

Evaluation of a New Water-Quality Study of the Rio Tinto QMM Ilmenite Mine, Southeastern Madagascar

By Dr Steven H. Emerman, Malach Consulting

Report submitted to Andrew Lees Trust on September 3, 2020, revised on October 9, 2020

Introduction by the Andrew Lees Trust

Following the independent hydrology and radioactivity studies commissioned by the Andrew Lees Trust in 2018, 2019 and 2020, the Trust has continued its research and advocacy regarding water quality around the Rio Tinto / QMM mine in Anosy region, southern Madagascar.

Elevated levels of uranium, and lead, 52 and almost 40 times higher than WHO safe drinking water guidelines respectively, have been identified in some parts of the waterways and lakes adjacent to the QMM mine where thousands of local people fish and collect their drinking water (Emerman 2019, Swanson 2019).

This latest report by Dr Emerman was commissioned by the Andrew Lees Trust in order to review and analyse initial water-quality data from a new twelve-month study undertaken by Rio Tinto's external consultants, JBS&G, who were contracted in late 2019. The JBS&G study responds to recommendations made by the independent radioactivity expert Dr Stella Swanson in her 2019 report, which called for improved radioactivity monitoring of the QMM mine in the wider environment and, in particular, ingestion pathways of soil, water, and food.

In July 2020, the promised set of initial water-quality data from JBS&G was shared with the Trust, Publish What You Pay (UK and Madagascar) and Craig Bennett (ex-CEO of Friends of the Earth in the UK) who have been jointly advocating for Rio Tinto to take responsibility for its QMM operation's contamination of the waters around the mine site at Mandena, and for the immediate provision of safe drinking water to the 15,000 affected villagers living in the surrounding communities.

Dr Emerman's analysis of the new water data from JBS&G strengthens his 2019 water evaluation findings, which demonstrated the detrimental impact of the QMM mine on regional water quality as 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. It thereby also strengthens the demand for the immediate provision of safe drinking water to affected communities.

To access and download the water and radioactivity studies (by Emerman and Swanson) please visit: http://www.andrewleestrust.org/studies_and_reports.html

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

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LIGHTNING SUMMARY

The Rio Tinto QMM ilmenite mine in southeastern Madagascar generates radionuclide-enriched water, which it releases through surface discharge and groundwater seepage. Rio Tinto contracted an additional 14 water-quality measurements and reported that “all results...were within the relevant WHO guidelines for drinking water quality.” However, the integration of the new data with the existing data confirms the detrimental impact of the mine on regional water quality by showing increases in uranium, thorium 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 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. A previous study combined surface water-quality data provided by Rio Tinto (two upstream and 10 downstream sites) with analyses of surface water samples collected by local residents (five upstream and four downstream sites). From the upstream to the downstream side of the mine, the geometric means of total uranium, total thorium and total lead increased from 0.00014 mg/L to 0.049 mg/L (1.63 times the WHO drinking-water guideline), from 0.00011 mg/L to 0.016 mg/L, and from 0.0026 mg/L to 0.0256 mg/L (2.56 times the WHO drinking-water guideline), respectively. The previous results were statistically significant at better than the 99% confidence level and confirmed the detrimental impact of the mine on regional water quality. Removal of three of the downstream sites that were not potential drinking water sources would increase the differences between upstream and downstream water quality and strengthen their statistical significance. Rio Tinto contracted 14 additional measurements of uranium and lead (four upstream and 10 downstream sites) and reported that “all results...were within the relevant WHO guidelines for drinking water quality.” However, the integration of the new data with the existing data further strengthens the statistical significance of the increases in uranium and lead from the upstream to the downstream sides of the mine by decreasing the variability within the upstream and downstream datasets. Even repeating the new water-quality study 20 times with the same results, and combining the additional results with the existing data, would still yield increases in aqueous uranium and lead from the upstream to the downstream sides of the mine that would be statistically significant at better than the 99% confidence level. The collection of new data for the sole purpose of reversing the statistical significance of an existing conclusion is not a recommended procedure.

TABLE OF CONTENTS

LIGHTNING SUMMARY	1
ABSTRACT	1
INTRODUCTION	2
<i>Plausibility of Release of Radionuclides and Lead from the QMM Mine</i>	2
<i>Previous Water-Quality Studies</i>	8
<i>New Water-Quality Study by JBS&G</i>	10
<i>Objectives of this Report</i>	12
TUTORIAL ON STATISTICAL SIGNIFICANCE	12
METHODOLOGY	15
RESULTS	16
<i>Response to Critique of Previous Water-Quality Studies</i>	16
<i>Integration of New Water-Quality Study with Previous Studies</i>	17
<i>Likelihood of Eventual Reversal of Conclusions of Previous Studies</i>	17
DISCUSSION	26
CONCLUSIONS	28
RECOMENDATIONS	29
ABOUT THE AUTHOR	29
REFERENCES	29

INTRODUCTION

Plausibility of 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, 2, and 3a-b). 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).

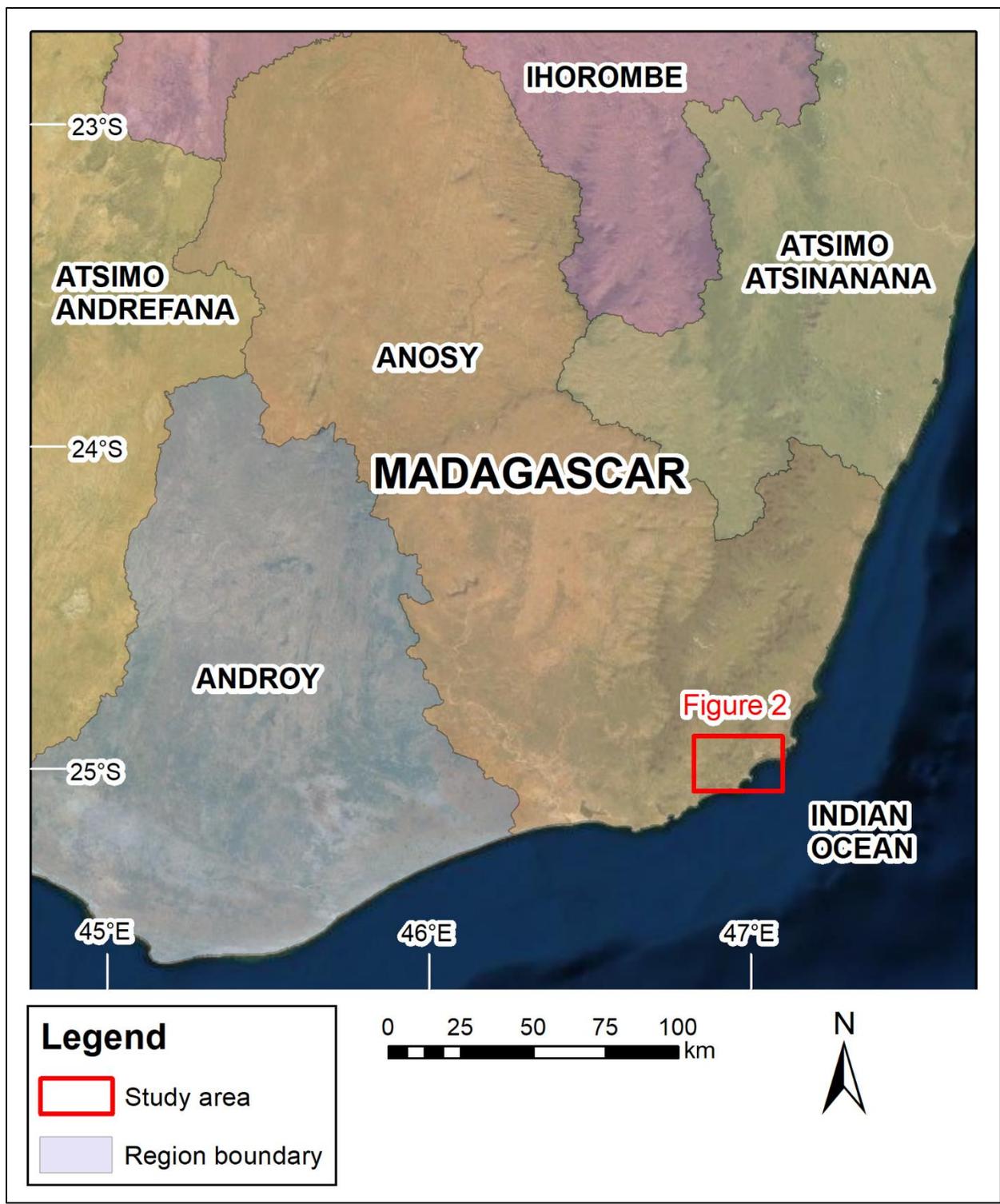


Figure 1. Three studies (Swanson, 2019a-b; Emerman, 2019; JBS&G, 2020b) have examined surface water quality upstream and downstream of the QMM mine, which is located within Anosy region on the southeastern tip of Madagascar.

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 Figs. 3a-b). The only treatment of the mine effluent water is a “biodiversity control pond” or “settling pond” (Swanson, 2019b) that is intended to 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 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, 2019b). (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 (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 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.”

