Impact on Regional Water Quality of the Rio Tinto QMM Ilmenite Mine, Southeastern Madagascar

By Dr Steven. H Emerman,

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Overview from Andrew Lees Trust

Following hydrology and radioactivity studies commissioned by the Andrew Lees Trust in 2018, the Trust has continued its enquiries and its advocacy regarding water quality around the Rio Tinto / QMM mine in Anosy region, southern Madagascar.

This latest study by Dr Emerman was commissioned to address a lack of QMM water monitoring data to establish the difference between natural background radiation levels in Anosy and the presence of elevated levels of uranium, 50 times higher than WHO safe drinking water guidelines, that have been identified in some parts of the waterways and lakes adjacent to the mine where local people fish and gather their drinking water (Swanson 2019). The study is based on water samples collected in Anosy in 2019 and complements additional analysis of uranium levels in the QMM mining basin that have also been researched this year.

The Trust has advocated the experts' recommendation that safe drinking water be provided to communities.

To access and download all the water and radioactivity studies please visit:
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LIGHTNING SUMMARY

The Rio Tinto QMM ilmenite mine in southeastern Madagascar generates radionuclide-enriched water, which it releases through surface discharge and groundwater seepage. The detrimental impact of the mine on regional water quality is indicated by the increases in uranium, thorium and lead in surface water from the upstream to the downstream side of the mine, which are statistically significant at better than the 99% confidence level.

ABSTRACT

The Rio Tinto QMM ilmenite mine on the coast of southeastern Madagascar generates radionuclide-enriched water in mining basins by extracting ilmenite from mineral sands and concentrating monazite in the mine tailings. The mine process water is released into a wetland adjacent to a river, while additional radionuclide-enriched water 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. According to data collected by the QMM mine at two upstream and 10 downstream surface water sites, 37% and 43% of samples exceed WHO drinking-water guidelines for uranium and lead, respectively. The lack of upstream sites (only one, zero and three measurements above a detection limit for uranium, thorium and lead, respectively) made it difficult to separate the impact of the mine from the natural background. Moreover, each water-quality parameter inexplicably had two detection limits (uranium measurements were reported as <0.642 mg/L and <0.047 mg/L), both of which were unrealistically high, and which brought into question the validity of the entire QMM dataset. Local residents collected nine additional surface water samples, including five upstream and four downstream samples, which were analyzed for 46 elements and isotopes at the University of Utah. Two of the upstream samples were outside of the watershed of the QMM mine, but were not downstream from any mineral sands mining. The direct comparison of the QMM and the new datasets was hampered by the lack of spatial overlap of the sample sites, but was somewhat facilitated by their occurrence in the same geologic units. One of the new sites was close to two QMM sites, at which the QMM mine reported measurements of only iron and lead above a detection limit. Since iron concentrations were the same order of magnitude for the two datasets, it was decided that the hypothesis that the QMM dataset was valid could not be rejected. For comparison of upstream and downstream concentrations, the two datasets were integrated by removing all QMM measurements that were below the detection limit. The detrimental impact of the mine on regional water quality is indicated by the increases in uranium, thorium and lead in surface water from the upstream to the downstream side of the mine, which were statistically significant at better than the 99% confidence level, based on either the dissolved or the total concentrations. The response of Rio Tinto has been that "care must be taken when comparing to

conservative guidelines such as the WHO Drinking Water Guidelines." It is recommended that Rio Tinto take immediate action to provide safe drinking water for the local residents.

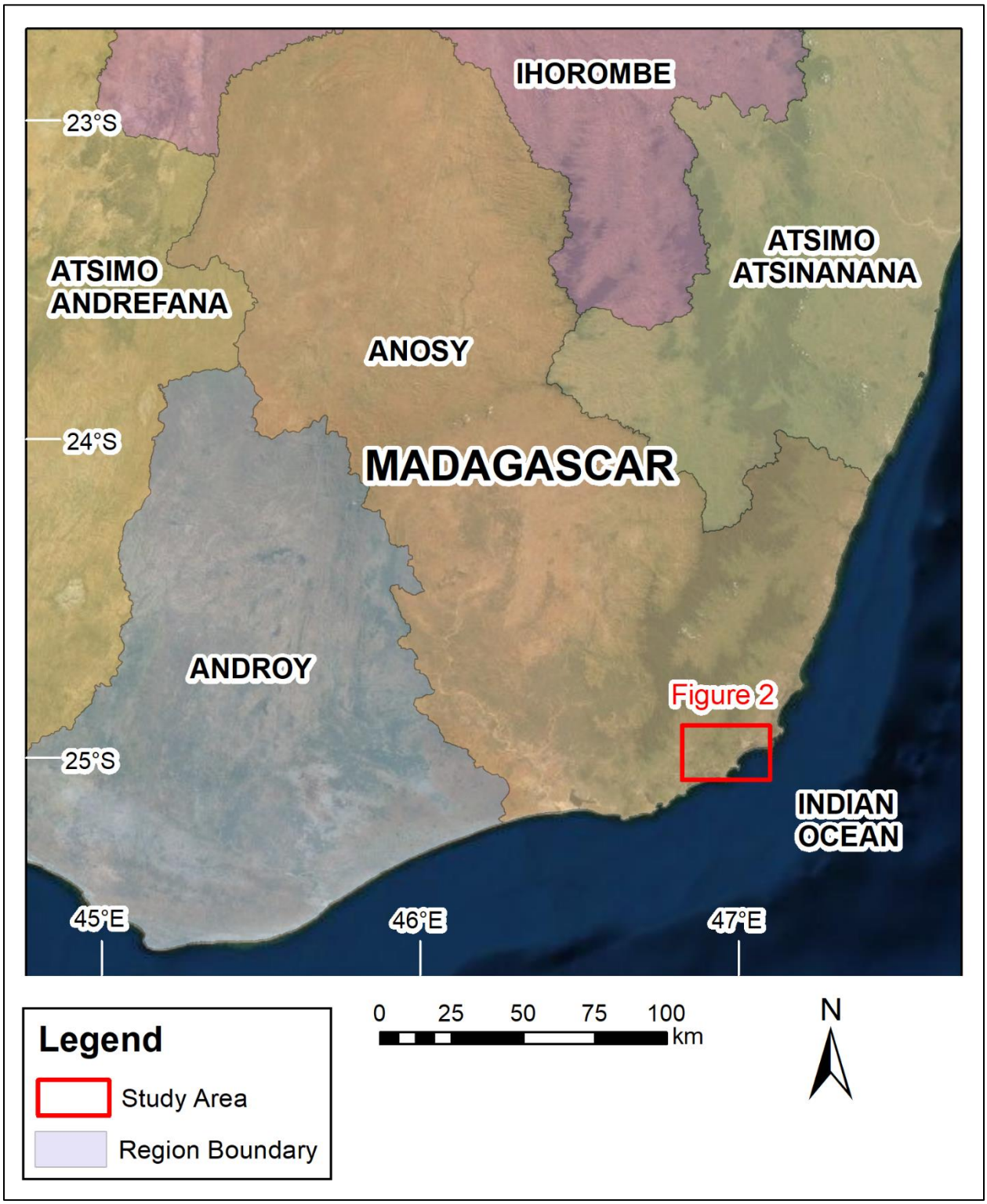

Figure 1. Surface water quality was studied upstream and downstream of the QMM mine, which is located within Anosy region on the southeastern tip of Madagascar.

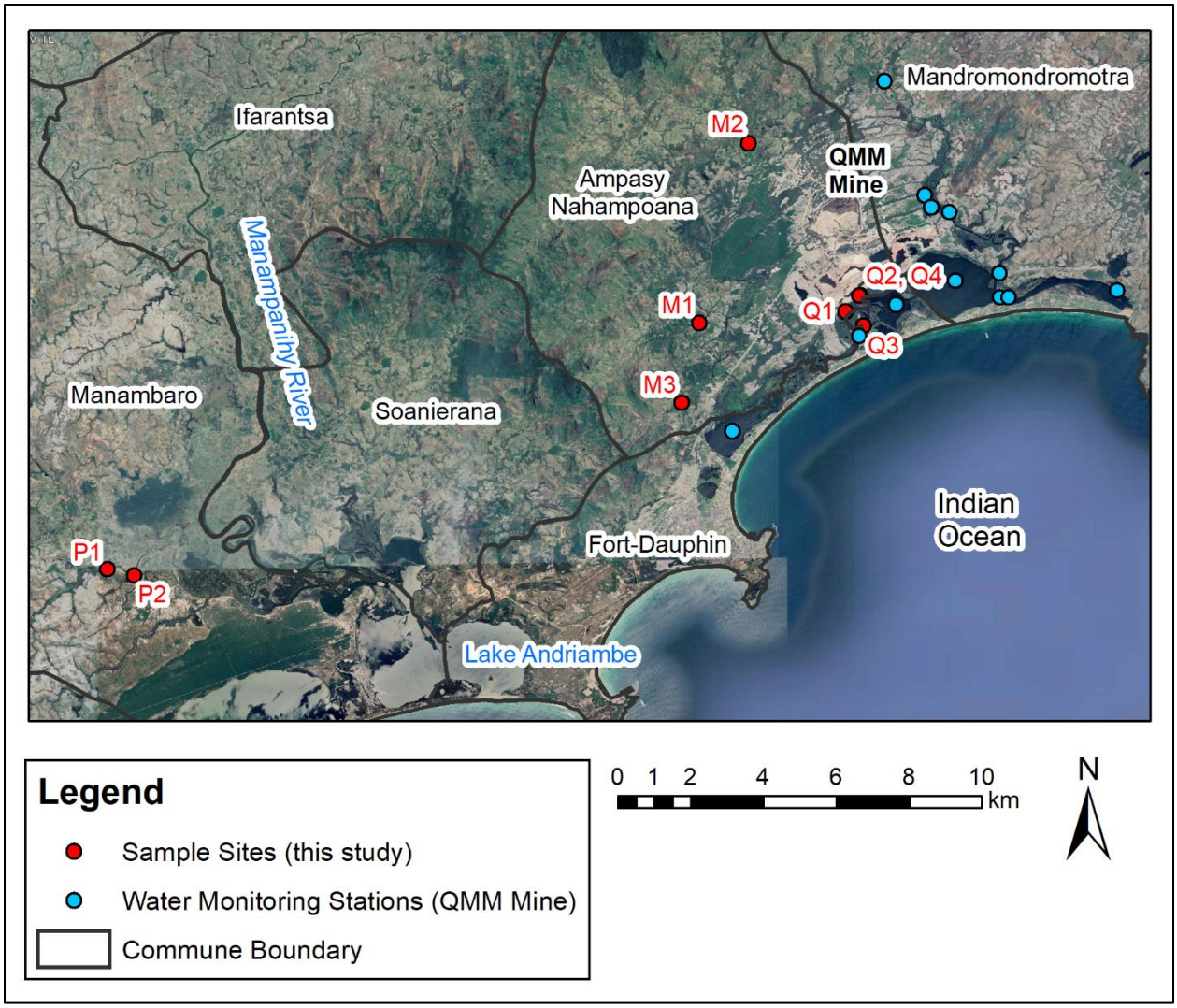

Figure 2. A previous study (Swanson, 2019b) compiled water-quality measurements from 12 water monitoring stations that are operated by the QMM mine, two of which are upstream from the mine and 10 of which are downstream. This study reports water-quality measurements from nine additional sites, three 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. See close-up of northeastern portion of map in Fig. 3.

INTRODUCTION

Possible Release of Radionuclides and Lead from the QMM Mine

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. 1-3). 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) 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). Extraction of the economic minerals (ilmenite and Zirsill) results in the concentration of the mineral monazite, which is enriched in the radionuclides uranium and thorium. These radionuclide-enriched minerals accumulate in the mining basin so that uranium, thorium and lead (the decay product of uranium and thorium) should be expected to dissolve into the water of the mining basin. The intentional or accidental release of the water from the mining basin into either surface water or groundwater could pose a significant threat to human and aquatic life. In the case of the QMM mine, even the Zirsill contains 463 ppm of uranium and thorium (Elmer, 2013). 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).

The release of water from the mining basins to surface water is, in fact, 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 wetlands that are adjacent to the Mandromondromotra River (see Fig. 3). The only treatment of the mine effluent water is a "biodiversity control pond" or "settling pond" (Swanson, 2019b) that will remove suspended solids and any heavy metals that will sorb onto the solid particles. From the wetlands, any contaminants could travel to the Mandromondromotra River and downstream the river to the Indian Ocean (see Fig. 3). However, because the water bodies along the shoreline constitute an estuary system in which water can also flow upstream as tidal currents, contaminants could travel upstream through Lakes Ambavarano and Besaroy and possibly as far as Lake Lanirano (Swanson, 2019b). (According to Rio Tinto (2019), the construction of a weir at the inlet/outlet between Lake Ambavarano and the Indian Ocean (see Fig. 3) 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 (the sands that remain after ilmenite and Zirsill have been extracted), 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 (2019b) noted that the predominant winds from the east to northeast could transport radionuclides as dust into the Méandre River, from where it could flow downstream into Lakes Besaroy and Ambavarano or upstream toward Lake Lanirano (see Fig. 3).

