Implications of a Wastewater Discharge Monitoring Report for Impact of the Rio Tinto QMM Ilmenite Mine on Downstream Water Quality, Southeastern Madagascar
By Dr Steven Emerman, April, 2021

Introduction by the Andrew Lees Trust (ALT UK)

Over the last three years, a number of studies have been undertaken about Rio Tinto's QMM mine in south-eastern Madagascar, in particular with regard to QMM's breach of an environmental zone, and accompanying concerns about and subsequent confirmation of contaminants (uranium and lead) being discharged into lakes and rivers around the mine where local people fish and collect drinking and domestic water.

As part of the ongoing research and advocacy into the issues arising, and following repeated requests from Publish What You Pay (PWYP) Madagascar, PWYP UK, the Andrew Lees Trust (ALT UK) and Craig Bennett (environmental campaigner) since February 2020, the company met demands to make QMM's wastewater data available and finally issued a wastewater report in March 2021.

The following study, commissioned by The Andrew Lees Trust and undertaken by Dr Steven Emerman of Malach Consulting, analyses the data in this new report and reviews the findings in light of previous studies.

In this introduction, we want to highlight some important issues for consideration:

1. The QMM wastewater report has been challenged with multiple questions, such as the failure to include relevant existing water data that has been seen and/or we are already aware of.
2. The 2020 QMM water report by its external provider, JBS&G, failed to include previous QMM water data, as is standard procedure, and withheld water data gathered from a "rehabilitation pond."
3. QMM has failed to include its methodology in the wastewater report, so the exclusion of certain water data is not transparently explained, as would be expected. The report also fails to highlight the lack of Malagasy regulation (limits) for uranium discharge, the absence of which is not a licence to exceed safe drinking water, aquatic or other relevant international standards in this fragile context.
4. Emerman has shown that adding more water data simply strengthens his 2019 conclusion that the QMM mine is having a detrimental impact on water quality with elevated levels of uranium and lead, over 50 and 40 times respectively above the WHO safe drinking water guidelines in some places.
5. QMM continue to insist more data is necessary before they take action, e.g., provide safe, alternative drinking water access to affected communities.
6. 15,000 people draw drinking water and fish in the local environment and are affected.
7. The majority of the villagers using natural water sources complain that the water quality has been impaired and relate this to the start of QMM activity/operations (PWYP MG study 2020).
8. QMM has twice broken Malagasy national law/regulations: firstly, by breaching the environmental buffer zone and also by discharging waters with levels of cadmium and aluminium above legal limits.
9. Compromised local governance and power asymmetry around QMM has rendered it impossible for local people to raise concerns and protect their rights without fear of criminalisation and reprisals.
10. QMM cannot show any modelling or evidence that the 'natural' system of settling ponds, a system they claim is designed to mitigate and remove contaminants from their discharge water, is working.
11. QMM has moved their wastewater monitoring sites, which they claim is a mitigation action. However, this does not affect the ability of the wetlands that receive QMM discharge waters to remove contaminants; it simply changes the point where they are measured (water data collection).
12. Emerman has shown that the settling pond system appears to be enhancing the concentrations of contaminants, with increases occurring since QMM's so-called 'mitigation' measures were taken.
13. QMM's addition of a new wetland area to receive discharge waters, its admission that the efficiency of the system might "vary over time," and ceasing the release of discharge waters for six months suggests QMM already knows its system is not working (and is no more than an experiment).
14. Experts and civil society agree: the community concerns and needs that have been expressed, together with the existing data, provide a strong enough reason and momentum for RioTinto/QMM to provide safe drinking water to local communities without further delay.

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Implications of a Wastewater Discharge Monitoring Report for Impact of the Rio Tinto QMM Ilmenite Mine on Downstream Water Quality, Southeastern Madagascar

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LIGHTNING SUMMARY

The Rio Tinto QMM ilmenite mine in southeastern Madagascar generates water enriched in radionuclides and lead, which it releases through surface discharge and groundwater seepage. A new mine wastewater discharge report shows numerous exceedances of the Malagasy limits for aluminum and cadmium in wastewater. The integration of new surface water data with the existing data confirms the detrimental impact of the mine on regional water quality by showing increases in uranium and lead in surface water from the upstream to the downstream side of the mine that are statistically significant at better than the 99% confidence level.

ABSTRACT

The Rio Tinto QMM ilmenite mine on the coast of southeastern Madagascar generates water in mining basins that is enriched in radionuclides and lead. The enrichment occurs partly by extracting ilmenite from mineral sands and concentrating monazite in the mine tailings and partly by the dredging process, which promotes the transfer of radionuclides and lead from monazite and zircon into the dissolved phase. The mine process water is released into a wetland adjacent to a river, while additional water enriched in radionuclides and lead enters adjacent lakes through groundwater seepage from the mining basin. Surface water is the primary source of drinking water for the 15,000 people who live near the mine site. A new mine wastewater discharge monitoring report by the QMM mine shows numerous exceedances of the Malagasy limits for aluminum and cadmium in wastewater. Mitigation actions have included moving the wastewater monitoring sites to the edge of the mine property about one kilometer farther into the wetland. However, such actions do not affect the ability of the wetland to remove contaminants, but only the point at which the contaminants are measured. The wastewater discharge report includes new surface water data from both upstream and downstream of the mine wastewater discharge sites, which was integrated with previous data to further strengthen the conclusion that the QMM mine has a detrimental impact on regional water quality. 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) are 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) are statistically significant at better than the 99.9% confidence level. Maximum downstream uranium and lead concentrations were 52 and 40 times the WHO guidelines, respectively. Increases in aluminum, cadmium and zinc from the upstream to the downstream side of the mine are not statistically significant.

TABLE OF CONTENTS

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, 2, 3a-b and 4). The mine is owned by QIT Madagascar Mining 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 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 (QIT Madagascar Minerals, 2015; Randriantseheno et al., 2015). The quartz grains that are not incorporated into Zirsill are returned to the mining basin. 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, 2021b).
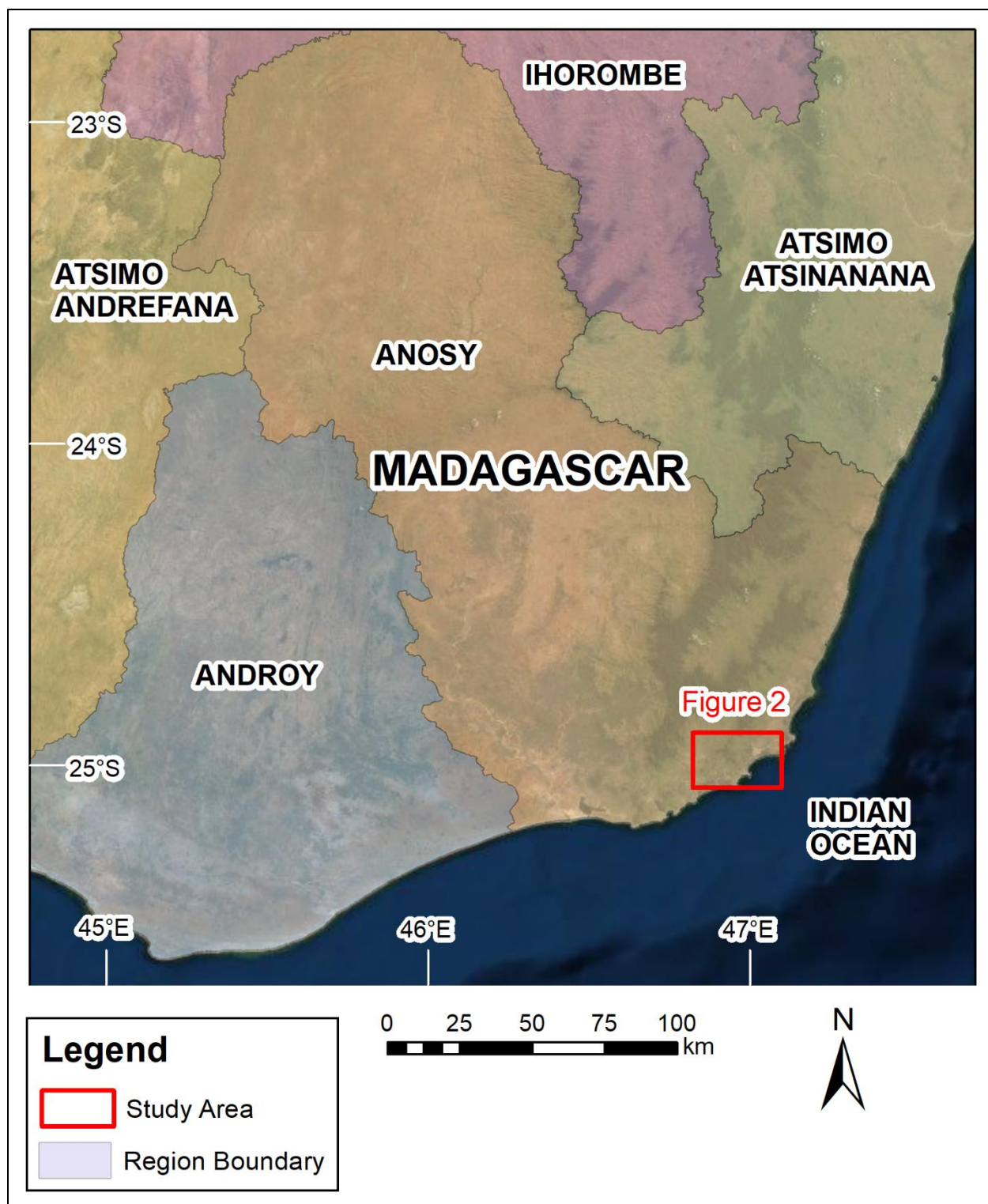
Figure 1. Four studies (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021a) have examined surface water quality upstream and downstream of the QMM mine, which is located within Anosy region on the southeastern tip of Madagascar.

Based upon a comparison of surface water quality upstream and downstream of the QMM mine, two previous reports (Emerman, 2019, 2020) have documented the detrimental impact of the mine on regional water quality in terms of lead and the radionuclides uranium and thorium. This detrimental impact 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 (Swanson, 2019a-b). In March 2021 Rio Tinto (2021a) released a report entitled "QMM Water Discharge Monitoring Data." In addition to data on the quality of mine wastewater, the report includes new water-quality data collected from the Mandromondromotra River both upstream and downstream from the mine wastewater discharge sites (see Figs. 3a-b and 4).
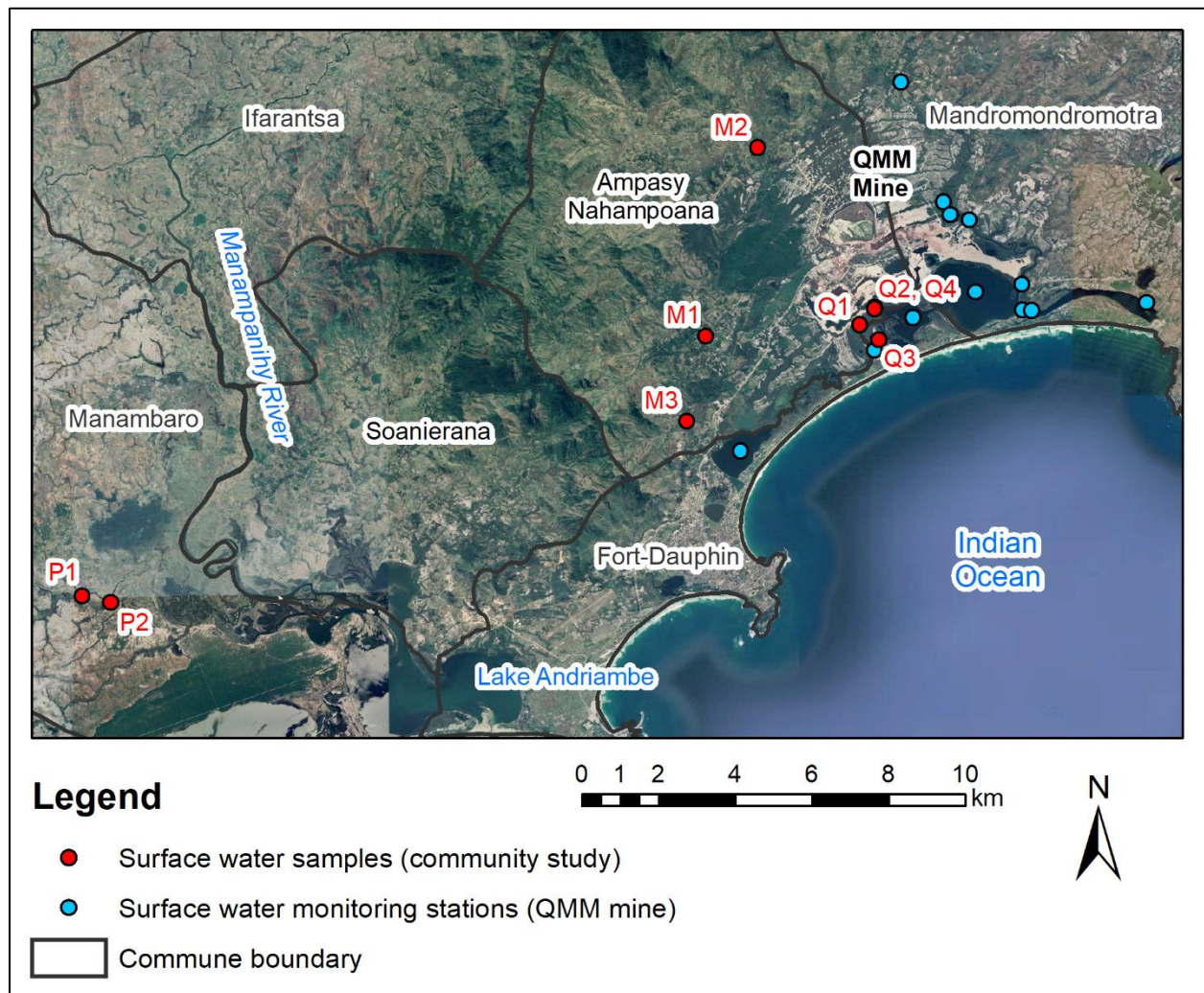
Figure 2. The Rio Tinto QMM mine has monitored surface water quality at 12 stations, two of which are upstream from the mine and 10 of which are downstream (Swanson, 2019a-b). Emerman (2019) reported water-quality analyses of samples collected by local residents from nine additional sites, three of which 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.
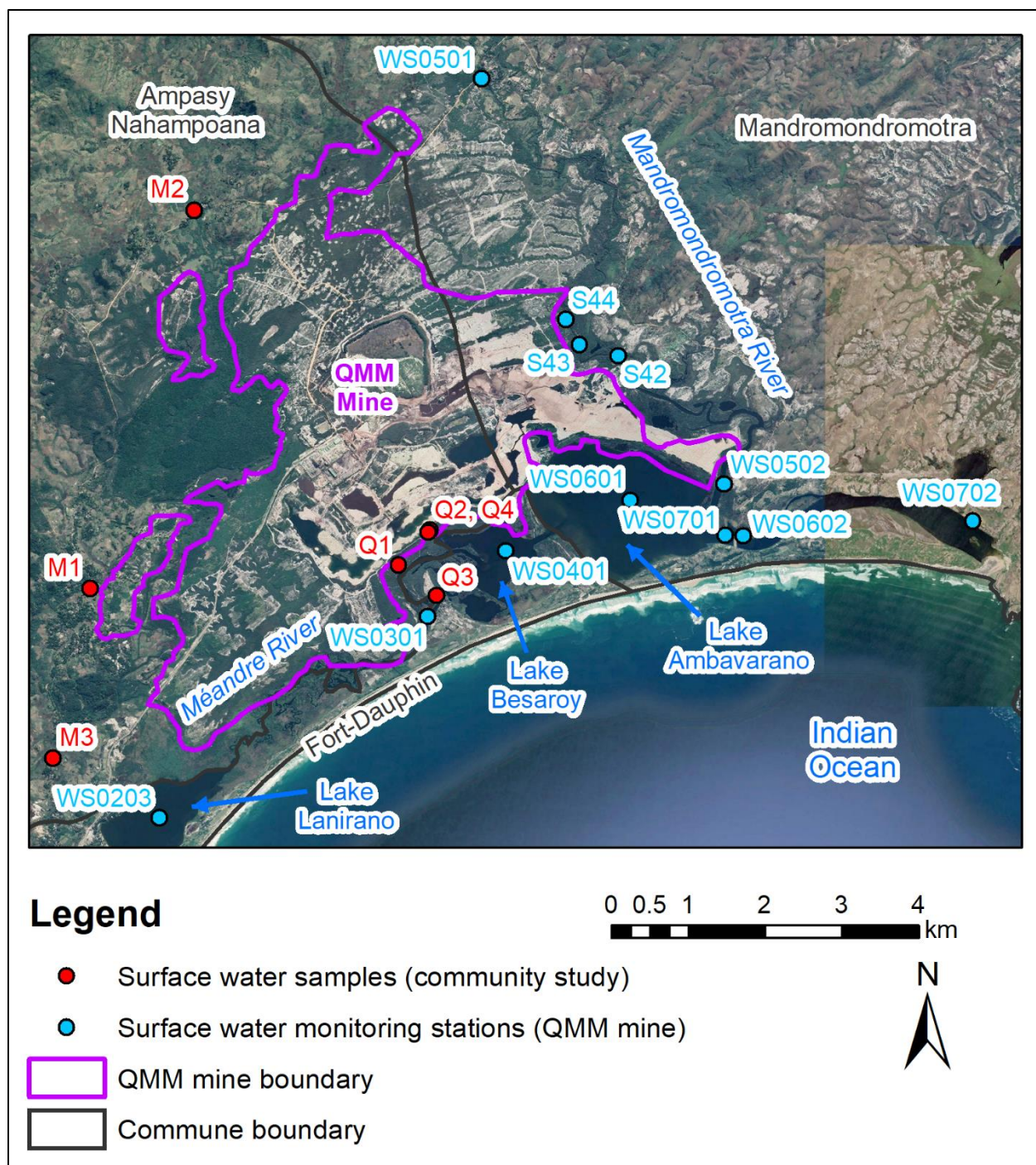
Figure 3a. QMM surface water monitoring stations WS0501 and WS0203 are upstream of the mine, while the other stations are downstream. QMM water-monitoring stations S42, S43, and S44 on the Mandromondromotra River are downstream sites because they are adjacent to the points where mine wastewater enters 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 image from August 24, 2020. See larger-scale map in Fig. 2.