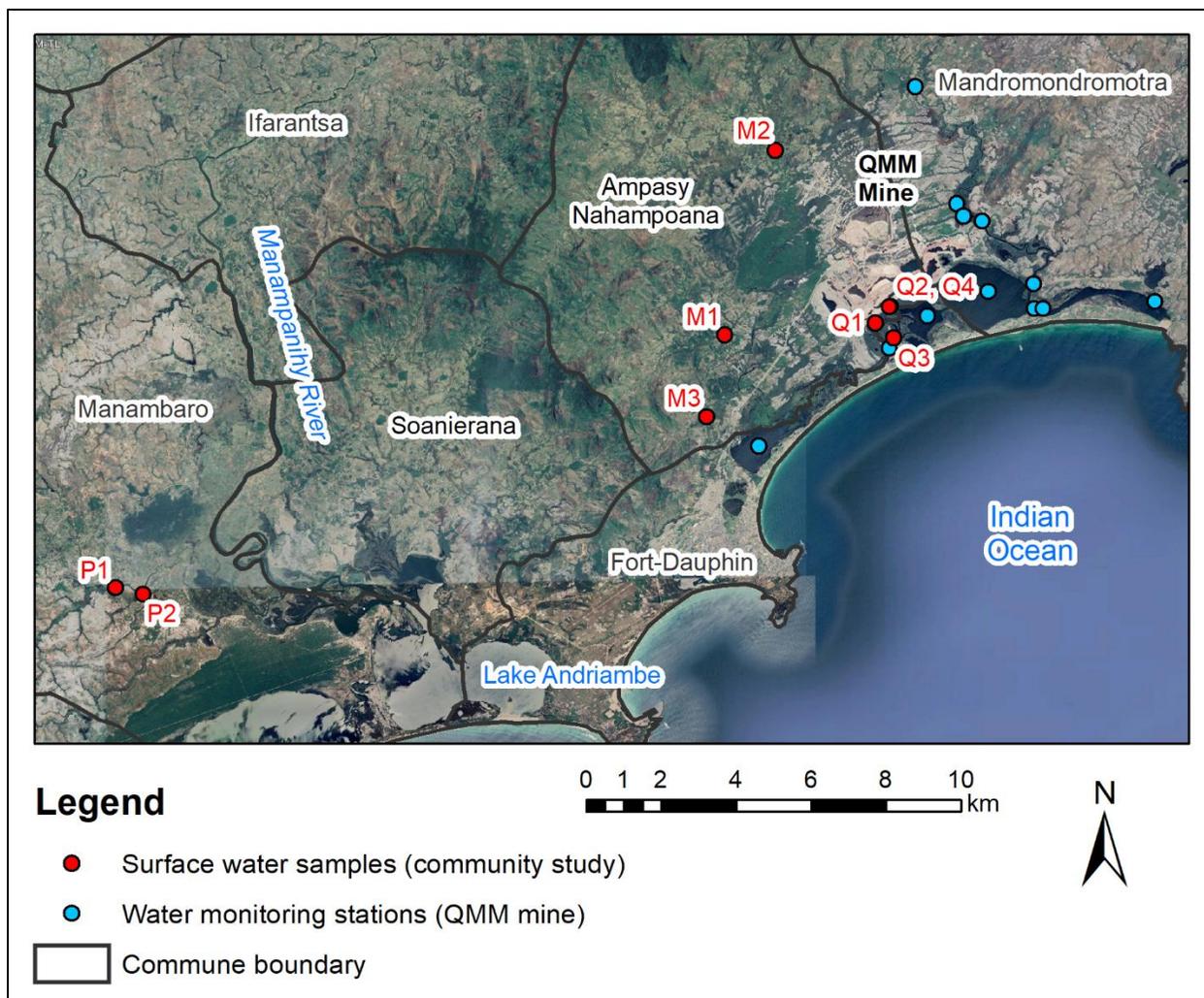


Figure 2. (Swanson, 2019a-b) compiled water-quality measurements from 12 water-monitoring stations that are operated by the QMM mine, two of which are upstream from the mine and 10 of which are downstream. Emerman (2019) reported water-quality analyses of samples collected by local residents from nine 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. Combining all of the data and regarding P1 and P2 as upstream sites showed statistically significant increases in lead, thorium and uranium from the upstream to the downstream side of the mine (Emerman, 2019). Background is Google Earth image from October 13, 2018. See larger-scale map in Fig. 1.

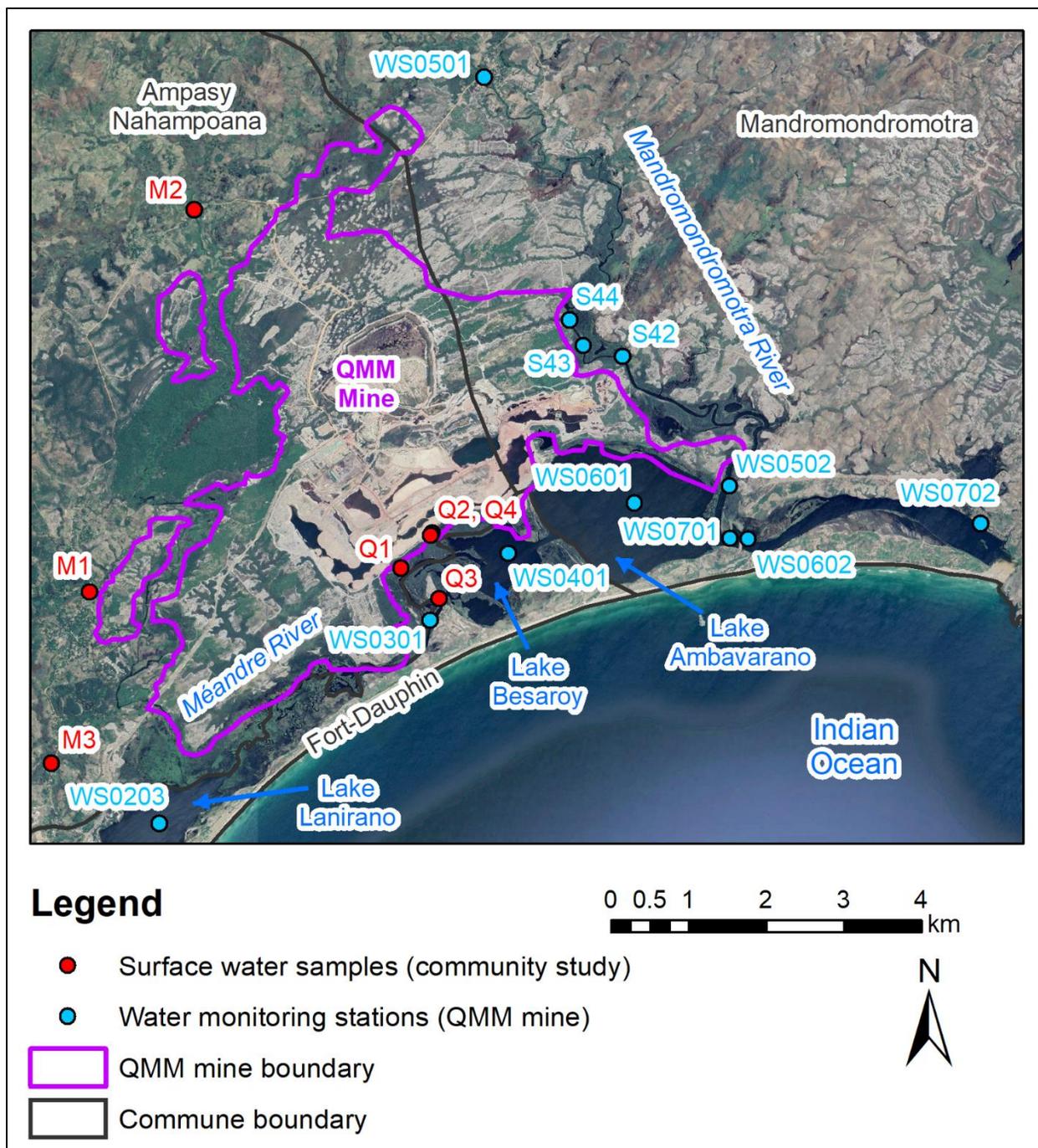


Figure 3a. QMM water-monitoring stations S42, S43, and S44 on the Mandromondromotra River are downstream sites because they are adjacent to the points where mine wastewater enters the river after being discharged into the wetlands to the southwest of the river. QMM mine boundary traced from JBS&G (2020b). Background is Google Earth image from October 13, 2018. See larger-scale map in Fig. 2.

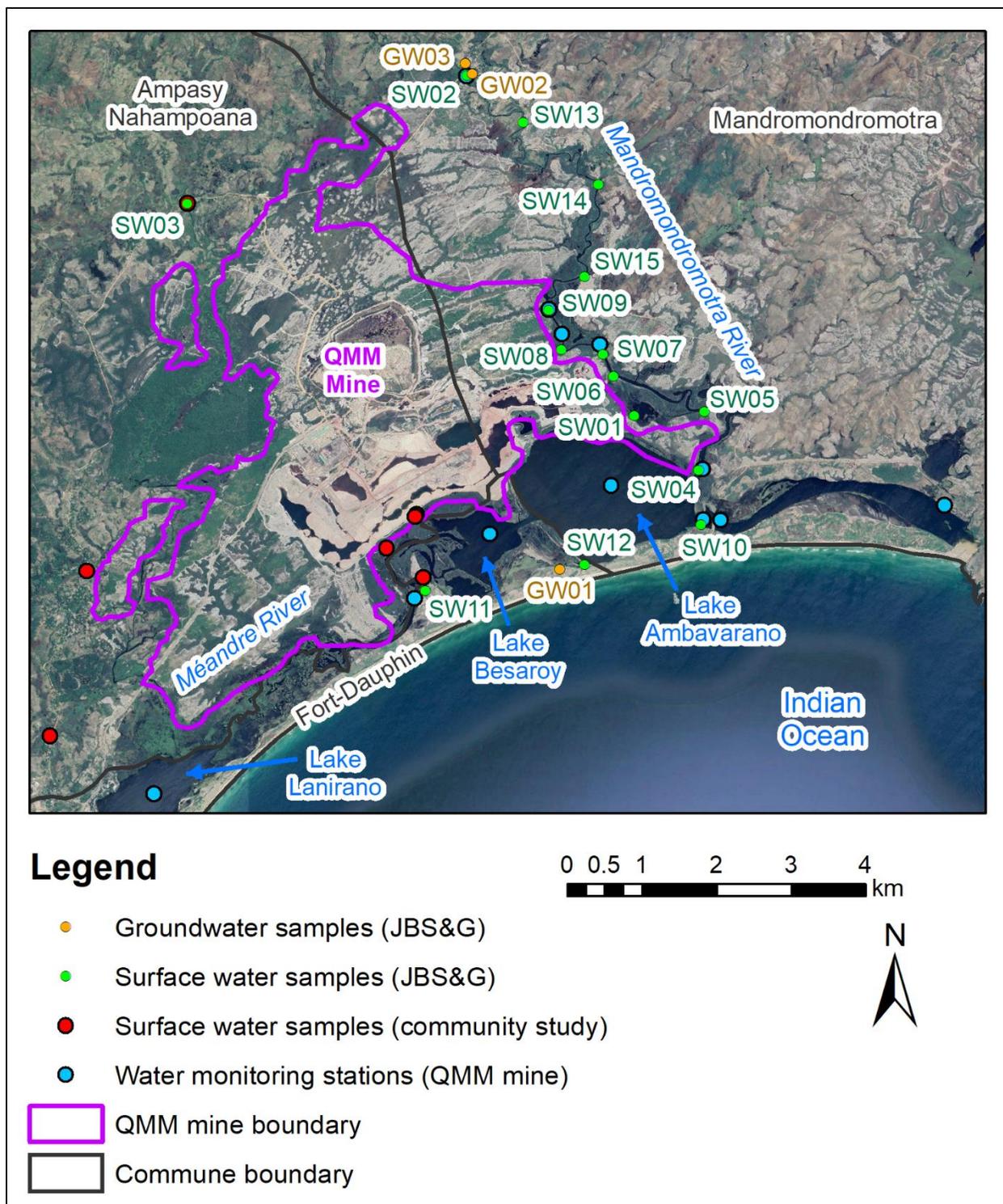


Figure 3b. JBS&G (2020b) reported analyses of groundwater samples from two upstream sites (GW02, GW03) and one downstream site (GW01), as well as surface water samples from four upstream sites (SW02, SW03, SW13, SW14) and ten downstream sites (SW04-SW12, SW15). The analysis of downstream site SW01 was 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). See larger-scale map in Fig. 2.

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

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 Fig. 3a; 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. It has not been specified whether elemental concentrations were measured from filtered samples (dissolved concentrations) or unfiltered samples (total concentrations).

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, and it is not known whether additional measurements were made after August 2018. 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 (2020a) 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 (2020a) aquatic standard. WHO (2017) 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 and the elderly, to drink water), rather than health effects. This secondary standard was exceeded in 11 (20%) out of 54 measurements.

