swanson (2019b). None of the wastewater or surface water monitoring data in Rio Tinto (2021a) were accompanied by any methodology, including no indication as to whether dissolved or total concentrations were measured. For that reason, in the comparisons between upstream and downstream aqueous concentrations, the same values were used for dissolved and total concentrations for all data from Rio Tinto (2021b).

Emerman (2021) carried out a statistical comparisons between water quality upstream and downstream of the QMM mine by an integration of all available data, including the data collected by the QMM mine and reported in Swanson (2019b), the additional data collected by the QMM mine and reported in Rio Tinto (2021b), the community-collected data reported in Emerman (2019), and the data reported in JBS&G (2020b). Emerman (2021) found that the increases in the geometric means of the aqueous uranium concentrations from the upstream to the downstream side of the mine, from 0.0074 mg/L to 0.1459 mg/L for dissolved uranium, and from 0.0080 mg/L to 0.0776 mg/L for total uranium (2.59 times the WHO drinking-water guideline) were statistically significant at better than the 99% confidence level. The increases in the geometric means of the aqueous lead concentrations from the upstream to the downstream side of the mine, from 0.0033 mg/L to 0.0223 mg/L for dissolved lead, and from 0.0032 mg/L to 0.0184 mg/L for total lead (1.84 times the WHO drinking-water guideline) were statistically significant at better than the 99.9% confidence level. Thus, the third report by the author (Emerman, 2021), which was an evaluation of all existing data through the 2021 QMM water report (Rio Tinto, 2021b) showed that total uranium and total lead concentrations increased by factors of 9.7 and 5.75, respectively, from the upstream to the downstream side of the mine. Maximum downstream uranium and lead concentrations were still 52 and 40 times the WHO guidelines, respectively. Increases in aluminum, cadmium and zinc from the upstream to the downstream side of the mine were not statistically significant. In summary, by the time of the release of the QMM 2021-2023 Water Report (Rio Tinto, 2023a) and the 2001 baseline study (CDN Water Management Consultants, 2001a-b), all compilations of existing surface water-quality data (Emerman, 2019, 2020, 2021) had demonstrated the detrimental impact of the QMM mine on regional water quality.

SUMMARY OF QMM 2021-2023 WATER REPORT

The QMM 2021-2023 Water Report (Rio Tinto, 2023a) included surface water-quality data only from April 2021 through December 2023 with no mention of any earlier data or interpretations (Swanson, 2019a-c; Emerman, 2019, 2020, 2021; JBS&G, 2020b; Rio Tinto, 2021b). There was no mention of the baseline water-quality study (CDN Water Management Consultants, 2001a-b), although it was available at the time of release of the 2021-2023 Water Report. In contrast to earlier reports that included data from a wide variety of sites around the QMM mine (see Figs. 2, 4a-b), the QMM 2021-2023 Water Report included data from only wastewater discharge site WMC603 (the only discharge site used during 2021-2023) and sites S46 and S41 on the Mandromondromotra River, upstream and downstream, respectively, from discharge site WMC603 (see Fig. 6).

The 2021-2023 Water Report included measurements of pH, turbidity, and electrical conductivity, and concentrations of aluminum, arsenic, cadmium, chromium, iron, lead, manganese, mercury, nickel, selenium, tin, uranium, and zinc. There were no measurements of barium, copper, thorium, titanium, dissolved oxygen, or total suspended solids. By contrast, measurements of titanium, thorium, dissolved oxygen, and total suspended solids by the QMM mine were reported in Swanson (2019b). Measurements of barium, copper, and titanium were reported by JBS&G (2020b). The 46 elements and isotopes reported by Emerman (2019) for the community-collected samples included barium, copper, and thorium. Finally, measurements of total suspended solids were included in the earlier water report (Rio Tinto, 2021b), although they were omitted from Rio Tinto (2023a). There are empirical relationships for estimating total suspended solids from turbidity, which was reported in Rio Tinto (2023a). However, Rio Tinto (2023a) did not discuss what empirical relationship, if any, was used or tested, so that there is no basis for comparing total suspended solids during the periods 2015-2020 (Swanson, 2019b; Rio Tinto, 2021b) and 2021-2023 (Rio Tinto, 2023a).

The QMM 2021-2023 Water Report includes measurements of pH, turbidity, electrical conductivity, and total concentrations in graphical form with comparison to the Malagasy decree limits (water-quality standards). The accompanying spreadsheet includes both dissolved and total concentrations with many more measurements of total concentrations. The Malagasy regulations (Ministère de l'Energie et des Mines [Ministry of Energy and Mines], 2003a-b; Ministère de l'Environnement [Ministry of the Environment], 2003, 2004) do not specify whether they apply to dissolved or total concentrations. However, as mentioned earlier, since mine wastewater is discharged into sources of drinking water, the comparison with total concentrations is appropriate. The only exception to the comparison with decree limits is uranium, which is not regulated in Madagascar.

Table 1. Comparison of Malagasy decree limits with selected international standards[1]

Element	Malagasy Decree Limit[2] (mg/L)	WHO Drinking Water Guideline[3] (mg/L)	US EPA Secondary Drinking Water Standard[4] (mg/L)	US EPA Aquatic Life Criteria[5] (mg/L)
Al (aluminum)	5.0	—	0.05	complex
As (arsenic)	0.5	0.01	—	0.150
Cd (cadmium)	0.02	0.003	—	complex
Cr (chromium)	2.0	0.05	—	0.085[6]
Fe (iron)	10	—	0.3	1
Hg (mercury)	0.005	0.006	—	0.00077
Mn (manganese)	5.0	0.08	0.05	—
Ni (nickel)	2.0	0.07	—	0.052
Pb (lead)	0.2	0.01	—	0.0025
Se (selenium)	0.02	0.04	—	complex
Sn (tin)	10	—	—	—
U (uranium)	—	0.03	—	—
Zn (zinc	0.5	—	5	0.120

[1] "Complex" indicates that the value is under review or depends upon other aspects of water chemistry.

[2] Rio Tinto (2023a)

[3] WHO (2022)

[4] US EPA (2024b)

[5] Chronic exposure in freshwater (US EPA, 2024a)

[6] Sum of aquatic life criteria for Cr (III) and Cr (IV)

The Malagasy decree limits are actually quite weak in comparison with internationally-recognized water-quality standards (see Table 1). For example, the Malagasy decree limit for lead is 0.2 mg/L, while the WHO (2022) drinking water guideline is 0.01 mg/L, and the US EPA (2024a) aquatic life criterion for chronic exposure in freshwater is 0.0025 mg/L (see Table 1). As a second example, the Malagasy decree limit for arsenic is 0.5 mg/L, while the WHO (2022) drinking water guideline is 0.01 mg/L, and the US EPA (2024a) aquatic life criterion is 0.150 mg/L (see Table 1). Finally, the Malagasy decree limit for aluminum is 5.0 mg/L, while the US EPA (2024b) secondary drinking water standard for aluminum is 0.05 mg/L (see Table 1).

The emphasis in the QMM 2021-2023 Water Report on compliance with Malagasy decree limits is surprising, since the QMM mine has committed to compliance with internationally-recognized water-quality standards, which has also been the expectation of the Government of Madagascar. According to the Framework Agreement between the State of Madagascar and the mining company, "QMM SA shall comply with national environmental legislation and regulations and shall conform to national guidelines and/or international mining operational and environmental practices, particularly with respect to limiting the negative impacts" (Office des Mines Nationales et des Industries Stratégiques [Office of National Mines and Strategic Industries] and QIT-Fer et Titane Inc., n.d.). Rio Tinto (2022c) stated a commitment to "collect data that are sufficiently reliable and robust to enable comparison to internationally recognized drinking water quality guideline values." Finally, according to Orengo (2022a), "Indeed, QMM did made a commitment to use WHO and Canadian standards for water quality in its 2001 Environmental Management Plan."

SUMMARY OF 2001 BASELINE STUDY

The 2001 baseline study of surface water quality became available only in July 2022 (Morrill, 2023) after repeated denials by Rio Tinto that any baseline study existed. At the 2022 Rio Tinto AGM, Yvonne Orengo, Director of Andrew Lees Trust, stated, "I want to add that QMM told us for years … we were told there was no baseline water data. But now we discover there is. We are still waiting for it" (Andrew Lees Trust, 2022). The Chair of Rio Tinto responded, "You have mentioned baseline and we will provide that, but the difficulty is that if you ask at short notice for data that is 27 years old we have to go back into the archives and get that data" (Andrew Lees Trust, 2022). Yvonne Orengo clarified, "Baseline water data has been requested from Rio Tinto/QMM for more than three years. There is absolutely no short notice to speak about. If water monitoring was happening as expected at QMM, this baseline data would have been a constant point of reference, readily available, since the project began … If QMM were to use (as they should) and put their baseline water data on the table it would be very apparent what changes to the water quality have either occurred from pre to post mining – or not. The failure to produce baseline water data required for monitoring purposes raises not only questions of transparency, but also of competence and negligence viz a viz QMM's PGEP 2001 commitments. These baseline data should be used for comparative purposes since the mine began" (Andrew Lees Trust, 2022).

The author confirms that the analysis by the Director of Andrew Lees Trust is correct. One of the most basic principles of environmental management is that baseline study are collected prior to the construction of large projects in order to assess whether the project has resulted in detrimental environmental impacts. Why these baseline data were not referenced in earlier releases of water-quality data (Swanson, 2019a-c; JBS&G, 2020b; Rio Tinto, 2021b) or why it should have been necessary to spend three years digging through archives and looking for the data is beyond the comprehension of the author. It is similarly incomprehensible as to why there were no comparisons with baseline data even in the most recent release of water-quality data (Rio Tinto, 2023a) after the baseline data became available.

Table 2. Sampling Sites in 2001 Baseline Study

Site No.[1]	Description[2]	Latitude[3,4] (°S)	Longitude[3,4] (°E)
1	Mandromondromotra River at the bridge	24.91492	47.02902
2	Anandrano River at the bridge	24.93049	46.99515
3	Lake Ambavarano near the staff gage	24.95803	47.04318
4	Lake Lanirano at the JIRAMA water intake	25.00532	46.98589
5	Mandromondromotra River near the mouth	24.95368	47.05982

[1] See Fig. 4c.
[2] Taken from CDN Water Management Consultants (2001a) with changes in spelling
[3] Measured from Figure 2.1 in CDN Water Management Consultants (2001b) by comparison with Google Earth
[4] Coordinate system WGS 84

Table 3a. Baseline surface water chemistry: December 1999[1,2]

Site No.[3]	Al (mg/L)	Cd (mg/L)	Fe (mg/L)	Pb (mg/L)	U (mg/L)	Zn (mg/L)
1	0.102	<0.0002	0.98	<0.001	0.00002	<0.005
2	0.116	<0.0002	1.42	<0.001	0.00002	<0.005
3	0.12	<0.002	0.28	<0.01	0.0003	<0.05
4	0.117	<0.0002	0.81	<0.001	0.00003	<0.005
5	0.13	<0.001	0.65	<0.005	0.0001	<0.03

[1] CDN Water Management Consultants (2001a)
[2] All values are total concentrations (unfiltered samples)
[3] See Table 2 and Fig. 6c.

Table 3b. Baseline surface water chemistry: February-March 2020[1,2]

Site No.[3]	Al (mg/L)	Cd (mg/L)	Fe (mg/L)	Pb (mg/L)	U (mg/L)	Zn (mg/L)
1	0.053	<0.0002	1.35	<0.001	0.00002	<0.005
2	0.098	<0.0002	1.59	<0.001	0.00002	<0.005
3	0.11	<0.002	<0.03	<0.01	0.0008	<0.05
4	0.09	<0.0002	0.99	<0.001	0.00003	<0.005
4-Duplicate	0.102	<0.0002	1.15	<0.001	0.00002	<0.005
5	0.007	<0.0002	0.08	<0.001	0.0001	<0.005

[1] CDN Water Management Consultants (2001a)
[2] All values are total concentrations (unfiltered samples)
[3] See Table 2 and Fig. 6c.

The author has both a 114-page version of the baseline study (CDN Water Management Consultants, 2001a) and a 215-page version (CDN Water Management Consultants, 2001b). Each version has sections that are missing in the other version. However, the two versions are completely identical for the overlapping sections. The 2001 baseline study collected surface water samples from five sites, three of which were upstream and two downstream from the future mining project (see Table 2 and Fig. 4c). Samples were collected in December 1999 and February-March 2020 and a duplicate sample was collected from Site No. 4 in February-March 2020 (see Tables 3a-b). Metals for which total concentrations were measured included aluminum, arsenic, barium, boron, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, mercury, potassium, selenium, sodium, uranium, and zinc (see Tables 3a-b). Other measured parameters included color, electrical conductivity, total dissolved solids, hardness, pH, total suspended solids, turbidity, alkalinity, nitrate nitrogen, nitrite nitrogen, and the dissolved anions chloride, fluoride, and sulfate.

Although the 2001 baseline study is invaluable, it still cannot be regarded as entirely adequate, even by the standards of 20-25 years ago. Surface water quality is highly variable, both spatially and temporally. While five sampling sites were a good start, 15 sites would have been better (compare Figs. 4c with Figs. 4a-b). The temporal variability can be quite strong in areas with pronounced dry and rainy seasons and with years in which strong storms (such as cyclones) may or may not occur. Thus, it is unfortunate that both sets of samples for the baseline study were collected during the typical rainy season of November to April (see Tables 3a-b). By comparison, an adequate baseline study should have involved the collection of monthly samples at 15 sites for a period of three years.

METHODOLOGY

The objective in this report has been to use all available and credible data to compare surface water quality downstream of the QMM mine with surface water quality upstream of the mine and surface water quality as it existed before construction of the mine. For the creation of maps of sampling locations (see Figs. 4a-c and Fig. 6), ESRI ArcMap 10.8.2 was used to measure the latitude and longitude of each sampling site for the water-quality data reported in Swanson (2019b) based upon a map in that report. The same software was used to measure the latitudes and longitudes of wastewater discharge sites WMC703A and WMC803A (see Fig. 6) based upon a map in Rio Tinto (2021b). For the sampling sites in JBS&G (2020b) (see Fig. 4b) and for wastewater discharge site WMC603, UTM coordinates were converted to latitude and longitude under the assumption that UTM coordinates were based on the WGS84 coordinate system. Tables of latitude and longitude for all sampling sites are available in Emerman (2019, 2020, 2021). As in Emerman (2020, 2021), the boundary of the QMM mine property was traced from a map available in JBS&G (2020b). Based on the most recent Google Earth images (May 4 and June 25, 2023), there appears to be some offset between the mapped mine perimeter and the actual perimeter (see Figs. 4a-c and 6).

The only exception based upon location to the integration of all available data was the exclusion of community monitoring sites Q1, Q2 and Q4 (see Figs. 2 and 4a), in response to a critique by Rio Tinto (2020a) that these sites were not possible sources of drinking water. According to Rio Tinto (2020a), "This point is made clearer when you consider the sample set includes downstream sites with naturally muddy, marshy water which one would not expect people to consume. This is compared to upstream designated sites that are flowing streams. Images 1 – 4 from the study [sites M1, P1, Q1, Q2; see Figs. 2 and 4a] show the differences in quality of water bodies used as the upstream and downstream samples. Whether inclusion of the upstream sites is defensible or not, given it is unclear whether people do in fact use them as sources of drinking water, it is clear that at least two downstream sites in a small sample set, of just nine, are definitely not sources of drinking water and not appropriate for inclusion in a drinking water analysis." Samples Q1 and Q2 were both obtained from the wetlands below the tailings dam, as was sample Q4 (Emerman, 2019). In fact, samples Q2 and Q4 were collected only 6-7 meters from the tailings dam. Therefore, any objection to the inclusion of samples Q1 and Q2 should apply equally to sample Q4. With regard to the critique of small sample size, it should be noted that Emerman (2019) never interpreted the analyses of the nine community-collected samples in isolation, but only in conjunction with the 60 measurements from 12 sites that were provided by the Rio Tinto QMM mine (Swanson, 2019b). In the same way, community monitoring sites Q1, Q2 and Q4 were excluded from the statistical comparisons in Emerman (2020) that included the additional data from JBS&G (2020b), and the statistical comparisons in Emerman (2021) that included the additional data from both JBS&G (2020b) and Rio Tinto (2021b). On the other hand, the two community sample sites (P1, P2) outside of the watershed (see Fig. 2) were included as upstream samples, since they are not downstream from any heavy mineral sands mining, as was done in previous reports by Emerman (2019, 2020, 2021).

Two important methodological issues were the highly variable frequency of sample collection and the use of inconsistent detection limits. The sampling dates for sites S46 (upstream) and S41 (downstream) in the QMM 2021-2023 Water Report for measurement of uranium, lead, aluminum, cadmium, iron, and zinc are shown in Tables 4a-f. As an example of the variable frequency, samples for measurement of lead were collected on 10 occasions from March 9-18, 2022, including twice on March 16, 2022. By contrast, the next sample collection for measurement of lead took place on June 20, 2022, while the previous collections took place on April 8, 2021, and July 30, 2021. As a second example, sample collections in the Méandre River and Lake Ambavarano have not taken place since December 2, 2019 (JBS&G, 2020b; see Fig. 4b), and no sample has been collected from Lake Besaroy since April 18, 2018 (Swanson, 2019b; see Fig. 4a). Rio Tinto (2023a) does not provide any information as to why each water sample was not analyzed for all elements of interest (compare sampling dates in Tables 4a-f). Rio Tinto (2023a) also does not provide any explanation for the apparently random dates of sample collection (see Tables 4a-f). Note that the data in Table 4a-f were compiled from the spreadsheet that accompanied the QMM 2021-2023 Water Report.

In order to avoid biasing the results toward periods with greater frequency of sample collection, statistics were carried out on monthly arithmetic means of each parameter at each sampling site (see Tables 5a-f). The reduction of the dataset into monthly averages applied almost entirely to the new data contained in the QMM 2021-2023 Water Report with a small number of exceptions from the earlier surface water-quality data. In particular, measurements of lead at WS0501 and WS0502 (see Fig. 4a) on June 4 and June 24, 2015 (Swanson, 2019b), were averaged for each site. Measurements of aluminum at WS0501 and WS0502 (see Fig. 4a) on June 4 and June 24, 2015 (Rio Tinto, 2021b), were also averaged for each site. Finally, measurements of zinc at WS0501 on June 4 and 24, 2015, and at WS0502 on June 4 and 23, 2015 (Rio Tinto, 2021b) were averaged for each site.

