Evaluation of a Buffer Zone at an Ilmenite Mine operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar

by

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Report to Andrew Lees Trust, submitted May 27, 2018
First, second, third and fourth revisions submitted June 19, July 20, July 26, and August 17, 2018

Introduction

The Andrew Lees Trust (ALT UK) has undertaken advocacy campaigns about the Rio Tinto/QMM mine in Madagascar since 1995 following the tragic death of its namesake, Andrew Lees, whilst filming the imperiled Petriky forest on the island's southeast coastline. The Trust's advocacy work has included promoting communities' rights, amplifying their voice, and undertaking research that can contribute towards accountability processes. Andrew Lees was Director of Campaigns at Friends of the Earth when he went to Madagascar to investigate the Rio Tinto mine (see: **www.andrewleestrust.org/andrew).**

QIT Madagascar Mining S.A. (QMM) is a subsidiary of Rio Tinto (RT), owned 80 per cent by Rio Tinto and 20 per cent by the Government of Madagascar. QMM is mining the mineral ilmenite, an industrial whitener (titanium dioxide) used in a multitude of products from toothpaste to paint. The mine is situated near Ft. Dauphin in the Anosy region, in the south of the island. Operations began in 2005 to dredge sands from 6000 hectares of littoral forest, which will yield an estimated 750,000 tons of the mineral per annum over the 40-year project lifetime.

Questions raised

In March 2017, the Director of The Andrew Lees Trust published an article in The Ecologist[1] raising concerns about QMM's violation of an environmental buffer zone protecting the estuary along the southeast coastline of Madagascar from the QMM mining operation.

The violation of the buffer zone is of concern because it is illegal, and it compromises the protection of Lakes Besaroy and Ambavarano in the estuary where local people fish for food, gather reeds and other water products. There are concomitant questions about the risks of radionuclide-enriched water from mine tailings flowing into the waterways by flooding or seepage.

Villagers in rural Madagascar are totally dependent on access to natural resources for their subsistence and livelihoods. Food supplies are gathered from local forest, land and water sources and, given the lack of economic opportunity for the largely non-literate rural populations, these resources are vital for survival.

Studies undertaken

Questions raised about the violation of the buffer zone at Rio Tinto's AGM in April 2017[2] led to an invitation from Rio Tinto to Andrew Lees Trust to meet and discuss the questions arising. At a meeting on 19th May 2017, Rio Tinto insisted that the Google Earth images used in The Ecologist article could not be considered reliable and proposed a study using an independent provider, such as the International Union for Conservation of Nature (IUCN).

Months later, in December 2017, Rio Tinto informed ALT UK that they had identified a private company, Ozius, to carry out the study. ALT UK insisted on full disclosure of all underlying data, and this was agreed. In March 2018 Ozius delivered their findings to Rio Tinto, which were shared with ALT UK. However, the sharing of underlying data was incomplete and delayed by three months.

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1 https://theecologist.org/2017/apr/03/tall-tales-and-tailings-truth-about-rio-tintos-rare-earth-mine-madagascar

2 *Transcript of questions raised at Rio Tinto AGM 2017, See: http://www.andrewleestrust.org/blog/?p=399 a http://londonminingnetwork.org/2017/04/saving-civilization-the-2017-rio-tinto-agm/*

In the meantime, ALT UK contracted Dr. Steven Emerman, retired from Utah Valley University and an expert in hydrology and geophysics, to carry out an independent review both of the Ozius report findings and the original premise of The Ecologist article. In May 2018, Dr Emerman produced his report, which was shared with Rio Tinto.

Findings

Both the Emerman report and Ozius study confirmed a serious violation of the buffer zone beyond the legal permissions. Referring to both studies, ALT UK again challenged Rio Tinto about the violation and QMM's claims of compliance.

As of the end of August 2018, three months after the Emerman findings were shared with Rio Tinto, the company had not issued a formal statement about the buffer violation; nor had they supplied answers to related questions posed by ALT UK.

The following report by Dr. Emerman was completed in August 2018 after three addenda had been added in order to address rebuttals from Rio Tinto and additional questions from ALT UK.