Although the water-quality results were alarming, especially for uranium and lead, the lack of water samples collected upstream of the QMM mine made it difficult to assess the impact of the mine based upon the data compiled in Swanson (2019b). Only two out of the 12 QMM water-monitoring stations are located upstream of the mine, which are WS0501 on the Mandromondromotra River and WS0203 on Lake Lanirano (see Fig. 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). 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). Swanson (2019c) agreed that “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,” but also stated 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; 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, 2019b), Emerman (2019) showed that, from the upstream to the downstream side of the mine, the geometric means of the total concentrations increased from 0.00014 mg/L to 0.049 mg/L, from 0.00011 mg/L to 0.016 mg/L, and from 0.0026 mg/L to 0.0256 mg/L, for uranium, thorium, and lead, respectively. From the upstream to the downstream side of the mine, the geometric means of the dissolved concentrations increased from 0.00008 mg/L to 0.042 mg/L, from 0.00016 mg/L to 0.014 mg/L, and from 0.0018 mg/L to 0.0224 mg/L, for uranium, thorium, and lead, respectively. Since it is not known whether the QMM mine has been measuring dissolved or total concentrations, the reported values (Swanson, 2019b) were used for both the dissolved and the total concentrations, the choice of which had little effect on the results. On the downstream side of the mine, the geometric means of the total concentrations of

uranium and lead were 1.63 times and 2.56 times the WHO (2017) drinking-water guidelines (which are based on 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 (2019b).

The preceding results indicated a pronounced detrimental impact of the QMM mine on regional water quality. A discussion of the statistical significance of the results will be deferred until the following section entitled Tutorial on Statistical Significance. On the other hand, from the upstream to the downstream side of the mine, the geometric means of the dissolved and total iron concentrations decreased from 0.248 mg/L to 0.194 mg/L and from 0.371 mg/L to 0.199 mg/L, respectively (Emerman, 2019), indicating no detrimental impact of the mine with respect to iron. Although the community-collected samples also showed elevated levels of aluminum, manganese and arsenic (Emerman, 2019), it is difficult to see how elevated levels of those elements or iron could be related to any aspect of mineral sands mining. 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.

In response, Rio Tinto (2020a) objected to the sample size used in the analysis by Emerman (2019) and to the inclusion of downstream sites that were not 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. All interpretations involved the analysis of the nine samples collected by local residents with the 60 measurements from 12 sites that were provided by the Rio Tinto QMM mine (Emerman, 2019).

New Water-Quality Study by JBS&G

In April 2020, JSB&G, consultants for Rio Tinto, released two reports, the first being a radioactivity study (JBS&G, 2020a) in the vicinity of the QMM mine in response to the recommendations of Swanson (2019b), and the second entitled “QMM Mandena Mine Madagascar – Incidental water quality sampling report” (JBS&G, 2020b). Nothing in the second report explained the sense in which the report was “incidental.” JBS&G (2020b) collected samples from 15 surface water sites and three groundwater sites on December 2, 2019 (see Table 1; Fig. 3b). The site locations were stated as UTM coordinates, but without specifying the coordinate system. This report has assumed that the coordinates were based on the WGS 84

coordinate system (see Table 1; Fig. 3b). Out of the three groundwater sites, two were upstream and one was downstream (see Fig. 3b). Out of the 14 surface water sites, four were upstream and 10 were downstream (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).

Table 1. Surface water quality results from JBS&G (2020b) study

Sample	Latitude ¹ (°S)	Longitude ¹ (°E)	Lead ² (mg/L)	Uranium ² (mg/L)
Upstream				
SW02	24.914740	47.048435	<0.001	<0.005
SW03	24.929713	47.048682	0.002	<0.005
SW13	24.920647	47.035723	<0.001	<0.005
SW14	24.928106	47.044795	<0.001	<0.005
Downstream				
SW01	24.955941	47.049116	— ³	— ³
SW04	24.962523	47.056851	<0.001	<0.005
SW05	24.955437	47.057515	<0.001	<0.005
SW06	24.951182	47.046622	<0.001	<0.005
SW07	24.948519	47.045320	<0.001	<0.005
SW08	24.947982	47.040351	<0.001	<0.005
SW09	24.943228	47.038807	<0.001	<0.005
SW10	24.969083	47.057118	<0.001	<0.005
SW11	24.976977	47.023943	0.007	<0.005
SW12	24.973835	47.043114	<0.001	<0.005
SW15	24.939215	47.043097	<0.001	<0.005

¹UTM coordinates in JBS&G (2020B) were converted to latitude and longitude under the assumption that UTM coordinates were based on the WGS84 coordinate system.

²Data from JBS&G (2020b)

³JBS&G (2020b) did not report results from SW01 because it was “not considered a potential POU drinking water sample as it was collected from a mining rehabilitation water pond.”

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).” At all surface water sites, the total uranium concentration was below the instrumental detection limit (0.005 mg/L; see Table 1). The lead concentration was below the detection limit (0.001 mg/L) at all sites, except for one upstream site (0.002 mg/L) and one downstream site (0.007 mg/L; see Table 1). 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.

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

Objectives of this Report

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

- 1) Does the critique of Rio Tinto (2020a) that three of the downstream sites used by Emerman (2019) were not potential sources of drinking water reverse the conclusion by Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to uranium, thorium and lead?
- 2) Do the results of the new water-quality study by Rio Tinto consultants JBS&G (2020b) reverse the conclusion by Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to uranium and lead?
- 3) Is it plausible that further water-quality studies of the type carried out by JBS&G (2020b) could ever reverse the conclusion by Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to uranium and lead?

It should be noted that the results of JBS&G (2020b) could not affect the conclusions of Emerman (2019) with respect to thorium or iron, since thorium and iron were not measured by JBS&G (2020b). Nor could the results of JBS&G (2020b) affect the conclusions of Emerman (2019) with respect to dissolved concentrations, since only total concentrations were measured by JBS&G (2020b). Possible impacts of the QMM mine on groundwater were not considered in this report, since there have been no previous measurements of groundwater chemistry for comparison with the results of JBS&G (2020b). Before discussing the methodology for addressing the above questions, I will first review the concept of “statistical significance,” which is critical to the methodology.

TUTORIAL ON STATISTICAL SIGNIFICANCE

Statistics begins with the concept of a null hypothesis and an alternative hypothesis. The null hypothesis is a baseline description that should be accepted as true, unless there is an overwhelming amount of evidence to the contrary. The null hypothesis is typically some version of “Nothing interesting or unusual is happening.” Examples of null hypotheses might be:

- 1) The defendant is not guilty.
 - 2) The factory is not polluting the river.
 - 3) The new drug does not improve health outcomes.
- The corresponding alternative hypotheses would then be:

- 1) The defendant is guilty.
- 2) The factory is polluting the river.
- 3) The new drug improves health outcomes.

The choice of which description is the null hypothesis and which is the alternative hypothesis depends upon the context. The null hypothesis is the one for which the false rejection would have serious consequences. The false rejection of a null hypothesis is so serious that it is called the Type I error in statistics. An example of a Type I error would be the decision that an innocent person was guilty. The standard practice has been that null hypotheses are accepted unless they can be rejected with at least 95% confidence. However, this cutoff confidence level depends upon the context and especially upon the consequences of being wrong. In some contexts, null hypotheses are accepted unless they can be rejected at the 99% or the 99.9% confidence levels.

In this report and in the previous report by Emerman (2019) the null hypothesis has been that the geometric means of the concentrations of contaminants (uranium, thorium, lead) in surface water are the same upstream of the QMM mine and downstream of the mine. That is, the null hypothesis is that the QMM mine does not have a detrimental impact on regional water quality. The above was chosen as the null hypothesis because a false rejection of the null hypothesis would have the following serious consequences:

- 1) There would be an unnecessary expenditure on water treatment, either on the part of Rio Tinto or the community or the Malagasy government.
- 2) There would be unnecessary alarm to the local population.
- 3) There would be unnecessary damage to the reputation of Rio Tinto.

In other words, the null hypothesis has been deliberately chosen in favor of the innocence of Rio Tinto, so that the burden of providing overwhelming evidence is on the party that seeks to demonstrate a detrimental impact of the QMM mine on regional water quality. It could reasonably be argued that, since, the consequences of lead and uranium poisoning can be so severe, and since elevated uranium and lead are such a common consequence of mineral sands mining, the burden of evidence should be on the party that seeks to demonstrate that the QMM mine does not have a detrimental impact on regional water quality. That distinction will not be explored further in this report, except to note that the entire controversy could have been avoided if Rio Tinto had carried out a baseline water-quality study (especially at the sites that are now downstream from the mine) prior to construction of the QMM mine.

In order to demonstrate a detrimental impact of the QMM mine, it would not be enough to show that the geometric mean of the uranium or lead concentration was greater on the downstream side than on the upstream side. The reason is that any water samples would be drawn from a much larger population of possible water samples, so that a higher geometric mean on the downstream side could occur simply due to chance. In other words, a different set of water samples might have shown the opposite result that the geometric mean of the uranium or lead concentration was greater on the upstream side. It is necessary to show that the difference between the geometric means on the upstream and downstream sides is large enough that the difference is “statistically significant.”

The determination of statistical significance arises from a comparison of the difference between the means of two populations and the variability within each population. The determination yields a P-value, which is the probability that the two means are the same. Using the previous terminology, the standard practice is that the null hypothesis is rejected only if $P < 0.05$, that is, only if it can be rejected at the 95% confidence level. In some contexts, the null hypothesis should be rejected only if $P < 0.01$ or $P < 0.001$, corresponding to rejection at the 99% or 99.9% confidence level, respectively. A common test for statistical significance, which was used in this report and in Emerman (2019) is the t-test, which is readily available as the function TTEST in MS Excel.

The concept of statistical significance is illustrated in Table 2. Each case study considers two populations, A and B, from each of which four samples are drawn. In Case Study I, there is considerable variation among the samples for each population. Although the difference between the means is relatively large, the P-value is $P = 0.3$, so that the difference between the means would not be statistically significant by any standard. In Case Study II, the variation among the samples for each population is considerably smaller. Although the difference between the means is relatively small, the P-value is $P = 0.0002$, so that the difference between the means would be statistically significant by nearly any standard. Note that a smaller P-value (lower probability that the means of A and B are the same) indicates a greater statistical significance for the conclusion that the two means are different.

Table 2. Illustration of statistical significance

	Case Study I		Case Study II	
	Population A	Population B	Population A	Population B
	2	4	13.6	15.6
	5	10	13.8	15.8
	15	30	14.2	16.2
	18	36	14.4	16.4
Mean	10	20	14.0	16.0
P-value	0.30452		0.0002	

¹In Case Study I, the difference between the means is large, but the difference is not statistically significant ($P > 0.05$). In Case Study II, the difference between the means is much smaller, but the difference is statistically significant ($P < 0.05$). The P-value is the probability that populations A and B (of which the four numbers are only random samples) have the same mean. The P-value results from a comparison of the difference between the means with the variability within each population.

It is important to note that “significance” and “statistical significance” are different concepts. It can be said that a difference is “significant” if it matters, and whether it matters depends upon the context. For example, a new teaching method might improve literacy scores from 45 to 55, and that might be large enough to matter, or it might not. A new drug might increase expected longevity by two months, and that might matter, or it might not. In the case of contamination of water sources by uranium, an increase from 0.001 mg/L to 0.005 mg/L would not matter (would not be significant) because both values are still well below the WHO (2017) drinking-water guideline (0.03 mg/L). On the other hand, “statistical significance” is a measure of whether the difference is “real.” In that way, an increase in uranium concentration from 0.02 mg/L to 0.04 mg/L (crossing the WHO (2017) guideline) with $P = 0.10$ would matter (would be significant), but it would not be real (would not be statistically significant). By contrast, an

increase in uranium concentration from 0.001 mg/L to 0.005 mg/L with $P = 0.0005$ might not be significant, although it would certainly be statistically significant.