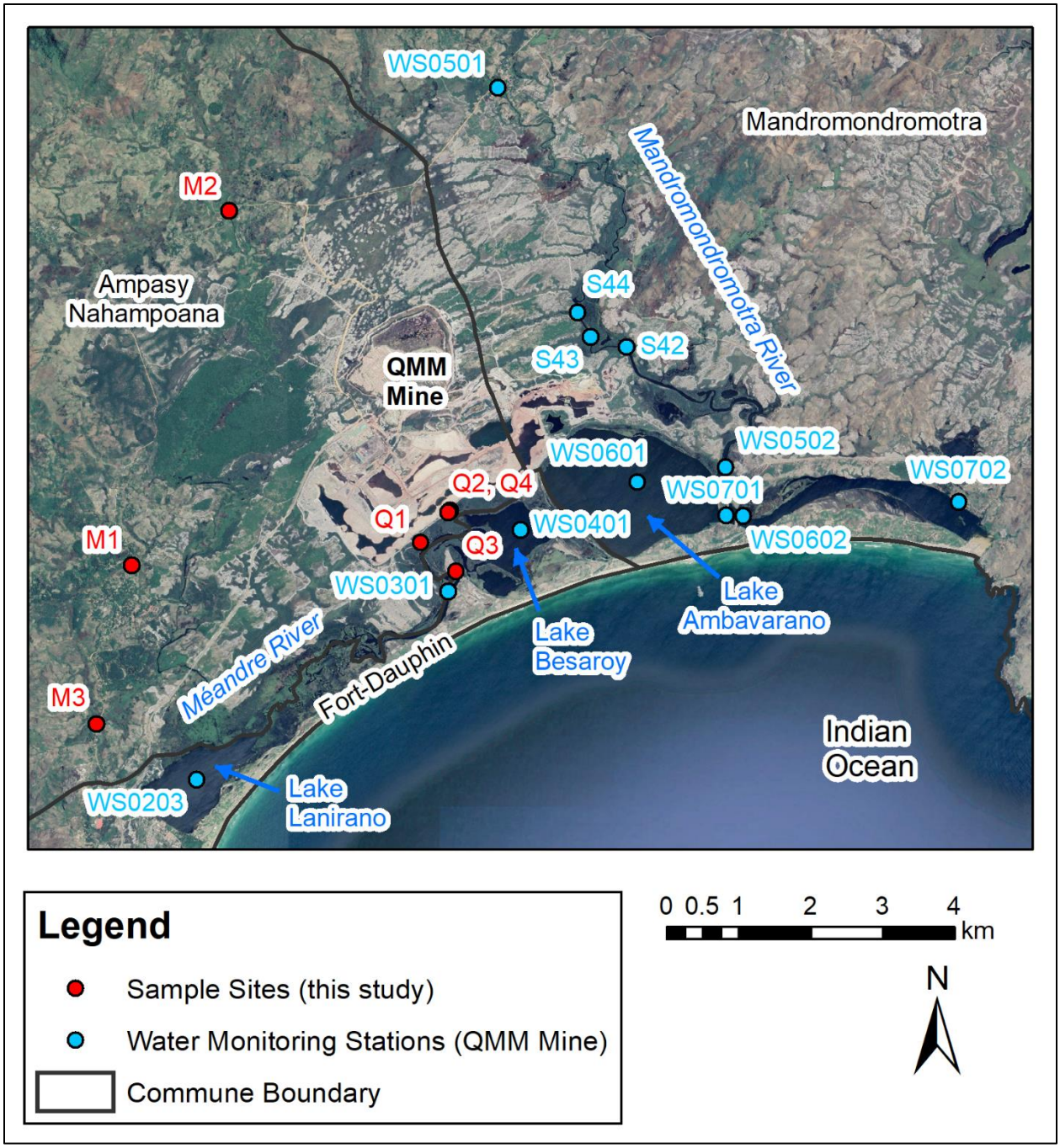

Figure 3. It is difficult to directly compare the water-quality results from the sample sites of this study with those from the water monitoring stations of the QMM mine because there is very little spatial overlap between the two sets of sites. The closest correspondence is between sites Q3 (this study) and WS0301 (QMM mine) since the sites are only 295 meters apart on the Méandre River, which flows into Lake Besaroy. The site Q3 has the most poorly-constrained location and may even be on the western shore of Lake Besaroy, in which case, it would correspond better with water monitoring station WS0401. See larger-scale map in Fig. 2.

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 (2019b), 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, 2019a) 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).

Monitoring of Water Contamination from the QMM Mine

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 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 Table 1a, Fig. 3; Swanson, 2019b). These samples have been analyzed for iron, lead, titanium, thorium, uranium, pH, electrical conductivity, dissolved oxygen, salinity, total dissolved solids, and total suspended solids. A total of 60 sets of measurements (a set consists of a site and a sampling date) have been made since June 2015. Not every parameter was measured during every set of measurements. For example, sometimes only total suspended solids was measured. In addition, there does not seem to be any pattern to the sampling dates. The water-quality data have not been accompanied by any methodology, except that elemental concentrations were measured using ICP (Inductively-Coupled Plasma) spectrometry (Swanson, 2019b). In particular, it is not known whether elemental concentrations were measured from filtered samples (dissolved concentrations) or unfiltered samples (total concentrations). There was no explanation as to why the particular water-quality parameters were chosen. As has already been explained, the accidental or

intentional release of uranium, thorium and lead should be expected. The measurement of iron and titanium was probably chosen due to their occurrence in ilmenite ($FeTiO_3$).

Table 1a. Water monitoring stations (QMM mine)[1]

Station	Commune[2]	Description	Latitude[3,4] (°S)	Longitude[3,4] (°E)
		Upstream[5]		
WS0203	Fort-Dauphin	Lake Lanirano	25.0014	46.9912
WS0501	Mandromondromotra	Mandromondromotra River	24.9150	47.0289
		Downstream[5]		
S42	Mandromondromotra	Mandromondromotra River[6]	24.9474[7]	47.0449[7]
S43	Mandromondromotra	Mandromondromotra River[6]	24.9461[7]	47.0404[7]
S44	Mandromondromotra	Mandromondromotra River[6]	24.9431	47.0388
WS0301	Fort-Dauphin	Méandre River	24.9779	47.0226
WS0401	Fort-Dauphin	Lake Besaroy	24.9702	47.0317
WS0502	Mandromondromotra	Mandromondromotra River	24.9624	47.0573
WS0601	Mandromondromotra	Lake Ambavarano	24.9643	47.0463
WS0602	Mandromondromotra	Lake Ambavarano outlet	24.9685	47.0595
WS0701	Mandromondromotra	Lake Ambavarano outlet	24.9684	47.0574
WS0702	Mandromondromotra	Unnamed lake	24.9667	47.0864

[1]Data reported by QMM mine (Swanson, 2019b)
[2]Taolagnaro district, Anosy region
[3]Latitude and longitude based upon WGS 84 coordinate system
[4]Latitudes and longitudes were measured from the map in Fig. 10 of Swanson (2019b). The map shows additional water monitoring stations for which no data were reported.
[5]Upstream and downstream refer to the QMM mine.
[6]Sites receive overland discharge from QMM water release points (Swanson, 2019b).
[7]On Fig. 10 of Swanson (2019b), stations S42 and S43 had labels, but no markers. Therefore, the location on the Mandromondromotra River closest to the label was chosen for the measurement of latitude and longitude. It is clarified in Swanson (2019b) that the stations are on the Mandromondromotra River.

All water-quality data reported by the QMM mine were compiled as part of an assessment of the release of radioactive material from the mine by Swanson (2019a-b). All data were provided to Dr. Swanson by August 2018, so that they were current as of that date. Nothing in the present report should be regarded as a criticism of Dr. Stella Swanson, who had no access to any data other than what was reported by the QMM mine. In fact, Swanson (2019b) was strongly critical of both the data and the lack of data that were provided to her. Some sample quotes are "Given the reliance of local people on surface water for drinking water and the use of locally produced foods, the complete lack of relevant monitoring data is unacceptable…To the knowledge of the author, there is no over-arching monitoring plan and no explicit connection between the results of environmental monitoring and management of radiation dose to the public…In some cases, the quality of the monitoring data is questionable. The quantity of data is often insufficient for understanding spatial or temporal trends" (Swanson, 2019b).

Although the available water quality data were sparse, the results were alarming. 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). Out of 54 measurements of lead, 27 exceeded a detection limit and 23 (43%)

exceeded the WHO drinking-water guideline for lead (0.01 mg/L). In addition, 27 (50%) measurements of lead exceeded the US EPA (2019b) aquatic standard for lead (0.0032 mg/L), based upon chronic exposure by freshwater organisms. The WHO does not have drinking-water guidelines for iron, thorium or titanium. However, the US EPA (2019b) 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, to drink water), rather than health effects. This secondary standard was exceeded in 11 (20%) out of 54 measurements. (All water-quality data are available in the Appendix of Swanson (2019b)).

Assessing the Impact of the QMM Mine on Regional Water Quality

Although the water-quality results are alarming, especially for uranium and lead, the lack of water samples collected upstream of the QMM mine made it difficult to assess the impact of the mine based upon the data compiled in Swanson (2019b). Only two out of the 12 QMM water monitoring stations were located upstream of the mine, which were WS0501 on the Mandromondromotra River upstream of the three points of mine effluent discharge and WS0203 on Lake Lanirano (see Table 1a, Fig. 3). In addition, the water monitoring station on Lake Lanirano involved only one set of measurements of elemental concentrations (for example, a single measurement of uranium). On the other hand, Swanson (2019b) pointed out that contaminants could possibly travel from the Mandromondromotra River as far upstream as Lake Lanirano (see Fig. 3) and that station WS0501 on the Mandromondromotra River "could still be influenced by site runoff" (Swanson, 2019c) and concluded that there was a "lack of true upstream reference sites that could be used to reliably determine natural uranium concentrations in water." This lack of water-quality data from upstream of the mine made it possible for Rio Tinto to deny that the QMM mine had any impact on regional water quality. In their response that was included as an addendum to Swanson (2019b), Rio Tinto wrote, "QMM acknowledges that the region has a high natural background radiation level that existed prior to the commencement of mining, and that fully understanding the impacts of mining is scientifically challenging…As was determined before the commencement of mining the area surrounding QMM has naturally elevated levels of radiation. This is a result of the surrounding geological conditions and this leads to naturally enhanced levels of uranium in drinking water. This is not a QMM related impact and is an aspect of the water used by local communities before the commencement of construction or operations at QMM" (Swanson, 2019b).

Besides the shortage of upstream samples, inconsistencies in the QMM water-quality data led to questions regarding whether the dataset was even valid. The most striking inconsistency was the existence of two detection limits for all elements except 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 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 aquatic standard). Most modern analytical instruments, such as the ICP spectrometer that was used by the QMM mine, have detection limits in the range 0.0001-0.00001 mg/L for most metals, including lead and uranium (see Appendix A). In fact, it is difficult to imagine how the QMM mine even acquired analytical instruments with such high detection limits. For example, the Hach DR6000 UV-VIS Spectrophotometer measures lead with a detection limit of 0.003 mg/L (Hach, 2019) and can be purchased for $9,448 (Cole-Parmer, 2019). The ANDalyze AND1100 Fluorimeter can measure both uranium and lead concentrations with a detection limit of 0.002 mg/L (ANDalyze, 2019a-b) and could be purchased for $2361 for the fluorimeter (Quasar Instruments, 2019a) and $407 each for the uranium and lead sensors (Quasar Instruments, 2019b). (A spectrophotometer or a fluorimeter would typically have a much higher detection limit than a much more expensive ICP spectrometer, which is what the QMM mine used (Swanson, 2019b)).

Table 1b. Sample sites (this study)

Sample	Commune[1]	Description	Latitude[2] (°S)	Longitude[2] (°E)
		Upstream[3]		
M1	Ampasy Nahampoana (Mandena)	Unnamed stream[4]	24.974611	46.983119
M2	Ampasy Nahampoana (Anandrana)	Unnamed stream	24.930383	46.995250
M3	Ampasy Nahampoana	Unnamed stream	24.994475	46.978717
		Background[5]		
P1	Manambaro (Petricky)	Unnamed stream	25.036981	46.843519
P2	Manambaro (Petricky)	Unnamed stream	25.035517	46.836850
		Downstream[3]		
Q1	Ampasy Nahampoana	Wetlands below tailings dam	24.971831	47.019228
Q2	Ampasy Nahampoana	Wetlands below tailings dam	24.967794	47.022861
Q3	Fort-Dauphin	Méandre River[6]	24.975421	47.023648
Q4	Ampasy Nahampoana	Wetlands below tailings dam	24.968056	47.022664

[1]Taolagnaro district, Anosy region (village in parentheses)
[2]Latitude and longitude based upon WGS 84 coordinate system
[3]Upstream and downstream refer to the QMM mine.
[4]Entrance to Namhampoana Reserve
[5]Background samples are not in the watershed of the QMM mine and not downstream from other mineral sands mining.
[6]Sample may be from the western shore of Lake Besaroy (see Fig. 3).