There is an additional study, also prepared by Dr Emerman, entitled *Risk Assessment for Loss of Radionuclides from Mining Basins operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar. August 2, 2018. Addendum submitted August 21, 2018.*

Both reports, in French and English versions, are available at:
http://www.andrewleestrust.org/andrew.htm

Profile of Dr. Steven H. Emerman

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 and has 66 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining on behalf of mining companies, as well as governmental and nongovernmental organizations.

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Explanation of Revisions

The first revision includes an addendum with a rebuttal to the response of Rio Tinto to the original report. The second revision includes a second addendum that addresses the additional data that were released by Rio Tinto following the first revision. The third and fourth addenda address additional questions from Andrew Lees Trust.

Lightning Summary

Rio Tinto operates an ilmenite mine within the bed of the estuary Lake Besaroy, southeastern Madagascar, in violation of the legal requirement of an 80-m undisturbed buffer zone from a natural water body. The dam separating the mining basin from the rest of the lake does not meet generally accepted safety guidelines.

Abstract

Andrew Lees Trust has claimed that an ilmenite mine operated by Rio Tinto along the shores of the estuaries Lakes Besaroy and Ambavarano, southeastern Madagascar, has encroached upon the legally required 80-m undisturbed buffer zone from a natural water body, and has questioned the safety of the dam that separates the mining basin from the lakes. Rio Tinto responded that the dam has a factor of safety of 1.3 in a 50-year storm, which is probably equivalent to the single safety criterion of a 270-year storm event. In addition, Rio Tinto contracted with Ozius Spatial to evaluate their compliance with the buffer zone based upon a Lidar survey conducted by Rio Tinto and the assumption that the lake level is 0.6 meters above sea level. Ozius Spatial showed significant encroachment of mining infrastructure well below the 0.6-m contour, which Rio Tinto falsely claimed was permitted under their agreement with the National Office of the Environment. In this study, the compliance with the 80-m buffer zone was re-evaluated using publicly available elevation data from the 30-m Shuttle Radar Topography Mission. Those data showed that mining infrastructure has been constructed within 24.1 meters of visible water and within 66.6 m of the 0.6-m contour. Moreover, the lake level is closer to 4.6 meters above sea level, so that a significant portion of the mining operation has filled in the lake bed. The (U.S.) Federal Emergency Management Agency recommends that, if the failure of a dam would be expected to result in the loss of at least one human life, the dam should be designed to accommodate the Probable Maximum Flood (PMF), which is significantly rarer than even a 10,000-year storm. Moreover, it is not clear from the documents provided by Rio Tinto that the dam was designed to actually meet any safety criteria.

Introduction

Rio Tinto is currently operating an ilmenite mine on the shores of Lakes Besaroy and Ambavarano in southeastern Madagascar for the manufacture of titanium dioxide (see Fig. 1). The ilmenite is extracted from mineralized sands by creating a shallow (5-15 m deep) water-filled basin and then physically separating the ilmenite using a floating dredge plant (QIT Madagascar Minerals, 2015; Randriantseheno et al., 2015). Extraction of the ilmenite results in the concentration of the minerals monazite and zircon, which are enriched in the radionuclides thorium and uranium. These enriched minerals accumulate in the mining basin and would pose a significant threat to both human and aquatic life if they were released into the neighboring lakes or the adjacent Rivière a Méandre.