5
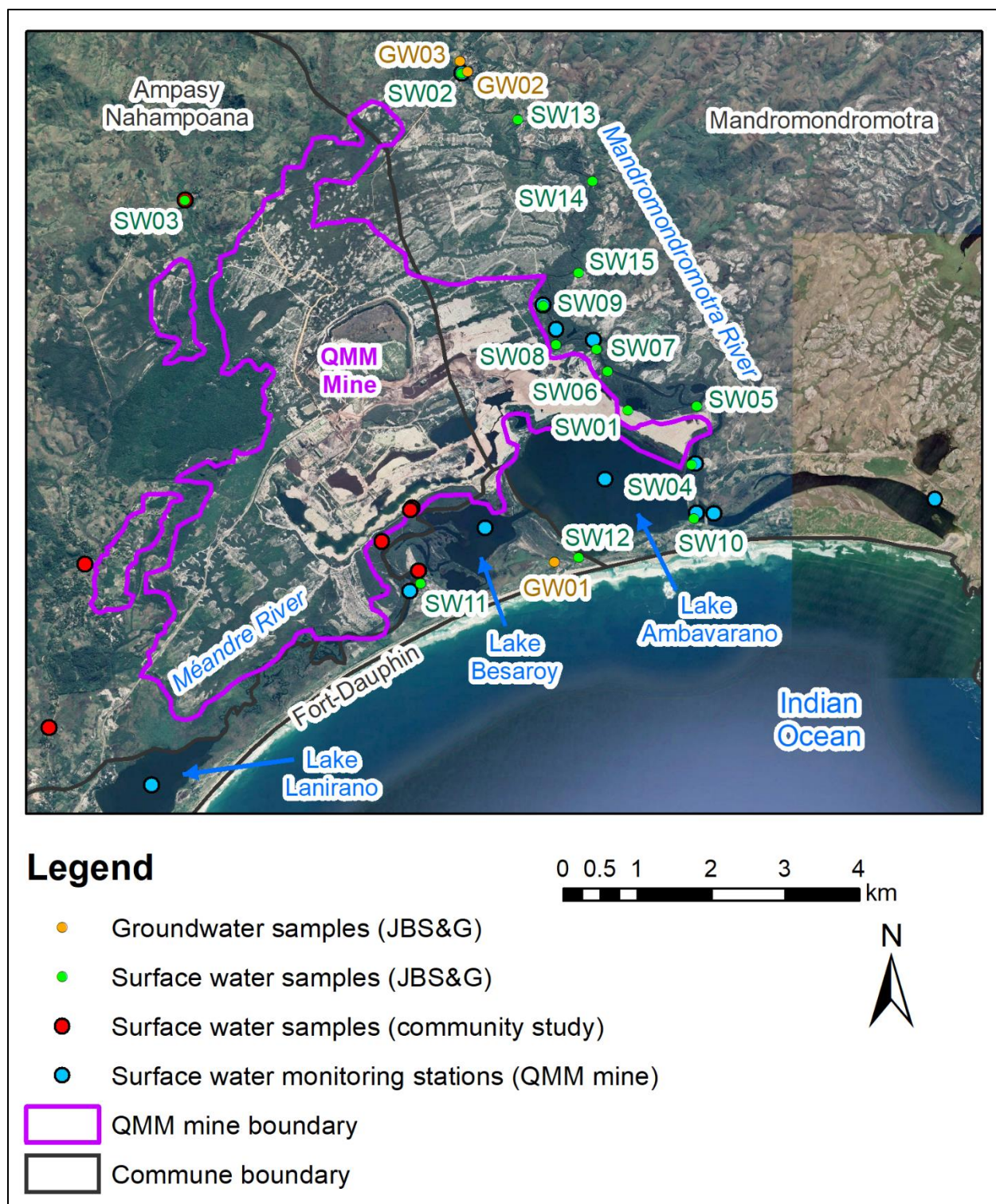
Figure 3b. JBS&G (2020b) reported analyses of groundwater samples from two upstream sites (GW02, GW03) and one downstream site (GW01), as well as surface water samples from four upstream sites (SW02, SW03, SW13, SW14) and ten downstream sites (SW04-SW12, SW15). The analysis of downstream site SW01 was withheld because it was "not considered a potential POU [Point of Use] drinking water sample" (JBS&G, 2020b). 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 image from August 24, 2020.

6
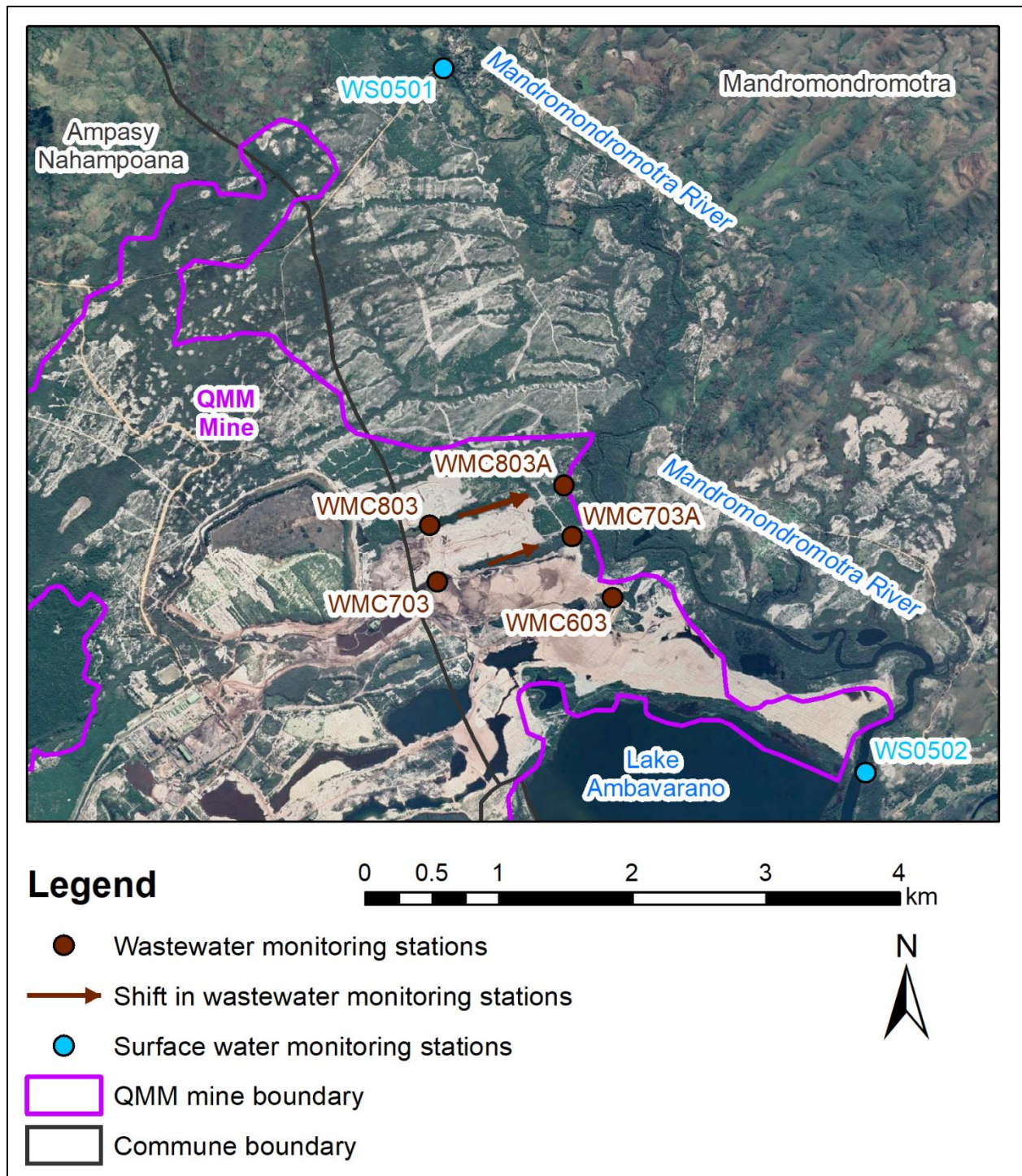
Figure 4. Wastewater from the mining basins is discharged into the wetlands from where it flows northeastward into the Mandromondromotra River. Due to exceedances of Malagasy limits for wastewater discharge for aluminum and cadmium (see Figs. 5a-b), monitoring sites WMC703 and WMC803 were replaced with sites WMC703A and WMC803A, 980 and 960 meters to the northeast, respectively, at the edge of the QMM mine property. According to Rio Tinto (2021b), "WMC 703 and WMC 803 were relocated to WMC 703A and WMC 803A to allow a longer filtration time in the swamp area." Monitoring site relocation does not change the filtration process, but only where the wastewater quality is measured. QMM mine boundary traced from JBS&G (2020b). Background is Google Earth image from August 24, 2020.

The objectives of this report are to address the following questions:

1) How do the new surface water-quality data from the wastewater discharge monitoring report affect previous conclusions regarding the impact of the QMM mine on regional water quality?

2) Based on the mine wastewater discharge monitoring report, does the QMM mine have an effective plan for treatment of mine wastewater?

Before discussing the methodology for answering the above questions, I will first review what is known about water contamination by the QMM mine and then summarize the results from the QMM mine wastewater discharge monitoring report. This report will include the use of the concept of statistical significance. If needed, please see Emerman (2020) for a tutorial on this concept. At the request of the client, this report includes tutorials on the subjects of dissolved and total concentrations and the geometric mean (see Appendix B).

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 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). Since the radionuclides uranium and thorium are present within the 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 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 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. Using data provided by the QMM mine, Swanson (2019c) 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. On the other hand, the most recent analysis of upstream uranium concentrations prior to this report documented a geometric mean uranium concentration of 0.00059 mg/L for total uranium (Emerman, 2020), so that a comparison of the two mean uranium concentrations would imply a mineral concentration factor of 1890. Such a high degree of concentration of radioactive minerals within the 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, 2021b).

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 mineral sands from the mining basins and then returning the mine tailings (materials that remain after the minerals of interest have been extracted) 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 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 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 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 cannot be confirmed either experimentally or computationally without detailed information regarding the chemistry and mineralogy of the 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 (2019c) using data provided by the QMM mine. At the time that Swanson (2019c) 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 (2019a), 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, 2019a). 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.

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 groundwater out of the mining basins, 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 basin through the highly-permeable beach sands, which must eventually be released into the environment. According to Swanson (2019a-b), this excess water is discharged at three release points into

9

wetlands that are adjacent to the Mandromondromotra River (see Figs. 3a-b and 4). The only treatment of the mine effluent water is a "biodiversity control pond" or "settling pond" (Swanson, 2019a) that is 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 results in further removal of suspended particles and sorption of metals, so that the wetlands are 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. 3a-b). 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, 2019a). (According to Rio Tinto (2019), the construction of a weir at the inlet/outlet between Lake Ambavarano and the Indian Ocean (see Figs. 3a-b) has eliminated the effect of tidal currents.)

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, 2018a). 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 (2018a) 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, any overtopping would be expected to destroy the dam completely because water flowing over the downstream embankment would erode away the unconsolidated tailings. Moreover, any monazite present in the tailings dam could be another unconfined source of radionuclides and lead. Finally, Swanson (2019a) 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. 3a-b).

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 (2018b) 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 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 breached 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."