The preceding discussion on statistical significance can now be applied to the results from Emerman (2019), which combined analyses of community-collected samples with data provided by Rio Tinto to show the detrimental impact of the QMM mine on regional water quality. The increases in uranium, thorium and lead concentrations from the upstream to the downstream side of the mine were all statistically significant at better than the 99% confidence level. For the increases in the geometric means of the total concentrations of uranium, thorium, and lead, the P-values were 0.008, 0.003, and 0.003, respectively. For the increases in the geometric means of the dissolved concentrations of uranium, thorium, and lead, the P-values were 0.007, 0.0001, and 0.01, respectively. The differences were not only statistically significant, but they were “significant” in the public health sense. On the upstream side of the mine, the geometric means of total uranium and lead concentrations were 0.00014 mg/L and 0.0026 mg/L, respectively, or well below the drinking-water guidelines of 0.03 mg/L for uranium and 0.01 mg/L for lead. On the downstream side of the mine, the geometric means of total uranium and lead concentrations were 0.049 mg/L and 0.0256 mg/L, respectively, or 1.63 times the WHO (2017) guideline for uranium and 2.56 times the WHO (2017) guideline for lead.

METHODOLOGY

The first question, as to whether removal of the analyses of the samples from the marshy sites (Q1, Q2 and Q4; see Fig. 3a) would affect the conclusions of Emerman (2019) was addressed simply by repeating the statistical analysis without the marshy sites. The second question, as to whether the new results from JBS&G (2020b) would affect the conclusions of Emerman (2019) was addressed by repeating the statistical analysis by combining the earlier data provided by Rio Tinto (Swanson, 2019b), the data from the community-collected samples (Emerman, 2019), and the most recent data (JBS&G, 2020b). Since JBS&G (2020b) had already removed the data from the site that was not a potential source of drinking water (SW01; see Table 1 and Fig. 3b), for a consistent comparison, it was necessary to also take out of consideration the three sites of community sampling (Q1, Q2 and Q4; see Fig. 3a) that were not potential water sources. The third question, as to whether further water-quality studies of the type carried out by JBS&G (2020b) could realistically reverse the conclusions of Emerman (2019), was addressed by repeating the statistical analysis while adding the results of hypothetical additional water-quality surveys with the same results found by JBS&G (2020b). In other words, the statistical analysis for uranium was re-done by repeatedly adding four upstream samples and 10 downstream samples with uranium concentration <0.005 mg/L. The statistical analysis for lead was re-done by repeatedly adding four upstream samples (one with $Pb = 0.002$ mg/L and the remainder with $Pb <0.001$ mg/L) and 10 downstream samples (one with $Pb = 0.007$ mg/L and the remainder with $Pb <0.001$ mg/L). In this way, it was determined how many additional water-quality surveys with the same results found by JBS&G (2020b) would be needed to reach $P > 0.05$, so as to reverse the statistical significance of the conclusions reached by Emerman (2019). It should be noted that this third exercise was strictly hypothetical, in that the collection of additional data for the sole purpose of reversing the statistical significance of an existing conclusion is not a recommended procedure.

To carry out the statistical analysis, the non-detectable concentrations from JSB&G (2020b) were set equal to the detection limit (0.005 mg/L for uranium and 0.001 mg/L for lead).

Sometimes non-detectable concentrations are set equal to one-half of the detection limit. However, this choice is entirely arbitrary, and the only good solution for the inclusion of values below the detection limit in statistical analyses is to use analytical instrumentation with sufficiently low detection limits (as was done for the community-collected samples in Emerman (2019)). The non-detectable concentrations could not be set equal to zero, since the geometric means were calculated, which use the logarithms of the measurements. As discussed in Emerman (2019), the comparison of geometric means was appropriate due to the variation in elemental concentrations over five orders of magnitude. Carrying out the statistical analyses with non-detectable concentrations from JBS&G (2020b) set equal to one-half of the detection limit had very minor effect on the results.

On the other hand, the non-detectable concentrations from the earlier data from the QMM mine (Swanson, 2019b) were excluded from the statistical analysis because the detection limits were so high. For example, the detection limit for uranium was already higher than the WHO (2017) drinking-water guideline. There were also concerns about why uranium and lead each had two different detection limits, although this probably relates to the use of different analytical instruments. Further discussion about the choice to exclude the non-detectable concentrations can be found in Emerman (2019). All statistical comparisons were based upon the two-sided unpaired t-test with the assumption of unequal variance.

RESULTS

Response to Critique of Previous Water-Quality Studies

In all cases, the exclusion of the three marshy sites (Q1, Q2 and Q4; see Fig. 3a) as critiqued by Rio Tinto (2020a) strengthened the conclusions of Emerman (2019) both with regard to the differences between the geometric means of the upstream and downstream concentrations and with regard to the statistical significance of the differences. (A decrease in the P-value indicates a strengthening of the statistical significance). The conclusions were strengthened because these three sites happened to have relatively low concentrations of uranium, thorium, and lead, which were much more similar to the concentrations found on the upstream side of the mine (Emerman, 2019). The removal of the three downstream samples would not change any upstream concentrations. However, the removal of the three samples would increase the geometric means of the downstream concentrations from 0.042 mg/L (Emerman, 2019) to 0.114 mg/L for dissolved uranium, and from 0.049 mg/L (Emerman, 2019) to 0.118 mg/L for total uranium (see Fig. 4a). The statistical significance of the increase in aqueous uranium from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from $P = 0.007$ (Emerman, 2019) to $P = 0.003$ for dissolved uranium and from $P = 0.008$ (Emerman, 2019) to $P = 0.004$ for total uranium (see Fig. 4a). The removal of the three samples would increase the geometric means of the downstream concentrations from 0.014 mg/L (Emerman, 2019) to 0.026 mg/L for dissolved thorium, and from 0.016 mg/L (Emerman, 2019) to 0.027 mg/L for total thorium (see Fig. 4b). The statistical significance of the increase in aqueous thorium from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from $P = 0.0001$ (Emerman, 2019) to $P = 0.00009$ for dissolved thorium and from $P = 0.003$ (Emerman, 2019) to $P = 0.002$ for total thorium (see Fig. 4b). Finally, the removal of the three samples would increase the geometric means of the downstream concentrations from 0.0224 mg/L (Emerman, 2019) to

0.0367 mg/L for dissolved lead, and from 0.0256 mg/L (Emerman, 2019) to 0.0374 mg/L for total lead (see Fig. 4c). The statistical significance of the increase in aqueous lead from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from $P = 0.01$ (Emerman, 2019) to $P = 0.005$ for dissolved lead and from $P = 0.003$ (Emerman, 2019) to $P = 0.0009$ for total lead (see Fig. 4c).

The exclusion of the three samples from downstream marshy areas would also strengthen the conclusion of Emerman (2019) that the QMM mine was not responsible for elevated iron in local streams, lakes and estuaries. The removal of the three samples would not change the upstream iron concentrations, but would decrease the geometric means of the downstream concentrations from 0.194 mg/L (Emerman, 2019) to 0.151 mg/L for dissolved iron, and from 0.199 mg/L (Emerman, 2019) to 0.151 mg/L for total iron (see Fig. 4d). In fact, the decrease in iron from the upstream to the downstream side of the QMM mine became even more statistically significant as the P-values for dissolved and total iron decreased from $P = 0.47$ (Emerman, 2019) to $P = 0.12$, and from $P = 0.04$ (Emerman, 2019) to $P = 0.02$, respectively (see Fig. 4d).

Integration of New Water-Quality Study with Previous Studies

The integration of the new water quality results from JBS&G (2020b) with the results from previous studies (Swanson, 2019a-b; Emerman, 2019) again strengthens the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on water quality with respect to both uranium and lead. 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 $P = 0.003$ (see Fig. 5a). The geometric mean of the downstream uranium concentration decreased to 0.03823 mg/L, but it is still 1.27 times the WHO (2017) guideline for uranium in drinking water (see Fig. 5a). 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 $P = 0.0004$ (see Fig. 5b). The geometric mean of the downstream lead concentration decreased to 0.0141 mg/L, but it is still 1.41 times the WHO guideline for lead in drinking water (see Fig. 5b).

Likelihood of Eventual Reversal of Conclusions of Previous Studies

The addition of a hypothetical new dataset equivalent to the dataset of JBS&G (2020b) to the existing datasets from the QMM mine (Swanson, 2019b), the community-collected samples (Emerman, 2019) and the data collected by JBS&G (2020b) would cause the P-value to decrease from $P = 0.0028$ (one JBS&G-type sampling event; see Fig. 6a) to $P = 0.0022$ (two JS&B-type sampling events; see Fig. 6a) for the increase in uranium concentration from the upstream to the downstream side of the QMM mine. In other words, if the water-quality survey by JBS&G (2020b) were to be repeated, with the exact same results, the statistical significance of the detrimental impact of the QMM mine on uranium in surface water would become even stronger (see Fig. 6a). In fact, each addition of such an identical sampling event (four upstream samples and ten downstream samples, each with uranium concentration <0.005 mg/L) would further strengthen the statistical significance (decrease the P-value even further). After the addition of 20 such identical sampling events (for example, a water-quality survey like the JSB&G (2020b) survey once a year for 20 years), the P-value would decrease to $P = 0.0013$, so that the null

hypothesis (no detrimental impact of the QMM mine on uranium in surface water) could still be rejected at the 99.87% confidence level.