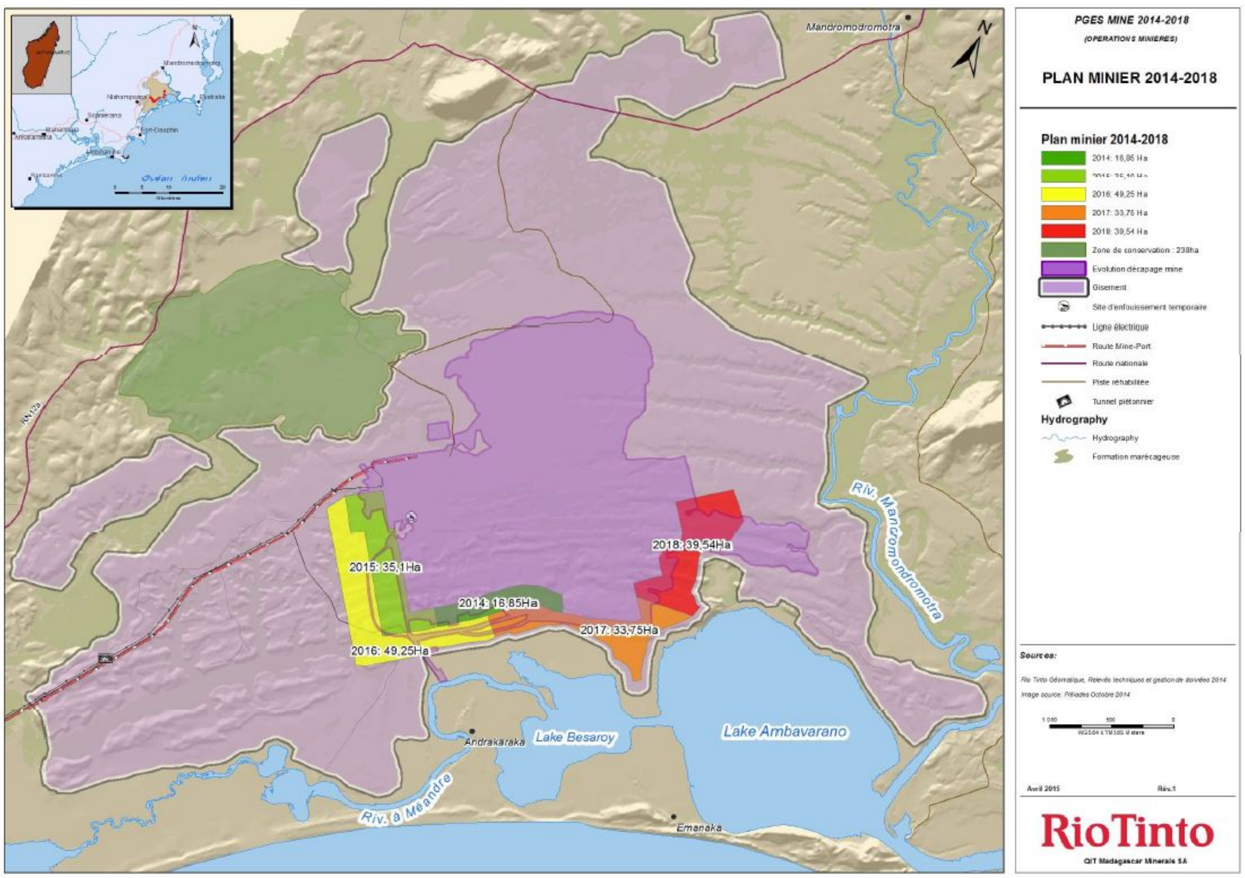

Figure 1. Rio Tinto is currently operating an ilmenite mine along the shores of Lakes Besaroy and Ambavarano in Madagascar. A by-product of the extraction process is the concentration of the radionuclide-enriched minerals monazite and zircon, which would pose a significant threat to aquatic and human life if they were released into the lakes or the adjacent Rivière a Méandre. Mining operations in Madagascar are legally required to maintain an 80-m undisturbed buffer zone from any natural water body. Map from QIT Madagascar Minerals (2015).

The primary environmental threat is that an extreme precipitation event could cause the mining basin to overflow and spill radionuclide-enriched water into the adjacent water bodies. Even without overflowing, a rise in the water level of the mining basin above the level of the lakes or river would cause seepage from the mining basin into the nearby water bodies. Since the mining basin has no surface outlet, a major precipitation event would result in a rise in the water level of the mining basin that would be faster than a rise in the lakes or river. (Note that the lakes are actually estuaries connected to the Indian Ocean, see Fig. 1.)