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 (2018b), 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 (2018a, 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" (Rio Tinto, 2019). 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

In order to monitor the impact of the mine on the regional water quality, the QMM mine collects and analyzes water from 12 surface water sites (see Fig. 3a; Swanson, 2019a). As part of an assessment of the release of radioactive material from the mine, Swanson (2019a) 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 (2019a), 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).

Out of 54 measurements of uranium, 20 (37%) were above a detection limit (minimum measurable concentration), all of which exceeded the WHO (2017) drinking-water guideline for uranium (0.03 mg/L). The maximum measured uranium concentration was 1.574 mg/L, or over 52 times the WHO (2017) guideline. Out of 54 measurements of lead, 27 exceeded a detection limit and 23 (43%) exceeded the WHO (2017) drinking-water guideline for lead (0.01 mg/L). In addition, 27 (50%) measurements of lead exceeded the US EPA (2021a) aquatic standard for lead (0.0032 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 (2017) drinking-water guideline and over 124 times the US EPA (2021a) aquatic standard. WHO (2017) does not have drinking-water guidelines for iron, thorium or titanium. However, the US EPA (2021b) has a secondary drinking-water standard for iron (0.3 mg/L), which is based upon taste and color (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 (2019a). 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. 3a). 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. 3a). According to Swanson (2019c), "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." Swanson (2019c) also emphasized that "monitoring data show that 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."

In response to the 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 3a-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 mineral sands mining (see Fig. 2). By combining the analyses of the community-collected samples with the analyses from the QMM mine (Swanson, 2019a), 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, 2019a) 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 (2017) 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 124 times the US EPA aquatic standard), respectively, as reported by Swanson (2019a).

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 (2019a), 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. 3b). Out of the three groundwater sites, two were upstream and one was downstream from the QMM mine (see Fig. 3b). Out of the 14 surface water sites, four were upstream and 10 were downstream from the QMM mine (see Fig. 3b). 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. 3b).

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. 3b). 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, 2019a).

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, 2019a-b) 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 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 uranium concentration decreased to 0.03823 mg/L, but it was still 1.27 times the WHO (2017) guideline for uranium in drinking water. In the same way, the statistical significance of the increase in the geometric means of 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 lead concentration decreased to 0.0141 mg/L, but it was still 1.41 times the WHO guideline for lead in drinking water.

NEW QMM WASTEWATER DISCHARGE MONITORING REPORT

Rio Tinto (2021a) has been monitoring mine wastewater at five sites within the wetlands west of the Mandromondromotra River (see Table 1 and Fig. 4) since 2015 for aluminum, cadmium, lead, uranium, zinc, pH, total dissolved solids, and total suspended solids. These sites

have shown numerous exceedances of the Malagasy limits for aluminum (5 mg/L) and cadmium (0.02 mg/L) in wastewater (see Figs. 5a-b). With only one exception, wastewater discharge from the QMM mine has been within the Malagasy limit for lead in wastewater (0.2 mg/L) (see Fig. 5c). Although wastewater discharge from the QMM mine has been monitored for uranium, there is no Malagasy limit for uranium in wastewater. However, for reference, the WHO (2017) drinking-water guideline for uranium is 0.03 mg/L, so that the upper range of uranium measurements (1.6 – 1.8 mg/L) is 53-60 times the WHO guideline (see Fig. 5d). Wastewater discharge from the QMM mine has been within the Malagasy limit for zinc in wastewater (0.5 mg/L) (see Fig. 5e).

Table 1. Wastewater discharge monitoring stations (QMM mine)[1]

Station	Latitude (°S)[2]	Longitude (°E)[2]
WMC603	24.9505	47.0396
WMC703	24.9496	47.0285
WMC703A	24.9465	47.0376
WMC803	24.9458	47.0280
WMC803A	24.9431	47.0370

[1]Coordinates measured from Figs. 2-3 of Rio Tinto (2021a), except for WMC603 for which UTM coordinates were given (assumed to be WGS 84 coordinate system, although not stated)
[2]Latitude and longitude based upon WGS 84 coordinate system

Rio Tinto (2021a) described mitigation actions that have been carried out in response to the frequent exceedances of the Malagasy limits for aluminum and cadmium (see Figs. 5a-b). These mitigation actions included replacing monitoring sites WMC703 and WMC803 with sites WMC703A and WMC803A, 980 and 960 meters to the northeast, respectively, at the edge of the QMM mine property (see Fig. 4). The first measurements at the new sites WMC703A and WMC803A appear to have taken place in March 2019 (see Figs. 5a-e). It should be noted that monitoring site WMC603 cannot be shifted any farther to the northeast since it is already nearly at the edge of the QMM mine property (see Fig. 4). According to Rio Tinto (2021a), "Mitigating actions validated and agreed with ANDEA [Autorité Nationale de l'Eau et de l'Assainissement (National Water and Sanitation Authority)] include: "Reducing flow for WMC 603 by splitting discharge water volume between WMC 603 and WMC 703; Optimizing swamp efficiency by increasing the length of the swamps; WMC 703 and WMC 803 were relocated to WMC 703A and WMC 803A to allow a longer filtration time in the swamp area…New discharge point requested in March 2020 (WMC 903)." Although Rio Tinto (2021a) uses the common word "swamp," the more scientific term "wetland" will be used in this report, except when quoting from Rio Tinto (2021a).

Of course, shifting the monitoring sites from WMC703 and WMC803 to WMC703A and WMC803A, respectively, cannot literally optimize the wetland efficiency, increase the length of the wetlands, or allow a longer settling time in the wetlands (see Fig. 4). The change in the monitoring sites only affects the location where the water quality is measured. It cannot alter the settling and sorption processes that occur in the wetlands. It should be clear that the farther the water samples are collected away from the actual release points, the lower will be the concentrations of contaminants (unless the wastewater is scavenging additional contaminants from the wetlands), and that the collection sites could not be moved much farther from the release points unless samples were collected directly from the Mandromondromotra River, instead of from the wetlands adjacent to the river (see Fig. 4). On that basis, it is alarming that

there were still exceedances of the Malagasy wastewater limits for aluminum and cadmium (see Figs. 5a-b) even after moving the sample collection sites nearly one kilometer farther into the wetlands (see Fig. 4).
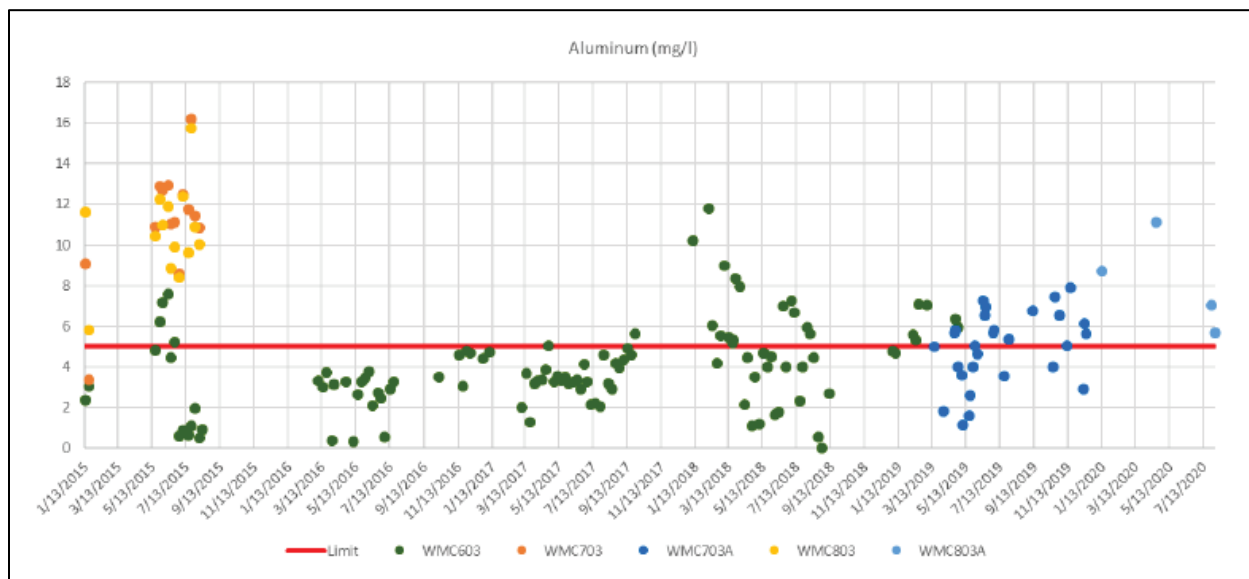

Figure 5a. Wastewater discharge from the QMM mine has shown numerous exceedances of the Malagasy limit for aluminum in wastewater (5 mg/L). According to Rio Tinto (2021b), "Mitigating actions validated and agreed with ANDEA include…Optimizing swamp efficiency by increasing the length of the swamps; WMC 703 and WMC 803 were relocated to WMC 703A and WMC 803A to allow a longer filtration time in the swamp area" (see Fig. 4). However, monitoring site relocation does not change the filtration process, but only where the wastewater quality is measured. Note that relocation of WMC703 and WMC803 to WMC703A and WMC803A, respectively, involved carrying out wastewater measurements at the edge of the QMM mine property (see Fig. 4). Monitoring site WMC603 could not be relocated because it was already nearly at the edge of the QMM mine property (see Fig. 4). Measurements at WMC603 (see Fig. 4) seem to show a long-term increase in aluminum concentrations. Figure from Rio Tinto (2021a).

Along the same lines, there is ambiguity throughout Rio Tinto (2021a) as to whether the five sites (WMC603, WMC703, WMC803, WMC703A, WMC803A) are actually mine wastewater discharge sites or only monitoring sites. Swanson (2019a-c) refers to WMC603, WMC703 and WMC803 as "water release points " or "effluent release points." Rio Tinto (2021a) sometimes refers to the five sites (WMC603, WMC703, WMC803, WMC703A, WMC803A) as "discharge points" and sometimes as "monitoring locations." However, there is no indication that a pipeline was constructed in order to release wastewater at WMC703A or WMC803A, so that WMC703A or WMC803A are clearly wastewater monitoring sites, not wastewater discharge sites. Of course, such a pipeline would make no sense in terms of allowing "a longer filtration time in the swamp area" (Rio Tinto, 2021a).
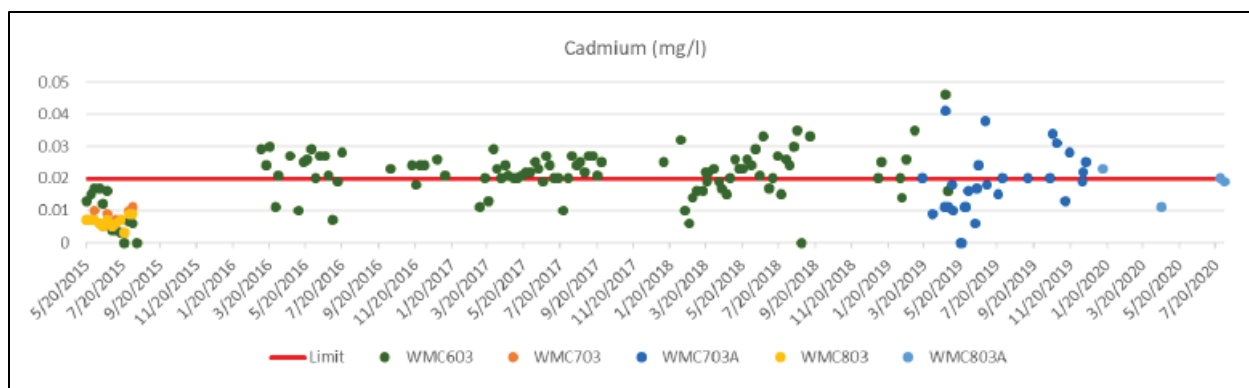
Figure 5b. Wastewater discharge from the QMM mine has shown numerous exceedances of the Malagasy limit for cadmium in wastewater (0.02 mg/L). According to Rio Tinto (2021a), "Mitigating actions validated and agreed with ANDEA include…Optimizing swamp efficiency by increasing the length of the swamps; WMC 703 and WMC 803 were relocated to WMC 703A and WMC 803A to allow a longer filtration time in the swamp area" (see Fig. 4). However, monitoring site relocation does not change the filtration process, but only where the wastewater quality is measured. Note that relocation of WMC703 and WMC803 to WMC703A and WMC803A, respectively, involved carrying out wastewater measurements at the edge of the QMM mine property (see Fig. 4). Monitoring site WMC603 could not be relocated because it was already nearly at the edge of the QMM mine property (see Fig. 4). Cadmium concentrations increased after monitoring sites were moved from WMC703 and WMC803 to WMC703A and WMC803A, respectively, so that mine wastewater appears to be scavenging cadmium out of the wetland. Note the nearly four-year gap between when measurements ceased at WMC703 and WMC803 and when they resumed at WMC703A and WMC803A. Measurements at WMC603 (see Fig. 4) seem to show a long-term increase in cadmium concentrations. Figure from Rio Tinto (2021a).
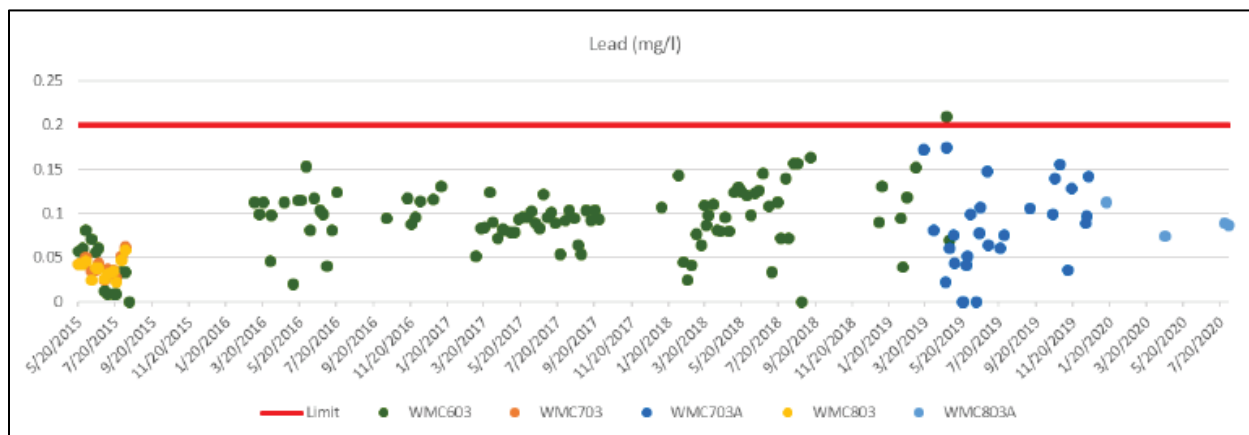
Figure 5c. With only one exception, wastewater discharge from the QMM mine has been within the Malagasy limit for lead in wastewater (0.2 mg/L). Lead concentrations increased after monitoring sites were moved from WMC703 and WMC803 to WMC703A and WMC803A, respectively, so that mine wastewater appears to be scavenging lead out of the wetland. Note the nearly four-year gap between when measurements ceased at WMC703 and WMC803 and when they resumed at WMC703A and WMC803A. See wastewater monitoring sites in Fig. 4. Figure from Rio Tinto (2021a).