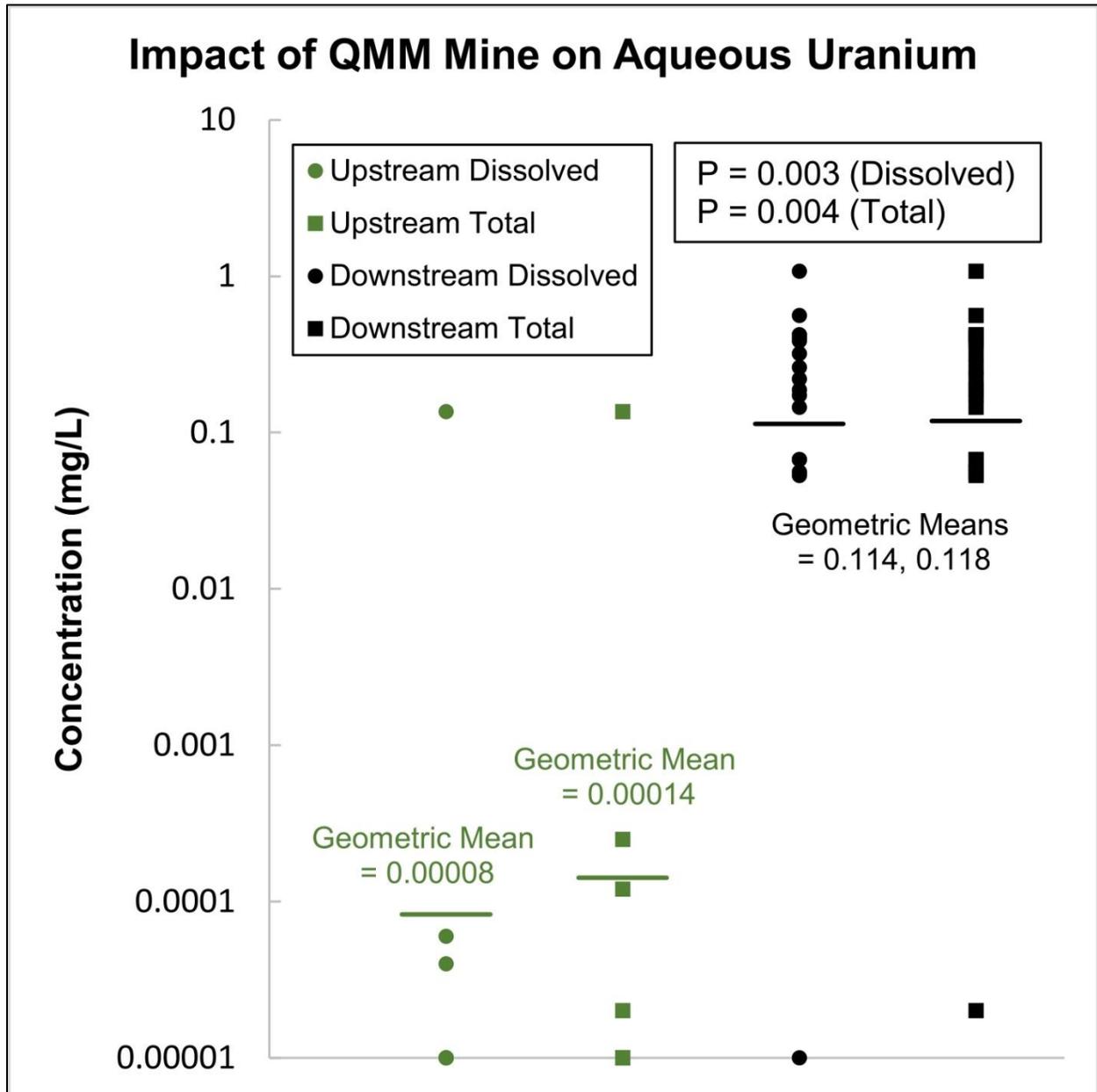


Figure 4a. Rio Tinto (2020a) critiqued the use of three downstream water samples (Q1, Q2, Q4) in Emerman (2019) because these were not “sources of drinking water.” However, the exclusion of these samples would strengthen the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to uranium. The removal of the three samples would not change the upstream uranium concentrations, but would increase the geometric means of the downstream concentrations from 0.042 mg/L (Emerman, 2019) to 0.114 mg/L for dissolved uranium, and from 0.049 mg/L (Emerman, 2019) to 0.118 mg/L for total uranium. The statistical significance of the increase in aqueous uranium from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from P = 0.007 (Emerman, 2019) to P = 0.003 for dissolved uranium and from P = 0.008 (Emerman, 2019) to P = 0.004 for total uranium. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. For comparison, the WHO drinking-water guideline for uranium is 0.03 mg/L (WHO, 2017).

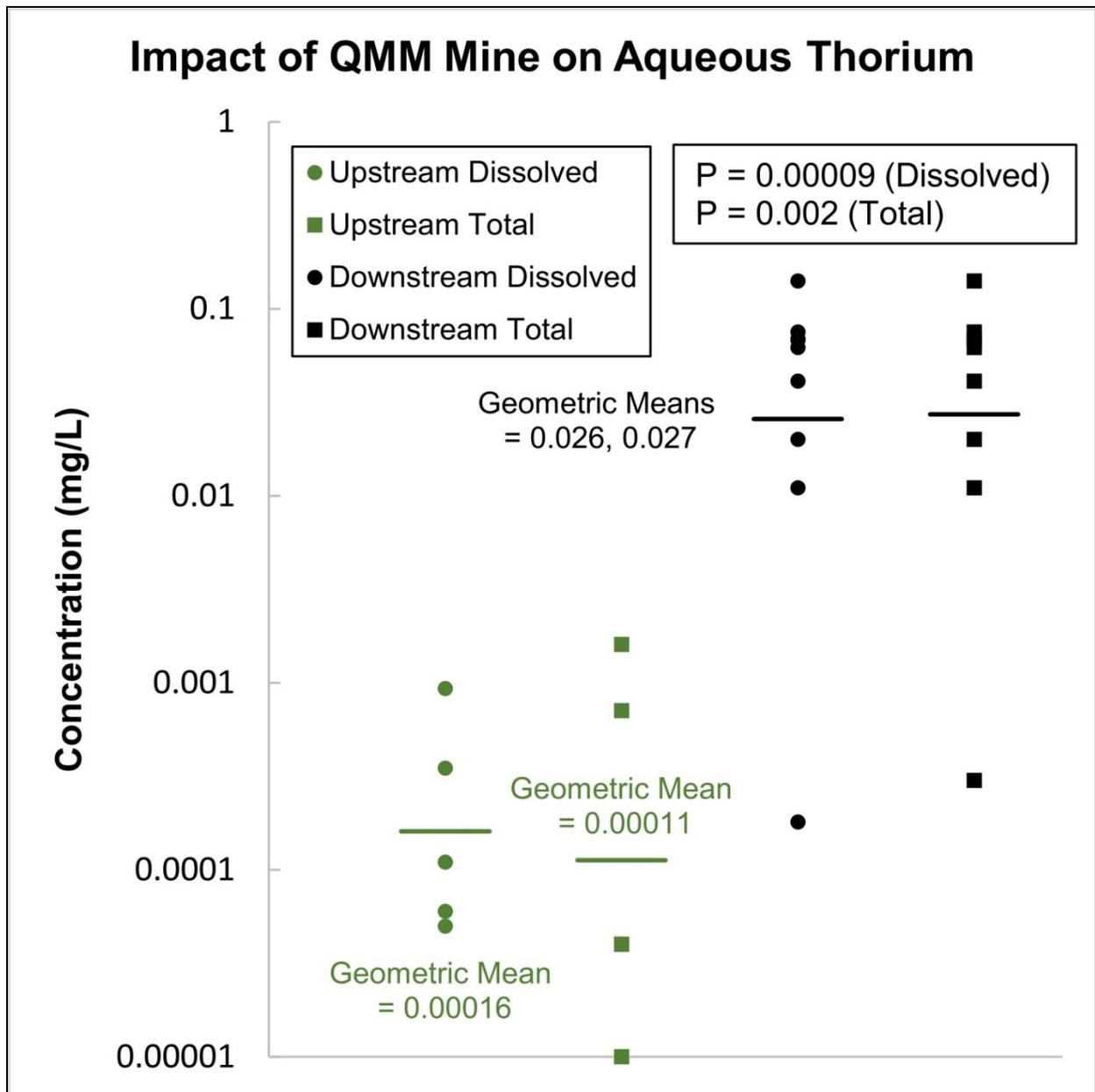


Figure 4b. Rio Tinto (2020a) critiqued the use of three downstream water samples (Q1, Q2, Q4) in Emerman (2019) because these were not “sources of drinking water.” However, the exclusion of these samples would strengthen the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to thorium. The removal of the three samples would not change the upstream thorium concentrations, but would increase the geometric means of the downstream concentrations from 0.014 mg/L (Emerman, 2019) to 0.026 mg/L for dissolved thorium, and from 0.016 mg/L (Emerman, 2019) to 0.027 mg/L for total thorium. The statistical significance of the increase in aqueous thorium from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from $P = 0.0001$ (Emerman, 2019) to $P = 0.00009$ for dissolved thorium and from $P = 0.003$ (Emerman, 2019) to $P = 0.002$ for total thorium. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same.

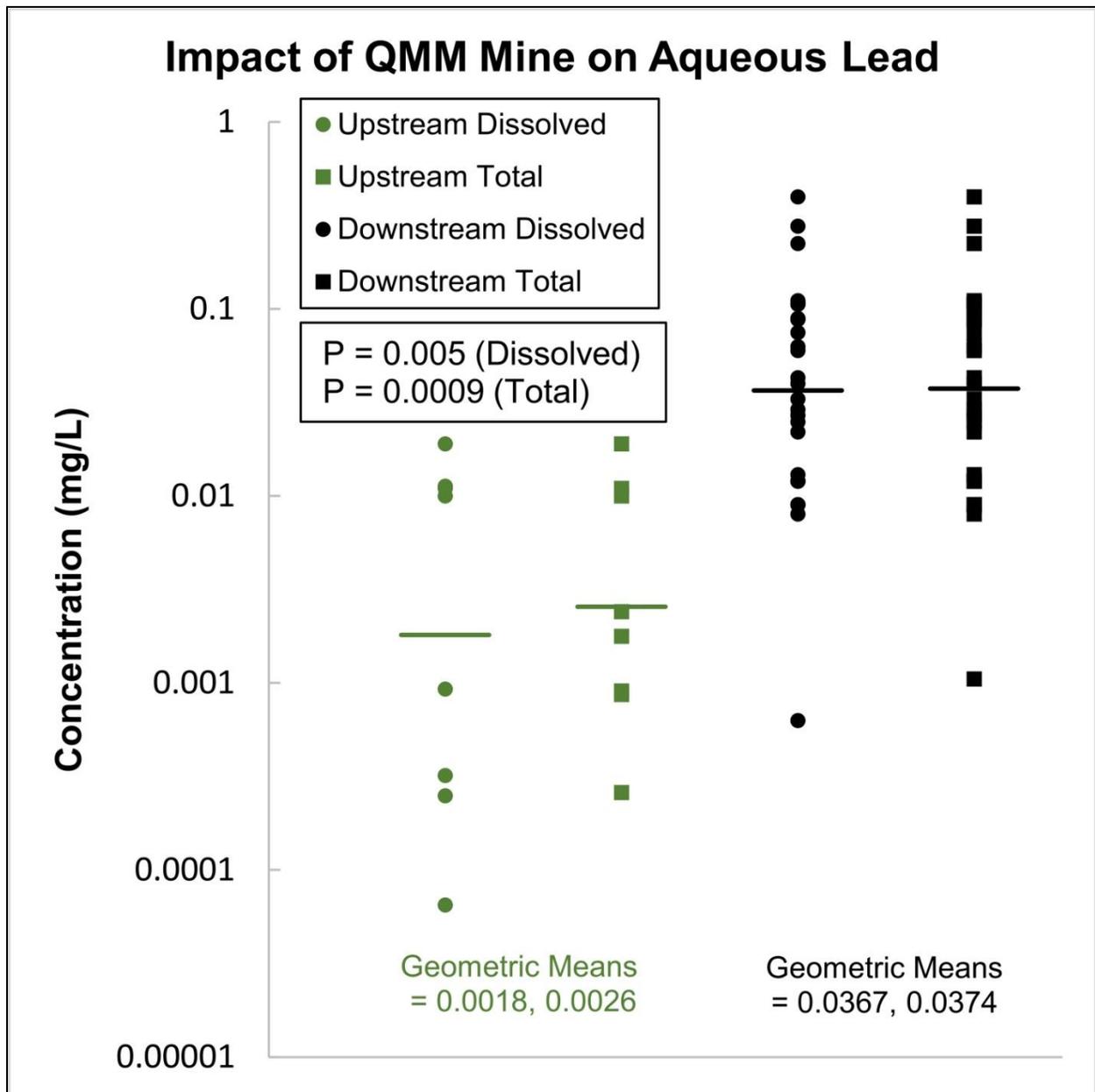


Figure 4c. Rio Tinto (2020a) critiqued the use of three downstream water samples (Q1, Q2, Q4) in Emerman (2019) because these were not “sources of drinking water.” However, the exclusion of these samples would strengthen the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to lead. The removal of the three samples would not change the upstream lead concentrations, but would increase the geometric means of the downstream concentrations from 0.0224 mg/L (Emerman, 2019) to 0.0367 mg/L for dissolved lead, and from 0.0256 mg/L (Emerman, 2019) to 0.0374 mg/L for total lead. The statistical significance of the increase in aqueous lead from the upstream to the downstream side of the QMM mine would strengthen, since the P-value would decrease from P = 0.01 (Emerman, 2019) to P = 0.005 for dissolved lead and from P = 0.003 (Emerman, 2019) to P = 0.00009 for total lead. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. For comparison, the WHO drinking-water guideline for lead is 0.01 mg/L.