Table 4a. QMM 2021-2023 water report: Aqueous uranium[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
4/8/2021	—	<0.005	—	<0.005
7/28/2021	—	<0.005	—	—
7/30/2021	—	—	—	<0.005
3/9/2022	<0.005	<0.005	<0.005	<0.005
3/10/2022	<0.005	<0.005	<0.005	<0.005
3/11/2022	<0.005	<0.005	<0.005	<0.005
3/12/2022	<0.005	<0.005	<0.005	<0.005
3/13/2022	<0.005	<0.005	<0.005	<0.005
3/14/2022	<0.005	<0.005	<0.005	<0.005
3/15/2022	<0.005	<0.005	<0.005	<0.005
3/16/2022	<0.005	<0.005	<0.005	<0.005
3/17/2022	<0.005	<0.005	<0.005	<0.005
3/18/2022	<0.005	<0.005	—	—
2/20/2023	<0.005	<0.005	—	—
3/11/2023	—	<0.005	—	<0.005
3/12/2023	—	<0.005	—	<0.005
3/13/2023	—	<0.005	—	<0.005
3/14/2023	—	<0.005	—	<0.005
3/15/2023	—	<0.005	—	<0.005
3/16/2023	—	<0.005	—	<0.005
3/17/2023	—	<0.005	—	<0.005
3/23/2023	—	<0.005	—	<0.005
3/28/2023	<0.005	<0.005	—	—
4/13/2023	<0.005	<0.005	—	—
5/8/2023	<0.005	<0.005	—	—
7/13/2023	—	<0.005	—	—
7/24/2023	—	<0.005	—	—
8/21/2023	—	<0.005	—	—
9/25/2023	<0.005	<0.005	—	—
10/16/2023	<0.005	<0.005	<0.005	<0.005

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 4b. QMM 2021-2023 water report: Aqueous lead[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
4/8/2021	—	<0.001	—	<0.001
7/30/2021	—	<0.001	—	<0.001
3/9/2022	<0.001	<0.001	<0.001	<0.001
3/10/2022	<0.001	<0.001	<0.001	<0.001
3/11/2022	<0.001	<0.001	<0.001	<0.001
3/12/2022	<0.001	<0.001	<0.001	<0.001
3/13/2022	<0.001	<0.001	<0.001	<0.001
3/14/2022	<0.001	<0.001	<0.001	<0.001
3/15/2022	<0.001	<0.001	<0.001	<0.001
3/16/2022	<0.001	<0.001	<0.001	<0.001
3/16/2022	<0.001	<0.001	<0.001	<0.001
3/18/2022	<0.001	<0.001	<0.001	<0.001
6/20/2022	<0.001	<0.001	<0.001	<0.001
7/11/2022	<0.001	<0.001	<0.001	<0.001
7/19/2022	<0.001	<0.001	<0.001	<0.001
8/1/2022	—	<0.001	—	—
8/8/2022	—	<0.001	—	<0.001
8/16/2022	—	<0.001	—	<0.001
8/17/2022	—	—	—	<0.001
8/18/2022	—	—	—	<0.001
8/19/2022	—	—	—	<0.001
8/20/2022	—	—	—	<0.001
8/22/2022	—	<0.001	—	<0.001
8/29/2022	—	<0.001	—	<0.001
8/30/2022	—	<0.001	—	<0.001
8/31/2022	—	<0.001	—	<0.001
9/1/2022	—	<0.001	—	<0.001
9/2/2022	—	<0.001	—	<0.001
9/4/2022	—	<0.001	—	<0.001
9/5/2022	—	<0.001	—	—
9/12/2022	—	<0.001	—	<0.001
9/22/2022	—	<0.001	—	<0.001
9/26/2022	—	<0.001	—	<0.001
10/3/2022	—	<0.001	—	<0.001
10/12/2022	—	<0.001	—	<0.001
10/19/2022	—	<0.001	—	<0.001
10/24/2022	—	<0.001	—	<0.001
10/31/2022	—	<0.001	—	<0.001
11/7/2022	—	—	—	<0.001
11/14/2022	—	<0.001	—	<0.001
11/21/2022	—	<0.001	—	<0.001

11/28/2022	—	<0.001	—	<0.001
12/5/2022	—	<0.001	—	<0.001
12/13/2022	—	<0.001	—	<0.001
12/22/2022	—	<0.001	—	<0.001
12/26/2022	—	<0.001	—	<0.001
1/2/2023	—	<0.001	—	<0.001
1/25/2023	<0.001	<0.001	—	—
2/20/2023	<0.001	<0.001	—	—
3/11/2023	—	<0.001	—	<0.001
3/12/2023	—	<0.001	—	<0.001
3/13/2023	—	<0.001	—	<0.001
3/14/2023	—	<0.001	—	<0.001
3/15/2023	—	<0.001	—	<0.001
3/16/2023	—	<0.001	—	<0.001
3/17/2023	—	<0.001	—	<0.001
3/23/2023	—	<0.001	—	<0.001
3/28/2023	<0.001	<0.001	—	—
4/13/2023	<0.001	<0.001	—	—
5/8/2023	<0.001	<0.001	—	—
7/13/2023	—	<0.001	—	—
7/24/2023	—	<0.001	—	—
8/21/2023	—	<0.001	—	—
9/25/2023	<0.001	0.001	—	—
10/16/2023	<0.001	<0.001	<0.001	<0.001

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 4c. QMM 2021-2023 water report: Aqueous aluminum[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
4/8/2021	—	0.15	—	0.39
7/28/2021	—	0.23	—	—
7/30/2021	—	—	—	0.82
3/9/2022	0.12	0.29	1.8	2.2
3/10/2022	0.11	0.24	1	1.7
3/12/2022	—	—	1.4	1.6
3/13/2022	0.12	0.3	0.91	1.6
3/14/2022	—	—	0.88	1.1
3/16/2022	0.07	0.48	—	1.3
3/16/2022	—	0.3	1.1	1.3
3/17/2022	—	—	1.1	1.2
3/18/2022	0.06	0.28	0.5	0.85
6/20/2022	—	0.17	—	0.67
7/11/2022	—	0.16	—	1.2
7/19/2022	—	0.32	—	0.47
8/1/2022	—	0.09	—	0.29
8/8/2022	—	—	—	0.22
8/16/2022	—	0.12	—	0.2
8/17/2022	—	—	—	0.36
8/18/2022	—	—	—	0.33
8/19/2022	—	—	—	0.25
8/20/2022	—	—	—	0.25
8/22/2022	—	0.11	—	0.28
8/29/2022	—	0.14	—	0.67
8/30/2022	—	0.15	—	0.6
8/31/2022	—	0.18	—	0.65
9/1/2022	—	0.19	—	1
9/2/2022	—	0.13	—	1.2
9/3/2022	—	0.13	—	1.2
9/4/2022	—	0.17	—	0.98
9/5/2022	—	0.11	—	0.66
9/12/2022	—	0.13	—	0.67
9/22/2022	—	0.1	—	0.45
9/26/2022	—	0.12	—	0.35
10/3/2022	—	0.11	—	0.31
10/12/2022	—	0.11	—	0.3
10/19/2022	—	—	—	0.26
10/24/2022	—	0.13	—	0.23
10/31/2022	—	0.09	—	0.18
11/7/2022	—	0.08	—	0.15
11/14/2022	—	—	—	0.13

11/21/2022	—	0.11	—	0.15
11/28/2022	—	—	—	0.1
12/5/2022	—	0.12	—	0.16
12/13/2022	—	0.08	—	0.15
12/22/2022	—	0.27	—	0.65
12/26/2022	—	0.13	—	0.22
1/2/2023	—	0.15	—	0.25
1/25/2023	0.08	0.64	—	—
2/20/2023	—	0.26	—	—
3/11/2023	—	0.29	—	0.63
3/12/2023	—	0.26	—	0.78
3/13/2023	—	0.24	—	1.2
3/14/2023	—	0.22	—	0.7
3/15/2023	—	0.18	—	0.78
3/16/2023	—	0.24	—	0.87
3/17/2023	—	0.24	—	0.71
3/23/2023	—	0.28	—	0.87
3/28/2023	—	0.27	—	—
4/13/2023	—	0.18	—	—
5/8/2023	—	0.15	—	—
7/13/2023	—	<0.5	—	—
7/24/2023	—	<0.5	—	—
8/21/2023	—	<0.5	—	—
9/25/2023	0.05	0.11	—	—
10/16/2023	<0.05	0.06	0.16	0.26

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 4d. QMM 2021-2023 water report: Aqueous cadmium[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
4/8/2021	—	<0.0002	—	<0.0002
7/28/2021	—	<0.0002	—	—
7/30/2021	—	—	—	<0.0002
3/9/2022	<0.0002	0.0002	<0.0002	<0.0002
3/10/2022	<0.0002	0.0002	<0.0002	<0.0002
3/11/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/12/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/13/2022	<0.0002	<0.0002	0.0002	<0.0002
3/14/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/15/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/16/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/16/2022	<0.0002	<0.0002	<0.0002	<0.0002
3/17/2022	<0.0002	0.0002	<0.0002	<0.0002
3/18/2022	<0.0002	<0.0002	<0.0002	<0.0002
6/20/2022	<0.0002	<0.0002	<0.0002	<0.0002
7/11/2022	<0.0002	<0.0002	<0.0002	<0.0002
7/19/2022	<0.0002	<0.0002	<0.0002	<0.0002
8/1/2022	—	<0.0002	—	<0.0002
8/8/2022	—	<0.0002	—	<0.0002
8/16/2022	—	<0.0002	—	<0.0002
8/17/2022	—	—	—	<0.0002
8/18/2022	—	—	—	<0.0002
8/19/2022	—	—	—	<0.0002
8/22/2022	—	<0.0002	—	<0.0002
8/29/2022	—	<0.0002	—	<0.0002
8/30/2022	—	<0.0002	—	<0.0002
8/31/2022	—	<0.0002	—	<0.0002
9/1/2022	—	<0.0002	—	<0.0002
9/2/2022	—	<0.0002	—	<0.0002
9/3/2022	—	<0.0002	—	<0.0002
9/4/2022	—	<0.0002	—	<0.0002
9/5/2022	—	<0.0002	—	<0.0002
9/12/2022	—	<0.0002	—	<0.0002
9/22/2022	—	<0.0002	—	—
9/26/2022	—	<0.0002	—	<0.0002
10/3/2022	—	<0.0002	—	<0.0002
10/12/2022	—	<0.0002	—	<0.0002
10/19/2022	—	<0.0002	—	<0.0002
10/24/2022	—	<0.0002	—	<0.0002
10/31/2022	—	<0.0002	—	<0.0002
11/7/2022	—	<0.0002	—	<0.0002

11/14/2022	—	<0.0002	—	<0.0002
11/21/2022	—	<0.0002	—	<0.0002
11/28/2022	—	<0.0002	—	<0.0002
12/5/2022	—	<0.0002	—	<0.0002
12/13/2022	—	—	—	<0.0002
12/22/2022	—	<0.0002	—	<0.0002
12/26/2022	—	<0.0002	—	<0.0002
1/2/2023	—	<0.0002	—	<0.0002
1/25/2023	<0.0002	<0.0002	—	<0.0002
2/20/2023	<0.0002	<0.0002	—	<0.0002
3/11/2023	—	<0.0002	—	<0.0002
3/12/2023	—	<0.0002	—	<0.0002
3/13/2023	—	<0.0002	—	<0.0002
3/14/2023	—	<0.0002	—	<0.0002
3/15/2023	—	<0.0002	—	<0.0002
3/16/2023	—	<0.0002	—	<0.0002
3/17/2023	—	<0.0002	—	<0.0002
3/23/2023	—	<0.0002	—	<0.0002
3/28/2023	<0.0002	<0.0002	—	—
4/13/2023	<0.0002	<0.0002	—	—
5/8/2023	<0.0002	<0.0002	—	—
7/13/2023	—	<0.0002	—	—
7/24/2023	—	<0.0002	—	—
8/21/2023	—	<0.0002	—	—
9/25/2023	<0.0002	<0.0002	—	—
10/16/2023	<0.0002	<0.0002	<0.0002	<0.0002

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 4e. QMM 2021-2023 water report: Aqueous iron[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
3/16/2022	—	0.93	—	0.4
6/20/2022	—	0.76	—	0.26
7/11/2022	—	0.72	—	0.33
7/19/2022	—	0.48	—	0.56
8/1/2022	—	0.58	—	0.56
8/8/2022	—	0.92	—	0.21
8/16/2022	—	0.64	—	0.18
8/17/2022	—	—	—	0.21
8/18/2022	—	—	—	0.23
8/19/2022	—	—	—	0.31
8/20/2022	—	—	—	0.29
8/22/2022	—	0.76	—	0.2
8/29/2022	—	0.74	—	0.15
8/30/2022	—	0.75	—	0.2
8/31/2022	—	0.71	—	0.17
9/1/2022	—	0.71	—	0.21
9/2/2022	—	0.7	—	0.28
9/3/2022	—	0.72	—	0.23
9/4/2022	—	0.73	—	0.18
9/5/2022	—	0.63	—	0.1
9/12/2022	—	0.7	—	0.2
9/22/2022	—	0.19	—	0.2
9/26/2022	—	0.49	—	0.22
10/3/2022	—	0.64	—	0.28
10/12/2022	—	0.79	—	0.34
10/19/2022	—	0.89	—	0.31
10/24/2022	—	0.93	—	0.26
10/31/2022	—	1.9	—	1.3
11/7/2022	—	0.82	—	1
11/14/2022	—	0.91	—	1.3
11/21/2022	—	1.3	—	1.1
11/28/2022	—	0.89	—	0.61
12/5/2022	—	0.51	—	1.2
12/13/2022	—	0.78	—	0.71
12/22/2022	—	0.62	—	0.91
12/26/2022	—	0.51	—	0.51
1/2/2023	—	1	—	1
1/25/2023	0.38	1.3	—	—
3/11/2023	—	0.63	—	0.74
3/12/2023	—	0.69	—	0.74
3/13/2023	—	0.81	—	0.66

3/14/2023	—	0.82	—	0.89
3/15/2023	—	0.84	—	0.89
3/16/2023	—	1	—	0.53
3/17/2023	—	0.9	—	0.64
3/23/2023	—	0.56	—	0.57
3/28/2023	—	0.45	—	—
4/13/2023	—	0.86	—	—
5/8/2023	—	0.8	—	—
7/13/2023	—	0.91	—	—
7/24/2023	—	0.49	—	—
8/21/2023	—	0.78	—	—
9/25/2023	0.2	0.27	—	—
10/16/2023	0.13	0.16	0.18	0.28

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 4f. QMM 2021-2023 water report: Aqueous zinc[1]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	Total Concentration (mg/L)	Dissolved Concentration (mg/L)	Total Concentration (mg/L)
4/8/2021	—	<0.005	—	<0.005
7/28/2021	—	<0.005	—	—
7/30/2021	—	—	—	0.008
3/9/2022	0.012	0.012	0.026	0.032
3/10/2022	0.013	0.014	0.023	0.026
3/11/2022	0.013	0.014	0.014	0.017
3/12/2022	0.016	0.017	0.031	0.024
3/13/2022	0.06	0.06	0.31	0.33
3/14/2022	0.18	0.18	0.27	0.27
3/15/2022	0.13	0.13	0.017	0.037
3/16/2022	0.009	0.02	—	0.021
3/16/2022	—	0.01	0.014	0.028
3/17/2022	0.008	0.018	0.017	0.026
3/18/2022	0.007	0.018	0.013	0.023
6/20/2022	<0.005	<0.005	—	0.008
7/11/2022	<0.005	<0.005	—	0.018
7/19/2022	<0.005	<0.005	<0.005	<0.005
8/1/2022	—	<0.005	—	0.008
8/8/2022	—	<0.005	—	<0.005
8/16/2022	—	<0.005	—	<0.005
8/17/2022	—	—	—	<0.005
8/18/2022	—	—	—	0.01
8/19/2022	—	—	—	<0.005
8/20/2022	—	—	—	0.005
8/22/2022	—	<0.005	—	<0.005
8/29/2022	—	<0.005	—	0.009
8/30/2022	—	<0.005	—	0.012
8/31/2022	—	<0.005	—	0.007
9/1/2022	—	<0.005	—	0.012
9/2/2022	—	0.007	—	0.016
9/3/2022	—	<0.005	—	0.015
9/4/2022	—	0.007	—	0.015
9/5/2022	—	<0.005	—	0.008
9/12/2022	—	<0.005	—	0.012
9/22/2022	—	<0.005	—	0.012
9/26/2022	—	<0.005	—	0.011
10/3/2022	—	<0.005	—	0.022
10/12/2022	—	<0.005	—	0.014
10/19/2022	—	<0.005	—	0.014
10/24/2022	—	<0.005	—	—
10/31/2022	—	<0.005	—	0.005

11/7/2022	—	<0.005	—	0.009
11/14/2022	—	<0.005	—	<0.005
11/21/2022	—	<0.005	—	0.011
11/28/2022	—	<0.005	—	<0.005
12/5/2022	—	<0.005	—	<0.005
12/13/2022	—	<0.005	—	<0.005
12/22/2022	—	<0.005	—	0.006
12/26/2022	—	<0.005	—	0.006
1/2/2023	—	<0.005	—	0.01
1/25/2023	<0.005	<0.005	—	—
2/20/2023	<0.005	<0.005	—	—
3/11/2023	—	<0.005	—	0.008
3/12/2023	—	<0.005	—	0.01
3/13/2023	—	<0.005	—	0.018
3/14/2023	—	<0.005	—	0.008
3/15/2023	—	<0.005	—	0.008
3/16/2023	—	<0.005	—	0.009
3/17/2023	—	0.01	—	0.009
3/23/2023	—	0.005	—	0.007
3/28/2023	<0.005	<0.005	—	—
4/13/2023	<0.005	<0.005	—	—
5/8/2023	<0.005	<0.005	—	—
7/13/2023	—	<0.005	—	—
7/24/2023	—	<0.005	—	—
8/21/2023	—	<0.005	—	—
9/25/2023	0.067	0.069	—	—
10/16/2023	0.056	0.054	<0.005	<0.005

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

Table 5a. Monthly summary of QMM 2021-2023 water report: Aqueous uranium[1,2]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)
April 2021	—	<0.005	—	<0.005
July 2021	—	<0.005	—	<0.005
March 2022	<0.005	<0.005	<0.005	<0.005
February 2023	<0.005	<0.005	—	—
March 2023	<0.005	<0.005	—	<0.005
April 2023	<0.005	<0.005	—	—
May 2023	<0.005	<0.005	—	—
July 2023	—	<0.005	—	—
August 2023	—	<0.005	—	—
September 2023	<0.005	<0.005	—	—
October 2023	<0.005	<0.005	<0.005	<0.005

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

Table 5b. Monthly summary of QMM 2021-2023 water report: Aqueous lead[1,2]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)
April 2021	—	<0.001	—	<0.001
July 2021	—	<0.001	—	<0.001
March 2022	<0.001	<0.001	<0.001	<0.001
June 2022	<0.001	<0.001	<0.001	<0.001
July 2022	<0.001	<0.001	<0.001	<0.001
August 2022	—	<0.001	—	<0.001
September 2022	—	<0.001	—	<0.001
October 2022	—	<0.001	—	<0.001
November 2022	—	<0.001	—	<0.001
December 2022	—	<0.001	—	<0.001
January 2023	<0.001	<0.001	—	—
February 2023	<0.001	<0.001	—	—
March 2023	<0.001	<0.001	—	<0.001
April 2023	<0.001	<0.001	—	—
May 2023	<0.001	<0.001	—	—
July 2023	—	<0.001	—	—
August 2023	—	<0.001	—	—
September 2023	<0.001	0.001	—	—
October 2023	<0.001	<0.001	<0.001	<0.001