Figure 5d. Although wastewater discharge from the QMM mine has been monitored for uranium, there is no Malagasy limit for uranium in wastewater. However, for reference, the WHO drinking-water guideline for uranium is 0.03 mg/L, so that the upper range of uranium measurements (1.6 – 1.8 mg/L) is 53-60 times the WHO guideline. Uranium concentrations increased after monitoring sites were moved from WMC703 and WMC803 to WMC703A and WMC803A, respectively, so that mine wastewater appears to be scavenging uranium out of the wetland. Note the nearly four-year gap between when measurements ceased at WMC703 and WMC803 and when they resumed at WMC703A and WMC803A. See wastewater monitoring sites in Fig. 4. Figure from Rio Tinto (2021a).

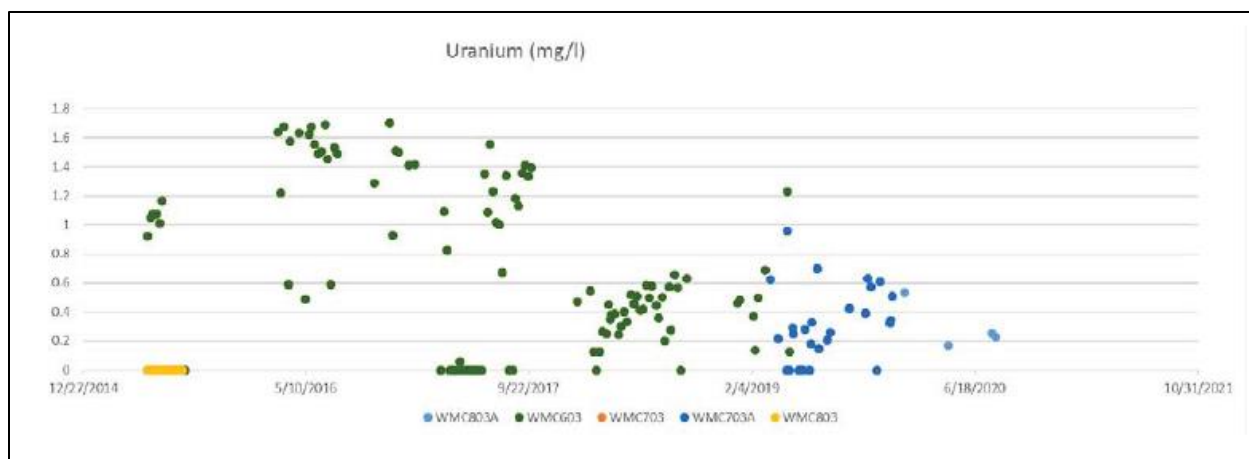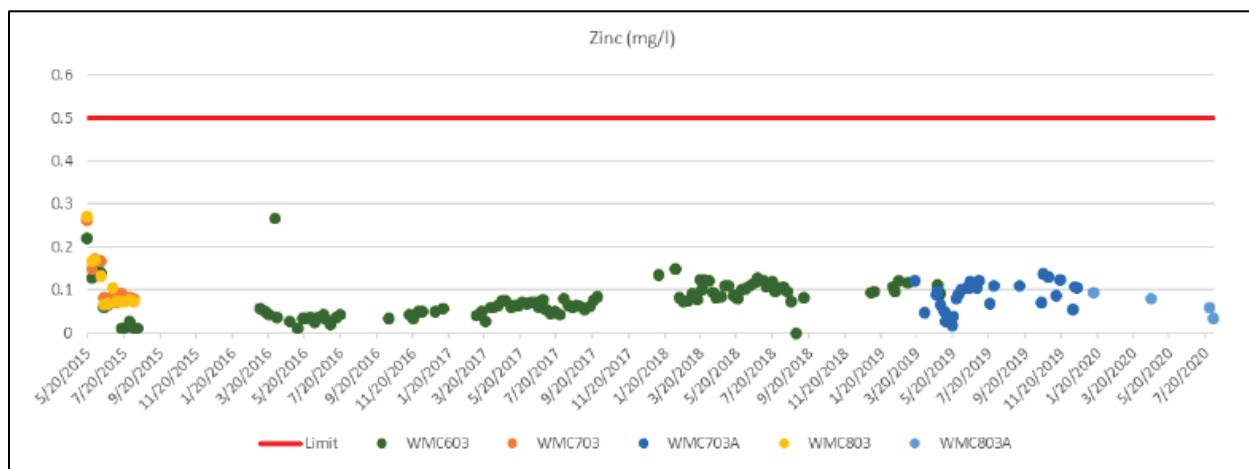**Figure 5e.** Wastewater discharge from the QMM mine has been within the Malagasy limit for zinc in wastewater (0.5 mg/L). Measurements at WMC603 (see Fig. 4) seem to show a long-term increase in zinc concentrations. See wastewater monitoring sites in Fig. 4. Figure from Rio Tinto (2021a).

There are numerous contradictions between the data reported in the new QMM wastewater discharge monitoring data (Rio Tinto, 2021a) and the uranium in wastewater data reported in Swanson (2019c), although Swanson (2019c) is only an interpretation and compilation of data provided to her by the QMM mine (see Fig. 6). First, Swanson (2019c) also presented data for "effluent release points" WMC604, WMC704, WMC804 and WMC900 (see Fig. 6), although those sites are not mentioned in Rio Tinto (2021a) or in any other available document. Second, Swanson (2019c) presented a "Summary of Uranium Monitoring Data from 2015-2018," (see Fig. 6) although, according to Rio Tinto (2021a), the last uranium measurement at WMC703 or WMC803 took place sometime in 2015 (see Fig. 5d). For all elemental concentrations for wastewater reported in Rio Tinto (2021a), there was nearly a four-year gap between when measurements ceased at WMC703 and WMC803 (around July 2015)

17

and when they resumed at WMC703A and 803A (around March 2019) (see Figs. 5a-e). Swanson (2019a-c) did not mention the existence of monitoring sites WMC703A and WMC803A, as her reports were based only on data available as of August 2018. The third and most important contradiction is that Swanson (2019c) showed mean and maximum uranium concentrations of 0.593 mg/L and 2.007 mg/L, respectively, at WMC703 and mean and maximum uranium concentrations of 0.252 mg/L and 0.864 mg/L, respectively, at WMC803 (see Fig. 6). By contrast, Rio Tinto (2021a) shows, at the scale of the plot, zero uranium concentrations at the same monitoring sites (see Fig. 5d). Rio Tinto (2021a) makes no mention of the earlier data compilations by Swanson (2019a-c) and there is no other information available that would help to resolve the contradictions.

Table 1. Summary of Uranium Monitoring Data from 2015-2018. Data provided by QMM. See Figure 2 for location of sites.

Process Water	Site ID	Mean Uranium Concentration	Minimum Uranium Concentration	Maximum Uranium Concentration	Number of Samples	Comments
Mine Basins/Dredging Ponds	BASMIN	1.115	<0.047	1.748	99	
Mineral Separation Facility	MSP01	1.24	0.824	1.513	11	
Mineral Separation Facility	MSP02	1.237	0.744	1.489	11	
Mineral Separation Facility	MSP03	1.095	<0.047	2.029	85	
Onsite storage basins	Paddock 3	1.144	<0.047	1.804	97	
Onsite storage basins	Paddock 6	1.096	<0.047	1.766	91	
Onsite storage basins	Paddock 7	1.12	<0.047	1.764	91	
Effluent Release Points	WMC603	0.99	<0.047	1.801	89	
Effluent Release Points	WMC604	0.301	<0.047	0.353	7	
Effluent Release Points	WMC703	0.593	<0.047	2.007	39	
Effluent Release Points	WMC704	<0.642	NA	NA	12	All samples <0.642
Effluent Release Points	WMC803	0.252	<0.047	0.864	54	
Effluent Release Points	WMC804	<0.642	NA	NA	13	All samples <0.642
Effluent Release Points	WMC900	0.373	0.352	0.389	3	
Process Water	WP95	0.065	<0.047	<0.642	146	All but 15 samples either <0.047 or <0.642
Process Water	WP097A	0.96	<0.047	1.976	138	
Between Paddock 6 and MSP03	WW0126	0.899	<0.047	1.68	50	
Receiving Environment						
SE of site, N of Lac Besaroy	WS0103	0.266	<0.047	<0.642	6	5 samples either <0.642 or <0.047

Figure 6. There are numerous contradictions between the data reported in the new QMM wastewater discharge monitoring data (Rio Tinto, 2021a) and the uranium in wastewater data reported in Swanson (2019c), although Swanson (2019c) is only an interpretation and compilation of data provided to her by the QMM mine. First, Swanson (2019c) presented data for "effluent release points" WMC604, WMC704, WMC804 and WMC900, although those sites are not mentioned in Rio Tinto (2021a). Second, Swanson (2019c) presented a "Summary of Uranium Monitoring Data from 2015-2018," although, according to Rio Tinto (2021a), the last uranium measurement at WMC703 or WMC803 took place sometime in 2015 (see Fig. 5d). For all elemental concentrations for wastewater reported in Rio Tinto (2021a), there was nearly a four-year gap between when measurements ceased at WMC703 and WMC803 (around July 2015) and when they resumed at WMC703A and WMC803A (around March 2019) (see Figs. 5a-e). The third and most important contradiction is that Swanson (2019c) showed mean and maximum uranium concentrations of 0.593 mg/L and 2.007 mg/L, respectively, at WMC703 and mean and maximum uranium concentrations of 0.252 mg/L and 0.864 mg/L, respectively, at WMC803. By contrast, Rio Tinto (2021a) shows, at the scale of the plot, zero uranium concentrations at the same monitoring sites (see Fig. 5d). Rio Tinto (2021a) makes no mention of the earlier data compilations by Swanson (2019a-c) and there is no other information available that would help to resolve the contradictions. Table from Swanson (2019c).

Rio Tinto (2021a) also included monitoring data on aluminum, cadmium, lead, uranium, zinc, pH, total dissolved solids, and total suspended solids from sites along the Mandromondromotra River both upstream (WS0501) and downstream (WS0502) from the sites of mine wastewater discharge (see Figs. 3a and 4). Samples were collected between June 2015 and December 2020 on 20 dates at WS0501 and 21 dates at WS0502 (see Figs. 7a-b and Tables A1-A2 in Appendix A). At WS0501, eight measurements each of lead and uranium repeat data that were available in Swanson (2019a), while at WS0502, three measurements each of lead and uranium repeat data available in Swanson (2019a). In addition to data collected after August 2018 (when all water-quality data were supposed to be provided to Swanson (2019a-b)), Rio Tinto (2021a) includes 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 (2019a-b). There is no indication in Swanson (2019a) that the QMM mine was also monitoring aluminum, cadmium and zinc, as was reported in Rio Tinto (2021a). Finally, Rio Tinto (2021a) includes no data on iron, titanium or thorium, as was reported in Swanson (2019a). 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.
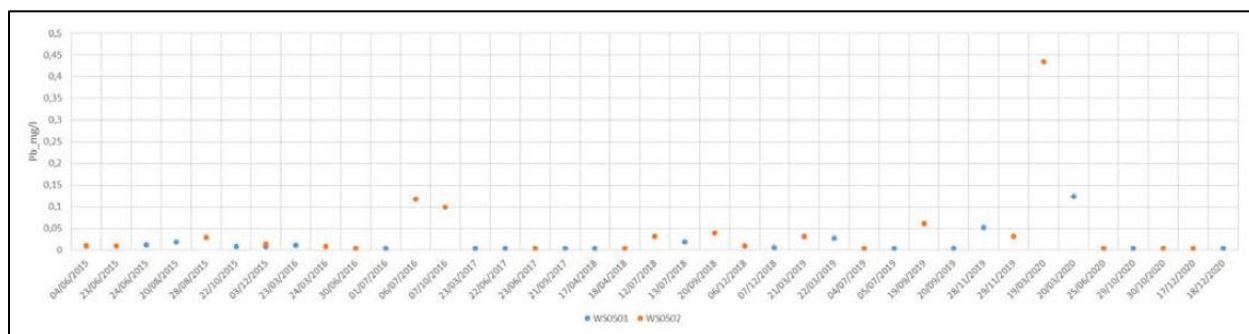

Figure 7a. Samples were collected between June 2015 and December 2020 on 20 dates at WS0501 and 21 dates at WS0502 (see locations in Fig. 4 and digitized values in Tables A1-A2 in Appendix A). At WS0501 and WS0502, eight and three measurements of lead, respectively, repeat data that were available in Swanson (2019a). In addition to data collected after August 2018 (when all water-quality data were supposed to be provided to Swanson (2019a-b)), the wastewater discharge report (Rio Tinto, 2021a) includes four and eight measurements of lead at WS0501 and WS0502, respectively, that were made prior to August 2018, but which were not made available to Swanson (2019a-b). In his integration of all available data, Emerman (2019) rejected lead measurements from Swanson (2019a) that were reported as either <0.005 mg/L or <0.008 mg/L, due to the high and ambiguous detection limits. Lead measurements that were reported as either <0.005 mg/L or <0.008 mg/L in Swanson (2019a), but repeated and plotted as values in Rio Tinto (2021a) were still rejected as invalid in this report. Figure from Rio Tinto (2021a).

METHODOLOGY

Lead and uranium data from QMM surface water monitoring stations upstream (WS0501) and downstream (WS0502) from wastewater discharge into the Mandromondromotra River (see Fig. 4) were digitized from graphs (see Figs. 7a-b and Tables A1-A2) in Rio Tinto (2021a) using tools available in ESRI ArcMap 10.8.1. These values are arbitrarily stated with five significant figures (see Tables A1-A2). Locations of wastewater monitoring sites were also measured using ArcMap 10.8.1 based on maps in Rio Tinto (2021a) (see Table 1). The only exception was WMC603, for which UTM coordinates were stated in Rio Tinto (2021a). Although the corresponding coordinate system was not stated, it was assumed to be WGS 84. As

in Emerman (2020), 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 (August 24, 2020), there appears to be some offset between the mapped mine perimeter and the actual perimeter (see Figs. 3a-b and 4).
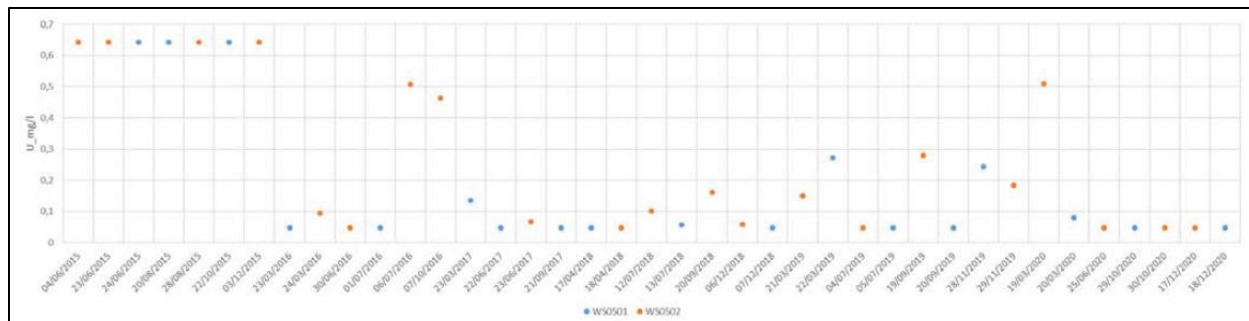

Figure 7b. Samples were collected between June 2015 and December 2020 on 20 dates at WS0501 and 21 dates at WS0502 (see locations in Fig. 4 and digitized values in Tables A1-A2 in Appendix). At WS0501 and WS0502, eight and three measurements of uranium, respectively, repeat data that were available in Swanson (2019a). In addition to data collected after August 2018 (when all water-quality data were supposed to be provided to Swanson (2019a-b)), the wastewater discharge report (Rio Tinto, 2021a) includes three and eight measurements of uranium at WS0501 and WS0502, respectively, that were made prior to August 2018, but which were not made available to Swanson (2019a-b). In his integration of all available data, Emerman (2019) rejected uranium measurements from Swanson (2019a) that were reported as either <0.047 mg/L or <0.642 mg/L, due to the high and ambiguous detection limits. Uranium measurements that were reported as either <0.047 mg/L or <0.642 mg/L in Swanson (2019a), but repeated and plotted as values in Rio Tinto (2021a) were still rejected as invalid in this report. Figure from Rio Tinto (2021a).