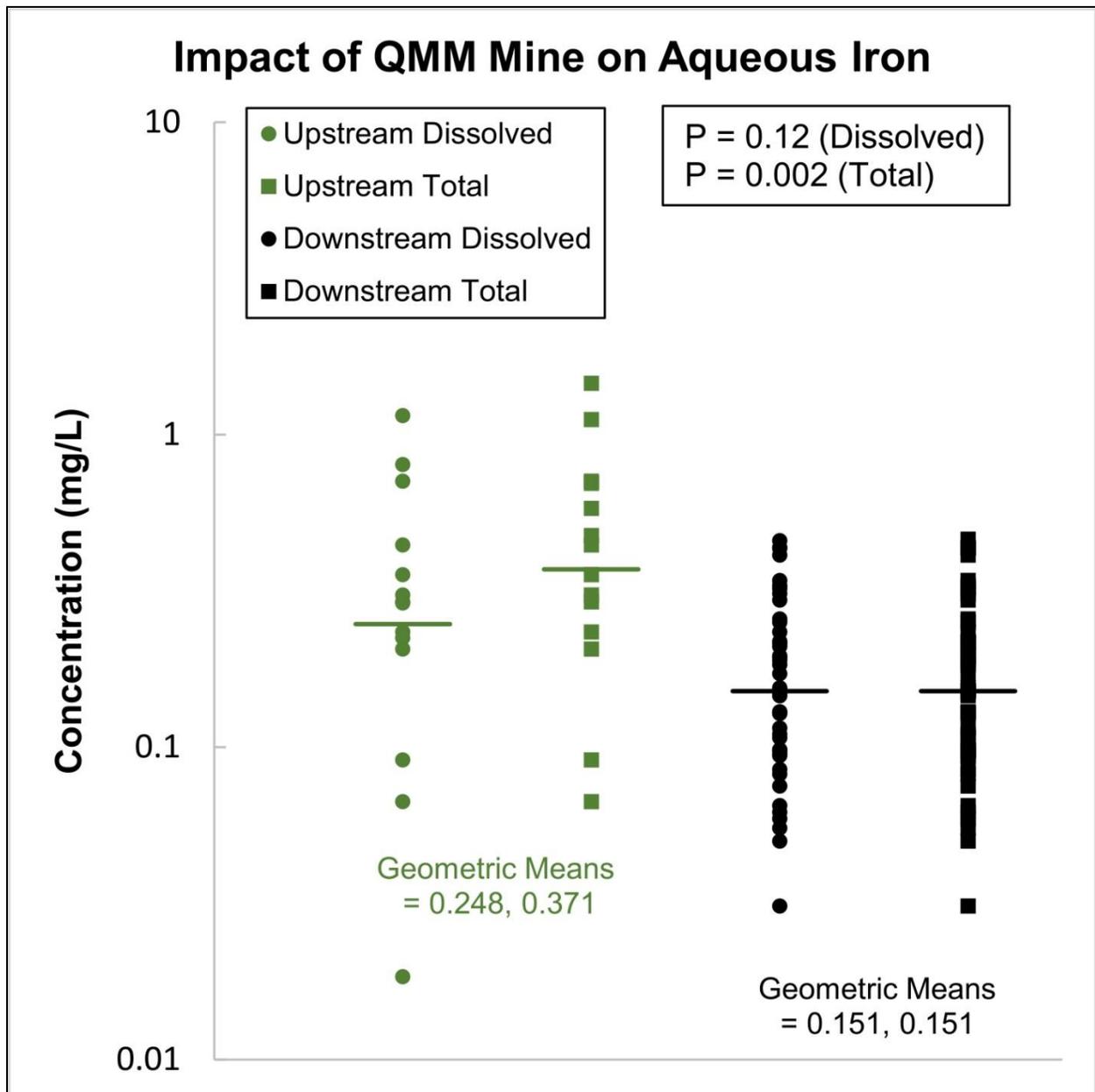


Figure 4d. Rio Tinto (2020a) critiqued the use of three downstream water samples (Q1, Q2, Q4) in Emerman (2019) because these were not “sources of drinking water.” However, the exclusion of these samples would strengthen the conclusion of Emerman (2019) that the QMM mine has no detrimental impact on regional water quality with respect to iron. The removal of the three samples would not change the upstream iron concentrations, but would decrease the geometric means of the downstream concentrations from 0.194 mg/L (Emerman, 2019) to 0.151 mg/L for dissolved iron, and from 0.199 mg/L (Emerman, 2019) to 0.151 mg/L for total iron.

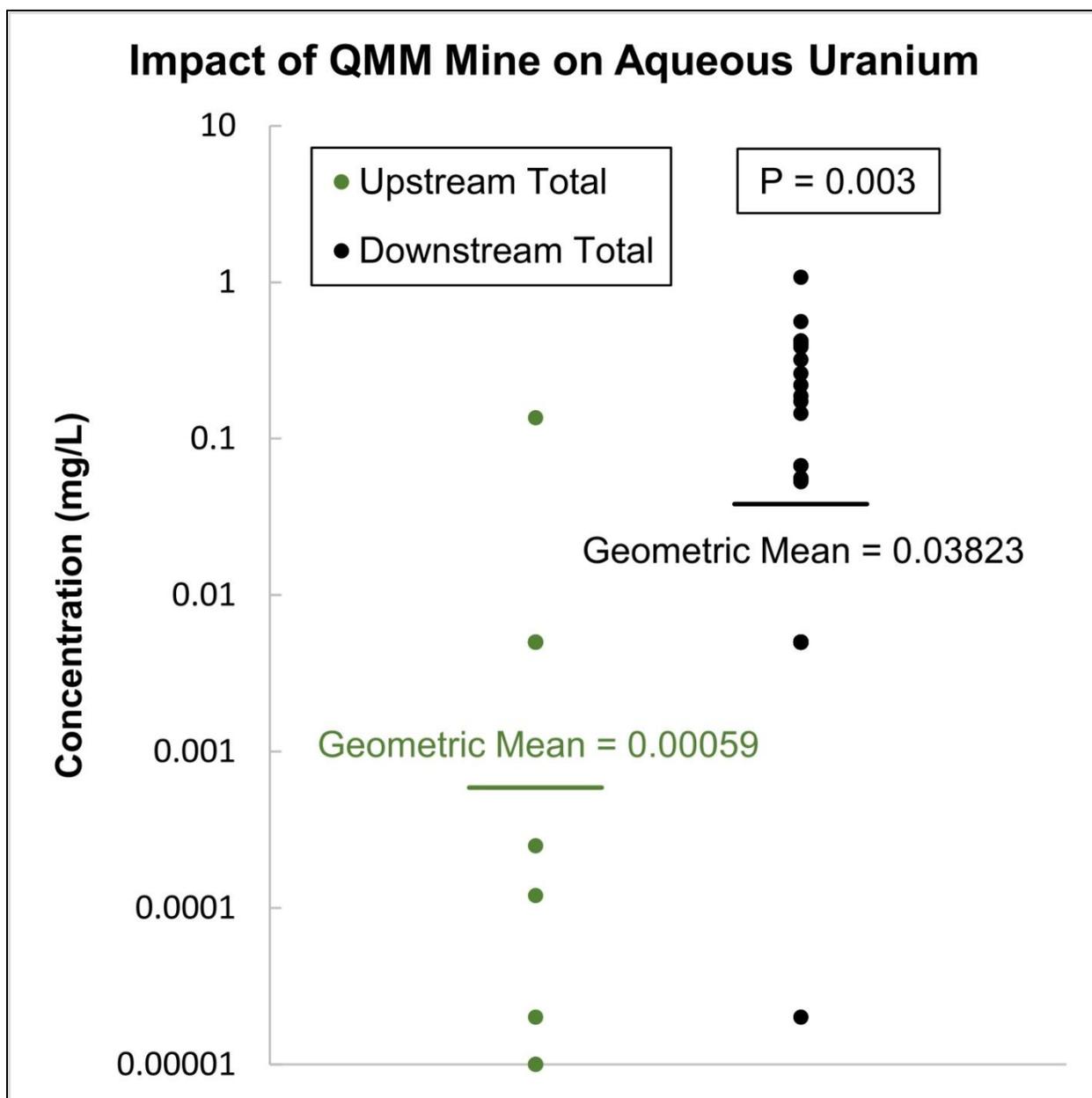


Figure 5a. The integration of the new water quality results from JBS&G (2020b) with the results from previous studies (Swanson, 2019a-b; Emerman, 2019) strengthens the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on water quality with respect to uranium. In particular, the statistical significance of the increase in the geometric means of uranium concentrations from the upstream to the downstream sides strengthened from $P = 0.008$ to $P = 0.003$. JBS&G (2020b) did not report one downstream measurement because it was “not considered a potential POU [Point of Use] drinking water sample.” For consistency, the three downstream water samples (Q1, Q2, Q4) from Emerman (2019) that were not potential water sources were also excluded (see Fig. 4a). Note that JBS&G (2020b) measured only total and not dissolved concentrations. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. For comparison, the WHO drinking-water guideline for uranium is 0.03 mg/L.