Objectives of this Study

In response to the difficulty of determining whether the QMM mine has an impact on regional water quality due to the lack of upstream samples and questions regarding the entire QMM water-quality dataset, the Andrew Lees Trust arranged for the collection of additional water samples by local residents. These samples were shipped to the author who analyzed the samples at the University of Utah ICP-MS (Inductively-Coupled Plasma – Mass Spectrometry) Metals Lab. The objectives of this report were then to answer the following questions:

1) How do the elemental concentrations of the new water samples compare with WHO Guidelines for Drinking Water (WHO, 2017), US EPA National Recommended Aquatic Life Criteria (US EPA, 2019a), and US EPA Secondary Drinking-Water Standards (US EPA, 2019b)?
2) What are the implications of the new samples for the validity of the QMM dataset?
3) What is the impact of the QMM mine on regional water quality?

Figure 4a. Sample M1 was collected from an unnamed stream at the entrance to the Namhampoana Reserve, near the village of Mandena (Ampasy Nahampoana commune, Taolagnaro district, Anosy region), and upstream from the QMM mine. Photo supplied by the Andrew Lees Trust.

SAMPLE COLLECTION

In August 2019 local residents collected water samples from nine surface water sites, of which three were upstream from the QMM mine and four were downstream (see Figs. 2-3, 4a-d, Table 1b). Samples Q1, Q2 and Q4 were collected from the wetlands on the seaward side of the tailings dams (see Fig. 3). Samples Q2 and Q4 were collected only 6-7 meters from a tailings dam. Two additional sites (P1 and P2) near the village of Petriky are outside of the watershed of the QMM mine (neither upstream nor downstream), but are not downstream from mineral sands or other mining operations (see Figs. 2-3, 4c-d). On that basis, the P1 and P2 sites should be

representative of background water quality prior to impact by mining. In fact, Rio Tinto is planning to expand mineral sands mining to the vicinity of Petriky (Swanson, 2019b; see Fig. 5).

Figure 4b. Sample M2 was collected from an unnamed stream near the village of Anandrana, (Ampasy Nahampoana commune, Taolagnaro district, Anosy region) upstream from and very close to the perimeter of the QMM mine. Photo supplied by the Andrew Lees Trust.

The water samples were collected in accordance with French-language instructions provided by the author (see Appendix B). In most cases, the sample collectors provided videos to demonstrate their compliance with the instructions. The samples were not filtered prior to collection and no reagents were added for preservation. The only exceptions to the instructions were that samples were collected in either plastic or glass bottles, and the sample collectors either did not have GPS receivers or did not record the coordinates. Coordinates were assigned by the Andrew Lees Trust by comparing photos and verbal information provided by the collectors with Google Earth images. The only sample for which there was uncertainty in the collection site was Q3 (see Figs. 2-3, Table 1b). This was a drinking-water sample that was probably collected from the Méandre River, but which could possibly have been collected from the western shore of Lake Besaroy (see Fig. 2). Samples were continuously refrigerated except for about a four-day period during which they were shipped to the author. All samples were analyzed within about four weeks after collection.

Figure 4c. Sample P1 was collected from an unnamed stream near the village of Petriky (Manambaro commune, Taolagnaro district, Anosy region). The site is neither upstream nor downstream of the QMM mine. However, since the site is near the mine and not downstream from any mining of mineral sands, it could be representative of background surface water chemistry. Photo supplied by the Andrew Lees Trust.

Figure 4d. Sample P2 was collected from an unnamed stream near the village of Petriky (Manambaro commune, Taolagnaro district, Anosy region). The site is neither upstream nor downstream of the QMM mine. However, since the site is near the mine and not downstream from any mining of mineral sands, it could be representative of background surface water chemistry. Photo supplied by the Andrew Lees Trust.

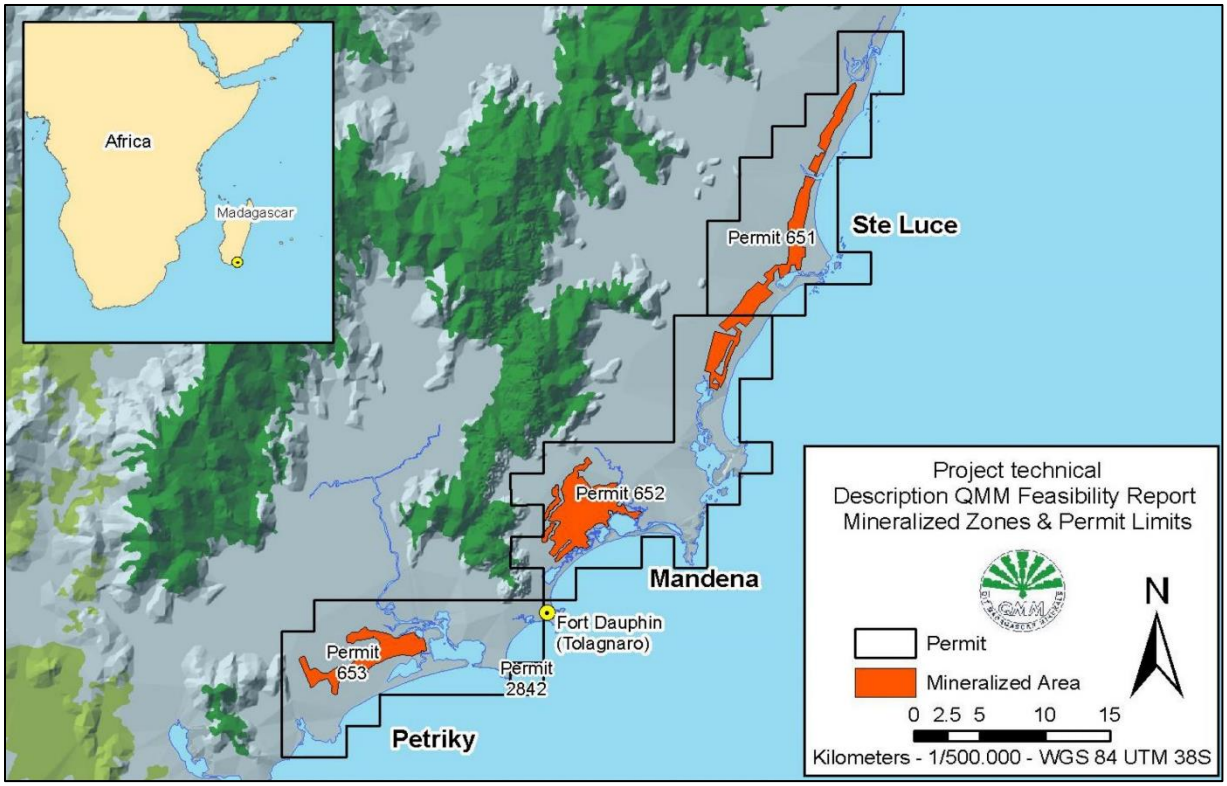

Figure 5. The QMM mine is currently located in the Mandena permit area, but plans to expand to the Petriky and Ste. Luce permit areas. Figure from Rio Tinto Iron and Titanium Inc. (2005).

METHODOLOGY

Water Analysis

Although the samples were not filtered before collection, both filtered and unfiltered aliquots were removed from each sample bottle for the measurement of dissolved and total concentrations, respectively. Due to the lack of preservation, some transfer of atoms between the sorbed and dissolved phases could have occurred between collection and analysis, so that the dissolved concentrations could have differed from what would have been measured if on-site filtration and preservation had been possible. On the other hand, it is very unlikely that there would have been any difference in the measured total concentrations. Due to the large number of colloidal particles in all of the sample bottles, any metallic atoms would have sorbed onto the particles instead of the walls of the containers.

The procedure for obtaining filtered and unfiltered aliquots began with homogenizing the original bottles with strong shaking, followed by pipetting 5 mL into an acid-leached centrifuge tube. The centrifuge was run at 4000 rpm for five minutes, after which 1 mL of the clear supernatant was removed, acidified, diluted to 10 mL and analyzed as the filtered sample (dissolved concentration). The solid particles in the centrifuge tube were then resuspended, 1 mL of 30% HCl was added, and the tube was left to sit overnight. The centrifuge was again run at 4000 rpm for five minutes, after which 1 mL of the clear supernatant was removed, diluted to 10 mL and analyzed as the unfiltered sample (total concentration).

The water samples were analyzed at the University of Utah ICP-MS Metals Lab using the Agilent 7500ce ICP-MS quadrupole mass-spectrometer with an octopole reaction system to preferentially remove polyatomic interferences. The samples were analyzed for 44 elements, including separate measurements for Pb-206, Pb-207 and Pb-208 (see Appendix A). For each aliquot (one for the filtered sample and one for the unfiltered sample), each element and isotope was measured 12 times and the coefficient of variance (ratio of the standard deviation to the mean as a percentage) was calculated as a measure of repeatability (see Appendix A).

Comparison of New Dataset and QMM Dataset

The QMM mine did not provide coordinates for the water monitoring stations, so that the coordinates were measured from the map (provided by the QMM mine) in Fig. 10 of Swanson (2019b) using ESRI ArcMap 10.7.1 (see Table 1a). The map shows additional water monitoring stations for which no data were reported (Swanson, 2019b). On Fig. 10 of Swanson (2019b), stations S42 and S43 had labels, but no markers. Therefore, the location on the Mandromondromotra River closest to the label was chosen for the measurement of latitude and longitude. It is clarified in Swanson (2019b) that the stations are on the Mandromondromotra River.

Extreme caution was used in the consideration of the validity of the water-quality data that were reported by the QMM mine. 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 sample sites of this study with those from the water monitoring stations of the QMM mine because there is very little spatial overlap between the two sets of sites (see Fig. 3). The closest correspondence is between sites Q3 (this study) and WS0301 (QMM mine) since the sites are only 295 meters apart on the Méandre River, which flows into Lake Besaroy (see Fig. 3). As was mentioned earlier, the site Q3 may be on the western shore of Lake Besaroy, in which case, it would correspond better with water monitoring station WS0401 (see Fig. 3). At each of sites WS0301 and WS0401, there were two measurements of iron and one measurement of lead, with all other elemental concentrations below one of the double detection limits. For example, both sites WS0301 and WS0401 had one uranium concentration reported as <0.642 mg/L and one as <0.047 mg/L, which could not usefully be compared with the uranium concentrations at Q3 of 0.00001 mg/L (dissolved) and 0.00002 mg/L (total). It was decided that the hypothesis that the QMM dataset was valid would not be rejected if either the measured iron concentrations or the measured lead concentrations were comparable (same order of magnitude) between the new sample sites and the QMM sites.

An encouraging observation both in terms of assessing the validity of the QMM dataset and comparing the upstream and downstream concentrations was that both the new sites and the QMM sites were interspersed among the same geologic units (Fig. 6). In particular, if the upstream sites had been in a different geologic unit than the downstream sites, it would have been very difficult to separate the impact of the QMM mine from the natural geological impact. Out of the nine sample sites of this study, one was located in igneous and metamorphic basement rocks, four were located in alluvial and lake deposits, and four were located in unconsolidated sands (see Fig. 6). Out of the 12 water monitoring stations of the QMM mine, four are located in igneous and metamorphic basement rocks, while eight are located in unconsolidated sands (see

Fig. 6). (It should be assumed that far more detailed geologic mapping is available to the QMM mine.)