Statistical comparisons between water quality upstream and downstream of the QMM mine were carried out by an integration of all available data, including the data collected by the QMM mine and reported in Swanson (2019a), the additional data collected by the QMM mine and reported in Rio Tinto (2021a), the community-collected data reported in Emerman (2019), and the data reported in JBS&G (2020b). Comparisons were carried out separately for dissolved and total concentrations. Since the QMM mine has not reported whether dissolved or total concentrations were measured (Swanson, 2019a; Rio Tinto, 2021a), the same values were used for both dissolved and total concentrations. Since JBS&G (2020b) reported only total concentrations, their data had no effect on the comparison of dissolved concentrations. In fact, the only dataset that included separate values for dissolved and total concentrations were the community-collected samples reported by Emerman (2019). This report includes no update on comparisons of iron and thorium upstream and downstream of the QMM mine because no new measurements of these elements were reported by Rio Tinto (2021a). On the other hand, this is the first report that has included comparisons of aluminum, cadmium and zinc upstream and downstream of the mine, based on measurements available in Emerman (2019) and Rio Tinto (2021a). Statistical comparisons were carried out using the t-test, based on the logarithms of values, as in previous reports (Emerman, 2019, 2020).

The only exception to the integration of all available data was the exclusion of community monitoring sites Q1, Q2 and Q4 (see Figs. 2 and 3a), 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 3a] 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, 2019a). 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). 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 mineral sands mining, as was done in previous reports by Emerman (2019, 2020).

The most difficult problem in the earlier integration of the datasets from the community-collected samples and the samples collected by the QMM mine were the high and ambiguous detection limits in the data from the QMM mine (Emerman, 2019). In particular, there were 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 (which makes no sense), the detection limits are far too high to be useful. 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 (2017) drinking-water guideline of 0.030 mg/L. Generally, detection limits should be no more than 10% of the standard under consideration, so that maximum appropriate detection limits would be 0.003 mg/L for uranium, 0.001 mg/L for lead (based on the WHO drinking-water guideline) or 0.00032 mg/L for lead (based on the US EPA (2021a) aquatic standard). Most modern analytical instruments, such as the ICP spectrometer that was used by the QMM mine (Swanson, 2019a), have 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 3a). 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. 3a). 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 new data from the QMM mine (Rio

Tinto, 2021a) do not help with this comparison because sites WS0501 and WS0502 are not close to any of the sites used in the community study (see Fig. 3a).

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. Typical choices are 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 <0.647 mg/L could be replaced with 0.647 mg/L or 0.3235 mg/L or 0.0647 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 <0.647 mg/L with even a value of 0.0647 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, 2019a) of 20 uranium measurements, 27 lead measurements, seven thorium measurements, and 16 titanium measurements (Emerman, 2019).

The most recent dataset from the QMM mine (Rio Tinto, 2021a) included no mention of a detection limit. Instead, values that were repeated from the earlier QMM dataset (Swanson, 2019a) and which were stated as below a detection limit in Swanson (2019a) 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 (2019a), but plotted as equal to 0.642 mg/L in Rio Tinto (2021a) (see Fig. 7b). As mentioned above, this is an arbitrary and misleading way to plot measurements that that are below a detection limit. In this report, all measurements from the earlier QMM dataset (Swanson, 2019a) 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, 2021a).

The problem arises when there are measurements within the more recent QMM dataset (Rio Tinto, 2021a) that are not repetitions from the earlier QMM dataset (Swanson, 2019a) that would seem to be equivalent to measurements that would have been rejected from the earlier dataset. For example, the more recent QMM dataset includes 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 (see Fig. 7b

and Tables A1-A2). Since these measurements were plotted as actual values and nothing stated that they were below detection limits, they were included in the statistical analysis of this report under the general principle that data should not 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 (see Table A1) and three additional very high measurements of uranium at the downstream site WS0502 (see Table A2), 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, 2021a) were discarded. It is unfortunate that the problem of high and ambiguous detection limits has not been resolved, although this was brought to the attention of Rio Tinto in 2019. This problem will be addressed further in the subsection Role of External Consultants for Rio Tinto in the Discussion section.

RESULTS

Impact of QMM Mine on Aqueous Uranium and Lead

The integration of all existing water-quality data (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021a) showed that the geometric mean of the dissolved uranium concentration in surface water increased from 0.0074 mg/L to 0.1459 mg/L (a factor of 20) from the upstream to the downstream side of the QMM mine (see Fig. 8a). In a similar way, the geometric mean of the total uranium concentration in surface water increased from 0.0080 mg/L to 0.0776 mg/L (a factor of 10) from the upstream to the downstream side of the QMM mine (see Fig. 8a). Both increases were statistically significant at better than the 99% confidence level ($P = 0.009$ for both the dissolved and total concentrations). (The P-value is the probability that the geometric means are statistically indistinguishable. See Emerman (2020) for a tutorial on this subject.)