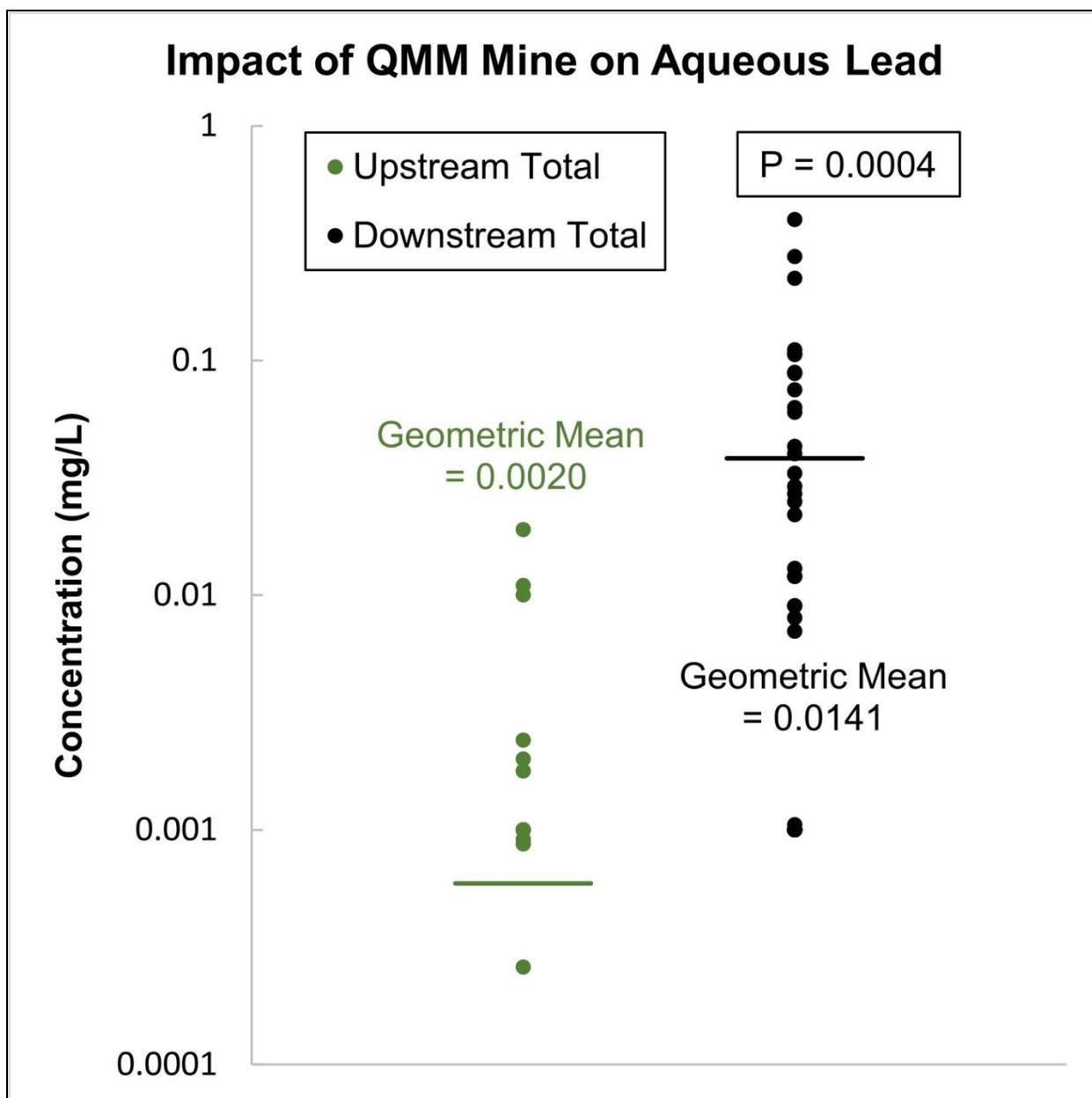


Figure 5b. The integration of the new water quality results from JBS&G (2020b) with the results from previous studies (Swanson, 2019a-b; Emerman, 2019) strengthens the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on water quality with respect to lead. In particular, the statistical significance of the increase in the geometric means of lead concentrations from the upstream to the downstream sides strengthened from $P = 0.003$ to $P = 0.0004$. JBS&G (2020b) did not report one downstream measurement because it was “not considered a potential POU [Point of Use] drinking water sample.” For consistency, the three downstream water samples (Q1, Q2, Q4) from Emerman (2019) that were not potential water sources were also excluded (see Fig. 4c). Note that JBS&G (2020b) measured only total and not dissolved concentrations. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. For comparison, the WHO drinking-water guideline for lead is 0.01 mg/L.

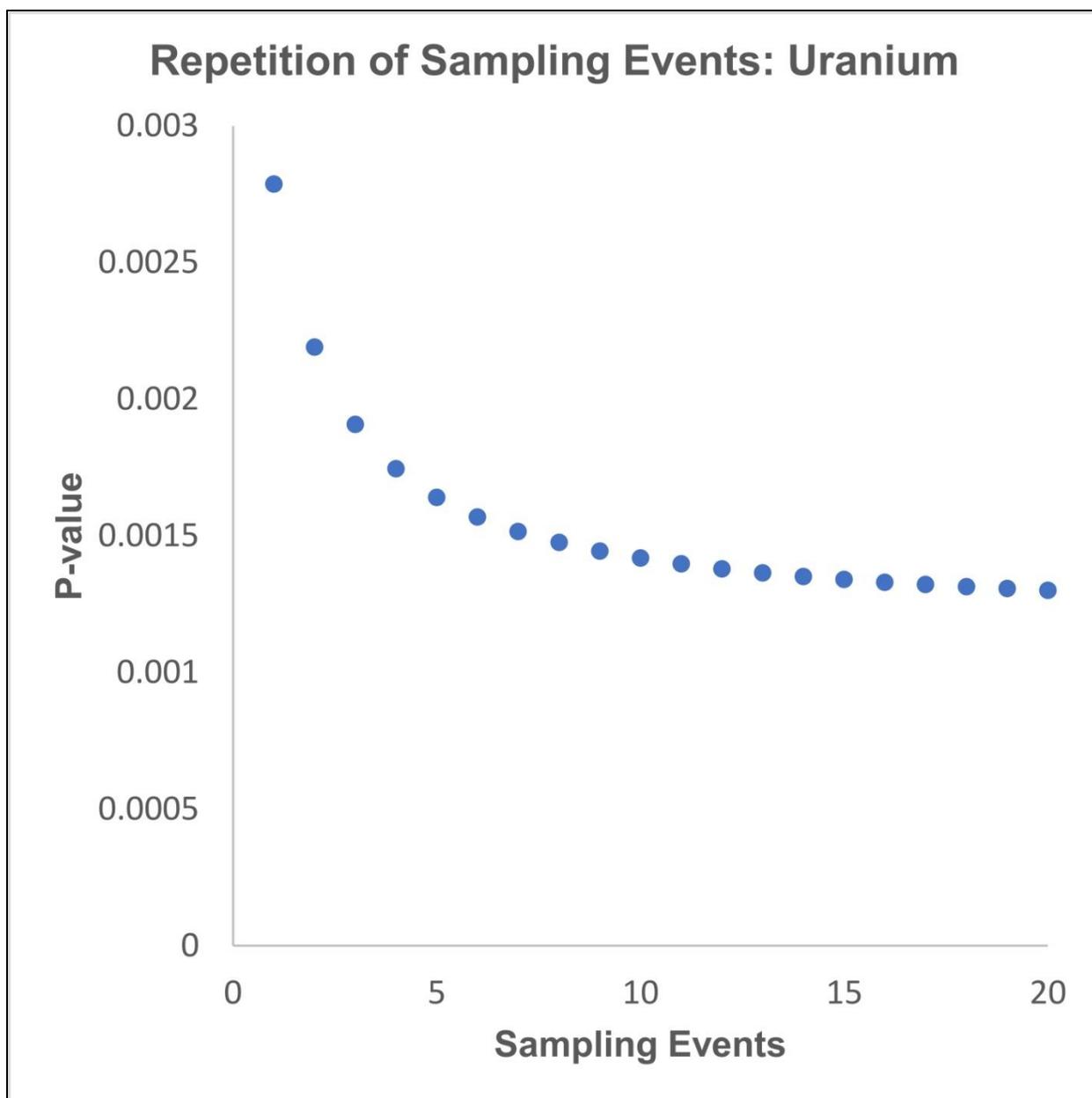


Figure 6a. The integration of the new water quality results from JBS&G (2020b) with the results from previous studies (Swanson, 2019a) resulted in a statistically significant increase in aqueous uranium from the upstream to the downstream side of the QMM mine with $P = 0.0028$ (see Fig. 5a), corresponding to the first sampling event in the above graph. Repeating those same results (four upstream samples and ten downstream samples, each with uranium concentration <0.005 mg/L) and integrating them with the existing dataset would not weaken the statistical significance of the detrimental impact. Two identical sampling events (four upstream samples and ten downstream samples, each with uranium concentration <0.005 mg/L) would result in $P = 0.0022$, while 20 such sampling events would yield $P = 0.0013$. For this dataset, the statistical significance strengthens (P decreases) because, with each additional identical sampling event, the variability within the upstream and downstream populations decreases faster than the geometric means of the upstream and downstream populations approach one another. Therefore, the statistical significance of the existing conclusion (an increase in aqueous uranium from the upstream to the downstream side of the mine) cannot be reversed by additional collection of samples with undetectable uranium. The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. Note that the collection of additional data for the sole purpose of trying to reverse the statistical significance of an existing conclusion is not a recommended procedure.