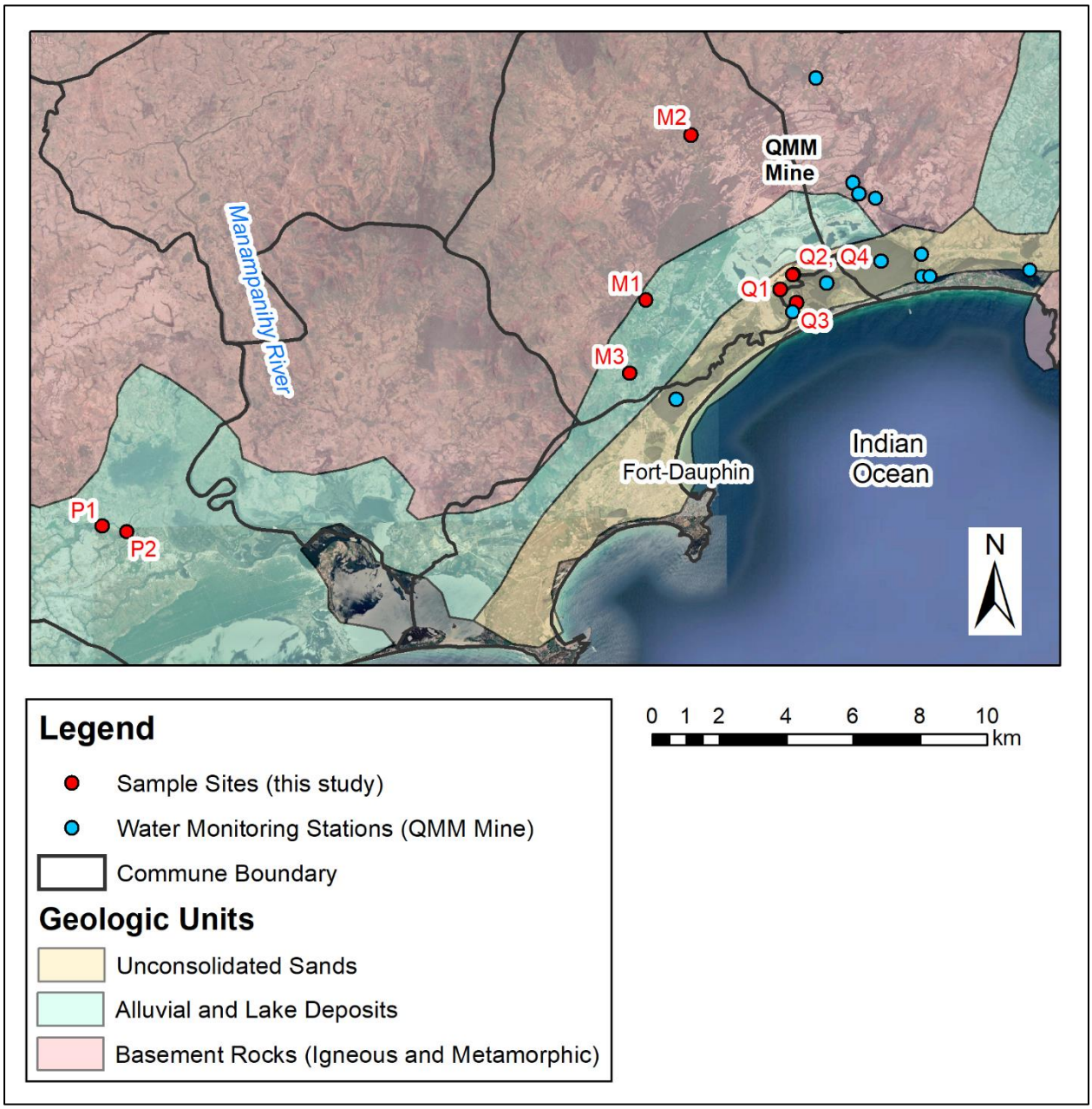

Figure 6. The direct comparison of water-quality results from the sample sites of this study with those from the water monitoring stations of the QMM mine is somewhat facilitated by the partial geologic overlap of the two sets of sites. Out of the nine sample sites of this study, one is located in igneous and metamorphic basement rocks, four are located in alluvial and lake deposits, and four are located in unconsolidated sands. Out of the 12 water monitoring stations of the QMM mine, four are located in igneous and metamorphic basement rocks, while eight are located in unconsolidated sands. Geological map from Besairie (1964).

Statistical Comparison of Upstream and Downstream Concentrations

Given that there is insufficient evidence that the QMM dataset can be discarded, the problem is how to integrate the new dataset with the QMM dataset. The issue is the very large number of measurements in the QMM dataset that were reported as below one of two detection limits, which included 34 (63%) of the uranium measurements, 27 (50%) of the lead measurements, 47 (65%) of the thorium measurements, and 38 (70%) of the titanium measurements. Meaningful statistics are challenging under any circumstances when there are a large number of samples below the detection limit, which is why, typically, analytical instruments are chosen that have detection limits lower than 10% of the standard of concern.

Two alternative statistical strategies were considered. 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, the real question is: Do the measurements below the detection limits actually constitute "data?" Given that the entire QMM dataset cannot be discarded, it is 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, the QMM dataset is valid, but the measurements under the detection limit are not valid. This second alternative was chosen, resulting in the inclusion from the QMM dataset of 20 uranium measurements, 27 lead measurements, seven thorium measurements, and 16 titanium measurements.

After combining the new dataset, there were seven sites upstream of the QMM mine and 10 sites downstream of the mine, in which the two background sites (P1 and P2) were regarded as upstream sites (see Tables 1a-b, Figs. 2-3). The above is the most probable correct separation of sites between upstream and downstream, but other separations are also possible. In particular, Swanson (2019b) questioned whether the QMM sites WS0203 (in Lake Lanirano) and WS0501 (upper Mandromondromotra River) were true upstream sites (see Fig. 3). Therefore, results were also reported for the following three alternatives:

1) P1 and P2 are not included at all, WS0203 and WS0501 are upstream sites
2) P1 and P2 are not included at all, WS0203 and WS0501 are downstream sites
3) P1 and P2 are upstream sites, WS0203 and WS0501 are downstream sites

The t-test was used to assess the statistical significance of the difference between the geometric means of the upstream and downstream concentrations with the threshold of statistical significance set at the 99% confidence level ($P = 0.01$). The t-test was carried out on the logarithms of values, which is appropriate considering the orders of magnitude over which the concentrations range. The t-test was done separately for dissolved and total concentrations. For the data from the QMM mine, the same values were used for dissolved and total concentrations, since it is not known which was measured. The elements considered for comparison between upstream and downstream concentrations were uranium, thorium, lead and iron.

Table 2. Samples exceeding drinking water or aquatic standards

Sample	Element	Total Concentration (mg/L)	Standard (mg/L)
WHO Guidelines for Drinking-Water Quality[1]			
Q4	As	0.01852	0.01
US EPA National Recommended Aquatic Life Criteria[2]			
M3	Fe	1.11853	1
P2	Fe	1.46137	1
Q1	Fe	5.60007	1
Q2	Fe	5.50997	1
Q4	Fe	87.01624	1
US EPA Secondary Drinking Water Standards[3]			
M1	Fe	0.58167	0.3
M2	Fe	0.69838	0.3
M3	Fe	1.11853	0.3
P1	Fe	0.47533	0.3
P2	Fe	1.46137	0.3
Q1	Fe	5.60007	0.3
Q2	Fe	5.50997	0.3
Q3	Fe	0.46305	0.3
Q4	Fe	87.01624	0.3
Q4	Mn	0.51821	0.05
M1	Al	0.15058	0.05
M2	Al	0.16936	0.05
M3	Al	0.07396	0.05
P1	Al	0.15922	0.05
P2	Al	0.51412	0.05
Q1	Al	0.64909	0.05
Q2	Al	0.64595	0.05
Q3	Al	0.10183	0.05
Q4	Al	4.92459	0.05

[1]WHO (2017)
[2]Freshwater Criterion Continuous Concentration (US EPA, 2019a)
[3]US EPA (2019b)

RESULTS

Comparison with Drinking-Water and Aquatic Standards

A comparison of the results from the new sample sites with drinking-water and aquatic standards showed that the most common exceedances were for iron and aluminum. In particular, all sites (both upstream and downstream) exceeded the US EPA (2017b) Secondary Drinking-Water Standards for iron (0.3 mg/L) and aluminum (0.05 mg/L) (see Table 2). In addition, five of the sites (two upstream and three downstream) exceeded US EPA (2017a) National Recommended Aquatic Life Criteria for iron (1 mg/L), based on the Freshwater Criterion Continuous Concentration (chronic exposure) (see Table 2). One of the downstream sites from the wetlands below the tailings dam (Q4; see Table 1b, Figs. 2-3) exceeded the WHO (2017) Guideline for Drinking-Water Quality for arsenic (0.01 mg/L) and the US EPA (2017b) Secondary Drinking-Water Standard for manganese (0.05 mg/L). All comparisons were based upon total concentrations, in accordance with the relevant standards (WHO, 2017; US EPA, 2019a-b).

Comparison of New Dataset and QMM Dataset

A comparison of the iron measurement at Q3 (dissolved concentration = 0.45831 mg/L, total concentration = 0.46305 mg/L) with the two iron measurements at WS0301 (0.098 mg/L and 0.433 mg/L) and the two iron measurements at WS0401 (0.059 mg/L and 0.329 mg/L) showed that the iron measurements at nearby sites from the new dataset and the QMM dataset are the same order of magnitude (see Fig. 7). On the other hand, a comparison of the lead measurement at Q3 (dissolved concentration = 0.00063 mg/L, total concentration = 0.00105 mg/L) with the single lead measurement at WS0301 (0.04 mg/L) and the single lead measurement at WS0401 (0.06 mg/L) showed that lead measurements from the QMM dataset were two orders of magnitude higher than the lead measurement from the new dataset (see Fig. 7). It should be noted that QMM water monitoring stations WS0301 and WS0401 each included a single measurement of lead that was below a detection limit (<0.005 mg/L), which could be comparable to the lead measurement at Q3. Based on the above, although the QMM dataset cannot be regarded as a high-quality dataset, the null hypothesis that the entire QMM dataset is valid cannot be rejected. Therefore, the data analysis proceeded with the integration of the new dataset and the QMM dataset as described in the Methodology section.

Comparison of Upstream and Downstream Concentrations

Based on the most likely separation of upstream and downstream sites (P1, P2, WS0203 and WS0501 are all treated as upstream sites), increases in the geometric means of uranium, thorium and lead from the upstream to the downstream side of the QMM mine were statistically significant at better than the 99% confidence level, using either the dissolved or the total concentrations (see Table 3, Figs. 8a-c). The geometric mean of uranium increased from 0.00008 mg/L to 0.042 mg/L ($P = 0.007$) based on the dissolved concentration, and from 0.00014 mg/L to 0.049 mg/L ($P = 0.008$) based on the total concentration (see Fig. 8a). The geometric mean of thorium increased from 0.00016 mg/L to 0.014 mg/L ($P = 0.0001$) based on the dissolved concentration, and from 0.00011 mg/L to 0.016 mg/L ($P = 0.003$) based on the total

concentration (see Fig. 8b). The geometric mean of lead increased from 0.0018 mg/L to 0.0224 mg/L ($P = 0.01$) based on the dissolved concentration, and from 0.0026 mg/L to 0.0256 mg/L ($P = 0.003$) based on the total concentration (see Fig. 8c). Any change in the geometric mean of the iron concentration from the upstream to the downstream side of the mine was not statistically significant, considering either the dissolved or the total concentrations (see Table 3, Fig. 8d).

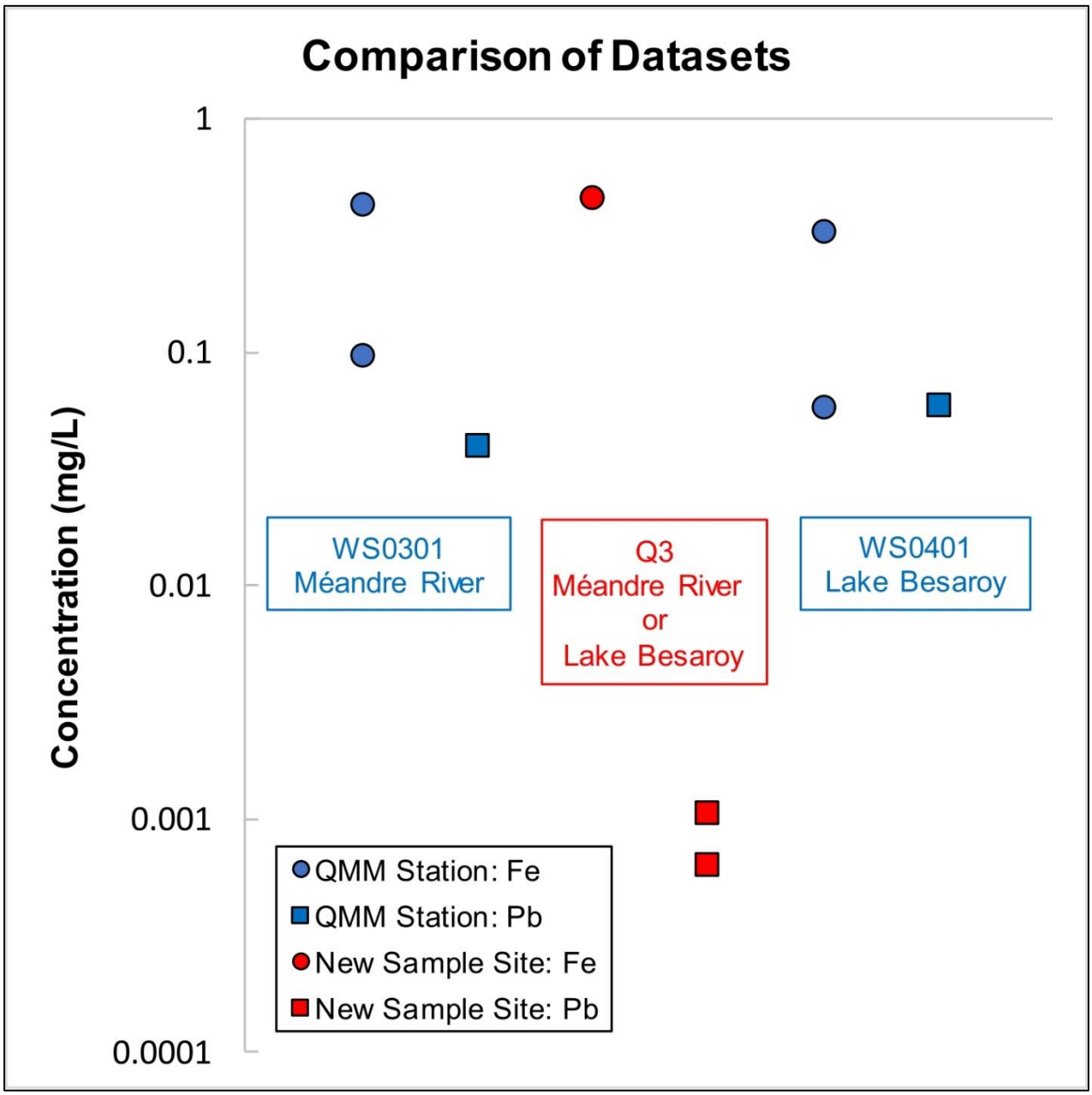

Figure 7. Concentrations of Fe and Pb were compared for new sample site Q3 and QMM water monitoring stations WS0301 (Méandre River) and WS0401 (Lake Besaroy). The most likely location for Q3 is on the Méandre River, but the western shore of Lake Besaroy is also a possibility (see Fig. 3). Concentrations of U and Th were below the detection limits at WS0301 and WS0401, so that they could not be compared with measurements at Q3. Measured concentrations of Pb are two orders of magnitude lower at Q3 than at WS0301 and WS0401. On the other hand, measured concentrations of Fe are the same order of magnitude at Q3 as at WS0301 and WS0401. Based on the above, there is insufficient evidence for rejecting the null hypothesis that the QMM water-quality dataset is a valid dataset.