Although the geometric mean uranium concentrations are significantly below the WHO (2017) drinking-water guideline (0.03 mg/L) upstream from the mine, the geometric mean of the total uranium concentration downstream from the mine is 2.59 times the WHO guideline. In this context, in which local residents take drinking and culinary water directly from streams and lakes without filtering, safe drinking-water guidelines should refer to total concentrations, as explained in the preceding quote from JBS&G (2020b). Note that, on the downstream side of the QMM mine, the geometric mean of the total uranium concentration is less than the geometric mean of the dissolved uranium concentration (see Fig. 8a). For a single water sample, a total concentration would always be greater than or equal to a dissolved concentration. However, both dissolved and total concentrations were not measured for all samples. In particular, JBS&G (2020b) measured only total concentrations. The maximum measured uranium concentration was still 1.574 mg/L (52 times the WHO drinking-water guideline) on the downstream side of the QMM mine (Swanson, 2019a).
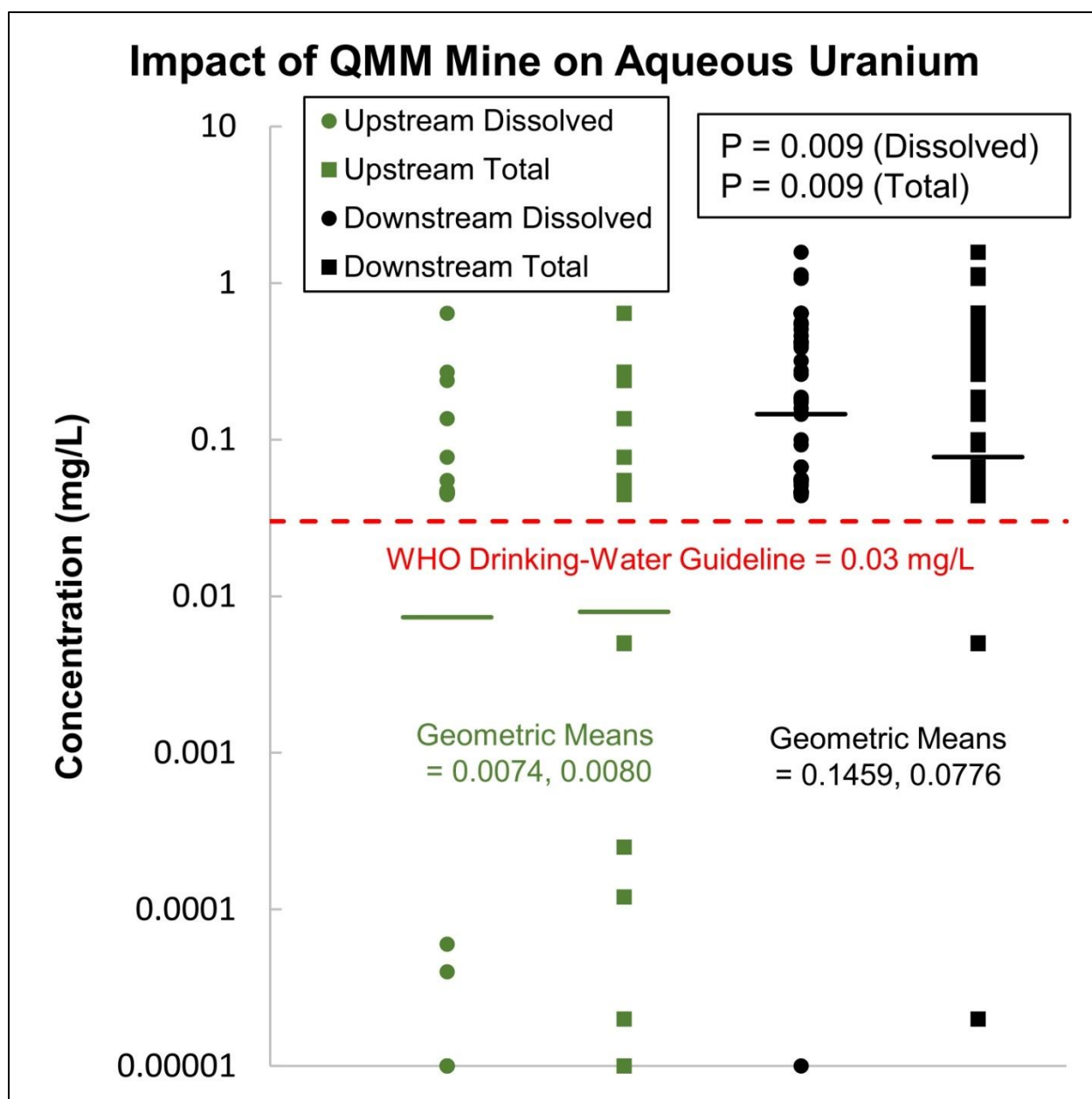
Figure 8a. Combining all of the existing water-quality data (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021a) shows that the increases in the geometric means of the aqueous uranium concentrations from the upstream to the downstream side of the QMM mine by a factor of 20 for dissolved concentrations and a factor of 10 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 ($P = 0.009$) and the total concentrations ($P = 0.009$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations (Swanson, 2019a-b; Rio Tinto, 2021a), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. The community-collected samples (Emerman, 2019) were analyzed for both dissolved and total concentrations, while JBS&G (2020b) measured only total concentrations. 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 8b. Combining all of the existing water-quality data (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021a) 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 6.7 for dissolved concentrations and a factor of 5.8 for total concentrations, are statistically significant at better than the 99.9% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.0007$) and the total concentrations ($P = 0.00007$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations (Swanson, 2019a-b; Rio Tinto, 2021a), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. The community-collected samples (Emerman, 2019) were analyzed for both dissolved and total concentrations, while JBS&G (2020b) measured only total concentrations. 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.
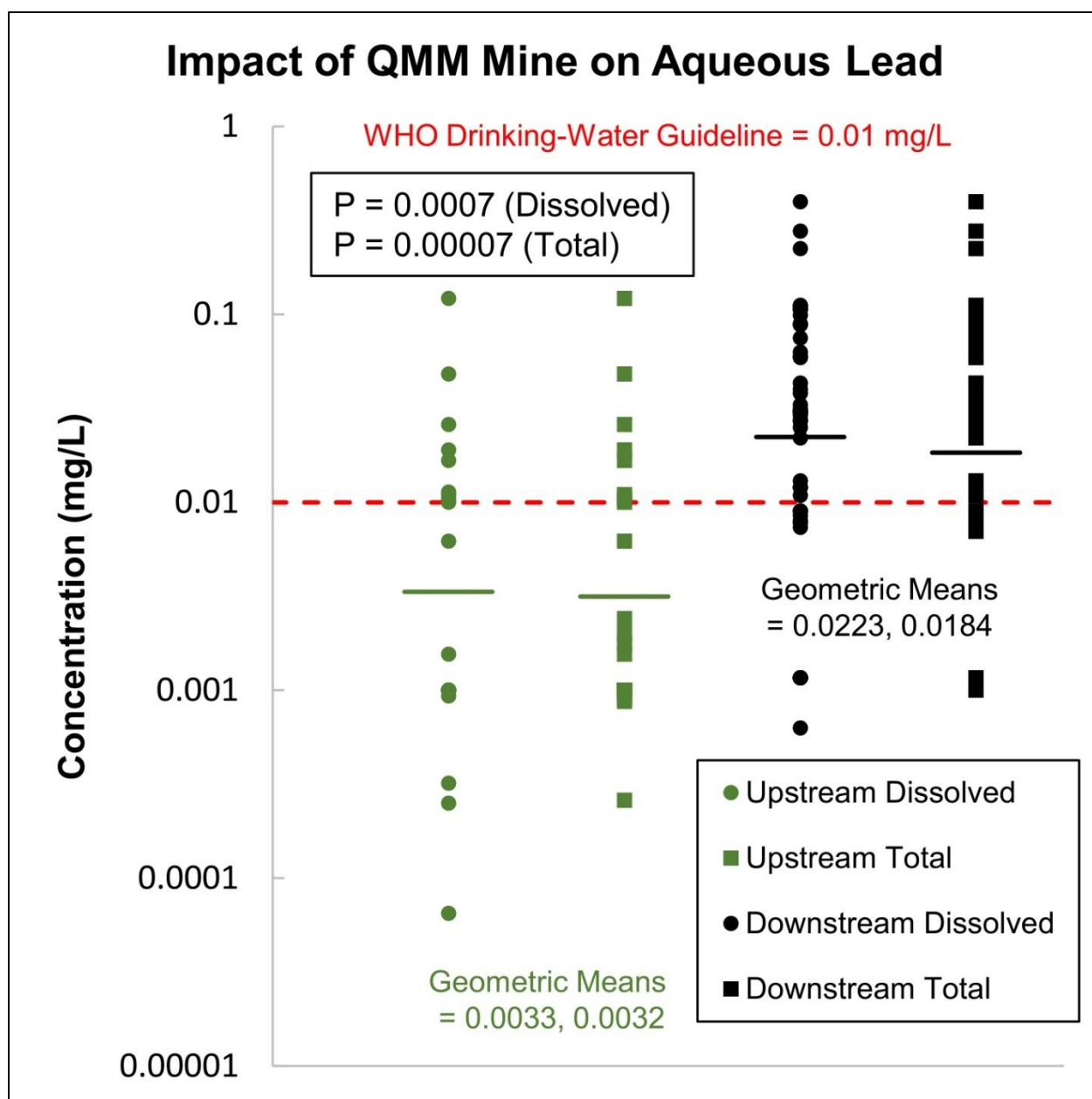
Figure 8c. Combining all of the existing water-quality data (Emerman, 2019; Rio Tinto, 2021a) shows that the increases in the geometric means of the aqueous cadmium concentrations from the upstream to the downstream side of the QMM mine are not statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.19$) and the total concentrations ($P = 0.20$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations (Rio Tinto, 2021a), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. The community-collected samples (Emerman, 2019) were analyzed for both dissolved and total concentrations. Swanson (2019a-b) and JBS&G (2020b) did not include cadmium measurements. 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.
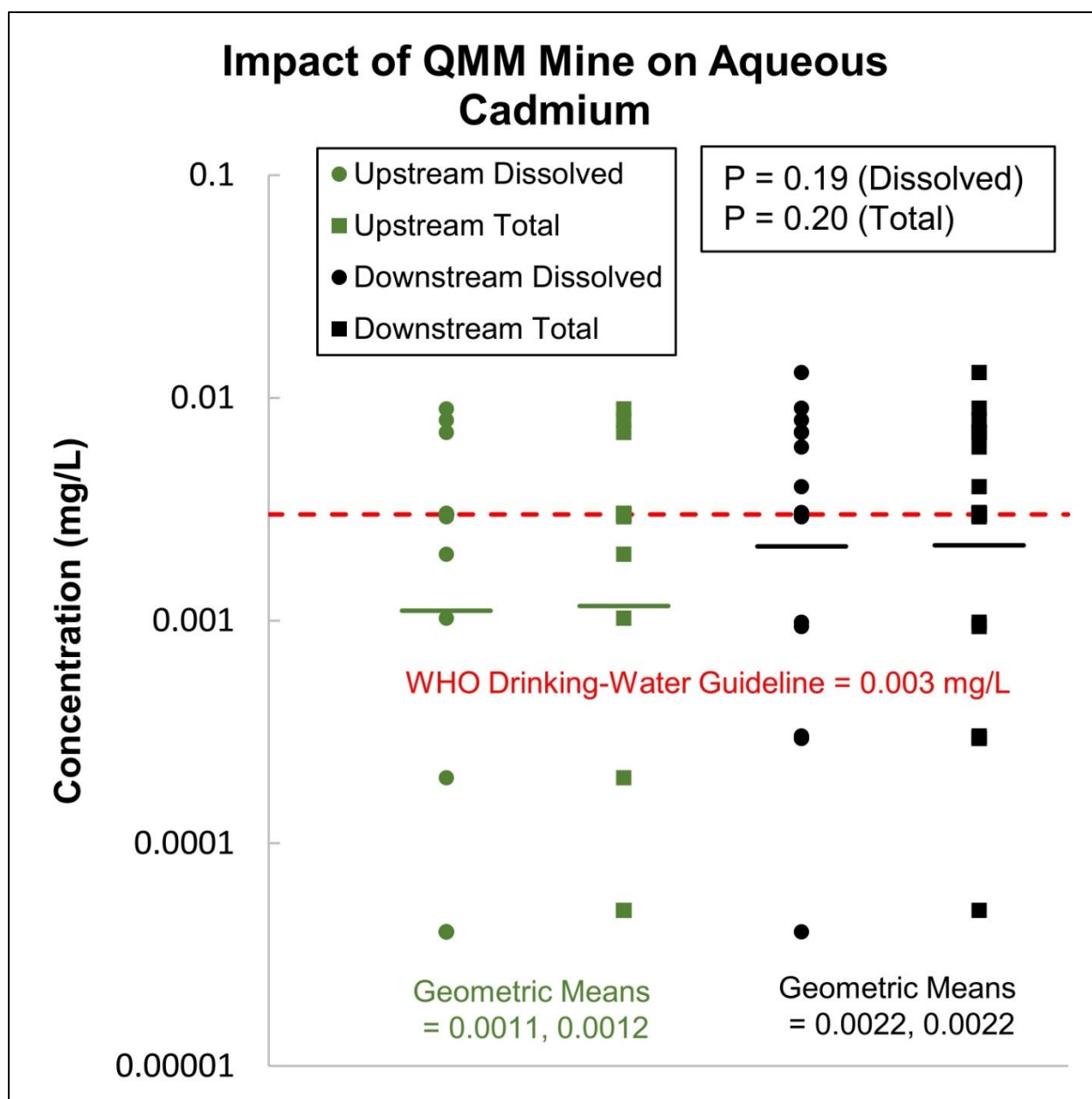
Figure 8d. Combining all of the existing water-quality data (Emerman, 2019; Rio Tinto, 2021b) shows that the increases in the geometric means of the aqueous aluminum concentrations from the upstream to the downstream side of the QMM mine are not statistically significant at the 95% confidence level, 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 (Rio Tinto, 2021a), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. The community-collected samples (Emerman, 2019) were analyzed for both dissolved and total concentrations. Swanson (2019a-b) and JBS&G (2020b) did not include aluminum measurements. 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. Note that there is no WHO drinking-water guideline for aluminum.
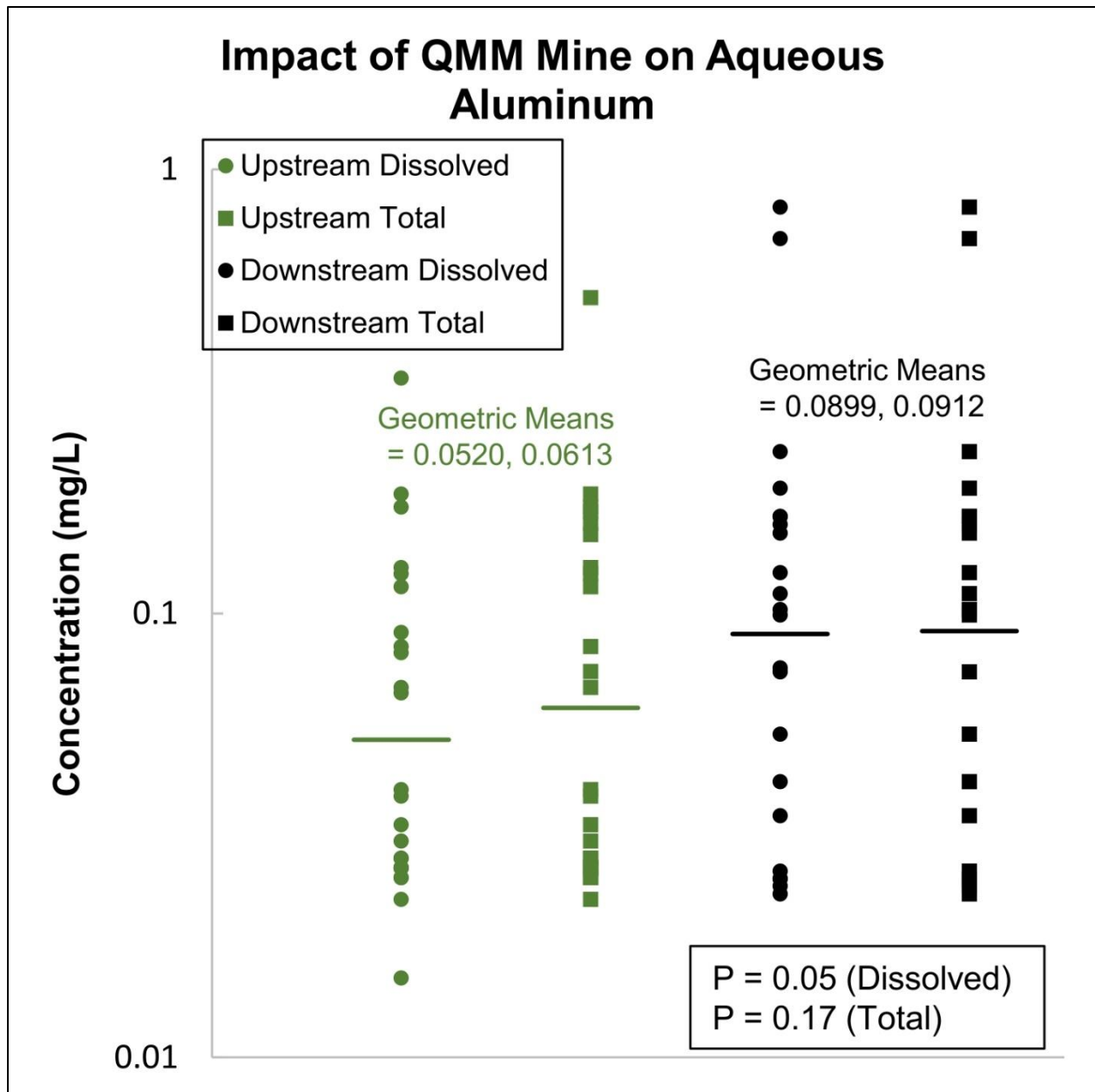
Figure 8e. Combining all of the existing water-quality data (Emerman, 2019; Rio Tinto, 2021a) shows that the increases in the geometric means of the aqueous zinc concentrations from the upstream to the downstream side of the QMM mine are not statistically significant at the 95% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.06$) and the total concentrations ($P = 0.12$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM surface water monitoring stations (Rio Tinto, 2021a), the same values were used for the dissolved and the total concentrations since no document has clarified whether dissolved or total concentrations were measured. The community-collected samples (Emerman, 2019) were analyzed for both dissolved and total concentrations, while JBS&G (2020b) measured only total concentrations. Swanson (2019a-b) did not include zinc measurements. 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. Note that there is no WHO drinking-water guideline for zinc.
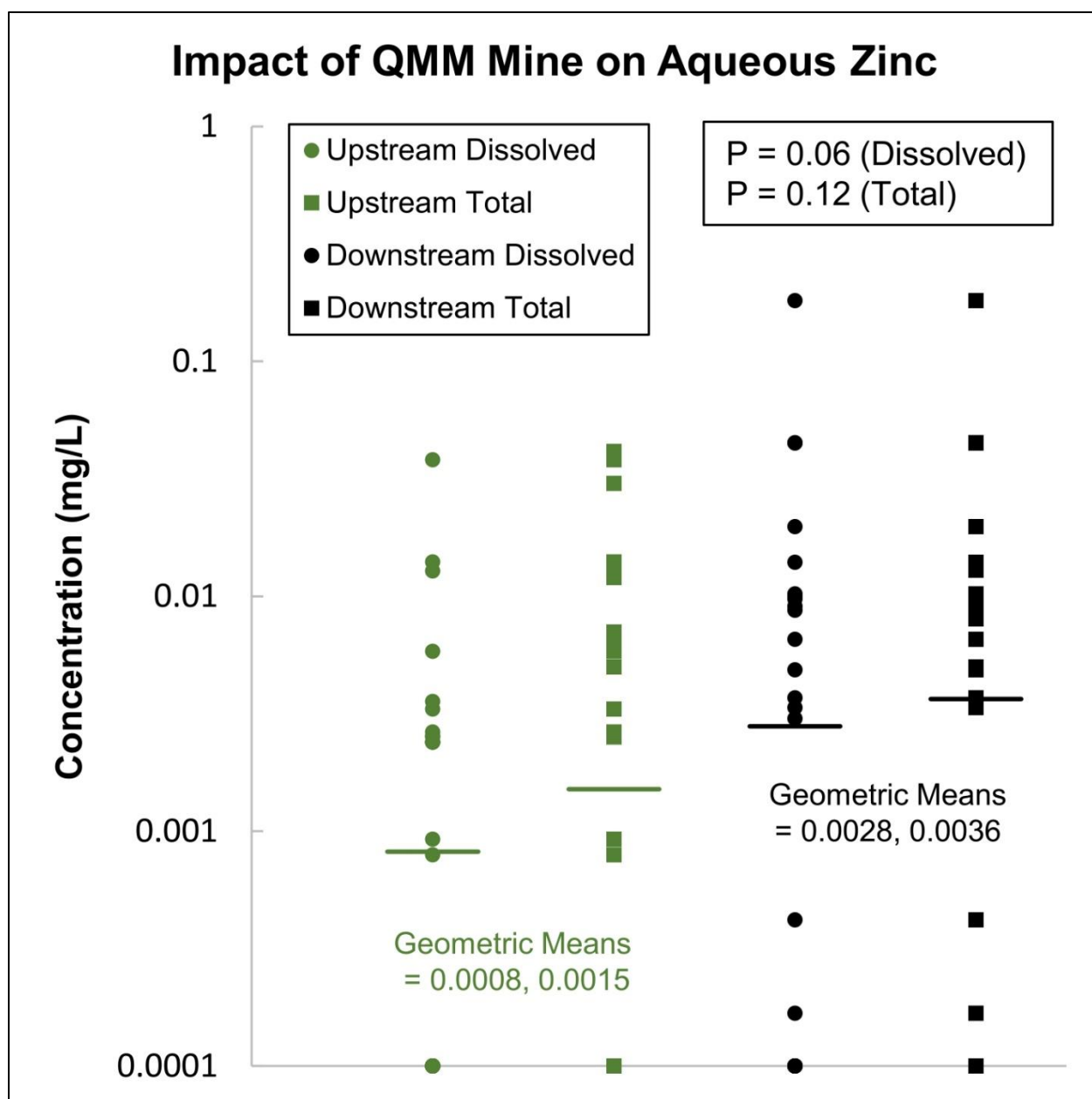
The integration of all existing water-quality data (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b; Rio Tinto, 2021a) further showed that the geometric mean of the dissolved lead concentration in surface water increased from 0.0033 mg/L to 0.0223 mg/L (a factor of 6.7) from the upstream to the downstream side of the QMM mine (see Fig. 8b). In a similar way, the geometric mean of the total lead concentration in surface water increased from 0.0032 mg/L to 0.0184 mg/L (a factor of 5.8) from the upstream to the downstream side of the QMM mine (see Fig. 8b). Both increases were statistically significant at better than the 99.9% confidence level ($P = 0.0007$ for the dissolved concentration and $P = 0.00007$ for the total concentration). Although the geometric mean lead concentrations are significantly below the WHO drinking-water guideline (0.01 mg/L) upstream from the mine, the geometric mean of the total lead concentration downstream from the mine is 1.84 times the WHO guideline. The maximum measured lead concentration was still 0.398 mg/L (nearly 40 times the WHO drinking-water guideline) on the downstream side of the QMM mine (Swanson, 2019a).