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

Table 5c. Monthly summary of QMM 2021-2023 water report: Aqueous aluminum[1,2]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)
April 2021	—	0.15	—	0.39
July 2021	—	0.23	—	0.82
March 2022	0.10	0.32	1.09	1.43
June 2022	—	0.17	—	0.67
July 2022	—	0.24	—	0.84
August 2022	—	0.13	—	0.37
September 2022	—	0.14	—	0.81
October 2022	—	0.11	—	0.26
November 2022	—	0.10	—	0.13
December 2022	—	0.15	—	0.30
January 2023	0.08	0.40	—	0.25
February 2023	—	0.26	—	—
March 2023	—	0.25	—	0.82
April 2023	—	0.18	—	—
May 2023	—	0.15	—	—
July 2023	—	<0.5	—	—
August 2023	—	<0.5	—	—
September 2023	0.05	0.11	—	—
October 2023	<0.05	0.06	0.16	0.26

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

Table 5d. Monthly summary of QMM 2021-2023 water report: Aqueous cadmium[1,2]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Mean Dissolved Concentration (mg/L)	**Mean Total Concentration (mg/L)**	**Mean Dissolved Concentration (mg/L)**	**Mean Total Concentration (mg/L)**
April 2021	—	<0.0002	—	<0.0002
July 2021	—	<0.0002	—	<0.0002
March 2022	<0.0002	0.0002	<0.0002	<0.0002
June 2022	<0.0002	<0.0002	<0.0002	<0.0002
July 2022	<0.0002	<0.0002	<0.0002	<0.0002
August 2022	—	<0.0002	—	<0.0002
September 2022	—	<0.0002	—	<0.0002
October 2022	—	<0.0002	—	<0.0002
November 2022	—	<0.0002	—	<0.0002
December 2022	—	<0.0002	—	<0.0002
January 2023	<0.0002	<0.0002	—	<0.0002
February 2023	<0.0002	<0.0002	—	<0.0002
March 2023	<0.0002	<0.0002	—	<0.0002
April 2023	<0.0002	<0.0002	—	—
May 2023	<0.0002	<0.0002	—	—
July 2023	—	<0.0002	—	—
August 2023	—	<0.0002	—	—
September 2023	<0.0002	<0.0002	—	—
October 2023	<0.0002	<0.0002	<0.0002	<0.0002

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

Table 5e. Monthly summary of QMM 2021-2023 water report: Aqueous iron[1,2]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Dissolved Concentration (mg/L)	**Total Concentration (mg/L)**	**Dissolved Concentration (mg/L)**	**Total Concentration (mg/L)**
March 2022	—	0.93	—	0.4
June 2022	—	0.76	—	0.26
July 2022	—	0.60	—	0.45
August 2022	—	0.73	—	0.25
September 2022	—	0.61	—	0.20
October 2022	—	1.03	—	0.50
November 2022	—	0.98	—	1.00
December 2022	—	0.61	—	0.83
January 2023	0.38	1.15	—	1
March 2023	—	0.74	—	0.71
April 2023	—	0.86	—	—
May 2023	—	0.8	—	—
July 2023	—	0.70	—	—
August 2023	—	0.78	—	—
September 2023	0.2	0.27	—	—
October 2023	0.13	0.16	0.18	0.28

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

Table 5f. Monthly summary of QMM 2021-2023 water report: Aqueous zinc[1,2,3]

Date	Upstream (S46 = SW15)		Downstream (S41 = SW06)	
	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)	Mean Dissolved Concentration (mg/L)	Mean Total Concentration (mg/L)
April 2021	—	<0.005	—	<0.005
July 2021	—	<0.005	—	0.008
March 2022	0.045	0.045	0.074	0.076
June 2022	<0.005	<0.005	—	0.008
July 2022	<0.005	<0.005	—	0.010
August 2022	—	<0.005	—	0.006
September 2022	—	0.004	—	0.013
October 2022	—	<0.005	—	0.014
November 2022	—	<0.005	—	0.006
December 2022	—	<0.005	—	0.004
January 2023	<0.005	<0.005	—	0.01
February 2023	<0.005	<0.005	—	—
March 2023	<0.005	0.004	—	0.010
April 2023	<0.005	<0.005	—	—
May 2023	<0.005	<0.005	—	—
July 2023	—	<0.005	—	—
August 2023	—	<0.005	—	—
September 2023	0.067	0.069	—	—
October 2023	0.056	0.054	<0.005	<0.005

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

[2] Mean refers to arithmetic mean.

[3] When a given month includes values both greater than and less than the detection limit, arithmetic means are calculated by replacing values less than the detection limit with half the detection limit.

Inconsistent detection limits have some or all of the following characteristics:

1) multiple detection limits for the same parameter
2) unrealistically high detection limits
3) measurements that are lower than the stated detection limit (such as a measurement of 0.008 mg/L when the detection limit is stated as 0.01 mg/L)

These types of inconsistencies are illustrated in the 2001 baseline study, in which measurements for cadmium were variously stated as <0.0002 mg/L, <0.001 mg/L, or <0.002 mg/L, measurements for lead were variously stated as <0.001 mg/L, <0.005 mg/L, or <0.01 mg/L, and measurements for zinc were variously stated as <0.005 mg/L, <0.03 mg/L, and <0.05 mg/L (see Tables 3a-b). A single detection limit should apply to the combination of an analytical instrument and a parameter, so that it is difficult to understand why a single parameter would have three detection limits. It is possible that three different analytical instruments were used to measure a single parameter in ten water samples, but that would be highly unusual and would require careful explanation with considerable discussion as to how the three instruments were cross-calibrated to ensure that they were producing the same results. Detection limits of 0.01 mg/L for lead and 0.05 mg/L for zinc seem quite high, since detection limits of 0.001 mg/L or lower were common for analytical instrumentation that was available in 2000. A common rule is that the detection limit should be no greater than 10% of the concentration of concern. CDN Water

Management Consultants (2001a) compares the measured lead concentrations with the WHO drinking water guideline of 0.01 mg/L as of 1998, so that a detection limit of no greater than 0.001 mg/L would have been appropriate.

The high and ambiguous detection limits in the data from the QMM mine (Swanson, 2019b) was the most difficult problem in the earlier integration of the datasets from the community-collected samples and the samples collected by the QMM mine (Emerman, 2019). In particular, the data from the QMM mine included two detection limits for all elements except for iron. Out of the 54 measurements of uranium, 13 were recorded as <0.642 mg/L, while 21 were recorded as <0.047 mg/L. Out of the 54 measurements of lead, four were recorded as <0.008 mg/L, while 23 were recorded as <0.005 mg/L. Out of the 54 measurements of thorium, 35 were recorded as <0.009 mg/L, while 12 were recorded as <0.045 mg/L. Out of the 54 measurements of titanium, eight were recorded as <0.004 mg/L, while 30 were recorded as <0.003 mg/L. Besides the existence of the double detection limits, the detection limits were far too high to be useful and even realistic. It should be clear that an analytical instrument with detection limits of 0.642 mg/L and 0.047 mg/L for uranium is not appropriate for determining whether a water sample meets the WHO (2022) drinking-water guideline of 0.030 mg/L. As discussed above, maximum appropriate detection limits would have been 0.003 mg/L for uranium, 0.001 mg/L for lead (based on the WHO drinking-water guideline) or 0.00025 mg/L for lead (based on the US EPA (2024a) aquatic standard). Most modern analytical instruments that were available around 2015, such as the ICP (Inductively-Coupled Plasma) spectrometer that was used by the QMM mine (Swanson, 2019b), had detection limits in the range 0.0001-0.00001 mg/L for most metals, including lead and uranium.

The high and ambiguous detection limits led Emerman (2019) to a concern as to whether the dataset from the QMM mine was even valid. Extreme caution was exercised in this matter, since discarding data is a very dangerous act, so that the assumption that the QMM dataset is valid is certainly the null hypothesis that should be rejected only at a very high confidence level. Unfortunately, it was difficult to directly compare the water-quality results from the community-collected sample sites with those from the water monitoring stations of the QMM mine because there was very little spatial overlap between the two sets of sites (see Figs. 2 and 4a). The closest correspondence was between sites Q3 (community study) and WS0301 (QMM mine) since the sites are only 295 meters apart on the Méandre River, which flows into Lake Besaroy (see Fig. 4a). For those two sites, measurements of iron and lead were reasonably close, so that it was decided that the QMM dataset could not be rejected. The subsequent data from the QMM mine (Rio Tinto, 2021b, 2023a) did not help with this comparison because none of the sites WS0501, WS0502, S41, and S46 are close to any of the sites used in the community study (see Figs. 4a and 6).

Emerman (2019) then considered two statistical strategies for the measurements by the QMM mine that were below the detection limit. The first was to replace the measurements that were less than the detection limit with actual values, which is a common procedure, but not when such a large fraction of the measurements are under the detection limit. According to Rio Tinto (2023a), “Graphical representation is DL/2 [half the detection limit] as per standard methodology.” The statement is partially correct, but it is just as common to replace measurements under the detection limit with the detection limit or half the detection limit or one-tenth of the detection limit or zero (which is not possible when logarithms of values are used, as in the present study), although these choices are completely arbitrary. For example, uranium measurements reported as <0.642 mg/L could be replaced with 0.642 mg/L or 0.321 mg/L or

0.0642 mg/L, while uranium measurements reported as <0.047 mg/L could be replaced with 0.047 mg/L or 0.0235 mg/L or 0.0047 mg/L. The absurdity of this procedure should be clear as almost any statistical result is possible, depending upon how the measurements below the detection limit are replaced with values. Moreover, it cannot be correct to replace a measurement of <0.642 mg/L with even a value of 0.0642 mg/L (still over twice the WHO drinking-water guideline) when the true concentration might be as low as 0.00001 mg/L.

The second alternative was to discard all measurements below the detection limits and carry out the statistical comparison using only the remaining values. This may seem equivalent to discarding data, for which extreme caution was urged above. However, Emerman (2019) pointed out that the real question was: Do the measurements below the detection limits actually constitute "data?" Given that the entire QMM dataset could not be discarded, it was deemed most likely that the analytical instrumentation was functioning properly and that the laboratory technicians knew the proper way to use the instrumentation. However, the double detection limits and the very high detection limits suggests that the laboratory technicians did not understand the meaning of "detection limit." In other words, Emerman (2019) decided that the QMM dataset was valid, but the measurements under the detection limit were not valid. This second alternative was chosen, resulting in the inclusion from the earlier QMM dataset (Swanson, 2019b) of 20 uranium measurements, 27 lead measurements, seven thorium measurements, and 16 titanium measurements (Emerman, 2019).

The subsequent dataset from the QMM mine (Rio Tinto, 2021b) included no mention of a detection limit. Instead, values that were repeated from the earlier QMM dataset (Swanson, 2019b) and which were stated as below a detection limit in Swanson (2019b) were plotted at the detection limit. For example, measurements of uranium at WS0501 on August 20, 2015, and October 22, 2015, and at WS0502 on June 4, 2015, were stated as <0.642 mg/L in Swanson (2019b), but plotted as equal to 0.642 mg/L in Rio Tinto (2021b). As mentioned above, this is an arbitrary and misleading way to plot measurements that are below a detection limit. In the integration of the data in the 2021 QMM water report (Rio Tinto, 2021b) with the existing data by Emerman (2021), all measurements from the earlier QMM dataset (Swanson, 2019b) that were below a detection limit were still rejected, as in the previous reports (Emerman, 2019, 2020), even if those same measurements were plotted as actual values in the more recent QMM dataset (Rio Tinto, 2021b). It should be noted that Rio Tinto (2021b) did not have an accompanying spreadsheet, so that the graphical data were digitized by Emerman (2021).

A problem arose when there were measurements within the more recent QMM dataset (Rio Tinto, 2021b) that were not repetitions from the earlier QMM dataset (Swanson, 2019b) that would seem to be equivalent to measurements that would have been rejected from the earlier dataset. For example, the more recent QMM dataset (Rio Tinto, 2021b) included measurements of uranium roughly equal to 0.642 mg/L at WS0501 on June 24, 2015, and at WS0502 on June 23, 2015, August 28, 2015, and December 3, 2015, that were not repetitions from the earlier QMM dataset (Emerman, 2021. Since these measurements were plotted as actual values in Rio Tinto (2021b) and nothing stated that they were below detection limits, they were included in the statistical analysis of Emerman (2021) under the general principle that data should not be discarded unless there is compelling evidence to do so. It should be noted that there was only one additional very high measurement of uranium (approximately equal to 0.642 mg/L) at the upstream site WS0501 and three additional very high measurements of uranium at the downstream site WS0502, so that the inclusion of the additional very high measurements of uranium had the effect of underestimating the impact of the QMM mine on regional water quality. In summary, no data from the more recent QMM dataset (Rio Tinto, 2021b) were discarded in the analysis by Emerman (2021).

This report follows the same procedures as in earlier reports (Emerman, 2019, 2020, 2021) for the statistical analysis of data with inconsistent detection limits. Those procedures are summarized as follows for each of the datasets that are integrated with the new data in the QMM 2021-2023 Water Report in this report:

1) Because of the inconsistent detection limits in the data from the QMM mine that were reported in Swanson (2019b), values that were below detection limits were excluded from the statistical analysis.
2) The analyses of the community-collected samples that were reported in Emerman (2019) did not have inconsistent detection limits. For these data, all values that were below a detection limit were set at one-half the detection limit.
3) The analyses that were reported in JBS&G (2020b) did not have inconsistent detection limits. For these data, all values that were below a detection limit were set at one-half the detection limit.
4) The new analyses that were reported in the 2021 QMM water report (Rio Tinto, 2021b) were plotted graphically with no mention of detection limits. These graphical data were digitized and used in the statistical analysis. Older data from Swanson (2019b) that were repeated in Rio Tinto (2021b) were treated as in Step #1.
5) The 2001 baseline study (CDN Water Management Consultants, 2001a-b) had inconsistent detection limits for cadmium, lead, and zinc (see Tables 3a-b). These data were evaluated only qualitatively and were excluded from any quantitative statistical analysis. However, the 2001 baseline study did have consistent detection limits for aluminum, iron, and uranium (see Table 3a-b). These data were included in statistical analyses with the single value of iron that was less than a detection limit being set to one-half the detection limit.

The management of the new data from the QMM 2021-2023 Water Report (Rio Tinto, 2023a) that were below a detection limit is discussed in the subsection “Data Consistency in QMM 2021-2023 Water Report” in the “Results” section.

Statistical comparisons between surface water quality upstream and downstream of the QMM mine were carried out by an integration of all available data, including the baseline data that were collected upstream from the mine and reported in CDN Water Management Consultants (2001a-b), the data collected by the QMM mine and reported in Swanson (2019b), the community-collected data reported in Emerman (2019), the data reported in JBS&G (2020b), the additional data collected by the QMM mine and reported in Rio Tinto (2021b), and the most recent data collected by the QMM mine and reported in Rio Tinto (2023a). Statistical comparisons between surface water quality pre-mining and downstream post-mining were carried out by comparing the baseline data in in CDN Water Management Consultants (2001a-b) with the downstream data in Swanson (2019b), Emerman (2019), JBS&G (2020b), Rio Tinto (2021b), and Rio Tinto (2023a). Comparisons were carried out separately for dissolved and total concentrations. Since Swanson (2019b) and Rio Tinto (2021b) did not specify whether total or dissolved concentrations were measured, the same values were used for both dissolved and total concentrations. All other datasets included separate values for total and dissolved concentrations (Emerman, 2019; Rio Tinto, 2023a) or specified that only total concentrations were measured (CDN Water Management Consultants, 2001a-b; JBS&G, 2020b). In addition to lead and the radionuclides uranium and thorium, statistical comparisons were carried out for aluminum, cadmium, iron, and zinc. It should be noted that no new additional thorium measurements have appeared since Swanson (2019b) and Emerman (2019). Statistical comparisons were carried out using the t-test, based on the logarithms of values, as in previous reports (Emerman, 2019, 2020, 2021). Expected values were expressed as geometric means, which is appropriate when values range over orders of magnitudes (see detailed explanation in Emerman (2021)).

RESULTS

Data Consistency in QMM 2021-2023 Water Report

The detection limits in the QMM 2021-2023 Water Report were largely consistent and reasonable with minimum measured concentrations equal to or higher than the stated detection limit (see Table 6). The exception was aluminum (see Table 6), for which total concentrations at site S46 were stated as <0.5 mg/L for July 13, July 24, and August 21, 2023, and a dissolved concentration was stated as <0.05 mg/L for October 16, 2023 (see Table 4c). Because there were numerous measurements of aluminum less than 0.5 mg/L (see Table 4c), it was decided that the expression "<0.5 mg/L" was a typographical error repeated three times that should have been typed as "<0.05 mg/L." The four measurements of aluminum that were stated as below a detection limit were all set equal to 0.025 mg/L (half a detection limit of 0.05 mg/L) for statistical analyses. In all other cases, data in the QMM 2021-2023 Water Report that were below a detection limit were set equal to half the detection limit for statistical analysis (see Table 6).

Table 6. QMM 2021-2023 water report: Detection limits and minimum concentrations[1]

Element	Detection Limits (mg/L)	Minimum Concentration (mg/L)
Al (aluminum)	0.05, 0.5	0.05
As (arsenic)	0.001	0.001
Cd (cadmium)	0.0002	0.0002
Cr (chromium)	0.001	0.001
Fe (iron)	0.05	0.06
Hg (mercury)	0.0001	0.0001
Mn (manganese)	0.005	0.006
Ni (nickel)	0.001	0.001
Pb (lead)	0.001	0.001
Se (selenium)	0.001	0.002
Sn (tin)	0.005	<0.005
U (uranium)	0.005	<0.005
Zn (zinc)	0.005	0.005

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)

The use of detection limits in the QMM 2021-2023 Water Report is certainly an improvement over previous data releases by the QMM mine (Swanson, 2019b; Rio Tinto, 2021b). However, it is disappointing that the problem of inconsistent detection limits in data from the QMM mine still persists, despite the numerous criticisms of this practice in Emerman (2019, 2020, 2021). It is especially disappointing since the QMM 2021-2023 Water Report even recognizes the problem. According to Rio Tinto (2023a), "The metal monitoring data presented in this Water Report is based only on external laboratory data obtained from the following recognised and accredited laboratory: - Eurofins Environment Testing Australia (ISO/IEC 17025 accredited laboratories) (Eurofins) … In addition to their accredited quality assurance procedures, this facility undertakes water quality analyses with limits of analytical detection that are more suitable for environment assessment.” The preceding is not literally true because the detection limit for lead is 0.001 mg/L (see Table 6), while the US EPA (2024a) aquatic life criterion for chronic exposure to lead for freshwater organisms is 0.0025 mg/L (see Table 1). Thus, a more appropriate detection limit for lead would be 0.00025 mg/L (10% of the aquatic life criterion). It should be noted that the wastewater from the QMM mine is released into both drinking water supply and aquatic habitat, so that there should be compliance with both drinking water and aquatic standards. The commitment of the QMM mine to comply with internationally-recognized standards (Office des Mines Nationales et des Industries Stratégiques and QIT-Fer et Titane Inc., n.d.; Orengo, 2022a; Rio Tinto, 2022c), as previously mentioned, should also be noted.