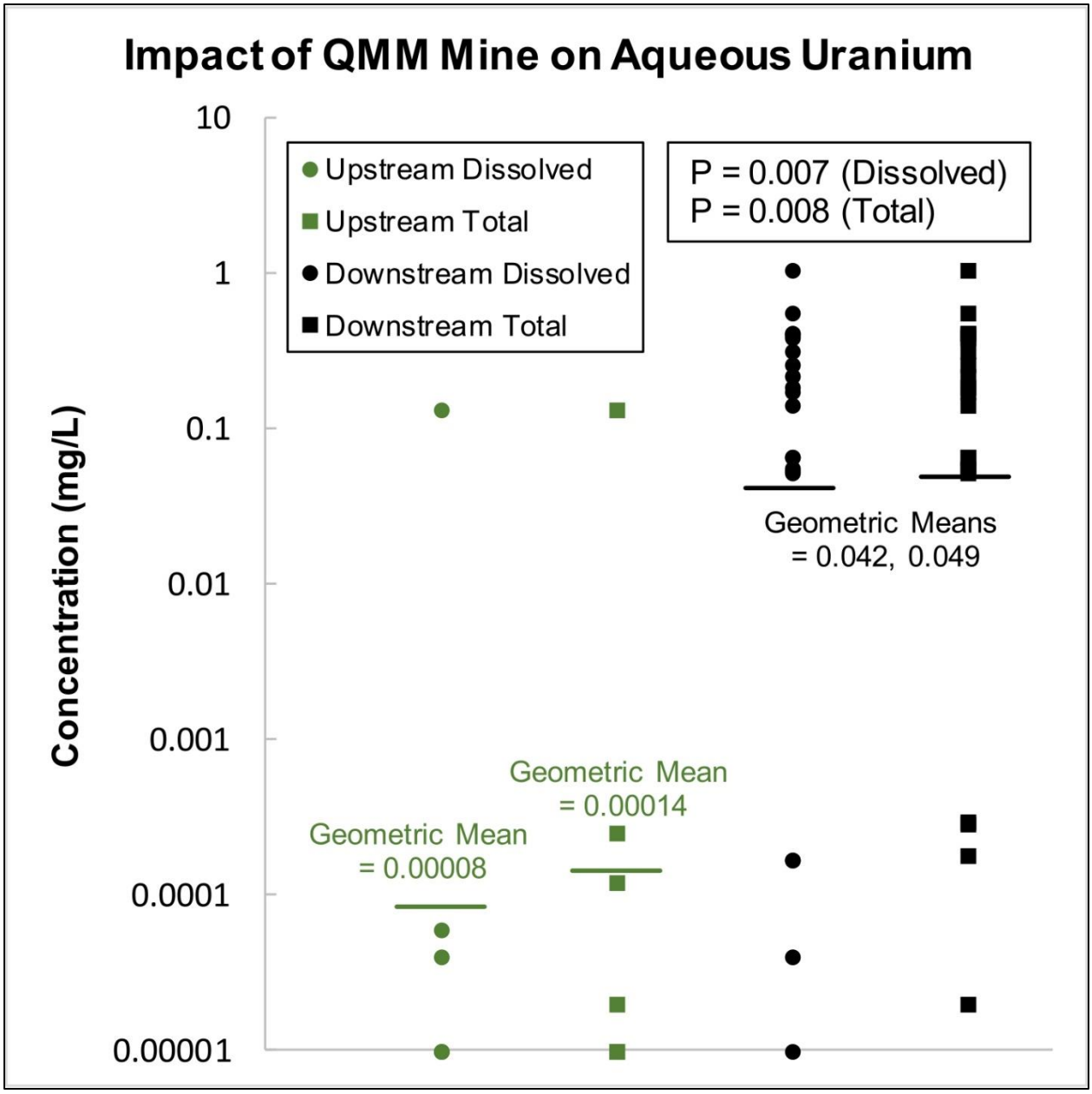

Figure 8a. The increase in the geometric mean of the aqueous uranium concentrations from the upstream to the downstream side of the QMM mine is statistically significant at better than the 99% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.007$) and the total concentrations ($P = 0.008$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM water monitoring stations, 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 upstream concentrations include sample sites P1 and P2 (see Table 1b and Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

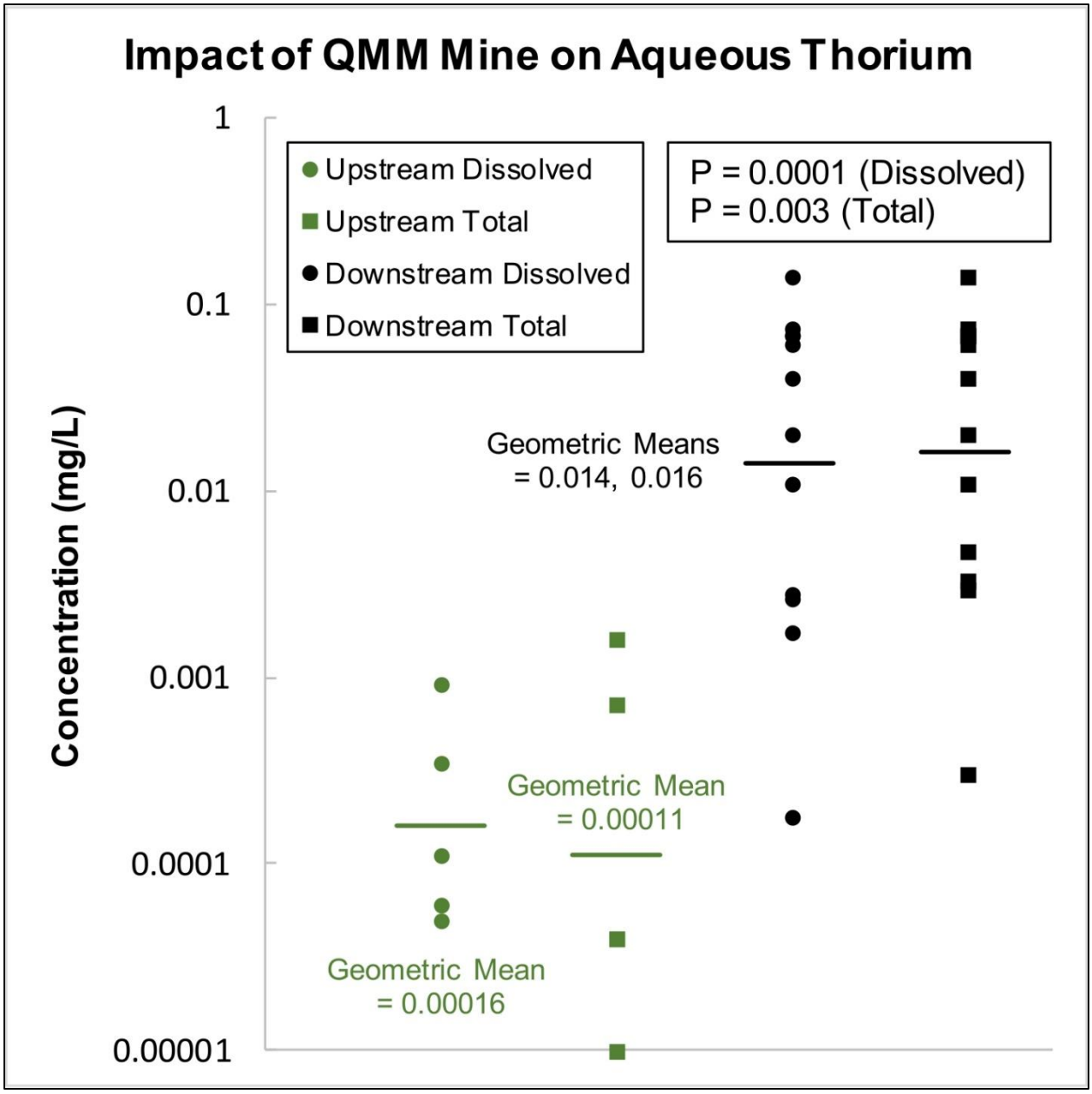

Figure 8b. The increase in the geometric mean of the aqueous thorium concentrations from the upstream to the downstream side of the QMM mine is statistically significant at better than the 99% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.0001$) and the total concentrations ($P = 0.003$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM water monitoring stations, 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 upstream concentrations include sample sites P1 and P2 (see Table 1b and Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

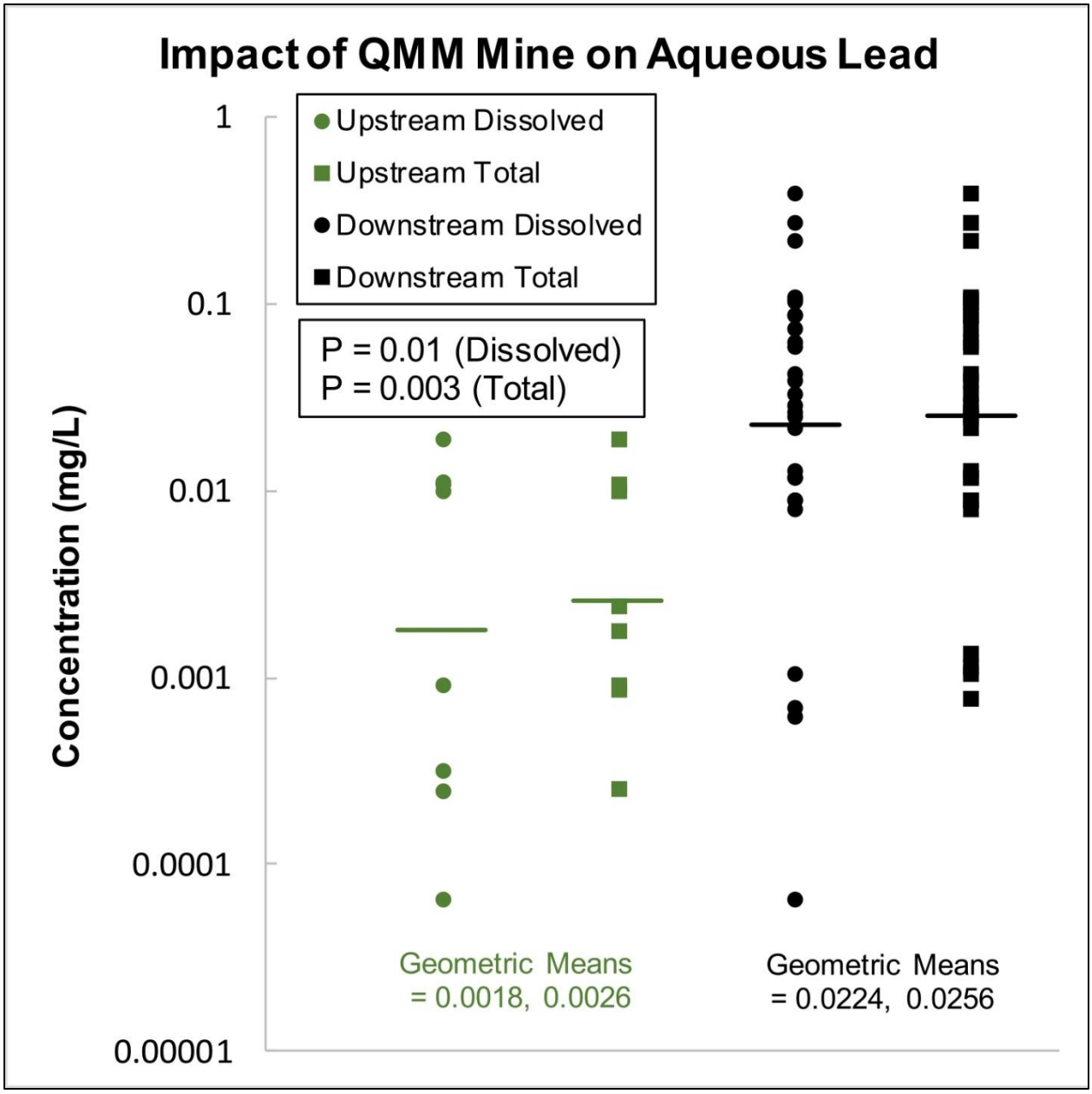

Figure 8c. The increase in the geometric mean of the aqueous lead concentrations from the upstream to the downstream side of the QMM mine is statistically significant at better than the 99% confidence level, according to the t-test carried out on the logarithms of values. The t-test was carried out separately for the dissolved ($P = 0.01$) and the total concentrations ($P = 0.003$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM water monitoring stations, 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 upstream concentrations include sample sites P1 and P2 (see Table 1b and Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