In order to mitigate this and other environmental threats, the law in Madagascar requires maintenance of an 80-m undisturbed buffer zone between a mining operation and any natural water body. Andrew Lees Trust (Orengo, 2017) has produced a series of Google Earth images in order to claim that Rio Tinto has constructed mining infrastructure within the 80-m buffer zone, has filled in the lake in order to move the buffer zone in the direction of the lake (see Fig. 2A), and has constructed road access on what was originally the lake bed (see Fig. 2B). Andrew Lees Trust (Orengo, 2017) also questioned whether the dam that separated the mining basin from the lake was “robust enough” to prevent the transfer of radionuclide-enriched water from the mining basin to the lakes (see Fig. 3).

Figure 2A. Andrew Lees Trust (Orengo, 2017) has used Google Earth images to claim that Rio Tinto has constructed mining infrastructure within the 80-m undisturbed buffer zone (left-hand photo) and has filled in the lake to order to move the buffer zone in the direction of the lake (right-hand photo). The location of these images is equivalent to Site 2 of Ozius Spatial (2018) (see Figs. 4, 5A, 7A-B).

Rio Tinto responded to the allegations and concerns from Andrew Lees Trust in a four-page memorandum (Rio Tinto, 2017) with references to an earlier document in French (QIT Madagascar Minerals, 2015). According to a 2014 agreement between Rio Tinto and the National Office of the Environment (ONE), Rio Tinto was permitted to construct a “lake protection berm” on the 80-m undisturbed buffer zone, so that the crest of the berm could be 50 meters from the lake (see Fig. 3). (The use by Rio Tinto of the word “berm” will be critiqued in the Results section.) The “berm” could also serve as a platform for pipes, anchors and mobile equipment supporting the floating dredge plant. The agreement provided for five exceptions where dredging was allowed within 50 meters of the natural water bodies (see Fig. 4). No explanation has ever been provided as to why these five exceptions were made. The memorandum confirmed that “no mining activities are allowed in the 50 m closest to the water body” (Rio Tinto, 2017).

The memorandum (Rio Tinto, 2017) explained that the position of the natural water bodies is set by their Ordinary High Water Mark (OHWM). (The OHWM of an estuary is the level of the mean high tide in the absence of storm activity.) The OHWM was set as 0.6 meters above sea level using elevation data obtained from a Lidar survey carried out by Rio Tinto in 2012. No document from Rio Tinto has ever explained the methodology that was used to determine the OHWM. Moreover, Rio Tinto has repeatedly refused to release the Lidar elevation data for an independent verification of the OHWM.

Figure 2B. Andrew Lees Trust (Orengo, 2017) has used Google Earth images to claim that road access has been constructed on what was originally the lake bed. The location of these images is equivalent to Site 2 of Ozius Spatial (2018) (see Figs. 4, 5A, 7A-B).