A far more serious problem than the persistent lack of appropriate and consistent detection limits is that the data plotted in the graphs in the QMM 2021-2023 Water Report (see selection in Figs. 8a-f) are different from the data in the accompanying spreadsheet that was provided to Andrew Lees Trust by Rio Tinto (see selection in Tables 4a-f). It was not possible for the author to assign values for all of the tiny data points in the graphs (see Figs. 8-f). However, it was relatively easy to compute minimum and maximum values for the data in the spreadsheet (see Tables 7a-b) and then to compare the minima and maxima with the graphs. No attempt was made in this report to document all contradictions between the spreadsheet and the graphs, but six categories of examples will suffice:

1) According to the spreadsheet, the maximum value of total arsenic at WMC603 was 0.002 mg/L as measured on 10 occasions between March 9 and December 5, 2022 (see Table 7b), while the graph in the 2021-2023 Water Report shows a maximum total arsenic concentration of 0.004 mg/L (see Fig. 8a). Although the graph shows all total arsenic concentrations at S41 and S46 below the detection limit (<0.001 mg/L) (see Fig. 8a), the spreadsheet indicated measured total arsenic concentrations of 0.001 mg/L at S41 on March 17, August 31, and October 24, 2022, and at S46 on October 31, 2022 (see Table 7b). Thus, it is incorrect to state that “All upstream and downstream Mandromondromotra River samples are below the arsenic laboratory limit of detection” (Rio Tinto, 2023a).
2) According to the spreadsheet, the maximum value of total cadmium at S46 was 0.0002 mg/L as measured on March 9, March 10, and March 17, 2022 (see Tables 4d and 7b). By contrast, the graph in the 2021-2023 Water Report shows all total cadmium concentrations at S46 below the detection limit (<0.0002 mg/L) (see Fig. 8b). Thus, it is incorrect to state that “All upstream and downstream Mandromondromotra River samples are below the cadmium laboratory limit of detection” (Rio Tinto, 2023a).
3) According to the spreadsheet, the maximum value of total chromium at WMC603 was 0.001 mg/L as measured on March 11, 2023 (see Table 7b). By contrast, the graph in the 2021-2023 Water Report shows two measurements of total chromium concentrations of 0.002 mg/L at WMC603 (see Fig. 8c). Although the graph shows all total chromium concentrations at S41 below the detection limit (<0.001 mg/L), the spreadsheet indicated measured total chromium concentrations of 0.001 mg/L at S41 on March 16 and August 30, 2022 (see Table 7b). Thus, it is incorrect to state that “All upstream and downstream Mandromondromotra River samples are below the chromium laboratory limit of detection” (Rio Tinto, 2023a).

4) According to the spreadsheet, the maximum total iron concentration at WMC603 was 2.9 mg/L as measured on July 4, 2022 (see Table 7b). By contrast, the graph in the 2021-2023 Water Report shows a maximum total iron concentration greater than 4 mg/L at WMC603 (see Fig. 8d). Although the measurement from July 4, 2022, includes the comment "sampling method/location ongoing investigation," that does not explain why the graph shows a measurement far in excess of 2.9 mg/L at a much later date.
5) According to the spreadsheet, the maximum total manganese concentration at WMC603 was 0.8 mg/L as measured on October 31, 2022 (see Table 7b). By contrast, the graph in the 2021-2023 Water Report shows a maximum total manganese concentration of approximately 0.95 mg/L at WMC603 (see Fig. 8e).
6) According to the spreadsheet, the maximum value of total lead at WMC603 was 0.004 mg/L as measured on March 16, March 17, and March 18, 2022 (see Table 7b). By contrast, the graph in the 2021-2023 Water Report shows a total lead concentration slightly greater than 0.005 mg/L at WMC603 (see Fig. 8f).

Table 7a. QMM 2021-2023 water report: Maximum and minimum values[1]

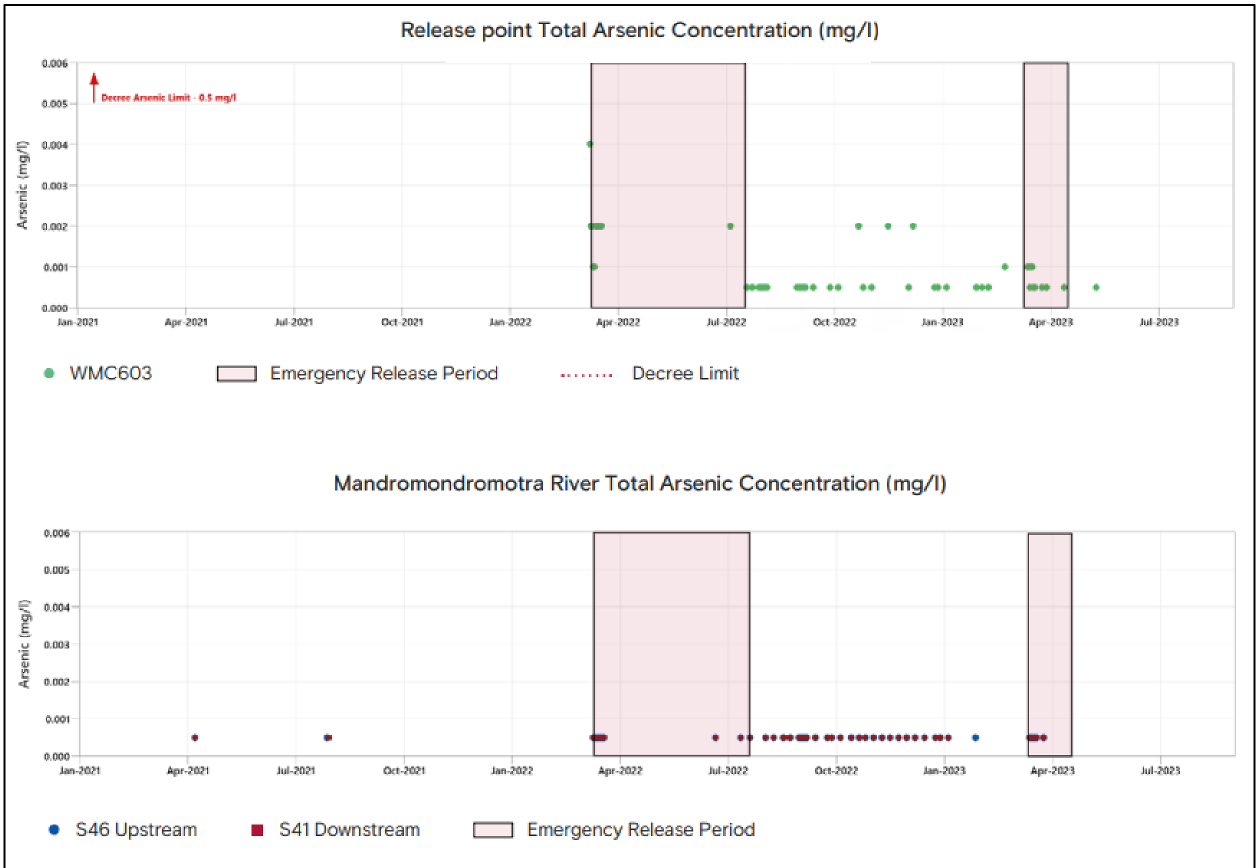
On-Site Parameter	Discharge Point (WMC603)	Upstream (S46 = SW15)	Downstream (S41 = SW06)
pH	3.30 – 7.30	4.2 – 6.4	3.38 – 5.84
EC[2] (µS/cm)	193.5 – 890	32.5 – 212.4	58.2 – 426.9
Turbidity (NTU)	1.62 – 75.63	1.71 – 36.28	0.63 – 28.96

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)
[2] EC = Electrical Conductivity

Table 7b. QMM 2021-2023 water report: Maximum total concentrations[1,2]

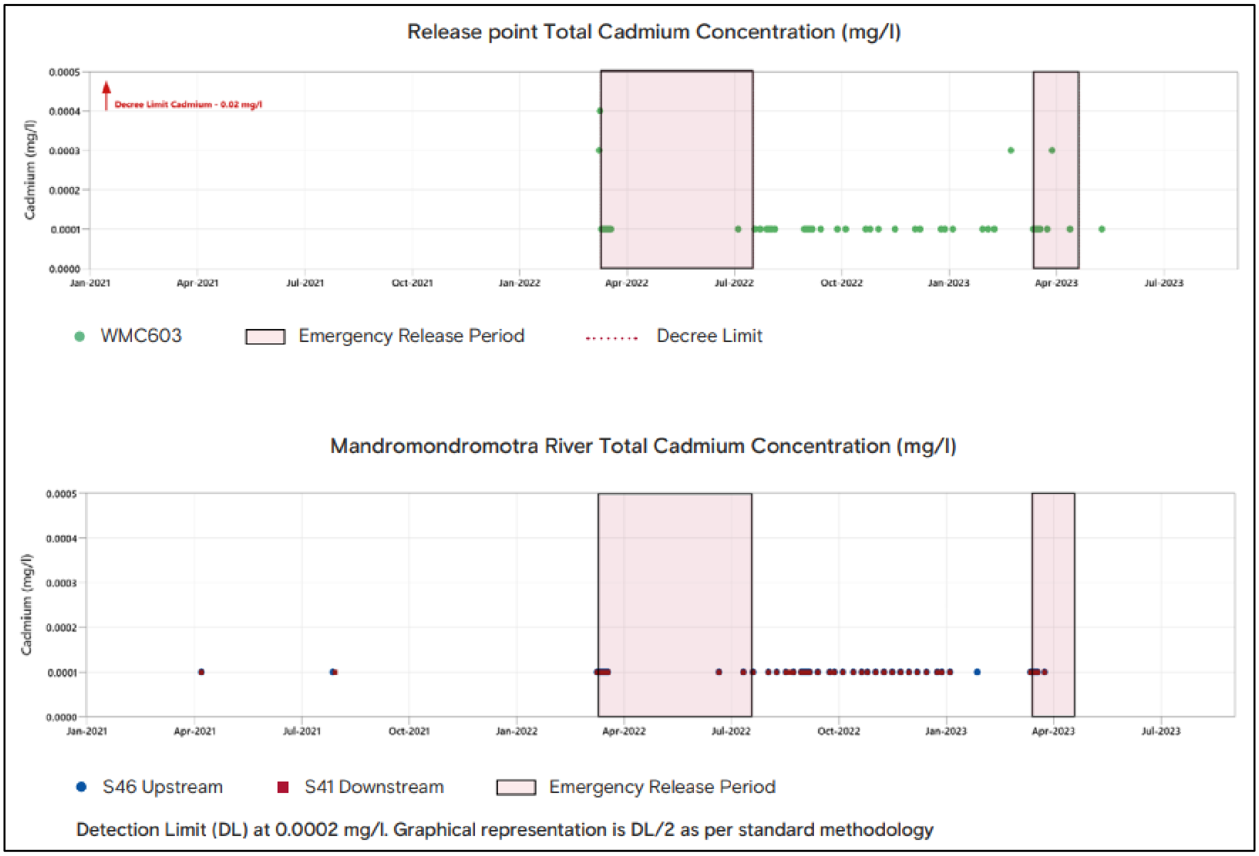
Element	Discharge Point (WMC603)	Upstream (S46 = SW15)	Downstream (S41 = SW06)
Al (aluminum) (mg/L)	13	0.64	2.2
As (arsenic) (mg/L)	0.002	0.001	0.001
Cd (cadmium) (mg/L)	0.0004	0.0002	<0.0002
Cr (chromium) (mg/L)	0.001	<0.001	0.001
Fe (iron) (mg/L)	2.9	1.9	1.3
Hg (mercury) (mg/L)	0.0001	<0.0001	0.0002
Mn (manganese) (mg/L)	0.8	0.067	0.18
Ni (nickel) (mg/L)	0.023	0.003	0.007
Pb (lead) (mg/L)	0.004	0.001[3]	<0.001
Se (selenium) (mg/L)	0.002	0.004	0.002
Sn (tin) (mg/L)	<0.005	<0.005	<0.005
U (uranium) (mg/L)	<0.005	<0.005	<0.005
Zn (zinc) (mg/L)	0.25	0.18	0.33

[1] Compiled from spreadsheet provided to Andrew Lees Trust by V. Bahon (Rio Tinto)
[2] Values in red indicate contradictions between spreadsheet and graphs in Rio Tinto (2023a)
[3] The total lead concentration of 0.001 mg/L occurred on September 25, 2023, which is not covered by the graph in the QMM 2021-2023 Water Report (see Fig. 8f).



Detection Limit (DL) at 0.001 mg/l. Graphical representation is DL/2 as per standard methodology

Figure 8a. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum value of arsenic at WMC603 was 0.002 mg/L as measured on 10 occasions between March 9 and December 5, 2022, while the above graph shows a maximum arsenic concentration of 0.004 mg/L (see Table 7b). Although the above graph shows all arsenic concentrations at S41 and S46 below the detection limit (<0.001 mg/L), the spreadsheet indicated measured arsenic concentrations of 0.001 mg/L at S41 on March 17, August 31, and October 24, 2022, and at S46 on October 31, 2022 (see Table 7b). Thus, it is incorrect to state that "All upstream and downstream Mandromondromotra River samples are below the arsenic laboratory limit of detection" (Rio Tinto, 2023a). No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).



Release point Total Cadmium Concentration (mg/l)

Mandromondromotra River Total Cadmium Concentration (mg/l)

Detection Limit (DL) at 0.0002 mg/l. Graphical representation is DL/2 as per standard methodology

Figure 8b. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum value of total cadmium at S46 was 0.0002 mg/L as measured on March 9, March 10, and March 17, 2022 (see Table 7b). By contrast, the above graph shows all cadmium concentrations at S46 below the detection limit (<0.0002 mg/L). Thus, it is incorrect to state that "All upstream and downstream Mandromondromotra River samples are below the cadmium laboratory limit of detection" (Rio Tinto, 2023a). No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).

Figure 8c. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum value of chromium at WMC603 was 0.001 mg/L as measured on March 11, 2023 (see Table 7b). By contrast, the above graph shows two measurements of chromium concentrations of 0.002 mg/L at WMC603. Although the above graph shows all chromium concentrations at S41 below the detection limit (<0.001 mg/L), the spreadsheet indicated measured chromium concentrations of 0.001 mg/L at S41 on March 16 and August 30, 2022 (see Table 7b). Thus, it is incorrect to state that “All upstream and downstream Mandromondromotra River samples are below the chromium laboratory limit of detection” (Rio Tinto, 2023a). No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).

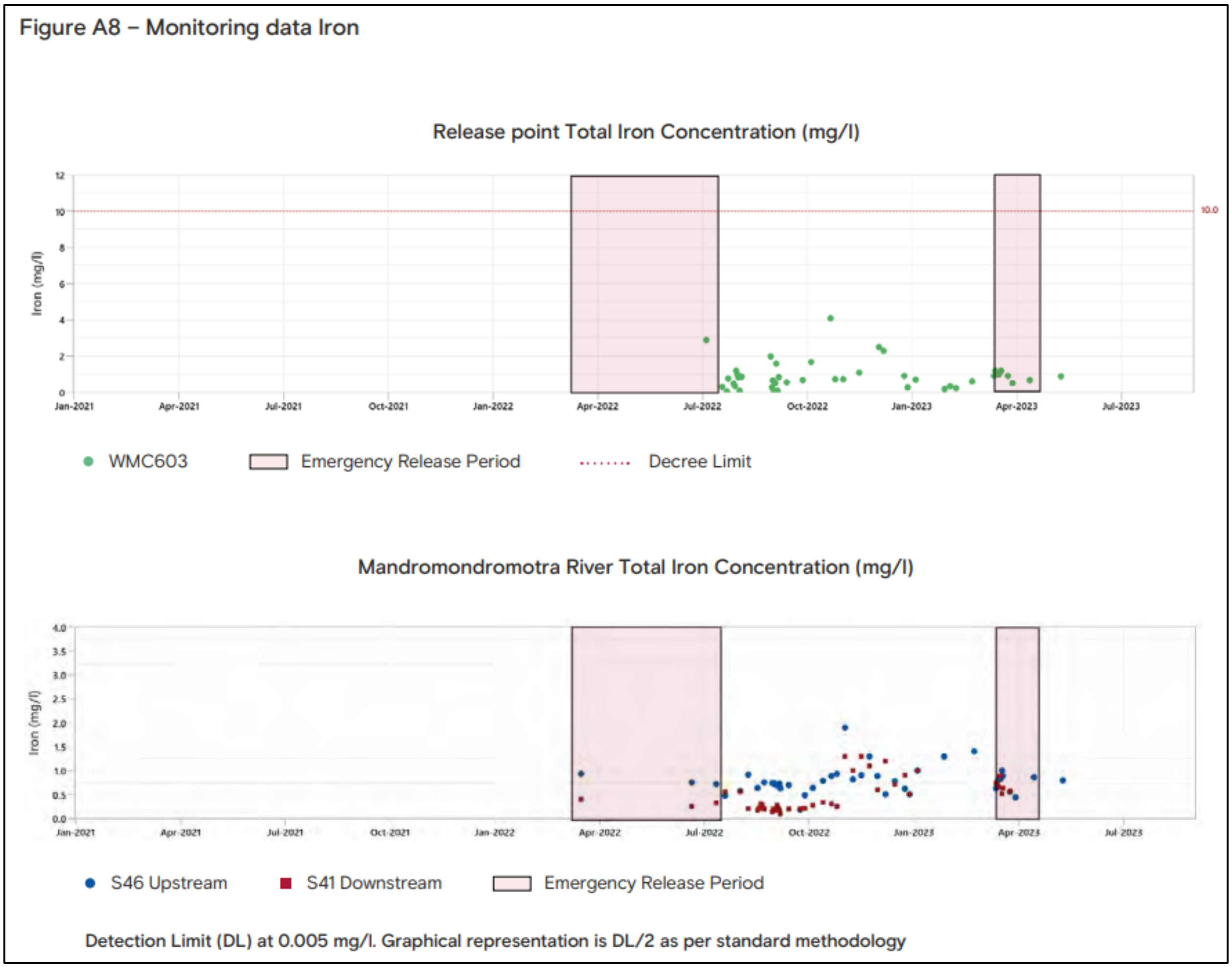


Figure 8d. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum iron concentration at WMC603 was 2.9 mg/L as measured on July 4, 2022 (see Table 7b). By contrast, the above graph shows a maximum iron concentration greater than 4 mg/L at WMC603. Although the measurement from July 4, 2022, includes the comment “sampling method/location ongoing investigation,” that does not explain why the graph shows a measurement far in excess of 2.9 mg/L at a much later date. No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).