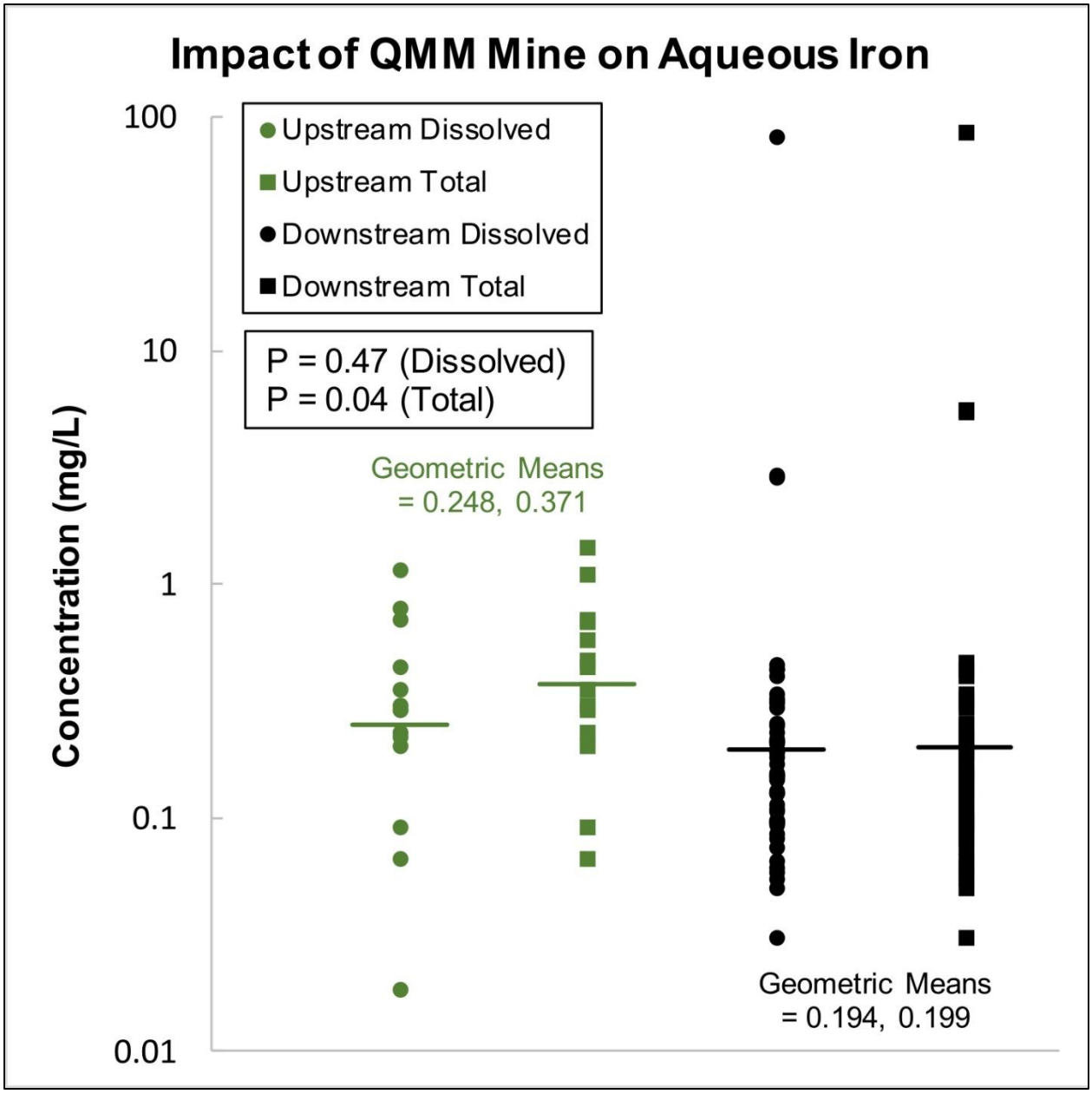

Figure 8d. According to the t-test carried out on the logarithms of values, the decrease in the geometric mean of the aqueous iron concentrations from the upstream to the downstream side of the QMM mine is not statistically significant for either dissolved ($P = 0.47$) or total concentrations ($P = 0.04$). The P-value is the probability that the geometric means are statistically indistinguishable. For the data from the QMM water monitoring stations, 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 upstream concentrations include sample sites P1 and P2 (see Table 1b and Fig. 2), which are not in the watershed of the QMM mine, but which should be representative of background concentrations.

The effect of alternative (but less likely, as argued above) separations of upstream and downstream sites can now be considered. If Alternative 1 is considered (P1 and P2 are not included at all, and WS0203 and WS0501 are upstream sites), only the increase in the geometric mean of thorium is statistically significant at the 99% confidence level (see Table 3). If Alternative 2 is considered (P1 and P2 are not included at all, and WS0203 and WS0501 are

treated as downstream sites), increases in the geometric means of uranium, thorium and lead are all statistically significant at the 99% confidence level, except for the dissolved concentration of lead (see Table 3). If Alternative 3 is considered (P1 and P2 are upstream sites, and WS0203 and WS0501 are downstream sites), increases in the geometric means of uranium, thorium and lead are all statistically significant at the 99% confidence level (see Table 3). In summary, only Alternative 1 draws into question the statistical significance of any impact of the QMM mine on uranium and lead in surface water. Alternatives 2 and 3 show a statistically significant change in the geometric mean of the total concentration of iron from the upstream to the downstream sides of the mine (see Table 3). However, both of those changes were decreases in the geometric mean (from 0.769 mg/L to 0.206 mg/L for Alternative 2, and from 0.794 mg/L to 0.206 mg/L for Alternative 3), so that they did not indicate any detrimental impact of the mine.

Table 3. Statistical significance (*P*-value) of difference between geometric means of elemental concentrations upstream and downstream of the QMM mine[1]

Upstream/Downstream Separation	Concentration Type	Uranium	Thorium	Lead	Iron
Most Likely[2]	Dissolved	0.007	0.0001	0.01	0.47
	Total	0.008	0.003	0.003	0.04
Alternative 1[3]	Dissolved	0.08	0.000001	0.07	0.2
	Total	0.08	0.000001	0.03	0.1
Alternative 2[4]	Dissolved	1×10^{-10}	0.000001	0.1	0.3
	Total	1×10^{-10}	0.000001	0.01	0.002
Alternative 3[5]	Dissolved	1×10^{-9}	0.0001	0.01	0.7
	Total	0.000003	0.003	0.00007	0.0004

[1]The *P*-value is the probability that the geometric means of the upstream and downstream concentrations are statistically indistinguishable. $P \leq 0.01$ indicates that the difference between the geometric means is statistically significant.
[2]The most likely separation of upstream and downstream sites involves regarding P1, P2, WS0203 and WS0501 as upstream sites.
[3]In Alternative 1, P1 and P2 are not included at all, and WS0203 and WS0501 are upstream sites.
[4]In Alternative 2, P1 and P2 are not included at all, and WS0203 and WS0501 are downstream sites.
[5]In Alternative 3, P1 and P2 are upstream sites, and WS0203 and WS0501 are downstream sites.

DISCUSSION

Impact of the QMM Mine on Regional Water Quality

The present study has demonstrated the detrimental impact of the QMM mine on regional water quality in terms of uranium, thorium and lead. This impact is both statistically significant and significant in a public-health sense, since the geometric mean of the total uranium concentration downstream of the mine (0.049 mg/L) is 1.6 times greater than the WHO drinking-water guideline (0.03 mg/L). This measurable detrimental impact should have been expected considering the many sources of intentional and accidental releases of radionuclides and their decay products that were discussed earlier. On the other hand, it is difficult to see how elevated levels of iron, aluminum, manganese and arsenic (see Table 2) could be related to any aspect of mineral sands mining. This is especially true in the case of iron, which decreases from the upstream to the downstream side of the mine, according to some alternatives for separating

upstream and downstream sites (see Table 3 and Fig. 8d). Without further information, it should be assumed that elevated levels of iron, aluminum, manganese and arsenic are all naturally occurring and are related to the reducing (low-oxygen) and acidic conditions that tend to occur in wetlands and estuaries. Along these lines, out of 48 measurements of pH at the QMM water monitoring stations (Swanson, 2019b), the mean pH was 5.44 (standard deviation = 1.05) with minimum pH of 3.96.

Response of Rio Tinto

As mentioned earlier, Swanson (2019b) included an addendum with a response by Rio Tinto, which included the claim that "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…" This claim is no longer tenable since samples from "true upstream reference sites" (Swanson, 2019b) have now been collected and analyzed. The last response from Rio Tinto (at the end of the addendum) was "Due to the vital need for access to water for local communities, care must be taken when comparing to conservative guidelines such as the WHO Drinking Water Guidelines." The following points should be emphasized:

1) Drinking-water guidelines are supposed to be conservative, since the purpose of the guidelines is the preservation of human lives, especially the most vulnerable, who are children and the elderly.
2) Swanson (2019b) did not report uranium concentrations that were barely above the WHO guideline, but uranium concentrations in surface water that exceeded the WHO guideline by over a factor of 52 (maximum measured uranium concentration = 1.574 mg/L).
3) Rio Tinto are not the experts in public health and water quality.

Requirements for Drinking-Water Treatment

This study and Swanson (2019b) identified uranium, lead and arsenic as the chief sources of chemical toxicity. Lead impedes physical and mental development in children and causes kidney problems and high blood pressure in adults. Uranium causes an increase in the risk of cancer, as well as kidney toxicity. Arsenic causes skin damage and problems with circulatory systems, in addition to increased risk of cancer (EPA, 2019c). Thorium by itself has no chemical toxicity, but is an element of concern due to its production of alpha and beta particles and photon emitters, which do lead to increased risk of cancer (EPA, 2019c).

Iron, aluminum and manganese do not have chemical toxicity, but can affect the taste and color of water. These aesthetic effects can impact the willingness of people to drink sufficient water, especially children (who will not drink anything that tastes or looks bad) and the elderly (who lose a sense of thirst). Water with elevated levels of iron can have a rusty color and metallic taste. Water with elevated manganese can have a black to brown color and a bitter metallic taste. Water with elevated aluminum can show a variety of colors (EPA, 2019b). In principle, there should be threshold values for all elements, above which detrimental health effects will occur. However, one of the reasons that there are no health-related standards for iron, aluminum and manganese is that no one would drink the water at the concentrations that would be high enough to cause toxicity.

In response to the report of elevated levels of uranium (Swanson 2019b), the Centre for Affordable Water and Sanitation Technologies and the Andrew Lees Trust 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 lead, thorium, arsenic, iron, aluminum and manganese. 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, iron, lead, manganese, thorium, uranium.

CONCLUSIONS

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

1) Although there are many questionable aspects of the QMM water-quality dataset, there is insufficient evidence for rejecting the validity of the entire dataset.
2) The measurements in the QMM dataset that are below the detection limits should be rejected and should not be included in any statistical analysis.
3) The detrimental impact of the mine on regional water quality is indicated by the increases in uranium, thorium and lead in surface water from the upstream to the downstream side of the mine, which were statistically significant at better than the 99% confidence level, based on either the dissolved or the total concentrations.
4) Elevated levels of aluminum, arsenic, iron and manganese in surface water are probably naturally occurring and unrelated to mining operations

RECOMMENDATIONS

It is recommended that Rio Tinto undertake immediate action to provide safe drinking water to the 15,000 people who live within a few kilometers of the QMM mine. This action should focus on the effective elimination of harmful levels of the following elements: aluminum, arsenic, iron, lead, manganese, thorium, uranium.