Impact of QMM Mine on Aqueous Cadmium, Aluminum and Zinc

With one exception, increases in aqueous cadmium, aluminum and zinc from the upstream to downstream side of the QMM mine were not statistically significant at the 95% confidence level (see Figs. 8c-e). The only possible exception was the increase in dissolved aluminum from the upstream to the downstream side of the QMM mine from 0.0520 mg/L to 0.0899 mg/L, which was barely statistically significant ($P = 0.05$) (see Fig. 8d). The geometric mean cadmium concentrations were within WHO drinking-water guidelines for cadmium (0.003 mg/L) both upstream and downstream of the mine. There are no WHO (2017) drinking-water guidelines for aluminum or zinc.

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. On the other hand, quartz has many possibilities for inclusion of impurities and substitution of aluminum for silicon is possible in both the silicate minerals quartz and zircon. Nothing more can be said on this subject without more information about the mineralogy of the mineral sands.

The US EPA (2021b) secondary drinking-water standards are 0.05 – 0.2 mg/L for aluminum and 5 mg/L for zinc. Exceedance of the secondary drinking-water standards does not have direct health impacts, although water will develop a discoloration in the case of excessive aluminum and a metallic taste in the case of excessive zinc. The geometric mean concentrations of aluminum exceeded US EPA (2021b) secondary drinking-water standards both upstream and downstream of the QMM mine (see Fig. 8d). On the other hand, all measurements of zinc concentrations were far below US EPA (2021b) secondary drinking-water standards (see Fig. 8e).

The US EPA (2021a) water-quality criterion for freshwater aquatic life is 0.120 mg/L for zinc, in the cases of both acute and chronic exposure. All zinc concentrations were well below that criterion except for a single downstream measurement of 0.1817 mg/L (see Fig. 8e and Table A2). According to US EPA (2021a), for aluminum, the water-quality criterion for

freshwater aquatic life depends upon the pH, hardness and dissolved organic carbon. Since data on hardness and dissolved organic carbon are not available for the Mandromondromotra River, any possible detrimental impacts of aluminum on aquatic life cannot be assessed. The US EPA (2021a) water-quality criteria for freshwater aquatic life are very low for cadmium, being 0.0018 mg/L for acute exposure and 0.00072 mg/L for chronic exposure. These criteria are based on total concentrations (US EPA, 2021a), so that the geometric mean of the cadmium concentration upstream of the mine (0.0012 mg/L) is within the criterion for acute exposure, but not for chronic exposure (see Fig. 8c). The geometric mean of the cadmium concentration downstream of the mine (0.0022 mg/L) exceeds the criteria for both acute and chronic exposure (see Fig. 8c). It is not clear whether the QMM mine has the ability to accurately measure such low concentrations. Another confounding factor is the difficulty in precisely digitizing the values from the plots in the wastewater discharge monitoring report (Rio Tinto, 2021a) (see Figs. 7a-b and Tables A1-A2).

Efficacy of Water Treatment System

In general, the system of mine wastewater treatment by discharging the wastewater into a wetland does not seem to be working as intended. There were still frequent exceedances of the Malagasy limit for aluminum in wastewater even after the monitoring sites were moved nearly one kilometer farther from the effluent sites and deeper into the wetland (see Figs. 4 and 5a). There also appears to be a long-term increase in the aluminum and zinc concentrations at WMC603 (see Figs. 5a and 5e). As mentioned above, monitoring site WMC603 is already nearly at the edge of the QMM mine property and cannot be moved any deeper into the wetland (see Fig. 4). In the cases of cadmium, lead and uranium, concentrations were higher as measured at WMC703A and WMC803A than at WMC703 and WMC803 (see Figs. 4 and 5b-d), so that the wastewater actually appears to be scavenging cadmium, lead and uranium out of the wetland. Part of the difficulty in determining whether the system of mine wastewater treatment is working as intended is the nearly four-year gap between when measurements ceased at sites on the western edge of the wetland (WMC703 and WMC803) and when they resumed at corresponding sites on the eastern edge of the wetland (WMC703A and WMC803A) (see Figs. 4 and 5a-e). There does not appear to be any occasion when roughly synchronous measurements were made for wastewater as it both entered and exited the wetland (such as synchronous measurements at sites WMC703 and WMC703A). Based on the nearly four-year gap between measurements on the eastern and western edges of the wetland, another possible explanation for the higher cadmium, lead and uranium concentrations on the eastern edge of the wetlands is that, over the intervening four years, the capacity of the wetlands to sorb more cadmium, lead and uranium has been exceeded, so that now wastewater is flowing through the wetlands with no removal of metals.

Since the wetlands downstream from the mine are not sites for collection of culinary water, only aquatic standards should be considered, rather than drinking-water standards. The wetlands routinely exceed US EPA (2021a) water-quality criterion for chronic exposure of freshwater aquatic life to cadmium (0.00072 mg/L) and lead (0.0025 mg/L), and occasionally to zinc (0.120 mg/L) (see Figs. 5b-c and 5e). The wetlands even routinely exceed US EPA (2021a) water-quality criterion for acute exposure of freshwater aquatic life to cadmium (0.0018 mg/L) and lead (0.065 mg/L), and occasionally to zinc (0.120 mg/L) (see 5b-c and 5e). As mentioned above, water-quality criteria for aquatic life for aluminum cannot be determined without more

knowledge of the water chemistry in the wetlands. In addition, there are no US EPA (2021a) water-quality criteria for aquatic life for uranium. Based on the above, the wetlands to the east of the QMM mine are a kind of "sacrifice zone" for aquatic life, although it is not clear that this is a result of activity at the mine, except in terms of elevated lead concentrations.

DISCUSSION

Need for Improved Wastewater Treatment System

The treatment of mine wastewater by passage through artificial settling ponds and natural wetlands is a type of purely passive water treatment. Examples of active water treatment might include the addition of reagents that would promote flocculation and more rapid settling of the solid particles or the use of reverse osmosis. The passive nature of the wastewater treatment is emphasized by Rio Tinto (2020a), "Note that the mining separation process in the dredge is mechanical and does not involve the addition of any chemical agents…To treat the water used in the mining and refining process, it is released into a series of flow-through holding ponds where its elevated suspended solids levels are naturally reduced through retention time and particle settling. No further treatment procedure is required to remove the suspended solids. Once the suspended solids have settled, the treated water is then directed through a natural wetland cell on the site prior to discharge back into the surrounding environment."

As described above, the passive wastewater treatment does not appear to be working as intended. In fact, it is not obvious that a passive water treatment system even ought to be working in the particular circumstances of the QMM mine. There is no evidence of any characterization of the mineralogy of the wetland sediments or the chemistry of the wetland water that would allow for the creation of a geochemical model that would predict the extent of sorption of metals that ought to occur in the wetlands. There is also no evidence of pilot or experimental studies of the extent of sorption of metals that ought to occur in these particular wetlands. In a similar way, there is no hydrologic budget for the wetlands that would make possible a calculation of the extent of dilution of contaminants that is occurring in the wetlands. According to Rio Tinto (2021a), a "new discharge point [was] requested in March 2020 (WMC 903)." No map has shown the location of WMC903. More discharge points could improve the efficacy of the wetlands by reducing the metal load that is released from the QMM mine at each discharge point, so as not to overwhelm the rate capacity or the total capacity of the wetlands to sorb metals at each location within the wetlands. However, in the absence of any geochemical modeling or pilot studies, it is not obvious that an additional discharge point would have a critical impact or any impact at all. In summary, the presumed successful operation of the passive wastewater treatment system is based upon wishful thinking, rather than science.

It must be emphasized that the sorption of metals within the sediments of either settling ponds or wetlands does not make the metals disappear. Lead and the radionuclides uranium and thorium are simply stored on sorption sites of the sediments. This storage of mining-related contaminants on sediments is known as the "chemical time bomb" of mining. Since the sorption bonds are very weak, small changes in water chemistry, such as changes in pH, dissolved oxygen or oxidation-reduction potential, can cause the sorbed contaminants to be remobilized in dissolved form in the water column. In fact, this remobilization of previously sorbed contaminants as a result of small changes in wastewater or wetland water chemistry could account for the apparent scavenging of cadmium, lead and uranium as the wastewater flows

across the wetlands (see Figs. 5b-d). (However, note the four-year gap between measurements at the western and eastern edges of the wetlands and the contradictions between the wastewater uranium data of Swanson (2019c) and Rio Tinto (2021a)). It is most important that this storage area for lead and radionuclides will exist in perpetuity and that there is no plan for the permanent prevention of remobilization of contaminants after the cessation of mining.

In summary, the treatment of mine wastewater needs to be addressed at three levels. First, any modification of the current passive wastewater treatment system needs to be based upon scientific studies, such as geochemical modeling or pilot experimental studies, not simply upon adding another discharge point, and hoping for the best. Second, based upon the results of geochemical modeling or pilot experimental studies, or simply upon the current history of ineffective passive wastewater treatment, there needs to be a consideration of the need for active wastewater treatment to precede the discharge of wastewater into the wetlands. Third, there needs to be a plan for the permanent immobilization of the mining-related contaminants that will be stored in the wetlands. A part of this plan will be to stop making the problem worse, that is, remove the contaminants from the wastewater before it is discharged into the wetlands.

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. Improvements to the passive wastewater treatment system or the installation of an active wastewater treatment system could prevent the long-term (years to decades) degradation of surface water in this region, but they 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 lead and radionuclides into downstream water sources are overtopping of the mining basins or seepage from the mining basins into groundwater. The breach of the required 50-meter buffer zone between the mining operation and the estuary is often misunderstood as a single event, such as the breaking of the tailings dam, followed by its repair. However, Emerman (2018b) 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. 3a-b), 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. Elevated levels of aluminum, arsenic, iron and manganese were found in some water samples

collected by local residents, although these are probably not related to the QMM mining operation (Emerman, 2019).

Role of External Consultants for Rio Tinto

At the 2021 Rio Tinto Annual General Meeting, Simon Thompson, Chairman of the Rio Tinto Board of Directors, described the JBS&G (2020b) study as an "independent audit." It is difficult to understand the purpose of an independent audit of the impact of the QMM mine on downstream water quality that takes place with no interaction with the ongoing water quality monitoring by the QMM mine. As mentioned above, neither the summary by JBS&G (2020b) nor the cover letter by Rio Tinto (2020b) mentioned the existence of any other water-quality data. With regard to the data from JBSG (2020b), Swanson (2020) wrote, "The results show that uranium was below the detection limit of 0.005 mg/L in all water samples, including samples downstream of QMM mine discharge. This is distinctly different from the results I reviewed for my report. However, I have much more confidence in the JBS&G data that I have in the QMM data provided to me for my report...The report illustrates the value of credible, reliable and comprehensive monitoring data and is in contrast to earlier QMM monitoring data – the quality and reliability of which is subject to question." It should be noted that the JBS&G (2020b) study also showed non-detectable uranium concentrations upstream from the mine, which contradicted earlier claims from Rio Tinto (Swanson, 2019b) that elevated uranium in surface water was naturally occurring.

I disagree with the assessment of the significance of the JBS&G (2020b) study by Swanson (2020). In the first place, one possible explanation for the non-detectable uranium concentrations found by JBS&G (2020b) is the episodic nature of release of mine wastewater. According to Rio Tinto (2021a), "The discharge of water is not continuous and may not occur for periods that could extend to more than one month." In the second place, Rio Tinto has never released any document that questions the validity of the water-quality data collected by the QMM mine that were provided to Swanson (2019a-b). Moreover, even after the release of the study by JBS&G (2020b), the Rio Tinto QMM mine has continued to release new water-quality data that are equivalent to the earlier data that were provided to Swanson (2019a-b) both in terms of a similar range of values and lack of accompanying methodology (Rio Tinto, 2021a). This creates a very dangerous situation in which Rio Tinto will continue to engage external consultants to provide one data stream (for consumption by NGOs, such as the Andrew Lees Trust), while they use their own resources to provide a completely different data stream with a different range of values (for consumption by the Malagasy regulatory agencies). 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. Along the same lines, it is disturbing that the JBS&G (2020b) study did not measure aluminum and cadmium at all, although the QMM mine has been monitoring these elements for compliance with Malagasy limits and has been carrying out mitigation actions in response to non-compliance (Rio Tinto, 2021a).

CONCLUSIONS

The chief conclusions of this report can be summarized as follows:

1) The integration of the new data on surface water quality in "QMM Water Discharge Monitoring Data" (Rio Tinto, 2021a) with previously existing data strengthens previous conclusions (Emerman, 2019, 2020) that the QMM mine has a detrimental impact on downstream water quality.
2) 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) are statistically significant at better than the 99% confidence level.
3) 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 uranium, and from 0.0032 mg/L to 0.0184 mg/L for total lead (1.84 times the WHO drinking-water guideline) are statistically significant at better than the 99.9% confidence level.
4) Maximum downstream uranium and lead concentrations are still 52 and 40 times the WHO (2017) drinking-water guidelines, respectively, as found in previous data from the Rio Tinto QMM mine.
5) Increases in aluminum, cadmium and zinc from the upstream to the downstream side of the mine are not statistically significant, so that these elemental concentrations are probably naturally occurring.
6) The mitigation actions in response to wastewater concentrations that exceed Malagasy limits for aluminum and cadmium involve moving the monitoring sites to the far side of the wetland at the edge of the QMM mine property. These are not true mitigation actions in that they do not change the wastewater treatment process, but only the locations where the wastewater is monitored.
7) The passive wastewater treatment system of discharge of mine wastewater into settling ponds and wetlands is not working because aluminum and cadmium still exceeded Malagasy limits even after the monitoring sites were moved. Moreover, the movement of monitoring sites showed higher cadmium, lead and uranium at the far side than the near side (close to the sites of wastewater discharge) of the wetlands.
8) There are numerous contradictions between the QMM mine wastewater data presented in the latest report (Rio Tinto, 2021a) and in the data provided to Swanson (2019a-c). The most important contradiction is that Rio Tinto (2021a) reported zero uranium concentrations for two wastewater monitoring sites (WMC703 and WMC803), while Swanson (2019c) showed mean and maximum uranium concentrations of 0.593 mg/L and 2.007 mg/L, respectively, at WMC703 and mean and maximum uranium concentrations of 0.252 mg/L and 0.864 mg/L, respectively, at WMC803.

RECOMMENDATIONS

The recommendations of this report are that the Andrew Lees Trust urge Rio Tinto to carry out the following actions in order of priority (1 = highest priority):
1) Rio Tinto should provide safe drinking water to the 15,000 people who live near the QMM mine without further delay.