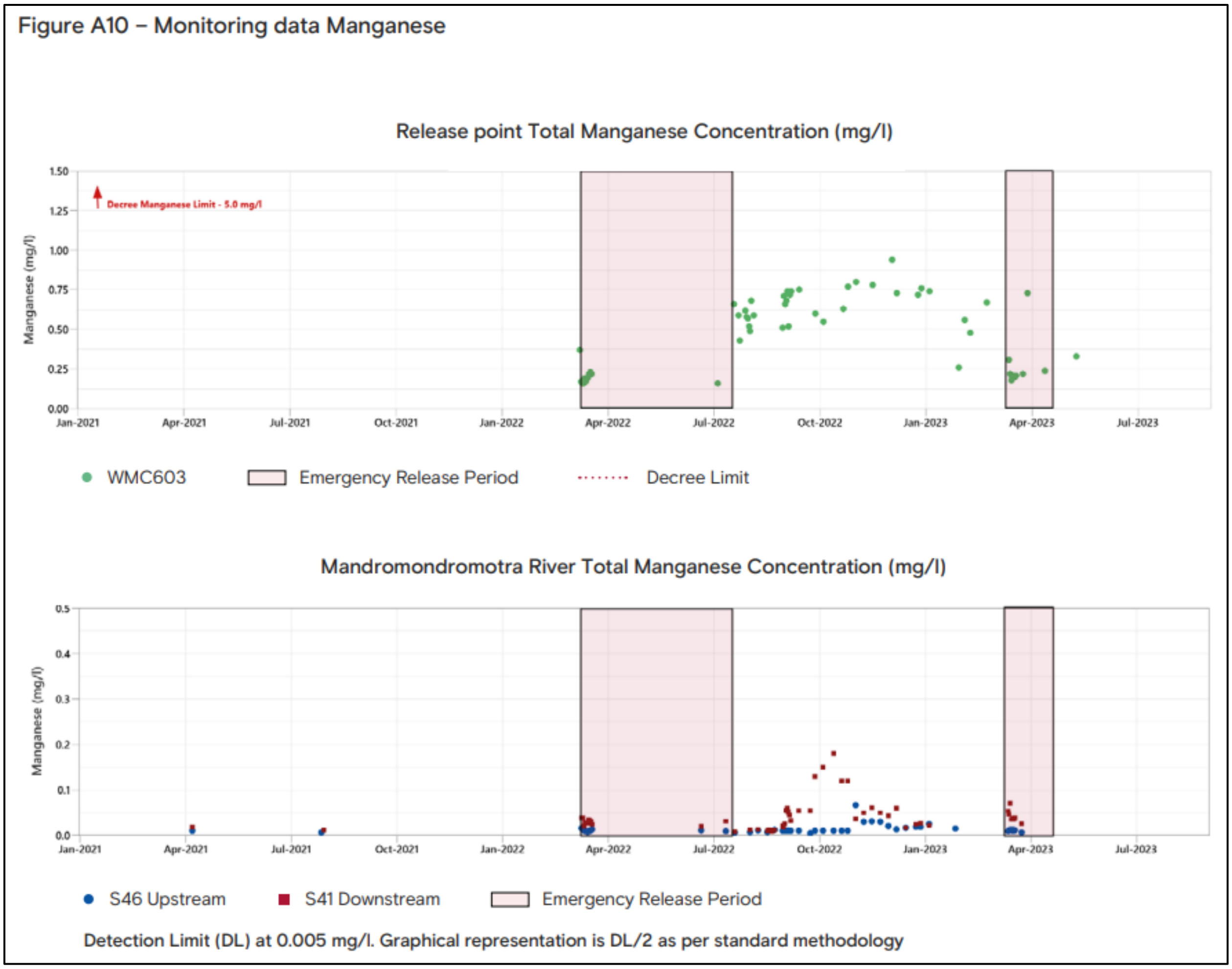
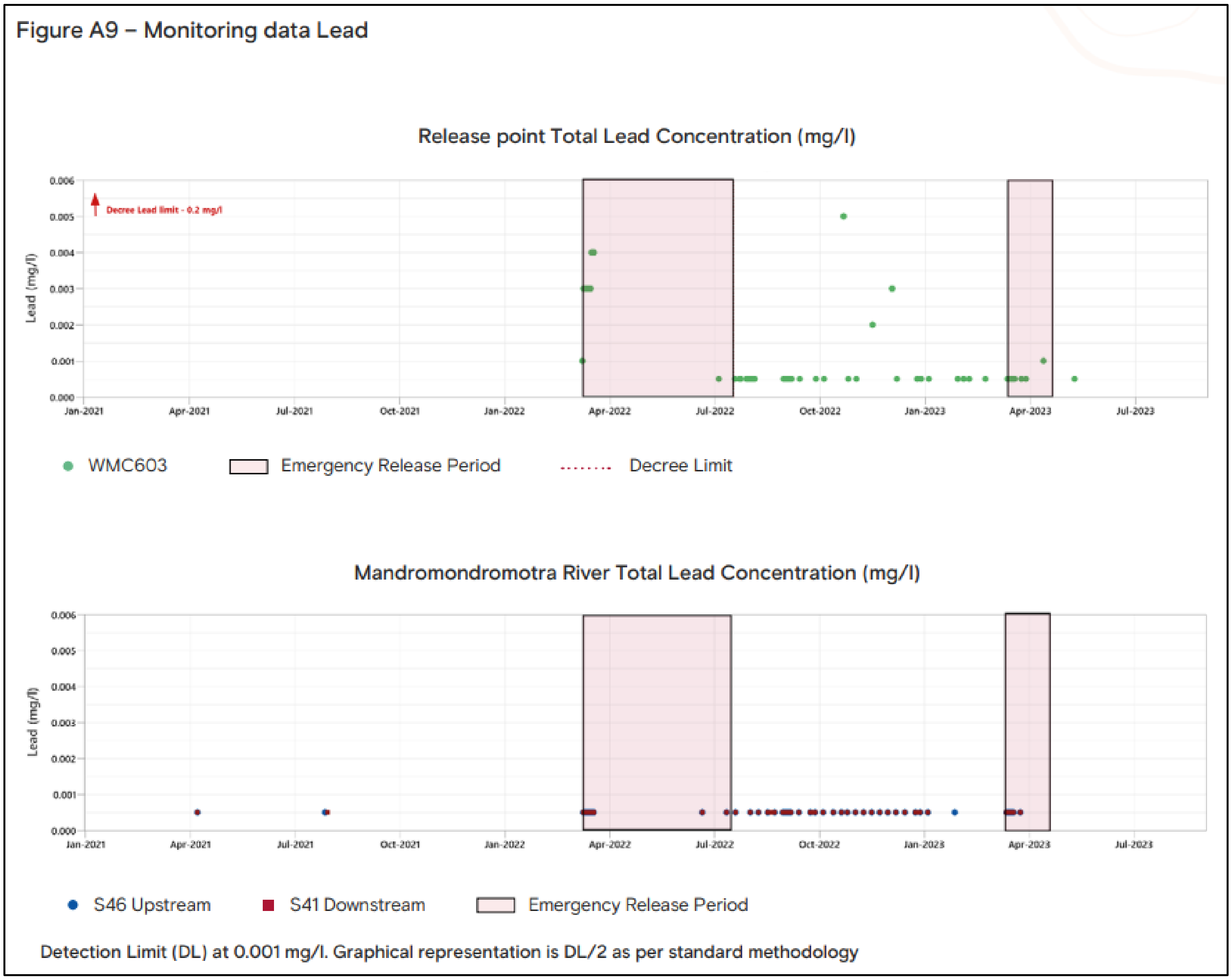


Figure 8e. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum manganese concentration at WMC603 was 0.8 mg/L as measured on October 31, 2022 (see Table 7b). By contrast, the above graph shows a maximum manganese concentration of approximately 0.95 mg/L at WMC603. No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).



Detection Limit (DL) at 0.001 mg/l. Graphical representation is DL/2 as per standard methodology

Figure 8f. Virginie Bahon (Head of Strategy of Community Engagement and Communications for Rio Tinto) provided Andrew Lees Trust with a spreadsheet to accompany the QMM 2021-2023 Water Report (Rio Tinto, 2023a). The spreadsheet values do not correspond to the graphs in Rio Tinto (2023a), so that it is impossible to determine which are the correct data or why there are two versions of the same dataset. According to the spreadsheet, the maximum value of lead at WMC603 was 0.004 mg/L as measured on March 16, March 17, and March 18, 2022 (see Table 7b). By contrast, the above graph shows a lead concentration slightly greater than 0.005 mg/L at WMC603. No attempt was made in this report to document all contradictions between the graphs in Rio Tinto (2023a) and the accompanying spreadsheet. Graph from Rio Tinto (2023a).

It is quite disturbing that Rio Tinto has two versions of the same dataset. It is impossible for the author to determine whether the graphs or the spreadsheet have the correct data, or whether either dataset is correct. It is not simply a question as to whether the preceding six categories of contradictions would have any effect on the determination of the impact of the QMM mine on regional water quality, but that the contradictions that were easily found raise the possibility that the spreadsheet and the graphs have very little in common or that the graphs refer to an entirely different dataset. Due to the great difficulty in assigning values to the data points in the graphs in the QMM 2021-2023 Water Report, this report uses the values from the spreadsheet, even when they visually contradict the graphs. On the basis of the numerous contradictions between the spreadsheet and the graphs, it could reasonably be argued that the entire dataset in the 2021-2023 Water Report should be rejected as invalid. Although the following subsections will update previous conclusions from Emerman (2019, 2020, 2021) regarding the detrimental impact of the QMM mine on regional water quality based on the QMM 2021-2023 Water Report and the 2001 baseline study, information will also be provided as to how the conclusions would be updated if the QMM 2021-2023 Water Report were rejected and the only additional information was the 2001 baseline study.

Ability of Monitoring Program to Detect Downstream Contamination

The QMM 2021-2023 Water Report includes surface water-quality data only from sites S46 and S41, which are 1487 meters upstream and 916 meters downstream, respectively, from the probable point of entry of contaminants into the Mandromondromotra River from wastewater discharge point WMC603 (see Fig. 6). These upstream and downstream sites are substantially closer to the wastewater discharge point than sites WS0501 and WS0502, for which data were reported in the previous QMM water report (Rio Tinto, 2021b) (see Fig. 6). As a consequence, the monitoring program described in the QMM 2021-2023 Water Report has the ability to detect only intentional releases of contaminants at the wastewater discharge point and no other type of contaminant release. In particular, the monitoring program cannot detect the following types of contaminant releases, all of which would result in the contamination of Méandre River, Lake Besaroy or Lake Ambavarano (see Figs. 4a-c):

1) accidental overtopping of a tailings dam by the water in the mining basin
2) accidental flow over the outer embankment of a tailings dam (which is constructed out of tailings) driven either by precipitation or overtopping
3) accidental seepage of water in the mining basin into groundwater followed by emergence in a downstream waterway or lake
4) accidental seepage into the estuary of water in the mining basin that was constructed on the bed of Lake Besaroy
5) accidental transport of fine tailings as wind-blown dust
6) intentional seepage of water in the mining basin into groundwater during the three-week periods when the water level is raised above sea level for floating the dredge and concentrator over a rocky ridge

It has already been mentioned that sample collections in the Méandre River and Lake Ambavarano have not taken place since December 2, 2019 (JBS&G, 2020b; see Fig. 4b), and no sample has been collected from Lake Besaroy since April 18, 2018 (Swanson, 2019b; see Fig. 4a). Beginning in 2020, sample collection has focused exclusively on the Mandromondromotra River and, beginning in 2021, exclusively on the 2403-meter reach of the Mandromondromotra River upstream and downstream from the discharge point WMC603 (see Fig. 6) (Rio Tinto, 2021b, Rio Tinto, 2023a). It is particularly disturbing that no sample collection has taken place in the lakes, especially in consideration of the description by Vyawahare (2023) that "the lake waters belched dead fish" after the tailings dam failure in December 2018 and that "thousands of dead fish were floating on Lake Ambavarano" after the tailings dam failures in February and March 2022.

Comparison of Upstream and Downstream Contaminant Concentrations

A comparison of all of the existing surface water-quality data for uranium, thorium, and lead (CDN Water Management Consultants, 2001a-b; Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) between the upstream and downstream sides of the

QMM mine confirmed the detrimental impact of the mine on regional water quality. The increases in the geometric means of the aqueous uranium concentrations from the upstream to the downstream side of the QMM mine by a factor of 22 for dissolved concentrations and a factor of 24 for total concentrations are statistically significant at better than the 99.9% confidence level ($P = 0.0003$) and 99.999% confidence level ($P = 0.000004$) for dissolved and total concentrations, respectively (see Fig. 9a). The geometric mean of the downstream total uranium concentration (0.0495 mg/L) is 1.65 times the WHO (2022) drinking water guideline for uranium (see Fig. 9a). The increases in the geometric means of the aqueous thorium concentrations from the upstream to the downstream side of the QMM mine by a factor of 163 for dissolved concentrations and a factor of 246 for total concentrations are statistically significant at better than the 99.99% confidence level ($P = 0.00009$) and 99% confidence level ($P = 0.002$) for dissolved and total concentrations, respectively (see Fig. 9b). The increases in the geometric means of the aqueous lead concentrations from the upstream to the downstream side of the QMM mine by a factor of 9.5 for dissolved concentrations and a factor of 4.9 for total concentrations are statistically significant at better than the 99.999% confidence level ($P = 0.000002$) and 99.99% confidence level ($P = 0.00002$) for dissolved and total concentrations, respectively (see Fig. 9c).

Increases in the geometric means of total concentrations of cadmium and zinc by factors of 1.5 and 1.75, respectively, from the upstream to the downstream side of the QMM mine were not statistically significant at the 95% confidence level (see Figs. 9d-e). These results were expected because there is no apparent reason as to why the mining operation should be mobilizing cadmium or zinc from the heavy mineral sands and the same results were found by Emerman (2021). According to Emerman (2021), "Based on the lack of statistically significant increases in aluminum, cadmium and zinc from the upstream to the downstream sides of the QMM mine, concentrations of these elements in the Mandromondromotra River appear to be naturally occurring, with no detrimental impact from the QMM mine. This result should be expected because there is no apparent reason as to why the mining process would be enriching the process water in aluminum, cadmium or zinc. Neither ilmenite nor monazite nor zircon commonly include either aluminum, cadmium or zinc within their crystal structures."

A surprising result in this report, which is different from what was found by Emerman (2021), is that the increases in the geometric means of the aqueous aluminum concentrations from the upstream to the downstream side of the QMM mine by a factor of 2.0 for dissolved concentrations and a factor of 1.9 for total concentrations are statistically significant at the 95% confidence level ($P = 0.02$ for dissolved concentrations and $P = 0.01$ for total concentrations) (see Fig. 9f). By contrast, using the smaller dataset that was available at the time, Emerman (2021) found that that the decrease in aluminum from the upstream to the downstream side of the mine was not statistically significant at the 95% confidence level.)The decreases in the geometric means of the aqueous iron concentrations from the upstream to the downstream side of the QMM mine were not statistically significant at the 95% confidence level for dissolved concentrations ($P = 0.08$), but the decrease by a factor of 3.1 was highly statistically significant ($P = 8 \times 10^{-10}$) for total concentrations (see Fig. 9g). The decrease in total concentration of iron was previously found by Emerman (2020) with statistical significance at better than the 99% confidence level ($P = 0.002$). In fact, the drop in total iron concentration from upstream site S46 to downstream site S41 is easily visually evident in the relevant graph in the QMM 2021-2023 Water Report (see Fig. 8d).

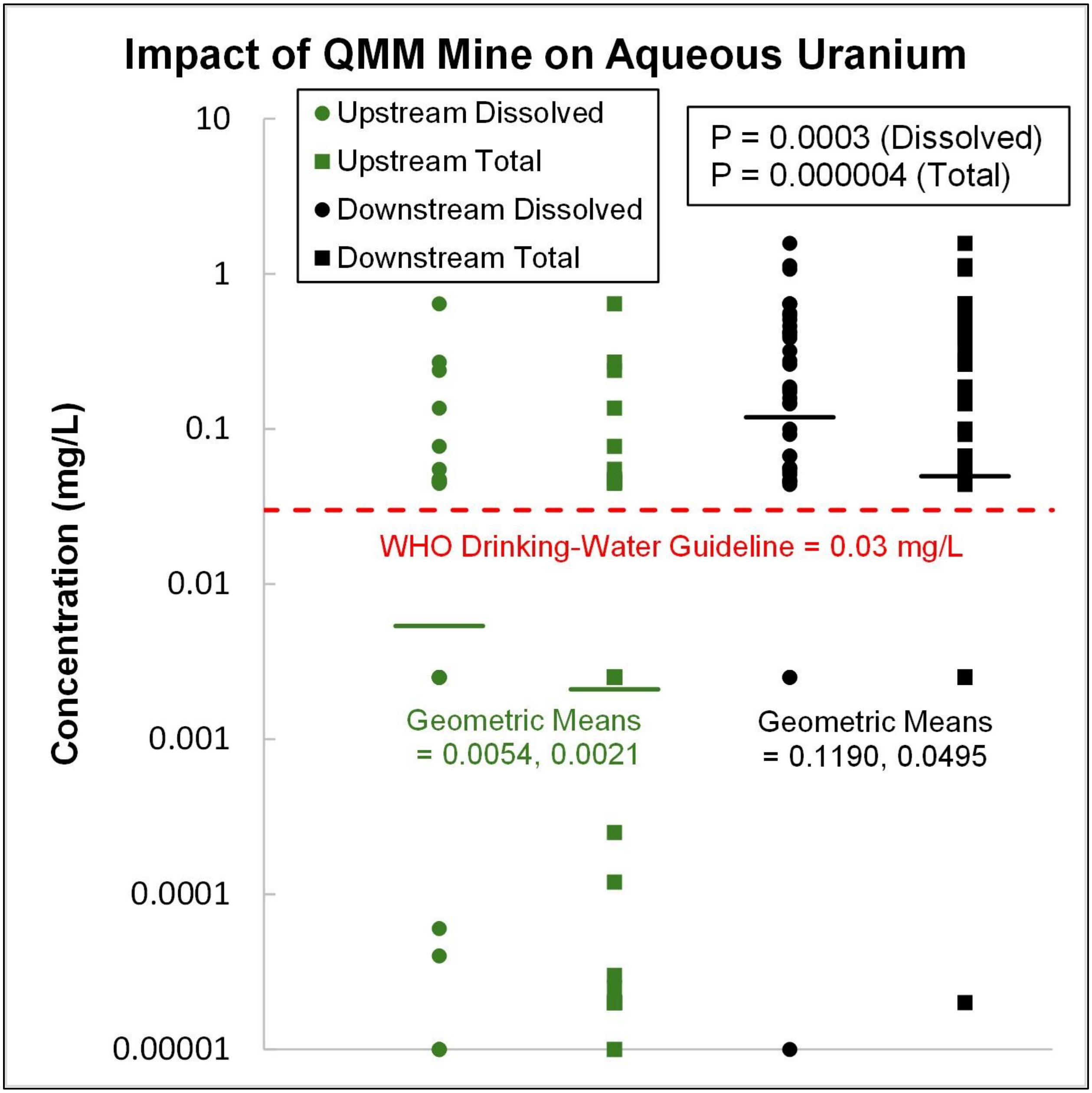


Figure 9a. Combining all of the existing water-quality data for uranium (CDN Water Management Consultants, 2001a-b; Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) shows that the increases in the geometric means of the aqueous uranium concentrations from the upstream to the downstream side of the QMM mine by a factor of 22 for dissolved concentrations and a factor of 24 for total concentrations are statistically significant at better than the 99.9% confidence level and 99.999% confidence level for dissolved and total concentrations, respectively, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.0003$) and the total concentrations ($P = 0.000004$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Swanson (2019b-c) and Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. JBS&G (2020b) measured only total concentrations. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