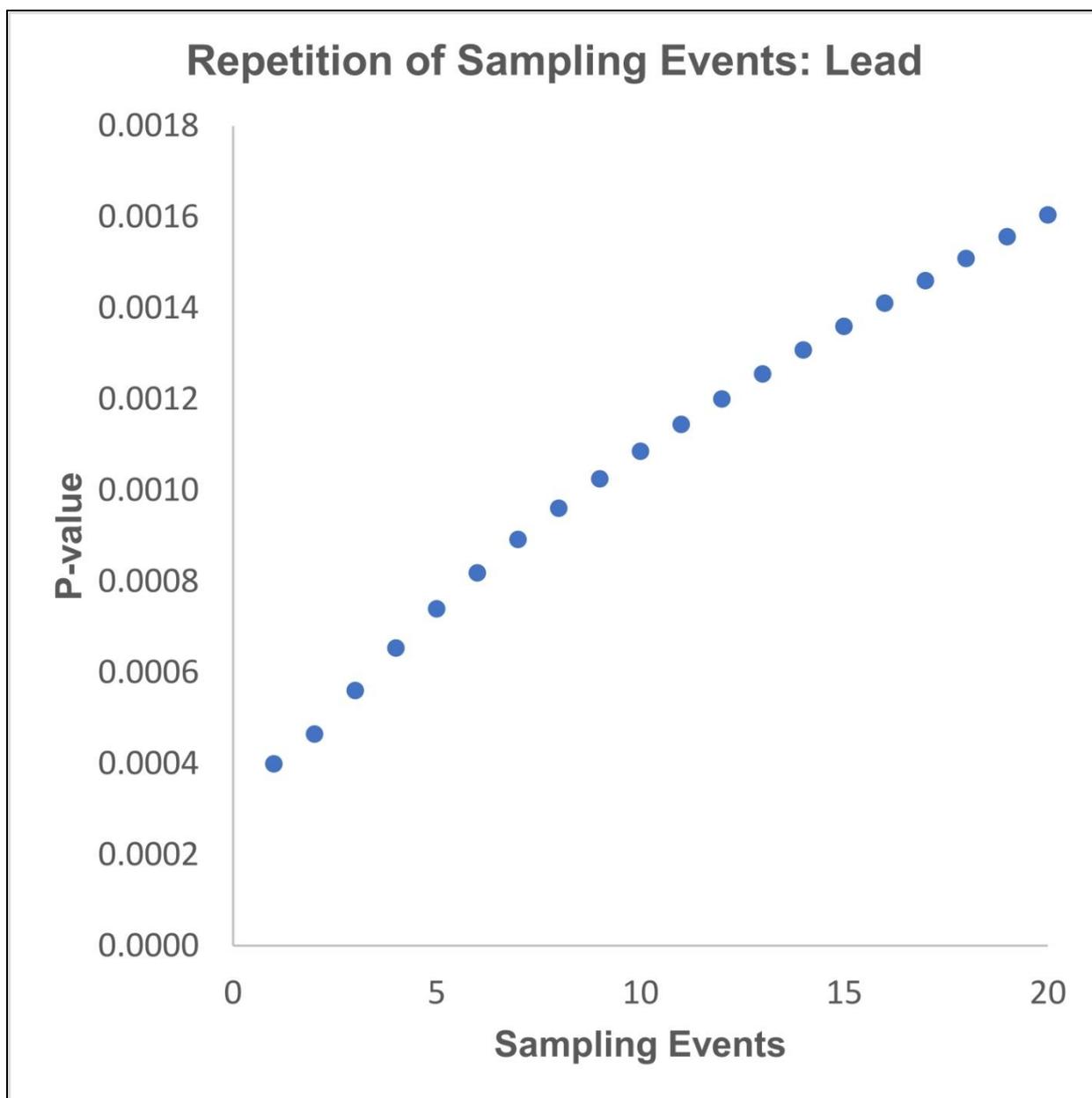


Figure 6b. The integration of the new water quality results from JBS&G (2020b) with the results from previous studies (Swanson, 2019a-b; Emerman, 2019) resulted in a statistically significant increase in aqueous lead from the upstream to the downstream side of the QMM mine with $P = 0.00040$ (see Fig. 5b), corresponding to the first sampling event in the above graph. Repeating those same results (four upstream samples and ten downstream samples, with one upstream $Pb = 0.002$ mg/L, one downstream $Pb = 0.007$ mg/L, and the remaining lead measurements <0.001 mg/L) and integrating them with the existing dataset would only slightly weaken the statistical significance of the detrimental impact to $P = 0.00046$ (slight increase in P). Even 20 such identical sampling events (four upstream samples and ten downstream samples, with one upstream $Pb = 0.002$ mg/L, one downstream $Pb = 0.007$ mg/L, and the remaining lead measurements <0.001 mg/L) would result in $P = 0.0016$. In fact, about 80 repetitions of the single sampling event (constituting 1120 measurements) of JBS&G (2020b) would be required to reach a state of non-statistical significance ($P > 0.05$). The P-value is the probability that the geometric means of the upstream and downstream concentrations are the same. Note that the collection of additional data for the sole purpose of trying to reverse the statistical significance of an existing conclusion is not a recommended procedure.

The above result might seem counter-intuitive because the addition of non-detectable uranium concentrations on the upstream and downstream sides might seem as if it would “bury” or “hide” the effect of the very large uranium concentrations on the downstream side of the mine that were provided by the Rio Tinto QMM mine in an earlier study (Swanson, 2019b). However, those large uranium concentrations do not go away just because non-detectable concentrations are added to the dataset. As discussed in the tutorial, the P-value arises from a comparison of the difference between the means of two populations with the variability within the populations (see Table 2). For this particular body of data, with each additional identical sampling event, the variability within the upstream and downstream populations decreases faster than the geometric means of the upstream and downstream populations approach one another. This phenomenon occurs because of the existence of a set of downstream uranium concentrations (as reported by Swanson (2019b)) that are extremely larger than any that are found on the upstream side of the mine. On that basis, additional sampling events identical to the single sampling event of JBS&G (2020b) could not reverse the statistical significance of the conclusion reached by Emerman (2019) regarding the detrimental impact of the QMM mine on uranium in surface water.

On the other hand, the addition of a hypothetical new dataset equivalent to the dataset of JBS&G (2020b) to the existing datasets from the QMM mine (Swanson, 2019b), the community-collected samples (Emerman, 2019) and the data collected by JBS&G (2020b) would cause the P-value to increase slightly from $P = 0.00040$ (one JBS&G-type sampling event; see Fig. 6b) to $P = 0.00046$ (two JS&B-type sampling events; see Fig. 6b) for the increase in lead concentration from the upstream to the downstream side of the QMM mine. In other words, if the water-quality survey by JBS&G (2020b) were to be repeated, with the exact same results, the statistical significance of the detrimental impact of the QMM mine on lead in surface water would become slightly weaker (see Fig. 6b). However, the addition of 20 such identical sampling events (for example, a water-quality survey like the JSB&G (2020b) survey once a year for 20 years), would cause the P-value to increase to only 0.0016, so that the null hypothesis (no detrimental impact of the QMM mine on lead in surface water) could still be rejected at the 99.84% confidence level. In fact, about 80 repetitions (such as an annual survey every year for the next 80 years) of the single sampling event (constituting 1120 measurements) of JBS&G (2020b) would be required to reach a state of non-statistical significance ($P > 0.05$). As with uranium, this phenomenon occurs because of the existence of a set of downstream lead concentrations (as reported by Swanson (2019b)) that are extremely larger than any that are found on the upstream side of the mine. In summary, just as in the case of uranium, it is not realistic that additional sampling events identical to the single sampling event of JBS&G (2020b) could reverse the statistical significance of the conclusion reached by Emerman (2019) regarding the detrimental impact of the QMM mine on lead in surface water.

DISCUSSION

It should go without saying that new data should always be interpreted in conjunction with or in light of existing data, unless the existing data can be convincingly discredited. However, Rio Tinto has consistently not followed this standard procedure. The first dataset was the water-quality data that the Rio Tinto QMM mine provided to the study by Swanson (2019a-b) that included numerous elevated concentrations of uranium, thorium and lead on the downstream side of the mine. At that time, Rio Tinto (2020a) dismissed the significance of the elevated concentrations by writing, “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.” The second dataset was the additional upstream and downstream samples that the local community provided, so that Emerman (2019) could combine the community-collected samples with the data provided by the QMM mine to show a statistically significant increase in uranium, thorium, and lead from the upstream to the downstream side of the mine. Rio Tinto (2020a) dismissed the combination of the two datasets by writing, “We do not agree that Emerman’s report [2019] sheds new light on this issue.” However, the only substantive criticism of the combination of the two datasets was that “the inclusion of water samples in the downstream set (i.e. sites ostensibly impacted by QMM activities) which are visibly naturally muddy, marsh areas and obviously not sources of community drinking water casts serious doubt on Emerman’s methods and conclusions” (Rio Tinto, 2020a). Neither the third dataset (JBS&G, 2020b) nor the cover letter that accompanies the third dataset (Rio Tinto, 2020b) in any way acknowledges the existence of any other data, but simply states that “all results for community drinking water supply samples were within the relevant WHO guidelines for drinking water quality” (Rio Tinto, 2020b). In fact, JBS&G (2020b) wrote, “The primary objectives of this supplementary analysis were to... Provide an initial assessment of whether concentrations of selected heavy metals are present in potable water supplies at levels that may present an unacceptable risk to consumers; and provide an initial assessment of whether surface water discharging from the Site into the MMM [Mandromondromotra] River is contributing to elevated metals concentrations at the point of discharge, and in downstream locations that may be accessed by the community for potable water supply.” The above objectives certainly imply that Rio Tinto (the clients for the study) were acting as if there were no pre-existing initial assessment.

It is most important that no document from Rio Tinto has ever critiqued the water-quality data that they provided for the study by Swanson (2019a-b). The apparent current practice seems to be to pretend as if the previous data never existed. This attitude is curious because, according to Rio Tinto (2020a), “By contrast [to the study by Emerman (2019)] appropriate comparison samples, along with samples of actual drinking water collection sites, is the focus of the current year-long study being undertaken by JBS&G.” In this respect, it should be noted that many of the sample sites used by JGS&G (2020b) are identical to or very close to the sample sites for the earlier data that Rio Tinto provided to Swanson (2019b), so that Rio Tinto apparently still regards these earlier sites as valid sites for sample collection. In fact, in her review of the report by JBS&G (2020b), Swanson (2020) wrote, “The location of surface water samples is appropriate. I am pleased to see that several locations are co-located with existing QMM monitoring sites.” In addition, although Rio Tinto (2020a) critiqued both the upstream and downstream sites that were chosen by local residents, one of the upstream sites chosen by JBS&G (2020b) is identical with one of the sites chosen by the community (compare SW03 (JBS&G) and M2 (community) in Figs. 3a-b).

By contrast, Emerman (2019) did consider the validity of the first dataset, which was provided by Rio Tinto (Swanson, 2019a-b). The issues were the high detection limits, the dual detection limits for uranium and lead (probably due to the use of two different analytical instruments), and the lack of detail in the methodology. However, by comparison of the data provided by Rio Tinto with the samples collected by the community and analyzed at the University of Utah, Emerman (2019) concluded that the validity of the data from the Rio Tinto QMM mine could not be rejected. In this respect, the validity of a dataset is typically regarded as

a “null hypothesis,” for which overwhelmingly convincing evidence should be required for rejection.

It has already been pointed out that the collection of additional data for the sole purpose of reversing the statistical significance of an existing conclusion is not a recommended procedure. Rio Tinto has never stated that this is their intention. Their intention seems to be to carry out an even less recommended procedure, that is, to start all over and see whether a different result can be obtained by producing a new dataset that does not take existing datasets into account. Whether additional data should be collected after a statistically significant conclusion has been reached depends upon the context of the study and the underlying problem. In these circumstances, enough data have been collected by both the mining company and the community to show the need for Rio Tinto to prevent further discharge of contaminated mine water and to provide appropriate water treatment to the community without further delay, especially considering the potentially serious consequences of uranium and lead poisoning. Bourgault and Orengo (2019) have provided a thorough analysis of the available options for affordable water treatment for the communities in the vicinity of the QMM mine. On that basis, further water-quality analysis should be carried out only as integral parts of programs for preventing further discharge of contaminated mine water and for providing safe drinking water for local residents, and not for making a decision as to whether Rio Tinto is responsible for providing safe drinking water.

CONCLUSIONS

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

- 1) The exclusion of three of the downstream sites that were not potential drinking water sources, as critiqued by Rio Tinto, would actually strengthen the argument of Emerman (2019) that the QMM mine has a detrimental impact on regional water quality. The geometric means of the downstream concentrations would increase from 0.042 mg/L to 0.114 mg/L for dissolved uranium, from 0.049 mg/L to 0.118 mg/L for total uranium, from 0.014 mg/L to 0.026 mg/L for dissolved thorium, from 0.016 mg/L to 0.027 mg/L for total thorium, from 0.0224 mg/L to 0.0367 mg/L for dissolved lead, and from 0.0256 mg/L to 0.0374 mg/L for total lead.
- 2) The integration of the new water quality results from JBS&G (2020b) with the results from previous studies again strengthens the conclusion of Emerman (2019) that the QMM mine has a detrimental impact on water quality with respect to both uranium and lead. The statistical significance of the increase in the geometric means of uranium concentrations from the upstream to the downstream sides strengthened from $P = 0.008$ to $P = 0.003$, while the statistical significance of the increase in the geometric means of lead concentrations from the upstream to the downstream sides strengthened from $P = 0.003$ to $P = 0.0004$.
- 3) Additional water-quality surveys with results identical to those reached by the study by JBS&G (2020b) could never reverse the statistical significance of the conclusion reached by Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to uranium. The water-quality survey by JBS&G (2020b) would have to be repeated about 80 times with the same results in order to reverse the statistical significance of the conclusion reached by Emerman (2019) that the QMM mine has a detrimental impact on regional water quality with respect to lead.

RECOMMENDATIONS

The recommendations of this study are that Rio Tinto initiate, without further delay, programs of preventing further discharge of contaminated mine water and of providing safe drinking water to the communities in the vicinity of the QMM mine. Further water-quality analysis should be carried out only as integral parts of these programs.

ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has 68 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and non-governmental organizations. Dr. Emerman has evaluated proposed and existing mining projects in North America, South America, Europe, Africa, Asia and Oceania, and has testified on mining before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States. Dr. Emerman is the author of the chapter on “Waste Disposal” for the upcoming SME (Society for Mining, Metallurgy and Exploration) Underground Mining Handbook.

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