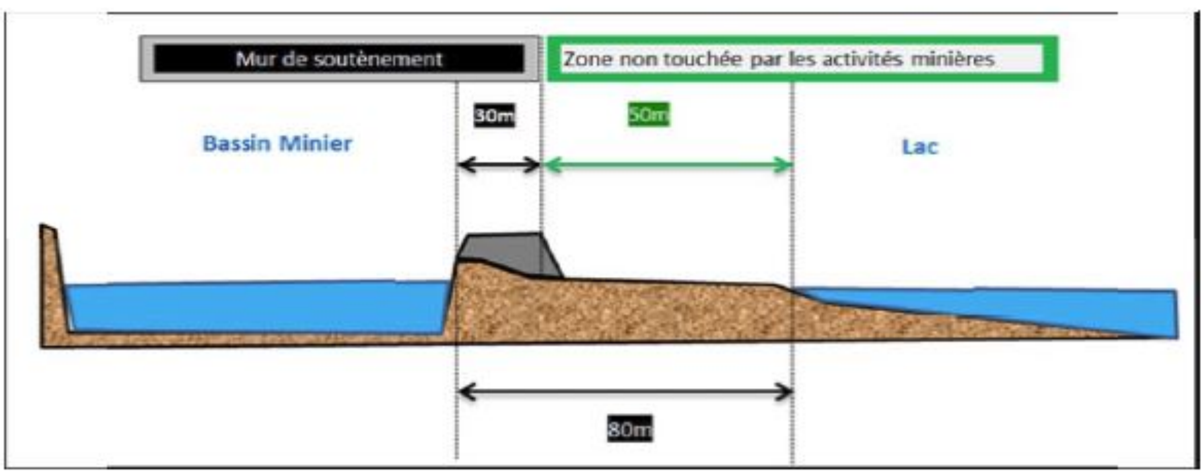

Figure 3. In order to prevent water movement from the mining basin into the lake or river, an 80-m undisturbed buffer zone is preserved between the mining basin and the water bodies. In addition, the water level in the mining basin is maintained 1-2 meters below the surface of the natural water bodies. Under an agreement between Rio Tinto and the National Office of the Environment (ONE), a 30-m wide, 4-m high earthen dam has been built on top of the undisturbed buffer zone. Diagram from QIT Madagascar Minerals (2015).

The “lake protection berm” is 4 meters high and 30 meters wide (QIT Madagascar Minerals, 2015, see Fig. 3) and was designed with a factor of safety of 1.3 for a 50-year flood (Rio Tinto, 2017). In addition, the water level in the mining basin is maintained 1-2 meters below the surface of the natural water bodies and 3 meters below the elevation of the adjacent topography (QIT Madagascar Minerals, 2015). According to QIT Madagascar Minerals (2015), the water level in the mining basin could not be maintained at any lower level without significant influx of groundwater into the mining basin. No document from Rio Tinto has provided any further information regarding the design or construction of the "berm."