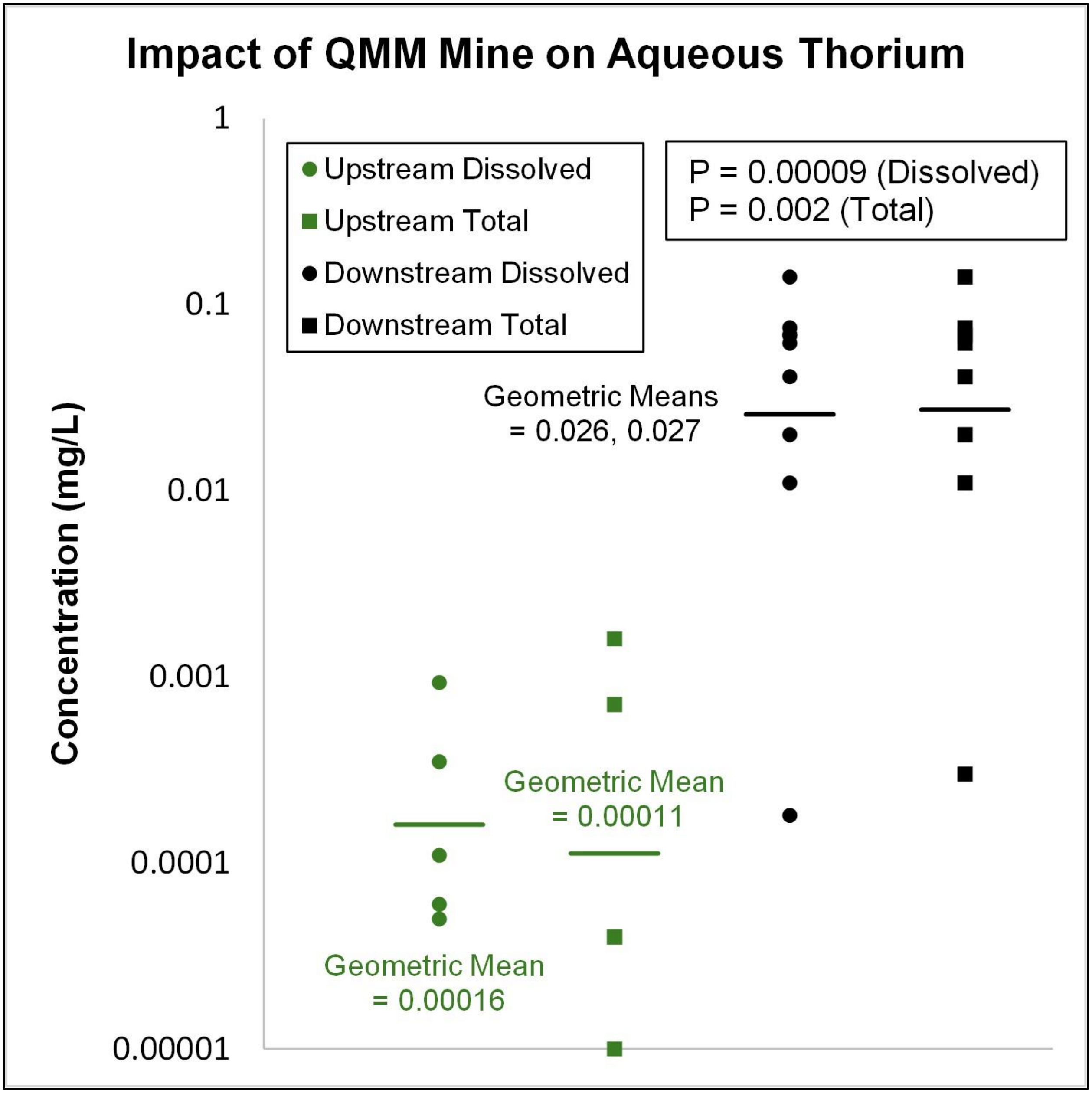


Figure 9b. Combining all of the existing water-quality data for thorium (Swanson, 2019b-c; Emerman, 2019) shows that the increases in the geometric means of the aqueous thorium concentrations from the upstream to the downstream side of the QMM mine by a factor of 162.5 for dissolved concentrations and a factor of 245.5 for total concentrations are statistically significant at better than the 99% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.00009$) and the total concentrations ($P = 0.002$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Swanson (2019b-c), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

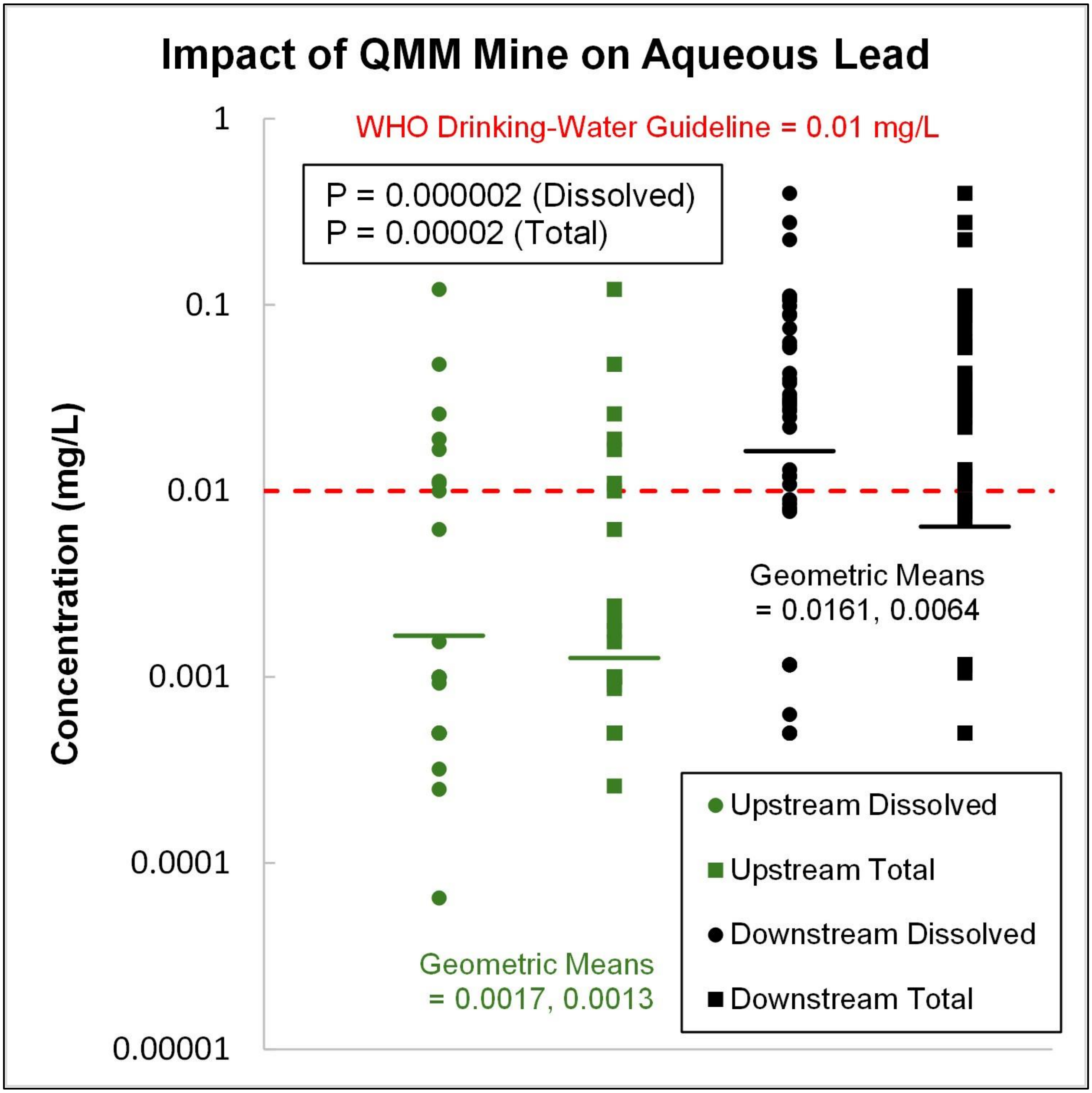


Figure 9c. Combining all of the existing water-quality data for lead (Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) shows that the increases in the geometric means of the aqueous lead concentrations from the upstream to the downstream side of the QMM mine by a factor of 9.5 for dissolved concentrations and a factor of 4.9 for total concentrations are statistically significant at better than the 99.99% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved (P = 0.000002) and the total concentrations (P = 0.00002). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Swanson (2019b-c) and Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. JBS&G (2020b) measured only total concentrations. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

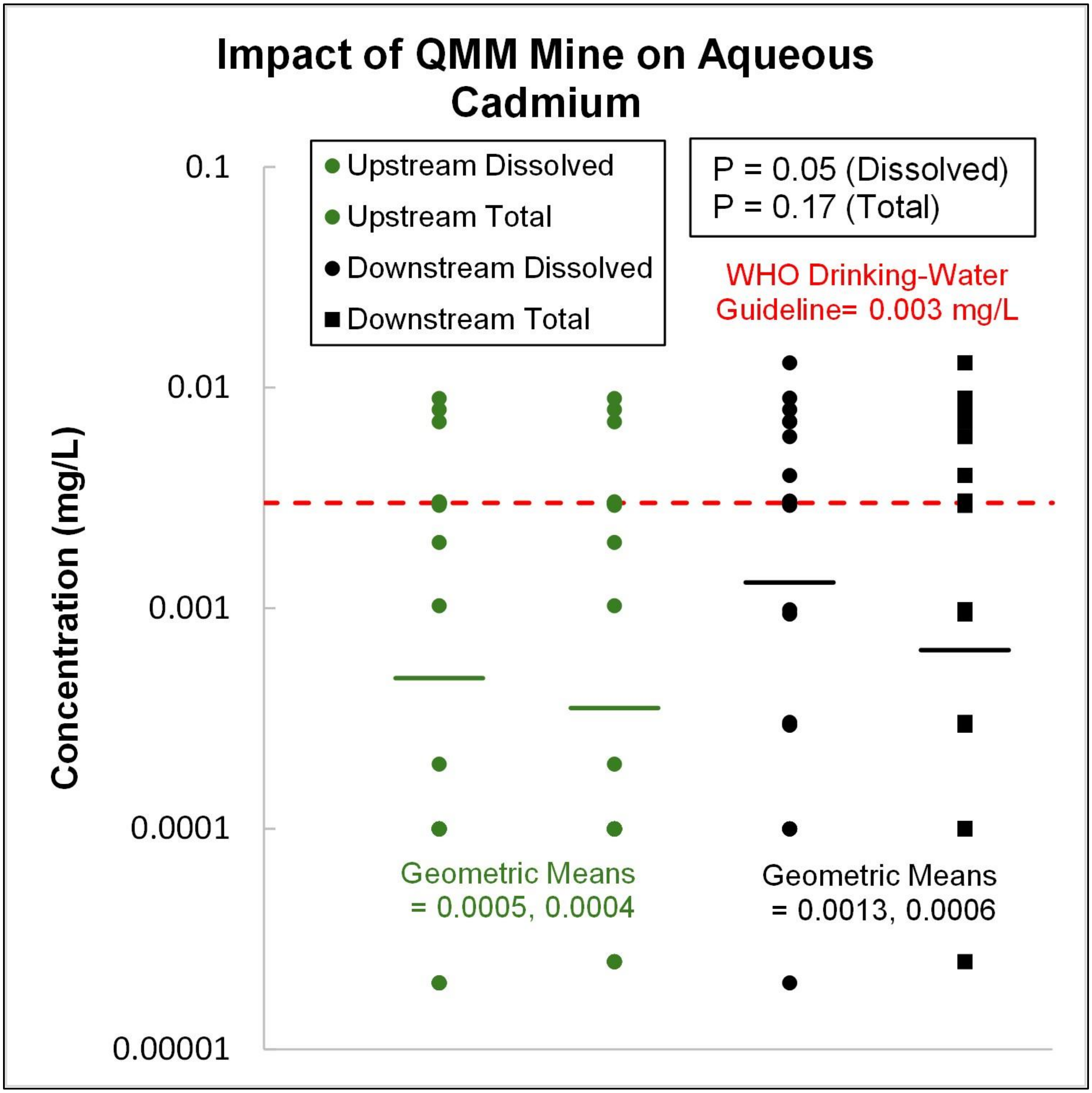


Figure 9d. Combining all of the existing water-quality data for cadmium (Emerman, 2019; Rio Tinto, 2021b, 2023a) shows that the increases in the geometric means of the aqueous cadmium concentrations from the upstream to the downstream side of the QMM mine by a factor of 2.6 for dissolved concentrations and a factor of 1.5 for total concentrations are not statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.05$) and the total concentrations ($P = 0.17$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

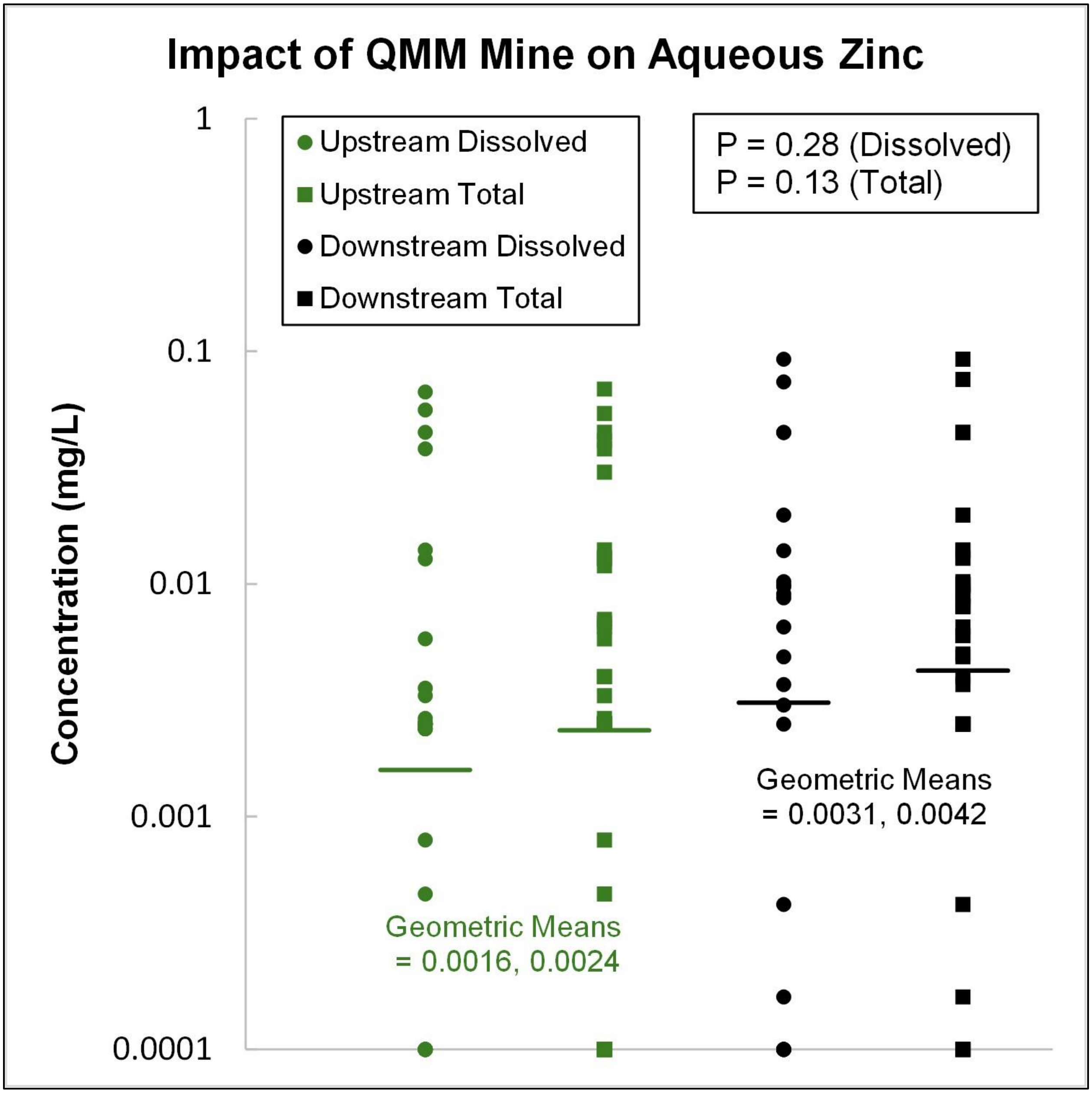


Figure 9e. Combining all of the existing water-quality data for zinc (Emerman, 2019; Rio Tinto, 2021b, 2023a) shows that the increases in the geometric means of the aqueous zinc concentrations from the upstream to the downstream side of the QMM mine by a factor of 1.9 for dissolved concentrations and a factor of 1.75 for total concentrations are not statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.28$) and the total concentrations ($P = 0.13$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