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APPENDIX A: WATER-QUALITY DATA FOR NEW SAMPLE SITES

Table A1. Dissolved concentrations: Upstream and background samples[1]

Element or Isotope	M1	M2	M3	P1	P2
Ag	<0.00002	<0.00002	<0.00002	<0.00002	<0.00002
	(721.2)	(918.2)	(N/A)	(1846.2)	(281.8)
Al	0.06625	0.08166	0.09065	0.0151	0.33909
	(11.4)	(13)	(6.9)	(15.3)	(4)
As	<0.00023	<0.00023	<0.00023	0.00053	0.00039
	(N/A)	(N/A)	(N/A)	(14.4)	(16.2)
B	<0.00890	<0.00890	<0.00890	0.21371	0.01765
	(16.8)	(N/A)	(56.3)	(2.9)	(6.1)
Ba	0.00748	0.00956	0.00663	0.02263	0.005
	(1.7)	(2)	(1.9)	(1.3)	(30.5)
Be	0.00001	<0.00001	0.00001	<0.00001	0.00001
	(123.2)	(161.7)	(122.9)	(141.1)	(124.7)
Ca	0.7589	0.65654	1.16187	20.79238	0.97163
	(3.4)	(4.3)	(3.5)	(1.7)	(3)
Cd	<0.00004	<0.00004	<0.00004	<0.00004	<0.00004
	(547.7)	(191.5)	(227.4)	(277)	(N/A)
Ce	0.00008	0.00011	0.00011	0.00067	0.00151
	(45.8)	(53.4)	(48.2)	(4.5)	(11.9)
Co	0.00013	0.00011	0.00018	0.00013	0.00012
	(25.3)	(26)	(17.2)	(19.7)	(20.5)
Cr	<0.00567	<0.00567	<0.00567	<0.00567	<0.00567
	(36.6)	(45.5)	(45)	(14.8)	(25.7)
Cs	0.00002	0.00003	0.00002	0.00004	0.00099
	(34.3)	(31.9)	(34.1)	(29.2)	(5.1)
Cu	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020
	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)
Dy	<0.00001	0.00001	0.00001	0.00001	0.00002
	(88.4)	(73.3)	(71.4)	(53.7)	(31.3)
Er	<0.00001	<0.00001	<0.00001	<0.00001	0.00001
	(101.2)	(67.6)	(69)	(68.6)	(44)
Eu	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
	(161.2)	(118.7)	(186.6)	(100.6)	(55.7)
Fe	0.22398	0.2896	1.15163	0.01843	0.80334
	(1.8)	(1.8)	(2.2)	(11.5)	(2.9)
Gd	<0.00001	<0.00001	<0.00001	0.00002	0.00005
	(96.2)	(76.1)	(79.7)	(31.8)	(26)
Ho	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
	(89.1)	(64.7)	(85.3)	(58.2)	(50)
K	0.80577	0.75394	0.62036	21.8436	0.94192
	(2.2)	(1.9)	(2.2)	(2.8)	(2.4)
La	0.00003	0.00003	0.00004	0.00012	0.00061

	(97.7)	(52.6)	(24.6)	(11.6)	(15.3)
Li	0.00059	<0.00052	<0.00052	0.01183	0.00057
	(8.8)	(14.2)	(12.3)	(3.8)	(9.6)
Lu	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
	(161.5)	(107.7)	(186.1)	(124)	(126.8)
Mg	1.03873	0.85126	1.33033	65.99261	1.8611
	(1.9)	(1.7)	(1.5)	(2.2)	(1.4)
Mn	0.00143	0.00224	0.01327	0.00396	0.00092
	(8.4)	(6.5)	(2.6)	(5.5)	(9.8)
Mo	<0.00012	<0.00012	<0.00012	0.00054	<0.00012
	(1591.1)	(N/A)	(N/A)	(13.7)	(77.7)
Na	8.98388	6.42836	15.79198	588.28104	15.0703
	(2.2)	(3.6)	(1.9)	(2.2)	(1.7)
Nd	0.00003	0.00003	0.00003	0.00022	0.00055
	(65.6)	(81.4)	(44)	(12.6)	(14.9)
Ni	<0.00064	<0.00064	<0.00064	<0.00064	<0.00064
	(31.8)	(25)	(37.2)	(27)	(33.8)
Pb-206	0.0001	0.00012	0.00395	<0.00006	0.00033
	(114.2)	(24.7)	(2.1)	(41.5)	(38)
Pb-207	0.00007	0.0001	0.00361	<0.00005	0.00028
	(61.6)	(37.1)	(3.2)	(66.7)	(17.3)
Pb-208	0.00008	0.00010	0.00375	<0.00002	0.00032
	(60.4)	(10.8)	(1.5)	(21.2)	(15.8)
Pr	0.00001	0.00001	0.00001	0.00005	0.00015
	(72.4)	(50.1)	(38.1)	(15.9)	(17.1)
Rb	0.00329	0.00311	0.00243	0.01098	0.00272
	(4.5)	(4.7)	(4.6)	(3.6)	(5.3)
Sb	<0.00016	<0.00016	<0.00016	<0.00016	<0.00016
	(29.6)	(22.4)	(27.3)	(30.4)	(29)
Se	0.00624	<0.00532	<0.00532	0.0073	<0.00532
	(13.4)	(40.4)	(642.2)	(9.5)	(31)
Sm	<0.00001	<0.00001	<0.00001	0.00003	0.00008
	(101.1)	(96.6)	(117.9)	(43.3)	(28)
Sr	0.00958	0.00787	0.00935	0.39752	0.01462
	(2.7)	(3.3)	(2.8)	(1.1)	(2.7)
Tb	<0.00002	<0.00002	<0.00002	<0.00002	<0.00002
	(129.6)	(81.6)	(93.2)	(58.4)	(30.7)
Th	0.00011	0.00005	0.00006	0.00035	0.00093
	(23.2)	(26.6)	(19)	(8)	(7.7)
Tl	0.00001	0.00001	0.00001	0.00002	0.00001
	(22.5)	(27)	(44.1)	(19.4)	(34)
U	0.00001	0.00001	0.00001	0.00006	0.00004
	(31.5)	(33.9)	(28.7)	(8.5)	(11.7)
V	0.00007	0.00013	0.00011	0.00013	0.00064
	(27)	(21.8)	(22.2)	(23.4)	(12)
Y	0.00002	0.00002	0.00003	0.00004	0.00006

	(41.4)	(30.6)	(33.5)	(28.3)	(22.5)
Yb	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
	(145)	(95.5)	(81.1)	(62.9)	(71.7)
Zn	0.00357	0.00255	<0.00239	<0.00239	<0.00239
	(7.6)	(9)	(12.6)	(11.6)	(10.6)

[1]Dissolved concentrations in mg/L (coefficient of variance as a percentage in parentheses).

Table A2. Total concentrations: Upstream and background samples[1]

Element or Isotope	M1	M2	M3	P1	P2
Ag	<0.00003	<0.00003	<0.00003	<0.00003	<0.00003
	(48.2)	(36.5)	(2255.4)	(28.8)	(47.8)
Al	0.15058	0.16936	0.07396	0.15922	0.51412
	(4.7)	(4.4)	(6.5)	(4.4)	(2.9)
As	<0.00029	<0.00029	<0.00029	0.00076	0.00063
	(30.9)	(61.3)	(331.7)	(11.5)	(10.8)
B	<0.01112	<0.01112	<0.01112	0.20372	0.01636
	(16.5)	(N/A)	(31.4)	(2.4)	(6.4)
Ba	0.02263	0.01657	0.00818	0.02377	0.00759
	(1.6)	(1.5)	(2.2)	(1.7)	(2.6)
Be	0.00002	0.00001	0.00001	0.00001	0.00001
	(77)	(84.6)	(102)	(102.5)	(99.3)
Ca	0.72629	0.5804	1.04635	19.24687	1.05499
	(5.1)	(3.9)	(3.2)	(1.6)	(4.1)
Cd	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
	(345.2)	(283.9)	(243.3)	(180.5)	(157.9)
Ce	0.00019	0.00039	0.00012	0.00519	0.00375
	(28.1)	(10.8)	(13.8)	(2.5)	(6.9)
Co	0.00196	0.00201	0.00198	0.00203	0.00196
	(2.8)	(3.7)	(3.5)	(3.3)	(4.4)
Cr	<0.00708	<0.00708	<0.00708	<0.00708	<0.00708
	(8.1)	(7.9)	(7.1)	(7.5)	(7.7)
Cs	0.00006	0.00015	0.0001	0.00026	0.00008
	(26.2)	(18.5)	(20.4)	(13.5)	(22)
Cu	0.00087	0.00054	0.00037	0.0006	0.00081
	(20.3)	(10.3)	(14.6)	(15.8)	(7.5)
Dy	0.00001	0.00002	0.00001	0.00006	0.00005
	(55.5)	(30.6)	(78.9)	(25.6)	(30.6)
Er	<0.00001	0.00001	<0.00001	0.00002	0.00002
	(72.3)	(40)	(70.9)	(28.7)	(40.4)
Eu	<0.00001	<0.00001	<0.00001	0.00001	0.00001
	(64.8)	(46.8)	(105.9)	(33.6)	(36.7)
Fe	0.58167	0.69838	1.11853	0.47533	1.46137
	(1.3)	(3.2)	(2.3)	(1.1)	(2.4)
Gd	0.00001	0.00002	<0.00001	0.00013	0.00011
	(61.4)	(45.2)	(87.7)	(20.3)	(18.8)
Ho	<0.00001	<0.00001	<0.00001	0.00001	0.00001
	(73.5)	(49.7)	(63.8)	(34.6)	(40.2)
K	0.70756	0.66321	0.54417	19.77906	0.88185
	(2.7)	(2.7)	(2.9)	(3)	(2.4)
La	0.00005	0.00009	0.00005	0.00085	0.00143
	(31.1)	(12.6)	(27)	(4.1)	(10.6)

Li	0.02436	0.012	0.00767	0.01402	0.00462
	(3.2)	(3.3)	(4.1)	(3.2)	(4.7)
Lu	<0.00001	<0.00001	<0.00001	0.00003	<0.00001
	(89.3)	(55.6)	(74.6)	(17.9)	(54.6)
Mg	0.92142	0.77227	1.18822	59.93051	1.80338
	(2.2)	(2.5)	(1.9)	(2.5)	(1.5)
Mn	0.00992	0.01329	0.01223	0.00768	0.00533
	(4)	(2.4)	(2.8)	(3.7)	(4.7)
Mo	<0.00016	<0.00016	<0.00016	0.0007	0.00018
	(88.7)	(761)	(N/A)	(12.9)	(32.2)
Na	8.09725	5.95805	14.03533	525.15352	14.27504
	(3.1)	(3)	(2)	(1.8)	(2.5)
Nd	0.00005	0.00009	0.00005	0.0014	0.00133
	(54)	(35.4)	(82.4)	(5.8)	(6.5)
Ni	0.0022	0.00217	0.00206	0.00257	0.00309
	(7.1)	(7.6)	(7.6)	(6)	(5.7)
Pb-206	0.0003	0.00061	0.00009	0.00032	0.00083
	(23.9)	(6.1)	(22.7)	(10)	(8.3)
Pb-207	0.00027	0.00058	0.00008	0.00028	0.00075
	(13.3)	(8.2)	(18.6)	(12)	(9.7)
Pb-208	0.0003	0.00059	0.00009	0.00031	0.00083
	(18.6)	(3.3)	(24.1)	(6.1)	(6)
Pr	0.00001	0.00002	0.00001	0.00033	0.00038
	(34)	(25.5)	(30.9)	(6.2)	(8.8)
Rb	0.00299	0.00291	0.00221	0.01013	0.00265
	(4.9)	(4.3)	(7)	(2.4)	(5.6)
Sb	0.00063	0.00035	0.00032	0.00028	0.00024
	(17.9)	(15.3)	(18.4)	(20.1)	(25.4)
Se	0.01378	0.01045	0.00934	0.01343	0.00829
	(8.8)	(9.4)	(8.7)	(6.7)	(7.9)
Sm	<0.00001	0.00002	<0.00001	0.00024	0.0002
	(78.2)	(67.6)	(103.6)	(15.3)	(20.5)
Sr	0.00974	0.00921	0.00898	0.36463	0.01519
	(3)	(3.4)	(3)	(1.1)	(2)
Tb	<0.00001	<0.00001	<0.00001	0.00001	0.00001
	(79.7)	(48.4)	(79.2)	(22.7)	(28.3)
Th	<0.00002	0.00004	0.00004	0.00071	0.0016
	(46.2)	(21.5)	(30.8)	(8.5)	(7.3)
Tl	0.00002	0.00001	<0.00001	0.00002	0.00001
	(23)	(32.9)	(38.2)	(20.5)	(36)
U	0.00001	0.00002	0.00001	0.00025	0.00012
	(19.1)	(17)	(30.9)	(4.6)	(10.3)
V	0.00191	0.00235	0.00226	0.00234	0.00311
	(11.1)	(8.6)	(7.6)	(13.9)	(6.6)
Y	0.00004	0.00009	0.00003	0.0002	0.00016
	(33)	(19.3)	(29.2)	(11.2)	(17.5)

Yb	<0.00001	0.00001	<0.00001	0.00002	0.00001
	(91.3)	(44.4)	(114.1)	(38.2)	(50.4)
Zn	0.00704	0.0068	0.00651	0.04136	0.03021
	(6.9)	(6.7)	(4.5)	(2.9)	(3.1)

[1]Total concentrations in mg/L (coefficient of variance as a percentage in parentheses).