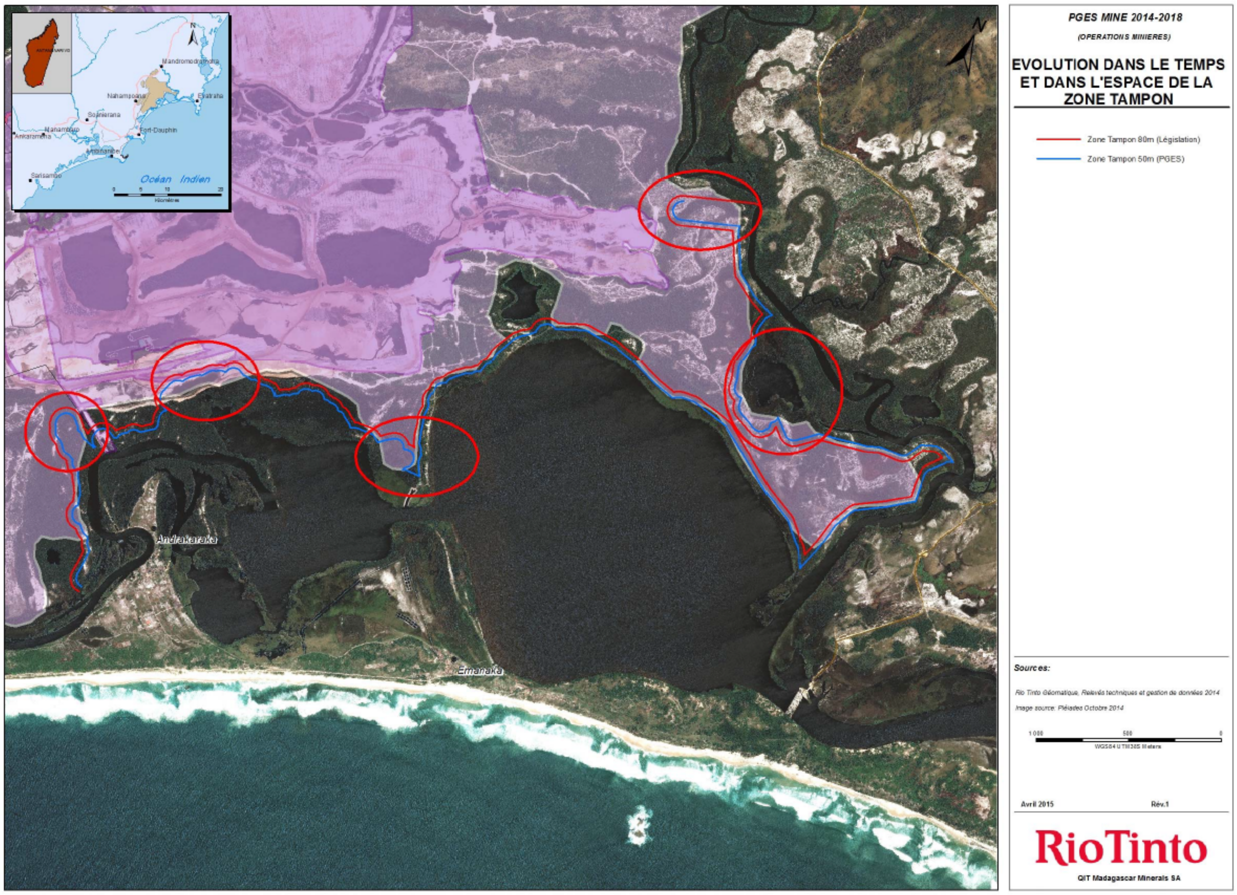

Figure 4. Under an agreement between Rio Tinto and the National Office of the Environment (ONE), there are five sites (indicated with red ellipses) where dredging is permitted up to 50 meters from a natural water body. These five sites are the only sites for which Rio Tinto contracted with Ozius Spatial to investigate compliance with the legally-mandated undisturbed buffer zone. Ozius Spatial (2017, 2018) labeled the sites as Sites 1-5 starting with the westernmost site and numbering counterclockwise (see Figs. 5A-C). Figure from QIT Madagascar Minerals (2015).

Rio Tinto contracted with Ozius Spatial to evaluate their compliance with the legally-required buffer zone only at the five exceptions where dredging was permitted within 50 meters of a natural water body (see Fig. 4) and at no other sites. The proposal (Ozius Spatial, 2017) and the final report (Ozius Spatial, 2018) from Ozius Spatial are discussed separately as they are very different documents with different methodologies. Ozius Spatial (2017) repeated the claim from Rio Tinto that the Google Earth satellite images presented by Andrew Lees Trust (Orengo, 2017) were obtained at unusually high stands of the lake level, so that it only appeared as if the construction of mining infrastructure had taken place within the buffer zone. Ozius Spatial (2017) proposed to use hydrologic modeling to predict the time series of lake levels in order to determine what the lake levels would have been at the times that the Google Earth images were obtained. Local precipitation data, Lidar topography and land use patterns would be used to predict surface runoff into the lakes. Piezometer data (water levels in wells) would be used to predict groundwater seepage into or out of the lakes. The modeling was to be carried out using Naxia, their proprietary land management software package. Although it was not stated in the proposal, presumably, hydrologic modeling was necessary because they assumed that there had been no monitoring of the lake levels. (See further discussion of lake gauge data in the Discussion section.)