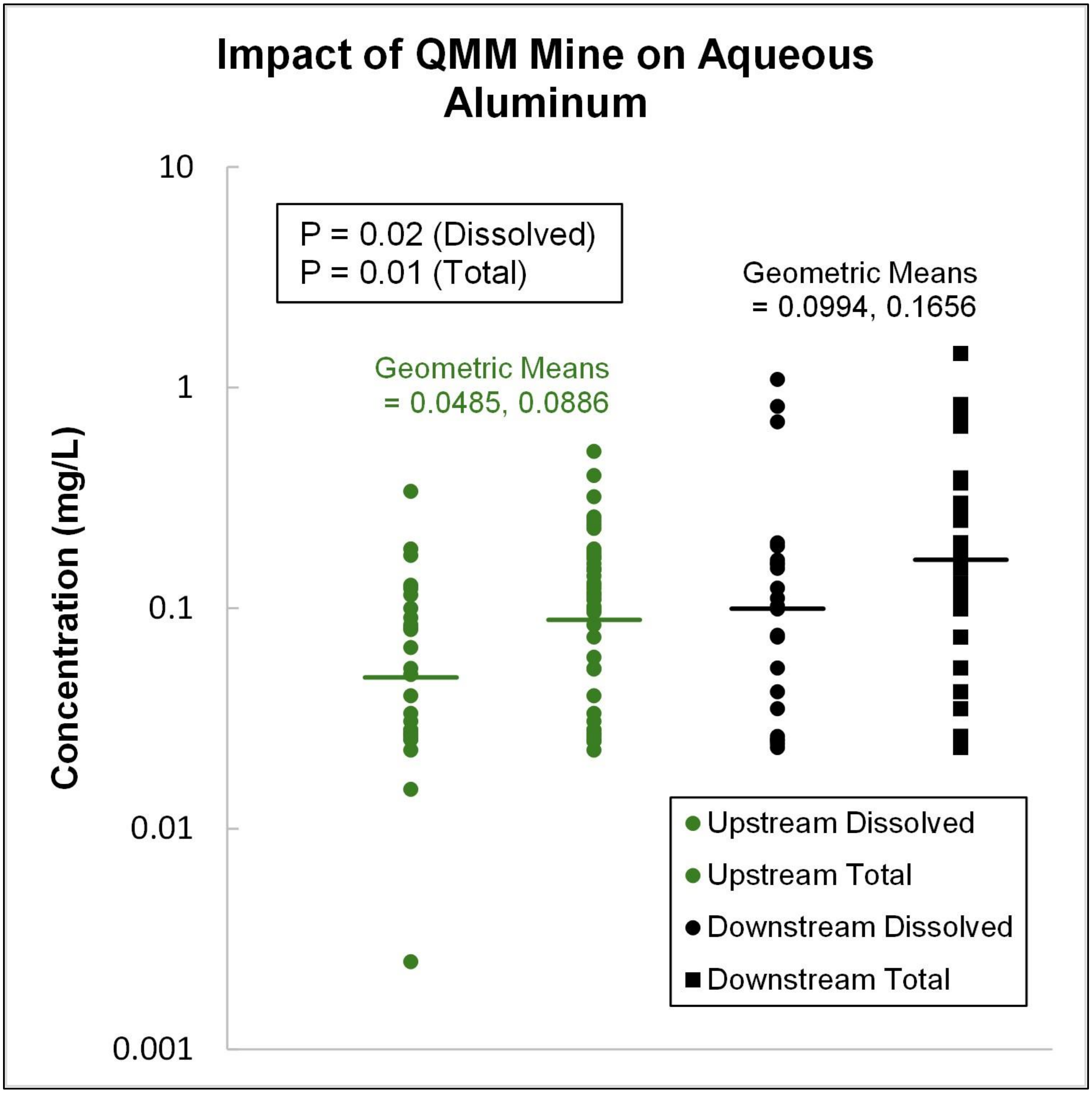


Figure 9f. Combining all of the existing water-quality data for aluminum (CDN Water Management Consultants, 2001a-b; Emerman, 2019; Rio Tinto, 2021b, 2023a) shows that the increases in the geometric means of the aqueous aluminum concentrations from the upstream to the downstream side of the QMM mine by a factor of 2.0 for dissolved concentrations and a factor of 1.9 for total concentrations are statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.02$) and the total concentrations ($P = 0.01$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

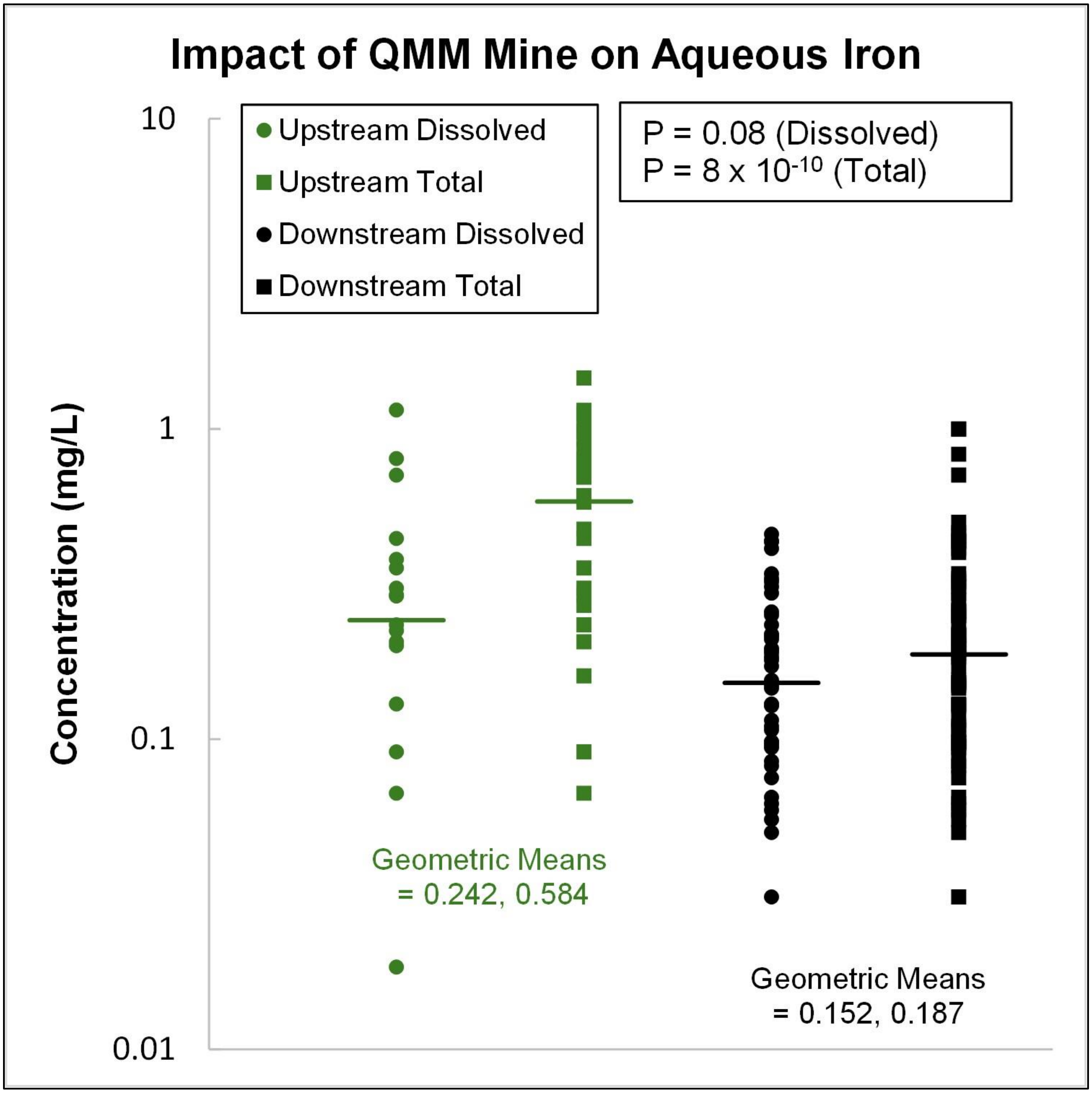


Figure 9g. Combining all of the existing water-quality data for iron (CDN Water Management Consultants, 2001a-b; Swanson, 2019b-c; Emerman, 2019; Rio Tinto, 2023a) shows that the decreases in the geometric means of the aqueous iron concentrations from the upstream to the downstream side of the QMM mine were not statistically significant at the 95% confidence level for dissolved concentrations, but were statistically significant at better than the 99.9999999% confidence level for total concentrations, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.08$) and the total concentrations ($P = 8 \times 10^{-10}$). The *P*-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations in Swanson (2019b-c), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site. The upstream concentrations include sample sites P1 and P2 (see Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

The QMM 2021-2023 Water Report relates the enrichment of the water in the mining basins in aluminum to the acidification that occurs during the mining process. According to Rio Tinto (2023a), "While no chemicals are added or used in the mining process, the mining operation does influence the quality of the process water. It lowers the pH of the water, which enables some heavy metals to dissolve in water, mainly aluminium." Rio Tinto (2019) further clarified, "Water in the dredge pond has a low pH and a high total suspended solids as the result of the churning action of the mining process." Thus, the acidification of the water in the mining basins is specifically connected to the dredging operation (see Fig. 3).

It is in no way clear to the author as to why the churning of the heavy mineral sands in the mining basins causes an acidification of the water. One possibility is to relate the acidification to the transfer of uranium from the sorbed state on sand grains to the dissolved state in water, which is the previously-discussed hypothesis of the author as to why the mining basins are enriched in uranium (Swanson, 2019a). Since uranium occurs in the aqueous form as an negatively-charged oxyanion, it would be attached to positively-charged sorption sites on sand grains. The detachment of uranium from a positively-charged site makes the site available to a negatively-charged hydroxide ion. The removal of hydroxide ions from the water column would, thus, make the water more acidic. The problem is that the transfer of uranium from the sorbed to the dissolved state would not be the only ion exchange process that is occurring during dredging. For example, lead is a positively-charged ion (cation) that attaches to negatively-charged sorption sites. Thus, the desorption of a lead ion makes the negatively-charged site available to a positively-charged hydrogen ion and the removal of hydrogen ions from the water column would make the water less acidic.

The decrease in the total iron concentration from the downstream to the upstream side of the mine is equally difficult to explain. One possibility is that some chemical species in the mine wastewater is causing iron to precipitate out of solution as it enters the Mandromondromotra River. It is difficult to imagine what aspect of the mining operation could be causing iron to move out of the dissolved phase in the mining basin and to attach to sand grains. The ore processing does include a magnetic circuit, which could possibly be related to the removal of iron. According to Swanson (2019b), "Ilmenite is the only conductive mineral in the concentrate produced by the wet circuit; therefore, it can be separated using electrostatic processing … The remaining non-conductive minerals pass again through a series of spirals to remove magnetic minerals such as monazite (the 'magnetic rejects'). One more pass through spirals to remove quartz is followed by more separation to remove residual conductive and magnetic minerals, resulting in zirsill." The point is that the difficulty in understanding why the downstream water is enriched in aluminum and depleted in iron seems to indicate that some aspect of the ore processing at the QMM mine either is not understood or has not yet been disclosed.

If the new data from the QMM 2021-2023 Water Report were rejected as invalid and only the newly-available 2001 baseline data were added to the existing data, the preceding results for radionuclides and lead would not change substantially. The increase in the total uranium concentration from the upstream to the downstream side of the QMM mine by a factor of 35 would be statistically significant at better than the 99.9% confidence level ($P = 0.0001$). The geometric mean of the downstream total uranium concentration (0.068 mg/L) would be 2.3 times the WHO (2022) drinking water guideline. Results for thorium would not change, since there were no thorium data either in the 2001 baseline study or the QMM 2021-2023 Water Report. Results for lead would revert back to those found by Emerman (2021), since, based upon the inconsistent detection limits, there were no useful quantitative data in the 2001 baseline study.

The only substantial change would be in the results for aluminum. If only the aluminum data from the 2001 baseline study were added to the existing data, the increases in aluminum concentrations from the upstream to the downstream side would not be statistically significant at the 95% confidence level, neither for dissolved concentrations ($P = 0.08$) nor for total concentrations ($P = 0.33$). Therefore, the evidence for enrichment of the downstream waterways in aluminum rests largely upon the new data in the QMM 2021-2023 Water Report. The preceding conclusion is somewhat opposite to the QMM 2021-2023 Water Report, which drew attention to a decrease in aluminum enrichment. According to Rio Tinto (2023a), "Noticeable reduction in aluminium levels from 2022 to 2023 emergency release period, due to the implementation of the water treatment plant."

A final point regarding the comparison of upstream and downstream concentrations is that the geometric mean of the dissolved concentration was greater than that of the total concentration for uranium, thorium, lead, and cadmium (see Fig. 9d). Of course, for a single water sample, the total concentration should be greater than the dissolved concentration. However, very few of the data points plotted in Figs. 9a-g represent dissolved and total concentrations measured in the same sample. By and large, the graphs represent many more total than dissolved concentrations (see Tables 4a-f).

Comparison of Baseline and Downstream Contaminant Concentrations

A comparison of the baseline data (CDN Water Management Consultants, 2001a-b) with all of the existing surface water-quality data for uranium downstream of the QMM mine (Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) further confirmed the detrimental impact of the mine on regional water quality. The increase in the geometric mean of the total uranium concentration by a factor of 884 from before to after opening the mine is statistically significant at the 99.999999999% confidence level (see Fig. 10a). The increase in the geometric mean of the total aluminum concentration by a factor of 2.1 from before to after opening the mine is statistically significant at better than the 95% confidence level ($P = 0.04$) (see Fig. 10b). The observed increase in aqueous aluminum concentration is consistent with the result from the previous subsection that compared total aluminum concentrations upstream and downstream from the mine, which suggests that the enrichment in aluminum by the mining operation is real (not an artifact of insufficient data). The decrease in total iron concentration from before to after opening the mine is not statistically significant at the 95% confidence level (see Fig. 10c).

The change in total lead concentrations from before to after opening of the QMM mine is carried out by a qualitative comparison of the baseline data (see Tables 3a-b) with the measurements in the far right-hand column of Fig. 9c. Thus, measurements of <0.001 mg/L (eight times), <0.005 mg/L (one time), and <0.01 mg/L (two times) (see Tables 3a-b) are compared with a geometric mean of 0.0064 mg/L (see Fig. 9c). It should be clear that total aqueous lead concentrations have increased from before to after opening the mine, although it is not possible to express this in a quantitative manner. Thus, a qualitative comparison of the baseline data (CDN Water Management Consultants, 2001a-b) with the existing surface water-quality data for lead downstream of the QMM mine (Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) further confirmed the detrimental impact of the mine on regional water quality.

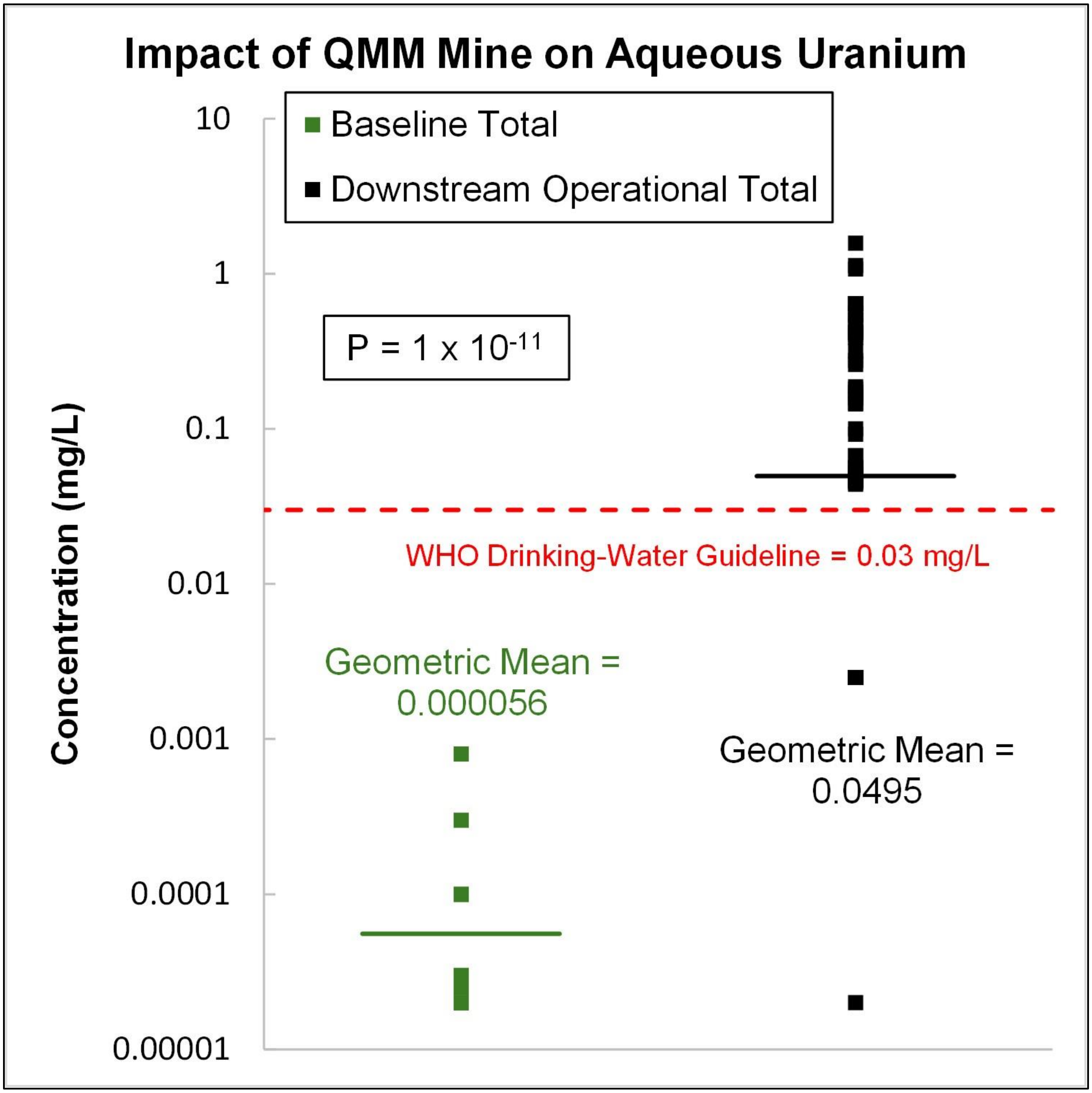


Figure 10a. A comparison of the baseline total uranium concentrations (CDN Water Management Consultants, 2001a-b) with all of the total uranium concentrations measured downstream of the QMM mine after the mine began operation (Swanson, 2019b-c; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021b, 2023a) shows that the increase in uranium concentration by a factor of 884 from before to after opening the mine is statistically significant at the 99.999999999% confidence level, according to the t-test carried out on the logarithms of values. For the data from the QMM surface water monitoring stations in Swanson (2019b-c) and Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. JBS&G (2020b) measured only total concentrations. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site.