Table A3. Dissolved concentrations: Downstream samples[1]

Element or Isotope	Q1	Q2	Q3	Q4
Ag	<0.00002 (621.4)	<0.00002 (121.5)	<0.00002 (129.4)	<0.00002 (149.3)
Al	0.65389 (2.9)	0.63539 (2.1)	0.07545 (5.4)	0.86535 (3)
As	0.00031 (24.2)	0.00037 (13.8)	<0.00023 (45.1)	0.01671 (2.6)
B	0.01 (7.6)	<0.00890 (7)	<0.00890 (11.9)	0.01977 (3.8)
Ba	0.01113 (1.8)	0.01367 (1.7)	0.00678 (2.1)	0.05447 (1)
Be	0.00003 (44.4)	0.00004 (46.8)	<0.00001 (139.6)	0.00002 (76.2)
Ca	2.90462 (2.5)	3.00386 (2.2)	1.4288 (3.2)	55.74248 (1.9)
Cd	<0.00004 (305.1)	<0.00004 (227.5)	<0.00004 (259.3)	<0.00004 (N/A)
Ce	0.01009 (1.4)	0.00988 (1.7)	0.00034 (10.3)	0.02738 (1.3)
Co	0.00026 (13.1)	0.00025 (11.5)	0.00011 (20.4)	0.00464 (2.7)
Cr	<0.00567 (10.9)	<0.00567 (9.1)	<0.00567 (43.7)	<0.00567 (12.8)
Cs	0.00004 (24.8)	0.00004 (17.5)	0.00005 (25.9)	0.00001 (55.9)
Cu	<0.00020 (N/A)	<0.00020 (N/A)	<0.00020 (N/A)	<0.00020 (N/A)
Dy	0.00007 (22.5)	0.00006 (15)	0.00001 (57.5)	0.00009 (15.8)
Er	0.00002 (23.5)	0.00003 (20.1)	<0.00001 (62.3)	0.00003 (24.4)
Eu	0.00001 (36.2)	0.00001 (30.7)	<0.00001 (83.2)	0.00001 (36.3)
Fe	2.96173 (2)	2.87554 (2)	0.45831 (1.3)	84.30342 (2)
Gd	0.00027 (11)	0.00026 (11.4)	0.00001 (44)	0.00052 (6.9)
Ho	0.00001 (28.2)	0.00001 (23.5)	<0.00001 (49.5)	0.00001 (21.5)
K	1.69915 (1.8)	1.67429 (1.6)	0.97378 (1.7)	10.50778 (2.5)
La	0.00381 (1.9)	0.00372 (2.2)	0.00011 (21.2)	0.0162 (1.7)

Li	0.00953	0.00906	<0.00052	0.01316
	(2.9)	(2.7)	(13)	(2.5)
Lu	<0.00001	<0.00001	<0.00001	<0.00001
	(60.1)	(61.4)	(101.1)	(77.4)
Mg	3.62994	3.5693	1.16496	37.77115
	(1.5)	(1.2)	(1.3)	(2.9)
Mn	0.01809	0.01817	0.00573	0.54364
	(2.2)	(1.9)	(3.6)	(1.7)
Mo	<0.00012	<0.00012	<0.00012	<0.00012
	(37.2)	(35.5)	(60.2)	(61.3)
Na	10.77309	10.5229	8.63211	17.34194
	(2.4)	(2.4)	(2.6)	(2.6)
Nd	0.00331	0.00321	0.00012	0.00612
	(4.2)	(2.5)	(26.3)	(2.7)
Ni	<0.00064	<0.00064	<0.00064	0.00245
	(12.8)	(15.7)	(42.7)	(7)
Pb-206	0.00024	0.00037	0.00023	<0.00006
	(10)	(8.1)	(31.4)	(39.5)
Pb-207	0.00022	0.00033	0.00019	<0.00005
	(10.4)	(8.8)	(18.7)	(55.5)
Pb-208	0.00024	0.00037	0.00021	<0.00002
	(6)	(3.7)	(10.8)	(19)
Pr	0.00089	0.00087	0.00003	0.00189
	(3.9)	(3.2)	(26.9)	(2)
Rb	0.00456	0.00461	0.00326	0.02466
	(4.1)	(4)	(5.9)	(2.2)
Sb	<0.00016	<0.00016	<0.00016	<0.00016
	(33.2)	(23.3)	(30.7)	(28.5)
Se	<0.00532	<0.00532	<0.00532	<0.00532
	(35.6)	(20.4)	(69.3)	(20.8)
Sm	0.00049	0.00048	0.00002	0.00064
	(12)	(7.9)	(55.3)	(9.4)
Sr	0.04963	0.04908	0.01583	0.85948
	(1.2)	(1.4)	(2.4)	(2.2)
Tb	0.00002	0.00002	<0.00001	0.00003
	(15.8)	(15.4)	(102.4)	(12.1)
Th	0.00281	0.00263	0.00018	0.00173
	(3.5)	(3.5)	(10.9)	(2.9)
Tl	0.00001	0.00001	0.00001	<0.00001
	(35.2)	(27.1)	(36.4)	(150.8)
U	0.00017	0.00017	0.00001	0.00004
	(6.7)	(6.7)	(23.6)	(13.9)
V	0.00035	0.00036	0.00017	0.00029
	(12)	(13.9)	(20.7)	(15.2)
Y	0.00027	0.00027	0.00004	0.00058
	(9.4)	(12.6)	(25.8)	(7.7)

Yb	0.00002	0.00001	<0.00001	0.00001
	(39.2)	(34.7)	(82.4)	(58.8)
Zn	0.00365	0.0058	0.00302	<0.00239
	(7.1)	(6.6)	(6.8)	(14.3)

[1]Dissolved concentrations in mg/L (coefficient of variance as a percentage in parentheses).

Table A4. Total concentrations: Downstream samples[1]

Element or Isotope	Q1	Q2	Q3	Q4
Ag	<0.00003 (42.4)	<0.00003 (36.1)	<0.00003 (57.4)	<0.00003 (35.8)
Al	0.64909 (2.8)	0.64595 (3.1)	0.10183 (8.4)	4.92459 (2.7)
As	0.00069 (11.1)	0.00071 (11.9)	<0.00029 (26.4)	0.01852 (2.2)
B	<0.01112 (8.7)	<0.01112 (7.9)	<0.01112 (13.9)	0.01862 (5)
Ba	0.01683 (1.6)	0.0146 (1.3)	0.00807 (2.2)	0.0575 (1.1)
Be	0.00004 (45)	0.00005 (39.2)	0.00001 (106.5)	0.00007 (37.2)
Ca	2.76169 (2.6)	2.82347 (2.8)	1.36275 (2.7)	52.55536 (1.6)
Cd	<0.00005 (259.4)	<0.00005 (203.4)	<0.00005 (164.4)	<0.00005 (163.6)
Ce	0.0142 (1.8)	0.01431 (1.9)	0.00052 (9)	0.0992 (1.4)
Co	0.00207 (3.8)	0.00208 (4.1)	0.00192 (3.8)	0.00812 (2.6)
Cr	<0.00708 (4.2)	<0.00708 (5.1)	<0.00708 (9.4)	<0.00708 (5)
Cs	0.0001 (14.9)	0.00011 (21.7)	0.00011 (20.1)	0.00007 (18.9)
Cu	0.0004 (13.2)	0.00044 (14.1)	0.00054 (9.6)	0.00032 (13.8)
Dy	0.00009 (18.8)	0.00009 (18.2)	0.00001 (51)	0.00037 (9.3)
Er	0.00003 (29.2)	0.00003 (19.9)	0.00001 (78.3)	0.00009 (9.1)
Eu	0.00001 (34.8)	0.00001 (34.6)	<0.00001 (88.5)	0.00003 (24.8)
Fe	5.60007 (2.1)	5.50997 (1.7)	0.46305 (0.9)	87.01624 (1.6)
Gd	0.00035 (9.7)	0.00034 (10.4)	0.00002 (41.3)	0.00183 (5.8)
Ho	0.00001 (19.8)	0.00001 (24.2)	<0.00001 (56.3)	0.00004 (16.1)
K	1.54807 (2.1)	1.54922 (2.1)	0.88767 (2.5)	9.60486 (3.2)
La	0.00534 (2.4)	0.00536 (2.1)	0.00017 (21.6)	0.05393 (1.4)

Li	0.01195	0.01223	0.00396	0.01377
	(2.1)	(2.7)	(3.2)	(2.5)
Lu	<0.00001	<0.00001	<0.00001	<0.00001
	(50.2)	(62.9)	(64.1)	(61)
Mg	3.35078	3.36177	1.08314	34.73381
	(1.9)	(1.8)	(1.8)	(2.6)
Mn	0.01701	0.0175	0.00547	0.51821
	(3)	(2.3)	(4.8)	(1.4)
Mo	0.00032	0.00018	<0.00016	0.00026
	(17.2)	(32.9)	(33.5)	(22.6)
Na	9.92613	10.02365	8.1507	15.88555
	(3.3)	(2.4)	(2.6)	(2.4)
Nd	0.00437	0.0044	0.00018	0.02161
	(3.6)	(4.8)	(18.4)	(2.1)
Ni	0.00329	0.00263	0.00232	0.00886
	(6)	(4.1)	(6.9)	(3.6)
Pb-206	0.00039	0.00045	0.00036	0.00026
	(8.7)	(9.5)	(12.4)	(14.7)
Pb-207	0.00036	0.00043	0.00034	0.00022
	(9.7)	(10.4)	(19.9)	(12.6)
Pb-208	0.00041	0.00047	0.00035	0.00029
	(4.5)	(4.3)	(6.7)	(7.4)
Pr	0.0012	0.00121	0.00004	0.00673
	(3.6)	(2.7)	(19.9)	(1.7)
Rb	0.00425	0.00435	0.00315	0.02316
	(3.6)	(3.8)	(5.3)	(1.8)
Sb	0.0002	0.0002	<0.00020	<0.00020
	(21.7)	(18.5)	(26.9)	(21.6)
Se	0.00777	0.00871	<0.00665	0.00815
	(11.2)	(11.6)	(13.2)	(12.1)
Sm	0.00064	0.00061	0.00003	0.00242
	(12)	(10)	(45.1)	(6.8)
Sr	0.04734	0.04722	0.01497	0.79121
	(2)	(1.8)	(1.9)	(1.1)
Tb	0.00002	0.00002	<0.00001	0.00012
	(21)	(15.3)	(67)	(6.3)
Th	0.00333	0.00295	0.0003	0.00475
	(4.4)	(4)	(15.2)	(3.9)
Tl	0.00001	0.00001	0.00001	<0.00001
	(33.6)	(31.4)	(34.2)	(137.1)
U	0.0003	0.00029	0.00002	0.00018
	(3.6)	(5.9)	(18.3)	(6.1)
V	0.00273	0.00249	0.00234	0.00281
	(9.3)	(11.5)	(8.6)	(7.1)
Y	0.00031	0.00032	0.00006	0.00171
	(11.2)	(12.2)	(26.2)	(5.2)

Yb	0.00002	0.00002	0.00001	0.00003
	(37.9)	(40.4)	(71.7)	(45.5)
Zn	0.01053	0.0093	0.01292	0.04059
	(3.9)	(5.5)	(4.3)	(2.1)

[1]Total concentrations in mg/L (coefficient of variance as a percentage in parentheses).

APPENDIX B: INSTRUCTIONS FOR WATER SAMPLING

FRENCH VERSION

Instructions pour la collecte des eaux d'infiltration à partir de la berme à la mine QMM

Vous aurez besoin du matériel suivant: bouteilles en plastique très solides, ruban adhésif, marqueur, carnet, récepteur GPS.

1) Donnez un nom au site. Je suggère de nommer les sites Q1, Q2, Q3, etc. Écrivez la latitude et la longitude du site dans le carnet. Écrivez la date dans le carnet.
2) Prenez des photos du site sous différents angles et grossissements. Écrivez les numéros des photos dans le carnet.
3) Lavez la bouteille (remplissez-la d'eau et versez-la) avec l'eau d'infiltration trois fois.
4) Remplissez la bouteille avec de l'eau.
5) Visser le capuchon fermement.
6) Enroulez le ruban complètement autour de la bouteille.
7) Écrivez le nom du site sur le ruban et la bouteille.
8) Conservez les bouteilles au réfrigérateur autant que possible.

ENGLISH VERSION

Instructions for collecting seepage water from the berm at the QMM mine

You will need the following materials: very strong plastic bottles, tape, marker, notebook, GPS receiver.

1) Give the site a name. I suggest naming the sites Q1, Q2, Q3, etc. Enter the latitude and longitude of the site in the notebook. Write the date in the notebook.
2) Take pictures of the site from various angles and magnifications. Write the numbers of the photos in the notebook.
3) Rinse the bottle (fill it with water and pour it out) with the seepage water three times.
4) Fill the bottle with water.
5) Screw the cap tightly.
6) Wrap the tape completely around the bottle.
7) Write the name of the site on the tape and the bottle.
8) Keep the bottles in the refrigerator as much as possible.