2) Rio Tinto should resolve the contradictions between the wastewater and surface water data contained in QMM Water Discharge Monitoring Data" (Rio Tinto, 2021a) and the wastewater and surface water data provided to Swanson (2019a-c).
3) Rio Tinto should engage external consultants to review the water monitoring procedures followed by the QMM mine.
4) Rio Tinto should analyze the efficacy of the passive wastewater system using geochemical modeling and pilot or experimental studies and should redesign the passive wastewater system based on the results.
5) If the results of geochemical modeling and pilot or experimental studies show that it is not possible to redesign the passive wastewater system so as to prevent further detrimental impact on downstream water sources, Rio Tinto should design and install an active water wastewater treatment system.
6) Rio Tinto should develop a plan for the permanent immobilization of contaminants stored in the wetlands.

ABOUT THE AUTHOR

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APPENDIX A: DIGITIZATION OF QMM SURFACE WATER DATA

Table A1. WS0501 (Mandromondromotra River upstream from QMM mine)[1]

Date	Al (mg/L)	Cd (mg/L)	Pb (mg/L)	U (mg/L)	Zn (mg/L)
June 4, 2015	0.06815				0.00093
June 24, 2015	0.03875	0.00199	0.01048	0.64207	0.00000
August 20, 2015	0.17371	0.00020			0.00251
October 22, 2015	0.11492	0.00103			0.00079
December 3, 2015	0.18574		0.00621		
March 23, 2016	0.02673	0.00299			0.00000
July 1, 2016	0.02272	0.00299	0.00155	0.04728	0.00000
March 23, 2017	0.02539	0.00302			0.00000
June 22, 2017	0.02673	0.00299			0.00000
September 21, 2017	0.12294	0.00299			0.00000
April 17, 2018	0.02542	0.00302			0.00000
July 13, 2018	0.02806	0.00293	0.01668	0.05482	0.00000
December 7, 2018	0.02809	0.00304	0.00000	0.04454	0.00582
March 22, 2019	0.08418	0.00796	0.02599	0.26999	0.00000
July 5, 2019	0.02673	0.00297	0.00000	0.04591	0.03810
September 20, 2019	0.02673	0.00299	0.00000	0.04523	0.00265
November 28, 2019	0.12695	0.00894	0.04811	0.23915	0.01283
March 20, 2020	0.04009	0.00699	0.12143	0.07743	0.00000
October 29, 2020	0.03341	0.00299	0.00000	0.04523	0.01402
December 18, 2020	0.03073	0.00299	0.00000	0.04728	0.00331

[1]Measurements digitized from graphs in Rio Tinto (2021a). Measurements already present in Swanson (2019a) are not repeated. See Figs. 3a and 4 for location.

Table A2. WS0502 (Mandromondromotra River downstream from QMM mine)[1]

Date	Al (mg/L)	Cd (mg/L)	Pb (mg/L)	U (mg/L)	Zn (mg/L)
June 4, 2015	0.231445	0.00094			0.18170
June 23, 2015	0.165318	0.002994	0.007371	0.640702	0.003362
August 28, 2015	0.165318	0.000295	0.027545	0.641387	0.00000
December 3, 2015	0.151703	0.000984	0.010863	0.642072	0.00000
March 24, 2016	0.11086	0.003016	0.007759	0.092508	0.00000
June 30, 2016	0.025284	0.002994	0.001164	0.045911	0.00000
July 6, 2016	0.026256	0.007956	0.111639	0.506394	0.000168
October 7, 2016	0.024311	0.008983	0.098931	0.461169	0.009738
June 23, 2017	0.191574	0.002929			0.008730
April 18, 2018	0.025284	0.000297			0.00000
July 12, 2018	0.073907	0.004	0.031425	0.100045	0.009905
September 20, 2018	0.041816	0.006994	0.038021	0.158291	0.003694
December 6, 2018	0.102108	0.00306	0.008535	0.056194	0.006548
March 21, 2019	0.698864	0.007016	0.030261	0.146642	0.013935
July 4, 2019	0.823136	0.000304	0.001164	0.046596	0.044826
September 19, 2019	0.158511	0.012983	0.058971	0.276153	0.019811
November 29, 2019	0.123502	0.006011	0.029873	0.180904	0.009066
March 19, 2020	0.023359	0.002994	0.030649	0.050982	0.044994
June 25, 2020	0.053485	0.002994	0.001164	0.046596	0.004869
October 30, 2020	0.099191	0.003038	0.001164	0.043856	0.010241
December 17, 2020	0.035008	0.003016	0.001164	0.045226	0.000420

[1]Measurements digitized from graphs in Rio Tinto (2021a). Measurements already present in Swanson (2019a) are not repeated. See Figs. 3a and 4 for location.

APPENDIX B: TUTORIALS ON WATER CHEMISTRY AND STATISTICS

Dissolved and Total Concentrations

In brief, dissolved concentrations refer to concentrations measured in samples that were filtered prior to analysis, while total concentrations refer to samples that were not filtered prior to analysis. Whether water samples should or should not be filtered prior to analysis has been one of the most controversial issues in water sampling since the practice of sample filtering was introduced in the 1970s. Fortunately, some of the controversy has been settled since, due to the decrease in the cost of analytical instrumentation since about 2010, it has become standard practice to collected both filtered and unfiltered samples and, thus, to report both dissolved and total concentrations. In the case of the QMM mine, only the community-collected samples reported both dissolved and total concentrations (Emerman, 2019). JBS&G (2020b) reported only total concentrations, while the QMM mine has never clarified whether their water-quality data refer to dissolved or total concentrations (Swanson, 2019a-b; Rio Tinto, 2020a). Of course, the controversy as to whether the dissolved or total concentration is most relevant in a particular situation still remains. For simplicity, the controversy and the distinction between dissolved and total concentrations is explained below in terms of arsenic, although an equivalent explanation could be given for any other contaminant of concern.

Modern analytical instruments, such as the inductively coupled plasma spectrometer or the atomic absorption spectrometer, require that the water sample be free of solid particles that could become trapped within the instrument. For that reason, all analytical laboratories digest samples prior to analysis. Digestion refers to the dissolution of solid particles using various combinations of heat, acids, hydrogen peroxide, and other reagents. Because some solid particles may have resisted dissolution, the water samples are further forced through an ultrafine (0.45-μm) filter prior to their introduction into the analytical instrument. The arsenic that was already present in the sample in the dissolved phase will not be affected by digestion or filtering. However, since some of the arsenic in a water sample is in the solid phase, digestion of the sample will increase the arsenic concentration in the dissolved phase by moving arsenic from the solid to the dissolved phase. The various solid phases of arsenic include the following (listed in order from least to most resistant to digestion):
1) ionically bound arsenic
2) strongly adsorbed arsenic
3) arsenic coprecipitated with acid-volatile sulfides, carbonates, manganese oxides, and very amorphous iron oxyhydroxides
4) arsenic coprecipitated with amorphous iron oxyhydroxides
5) arsenic coprecipitated with crystalline iron oxyhydroxides
6) arsenic oxides and arsenic coprecipitated with silicates
7) arsenic coprecipitated with pyrite and amorphous orpiment As_2S_3 and remaining recalcitrant arsenic minerals (Keon et al., 2001).

If a sample was filtered through a 0.45-μm filter prior to digestion, then only the original dissolved component of arsenic would be measured, and the resulting arsenic concentration is referred to as "dissolved arsenic." If no pre-digestion filtering was done, and the digestion was carried out using hot concentrated nitric acid and 30% hydrogen peroxide so that all of the above solid phases were dissolved (US EPA, 2021c), then all components of arsenic would be measured, and the resulting arsenic concentration is referred to as "total arsenic." It should be

noted that water samples can contain colloidal particles smaller than 0.45 μm that will pass through the filter and then be dissolved during the digestion process. In that way, the arsenic adsorbed onto the dissolved formerly-solid particles will be measured as dissolved arsenic, even though the arsenic was not present in the dissolved form in the original water sample. Therefore, the dissolved arsenic concentration measured using the pre-filtered method is always greater than the true dissolved arsenic concentration (dissolved arsenic concentration in the original water sample). Moreover, the arsenic concentration measured using the non-pre-filtered method is always less than the true total arsenic concentration (total arsenic concentration in the original water sample) because not all of the solid particles will be fully digested (which is why water samples are always filtered even after digestion). For the above reasons, the phrases "dissolved arsenic" and "total arsenic" are often retained in quotes. Many studies have carried out sequential extractions, in which increasingly aggressive solvents are used to progressively extract arsenic from more resistant solid phases. For example, one hour of digestion using 1M HCl at 25°C will extract arsenic from the above Solid Phase 3, so that the measured arsenic concentration will be a sum of the dissolved arsenic, ionically bound arsenic, strongly adsorbed arsenic, and arsenic coprecipitated with acid-volatile sulfides, carbonates, manganese oxides, and very amorphous iron oxyhydroxides (Keon et al., 2001).

The important question is then: Should water samples be filtered prior to digestion or only after digestion? In other words, is it appropriate to measure "dissolved arsenic" or "total arsenic?" The answer is that it depends on the environmental and social context within which a water sample has been collected. Saar (1997) has written an excellent review of this subject and a briefer treatment can be found in Sanders (1998).

Four examples will help to illustrate this point. The first example is water sampled from a monitoring well that has been placed into a layer with low hydraulic conductivity, such as a clay or shale layer. The act of pumping or bailing this well can mobilize small particles that would not normally be moving with the flow of groundwater. These samples should be filtered prior to digestion, since the digestion of the particles would result in a measured arsenic concentration that was not representative of the pore water in the clay or shale layer. The second example is water drawn from a shallow "backyard well" that a family is keeping for their emergency water supply. In a study in Utah carried out by the author and his students (Gherasim et al., 2016), the wells were often poorly constructed, and the water was slightly muddy. None of the well owners was going to drink a glass of muddy water, nor were they going to force the water through an ultrafine filter. Any well owner would let the water sit until the solid particles settle and then pour off the clear water (which would still contain the particles that were too fine to settle). Therefore, the sampling procedure involved following the same steps that would be followed by a well owner. The samples were allowed to sit for 24 hours, after which the relatively clear water on top (the supernatant) was poured off into a separate sample bottle. Then the supernatant was digested without any pre-filtering. In a third example, flowing water samples were collected from a pipe that led from a spring and emptied into a cattle trough (Emerman et al., 2018c). Although these samples were muddy, the particles were in motion with the water and would be consumed by the cattle. Therefore, not only were the samples not filtered before digestion, but before removing an aliquot of sample for digestion, the sample bottle was vigorously shaken to ensure that a representative quantity of solid particles would be digested with the rest of the water sample. In fact, it is difficult to think of circumstances under which water samples that were collected from flowing water should be filtered prior to digestion.

The fourth and most important example is the case of a water sample collected from a tap that is intended for human consumption. If the water is relatively clear, then the typical practice would be to drink the water as it comes from the tap. Certainly, no householder is using a pump or syringe to force the water through an ultrafine filter. Filtering the samples prior to analysis has the potential to significantly underestimate the arsenic load that is being delivered to the consumer. This point is emphasized by Saar (1997), "If direct ingestion from a drinking water source is involved, whole, unfiltered samples…are needed." In the same way, WHO drinking-water guidelines typically refer to total concentrations, although that judgement depends upon the context of water collection and consumption. In some localities, there may be some typical pre-consumption practices. For example, consumers may boil the water or add bleach to the water or, as mentioned above, allow the water to settle. In those cases, the predigestion procedure should follow the same consumer practices. Additional case studies regarding the appropriateness of filtration are presented by Saar (1997). In some cases, both filtering and not-filtering can be shown to have shortcomings. As mentioned above, the contemporary practice is to collect both filtered and unfiltered water samples, and to publish results for both "dissolved arsenic" and "total arsenic," as was done by Emerman (2019), so that readers can decide for themselves which concentration is most appropriate for a given situation.

In the case of the QMM mine, JBS&G (2020b) collected only unfiltered samples for the measurement of total concentrations with the explanation, "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)." JBS&G (2020b) is probably correct that local residents do not process the water samples through ultrafine filters, but they did not explain how or whether they knew that local residents do not filter the samples at all, for example, by passing the water through a coffee-type or other coarse filter or by allowing the water to settle prior to consumption. The chief shortcoming of the JBS&G (2020b) procedure is that, by not measuring dissolved concentrations at all, it is not possible to distinguish between the contaminants carried in the dissolved and sorbed phases. Moreover, it is not possible to integrate their measurements with other measurements of dissolved concentrations, such as those that were reported for samples collected by the community (Emerman, 2019).

Geometric Mean

The average, or arithmetic mean, of a set of values is the sum of the values divided by the number of values. For example, Case I of Table B1 shows a set of 10 values, roughly centered around 1.00, for which the arithmetic mean is 0.989. In a more general sense, the arithmetic mean is the expected or typical value, so that the best estimate for the expected value for a set of values drawn from this population is 0.989.

Complications arise when the values range over orders of magnitude. For example, in Case I of Table B1, a single value of 1.04 has been changed to 10.40. As a result, the arithmetic mean has risen to 1.925. This arithmetic mean is almost meaningless because it is not an expected value for anything. The expected value for the population from which values are drawn in Case II should still be roughly 1.00 (although occasionally a much higher value could occur). Removing the value of 10.40 as an outlier is a possibility, although discarding data is generally not a recommended procedure (see discussion in Methodology section). Nothing in Case II suggests that the value of 10.40 is not valid, it is simply not a typical value. The problem is that

the single atypical value strongly biases the arithmetic mean in the direction of the atypical value, so much as to render the arithmetic mean nearly meaningless.

Table B1. Examples of arithmetic and geometric means

	Case I		Case II	
	Values	**Logarithms**	**Values**	**Logarithms**
	0.80	-0.2231	0.80	-0.2231
	0.95	-0.0513	0.95	-0.0513
	1.00	0.0000	1.00	0.0000
	1.20	0.1823	1.20	0.1823
	0.90	-0.1054	0.90	-0.1054
	1.15	0.1398	1.15	0.1398
	1.05	0.0488	1.05	0.0488
	0.92	-0.0834	0.92	-0.0834
	0.88	-0.1278	0.88	-0.1278
	1.04	0.0392	10.40	2.3418
Arithmetic mean	0.989	-0.0181	1.925	0.2122
Exp (Arithmetic mean)		0.982		1.236
Geometric mean[1]	0.982		1.236	

[1]The geometric mean is the exponential of the arithmetic mean of the logarithms of a set of values.

The standard approach to this problem to transform the values in such a way as to reduce the range of values. The most common transformation (when all values are positive) is to take the logarithms of the values. For example, Case II shows a much more restricted range for the logarithms (ranging from -0.2231 to 2.3418), as opposed to the untransformed values (ranging from 0.80 to 10.40). This transformation reduces the impact of the single atypically large value.

The geometric mean is the exponential function of the arithmetic mean of the logarithms (see Table B1). The geometric mean of the values in Case II is now 1.236, which is slightly high, but much closer to a typical or expected value. For Case I, in which the range of values was already restricted to a single order of magnitude, the geometric mean (0.982) is nearly equal to the arithmetic mean (0.989). The use of the geometric mean is a standard procedure in aqueous geochemistry, in which it is typical for elemental concentrations to range over several orders of magnitude (see Figs. 8a-e and Tables A1-A2).