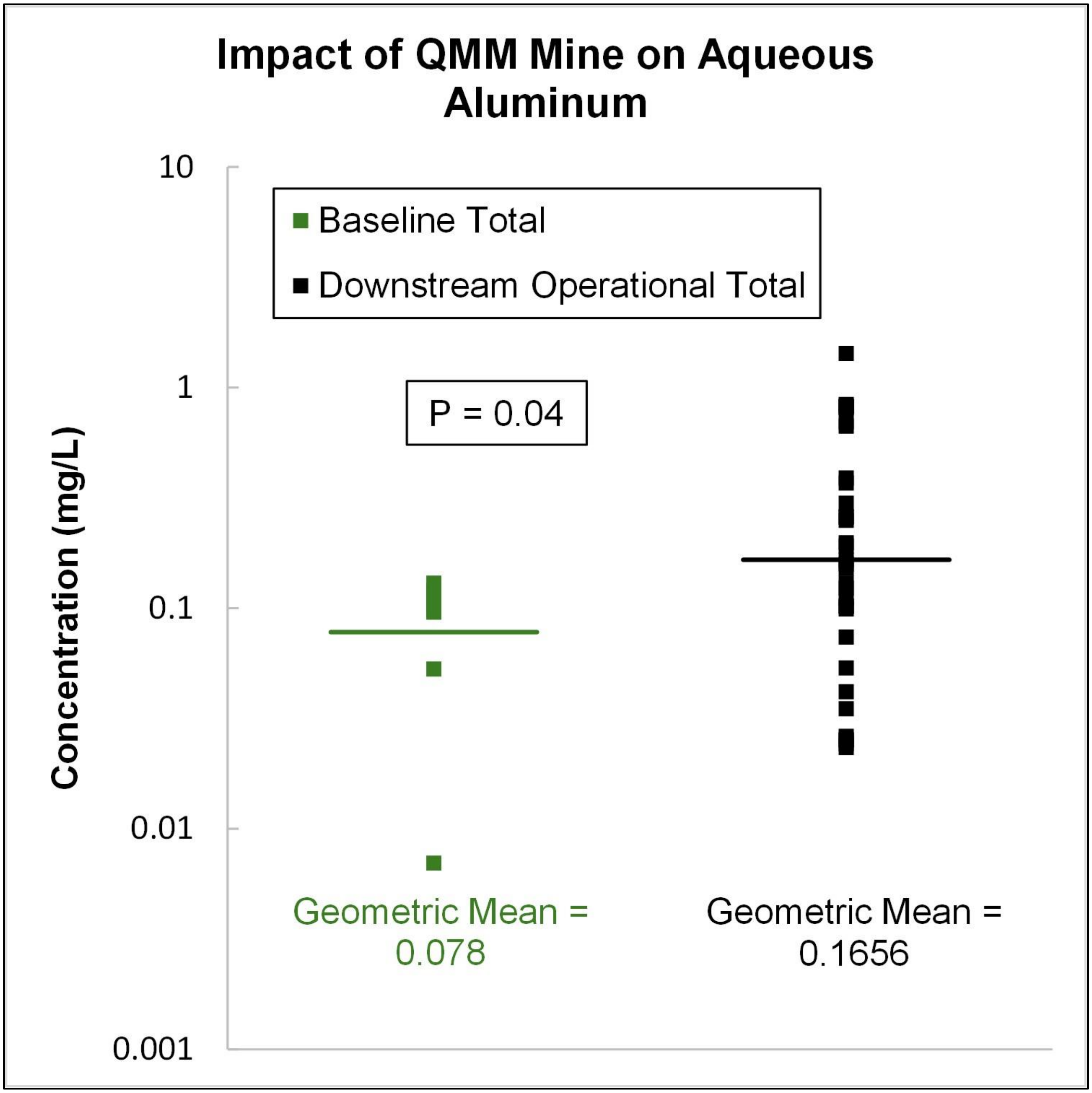


Figure 10b. A comparison of the baseline total aluminum concentrations (CDN Water Management Consultants, 2001a-b) with all of the total aluminum concentrations measured downstream of the QMM mine after the mine began operation (Emerman, 2019; Rio Tinto, 2021b, 2023a) shows that the increase in aluminum concentration by a factor of 2.1 from before to after opening the mine is statistically significant at the better than the 95% confidence level (*P* = 0.04), according to the t-test carried out on the logarithms of values. For the data from the QMM surface water monitoring stations in Rio Tinto (2021b), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site.

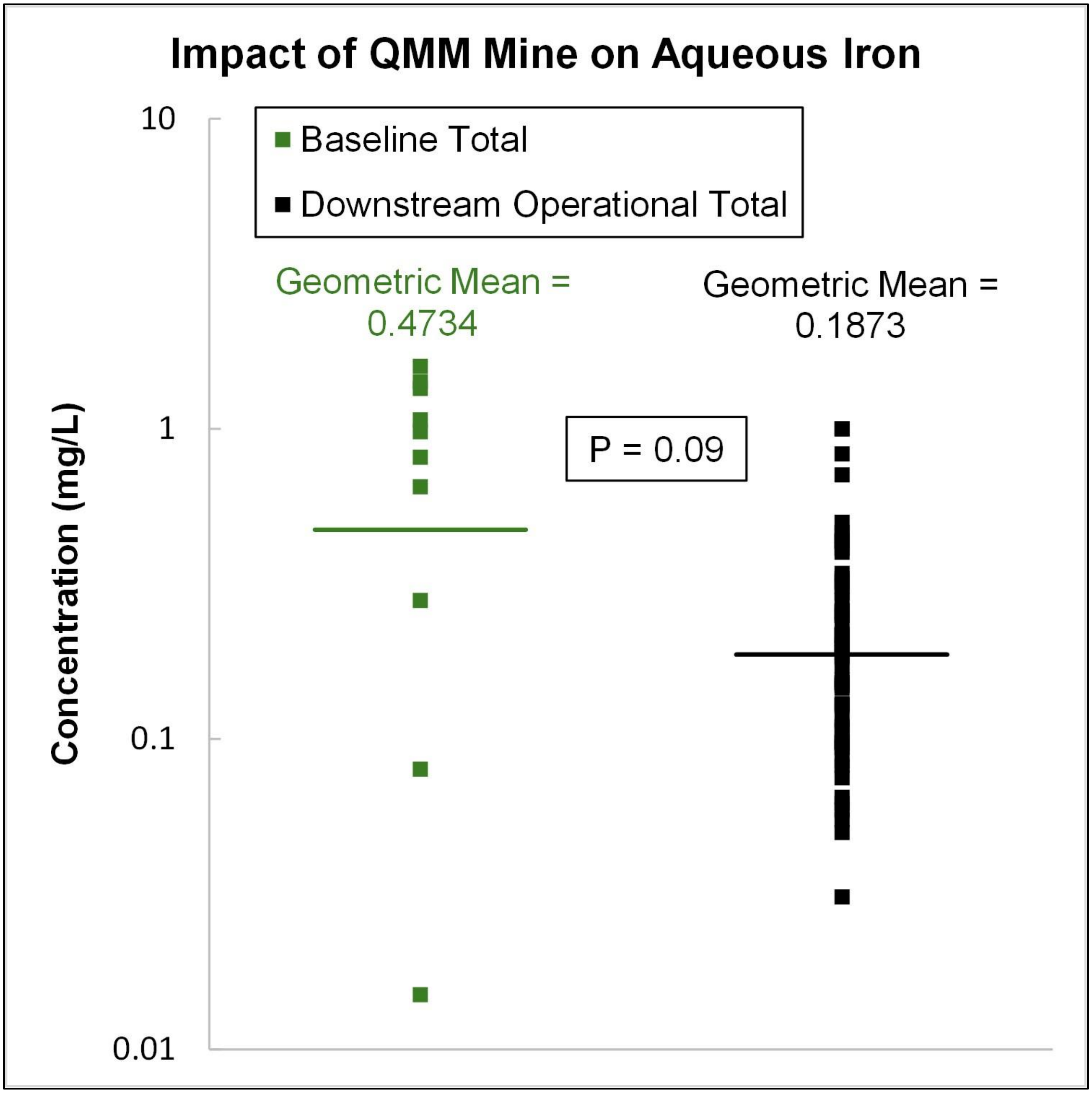


Figure 10c. A comparison of the baseline total iron concentrations (CDN Water Management Consultants, 2001a-b) with all of the total iron concentrations measured downstream of the QMM mine after the mine began operation (Swanson, 2019b-c; Emerman, 2019; Rio Tinto, 2023a) shows that the decrease in iron concentration from before to after opening the mine is not statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. For the data from the QMM surface water monitoring stations in Swanson (2019b-c), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. Dissolved and total concentrations were reported separately for the community-collected samples (Emerman, 2019) and the QMM surface water monitoring stations in Rio Tinto (2023a). The statistics were carried out on monthly arithmetic means for each site.

DISCUSSION

Need for Improved Water Monitoring and Reporting

It should be clear that any path forward toward the resolution of downstream surface water contamination by the QMM mine must include the collection of consistent, accurate, complete, and useful water-quality data. Water-quality data must have consistent detection limits and the data on graphs must correspond to the data in spreadsheets. Dual versions of what should be the same dataset must not be permitted under any circumstances. Samples must be collected at some regular and rational frequency, and not seemingly randomly, as at the present time. Surface water-quality data must be collected wherever contamination is likely to emerge, especially in the Méandre River, Lake Besaroy and Lake Ambavarano, and not only immediately upstream and downstream from the site of intentional wastewater discharge. Statements in the QMM 2021-2023 Water Report such as "Limited water quality data is presented for 2021 as no site release occurred during that year" (Rio Tinto, 2023a) are not helpful because they assume that water contamination can occur only due to intentional release at a designated site. The author has previously criticized Rio Tinto for engaging external consultants, such as JBS&G, to carry out one-off water-quality studies, instead of training QMM mine staff on proper data collection. According to Emerman (2021), "A much better use of external consultants would be to engage them to carry out an independent audit of the water monitoring procedures followed by the QMM mine, in order to ensure that the QMM mine is consistently producing high-quality data."

Need for Improved Wastewater Treatment System

Despite the increases in uranium, thorium, and lead from the upstream to the downstream side of the QMM mine documented in Emerman (2019, 2020, 2021), the water treatment system has focused on the need to reduce acidity and aluminum concentrations. According to the QMM 2021-2023 Water Report, "The water treatment plant and polishing pond further improve the water quality by adjusting the pH and reducing the aluminium concentration … We commissioned PROXA Water, a global company specialising in water treatment, to design and construct a pilot-scale unit to treat water using controlled addition of limestone so that it complies with the national decree for pH and aluminium concentration … Water treatment plant design has targeted water release compliance. Monitoring data for pH and aluminium show the influence of the water treatment plant on these parameters and supports the decision to expand the water treatment plant."

The first step in the water treatment plant is mixing the wastewater with crushed limestone in order to raise the pH of the wastewater (see Fig. 11). An increase in pH does remove dissolved aluminum from water by promoting the combination of aluminum cations with hydroxide ions to form solid aluminum hydroxide. However, an increase in pH can also have the effect of transferring elements that occur in the aqueous form as oxyanions, such as arsenic, selenium, and uranium, from the sorbed state into the dissolved state in water. As mentioned previously, uranium oxyanions attach to positively-charged sorption sites on solid particles. As the pH increases, the increased abundance of hydroxide ions competes with the uranium oxyanions for the same positively-charged sorption sites, thus displacing uranium into the dissolved form in water. In other words, an increase in pH will tend to precipitate cations, such as aluminum, but mobilize anions, such as uranium.

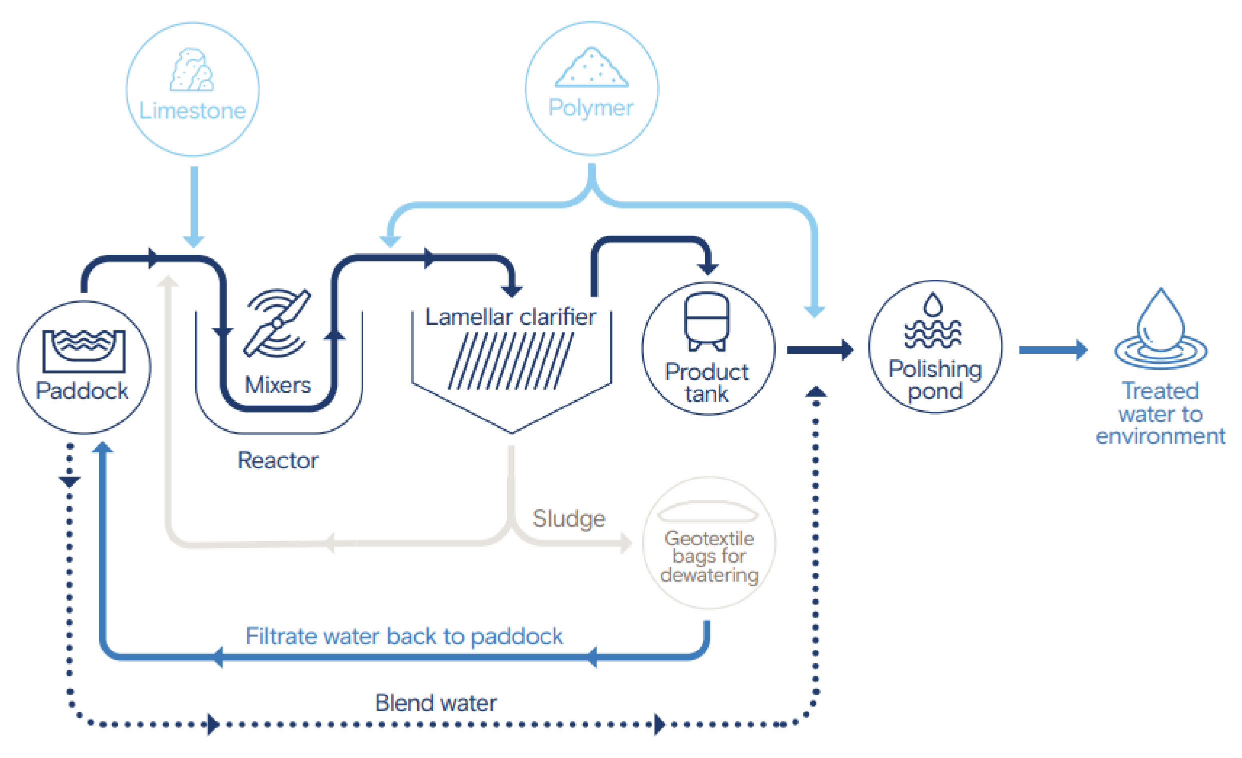


Figure 5: QMM water treatment plant

Figure 11. The addition of limestone to the mine wastewater raises the pH, which results in the precipitation of cations, such as aluminum. However, raising the pH can mobilize elements that occur as oxyanions, such as arsenic, selenium, and uranium. There are various polymers that can immobilize a wide variety of elements. The specific polymer is not stated in Rio Tinto (2023a), nor are there any publicly available test results that would demonstrate the ability of the water treatment process to adequately treat the wastewater from the QMM mine. The "polishing pond" in the figure above is a settling pond through which the treated wastewater flows before it is discharged into the wetlands that border the Mandromondromotra River (see Fig. 6). "Polishing" normally refers to improving water quality from a relatively pure state to an "ultrapure" state. Discharge of treated wastewater into a settling pond is not normally referred to as "polishing." Figure from Rio Tinto (2023a).

The next step in the water treatment plant is the addition of an unknown polymer, supposedly, to sorb a wide range of elements. Rio Tinto has not identified nor provided any information about this polymer. Rio Tinto has also not provided any test results that might persuade the public of the efficacy of the polymer or any other aspect of the water treatment process. In particular, there are no test results regarding the ability of the water treatment plant to remove uranium at the very high concentrations that have been documented in the mining basins (Swanson, 2019a).

The final step before release of the wastewater into the wetlands bordering the Mandromondromotra River is the passage of the wastewater through a "polishing pond" (see Fig. 11). According to the QMM 2021-2023 Water Report, "As a final treatment step, the water is pumped to a polishing pond from which it flows to the release location. The polishing pond is a water basin that provides additional retention time for improved water clarity and homogeneity" (Rio Tinto, 2023a). "Polishing" normally refers to improving water quality from a relatively pure state to some form of an "ultrapure" state. Discharge of treated wastewater into a settling pond is not normally referred to as "polishing."

Need for Provision of Safe Drinking Water

Enough water-quality data has been collected to indicate that there is an immediate need for the provision of safe drinking water to the local residents by the Rio Tinto QMM mine without further delay. The installation of an active wastewater treatment system could prevent the long-term (years to decades) degradation of surface water in this region, but it will not produce safe drinking water in the short term (this year). Moreover, it is not even clear that the discharge of mine wastewater into the wetlands is the chief source of poor downstream water quality. As discussed earlier, other pathways for the release of radionuclides and lead into downstream water sources are overtopping of the mining basins and seepage from the mining basins into groundwater. The encroachment of the required 50-meter buffer zone between the mining operation and the estuary is often misunderstood as a single event, such as the breach of the tailings dam, followed by its repair. However, Emerman (2018a) showed that the tailings dam (the embankment at the downstream edge of the mining basin) was actually constructed 117 meters into the bed of Lake Besaroy (see Figs. 4a-c), so the input of lead and radionuclides into the downstream groundwater and surface water should be regarded as a continuous and ongoing process.

The Rio Tinto QMM mine is urged to consider the recommendations of the Centre for Affordable Water and Sanitation Technologies and the Andrew Lees Trust, who have studied the options for uranium removal at the household level in Anosy region of Madagascar (Bourgault and Orengo, 2019). Based upon price, operational complexity, and the ease and level of required maintenance, Bourgault and Orengo (2019) recommended either coagulation/flocculation or the use of clay ceramics. These are highly generic technologies (not specific to particular elements) and, in principle, should be effective for the additional removal of aluminum, arsenic, cadmium, iron, lead, manganese and thorium. However, this should be verified by the Centre for Affordable Water and Sanitation Technologies, who are the experts on low-cost water treatment. Moreover, any on-site testing of these technologies should focus on the ability to remove all of the following elements: aluminum, arsenic, cadmium, iron, lead, manganese, thorium, uranium.

CONCLUSIONS

The four questions posed in the "Overview" section are repeated below, followed by very brief responses. More complete responses can be found in the "Results" section.

1) Does the QMM 2021-2023 Water Report include consistent and credible data?

No, the most serious shortcoming is that the data plotted on the graphs do not correspond to the data in the accompanying spreadsheet. It is impossible for the author to determine which are the correct data or why there are two versions of the same dataset.

2) Is the monitoring program described in the QMM 2021-2023 Water Report adequate for the detection of downstream contamination?

No, the monitoring program can detect only intentional releases of contaminants at the wastewater discharge site into the wetlands bordering the Mandromondromotra River. There has been no monitoring of either intentional or accidental releases of contaminants into the Méandre

River or Lake Ambavarano since December 2019 and no monitoring of Lake Besaroy since April 2018.

3) ***When the new data in the QMM 2021-2023 Water Report are integrated with all of the existing surface water-quality data, do aqueous concentrations of radionuclides and lead increase from the upstream to the downstream side of the mine?***

Combining the spreadsheet data with all of the existing surface water-quality data showed that the increases in the geometric means of the total uranium and lead concentrations from the upstream to the downstream side of the QMM mine by factors of 24 and 4.9, respectively, were statistically significant at better than the 99.999% confidence level for uranium and the 99.99% confidence level for lead, thus confirming the detrimental impact of the QMM mine on regional water quality.

4) ***When the newly available data in the 2001 baseline study are compared with all of the existing surface water-quality data downstream of the mine, do aqueous concentrations of radionuclides and lead increase from before to after the opening of the mine?***

The comparison of the baseline total uranium concentrations with all of the concentrations measured downstream of the QMM mine after the mine began operation showed that the increase in uranium concentration by a factor of 884 from before to after opening the mine was statistically significant at the 99.999999999% confidence level, thus further confirming the detrimental impact of the QMM mine on regional water quality. The total lead concentrations clearly increased after opening of the mine, but the increase could not be evaluated quantitatively due to inconsistencies in the detection limits.

RECOMMENDATIONS

This report makes the following recommendations:

1) Rio Tinto must provide consistent and credible data on surface water quality in the vicinity of the QMM mine.
2) Rio Tinto must monitor surface water quality in the Méandre River, Lake Ambavarano and Lake Besaroy.
3) Rio Tinto must provide evidence that the water treatment plant can adequately treat the wastewater from the QMM mine, especially in terms of uranium, thorium, and lead.
4) Rio Tinto must provide safe drinking water to the 15,000 people who live in the vicinity of the QMM mine.

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 mining projects in North America, South America, Europe, Africa, Asia and Oceania, and has testified on issues of mining and water 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.

Steven H. Emerman

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