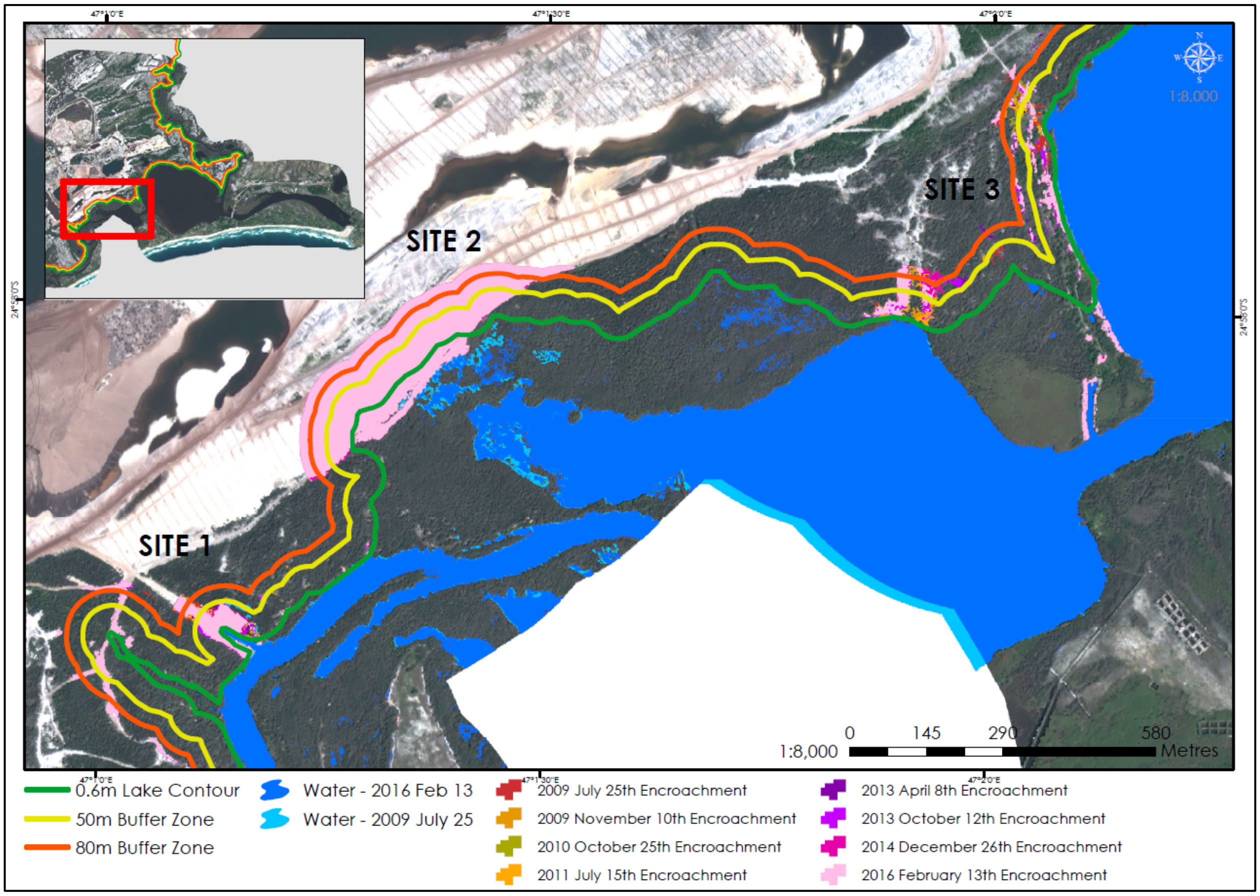

Figure 5A. Using satellite images and a 2012 Lidar survey (Rio Tinto, 2017), Ozius Spatial (2018) documented encroachment into the buffer zone at Sites 1-3 under the assumption that the Ordinary High Water Mark (OHWM) of the lake occurred at 0.6 meters above sea level. Although Rio Tinto (2018) claimed that the encroachment of mining infrastructure at Site 2 was permitted under the agreement with the National Office of the Environment (ONE), the figure shows that the infrastructure was constructed onto the lake bed itself (below the 0.6-m contour). Figure from Ozius Spatial (2018).

The final report by Ozius Spatial (2018) did not mention any hydrologic modeling, but only the interpretation of satellite images using simple measurement tools. Although they presumably did use their proprietary software, the same analyses could have been carried out using any mapping software, such as the free mapping software QGIS (QGIS, 2018). Ozius Spatial (2018) did not provide any information regarding their methodology or the sources of their satellite images. Using the Lidar elevation data provided by Rio Tinto and the assumption that the lake level was the 0.6-m contour, Ozius Spatial (2018) documented encroachment below the 0.6-m contour (onto the lake bed) at the sites of all five exceptions and at a sixth site of their choosing (see Figs. 5A-C, Fig. 6). Ozius Spatial (2017, 2018) labeled the five exceptions as Sites 1-5 starting with the westernmost site and numbering counterclockwise (see Figs. 4, 5A-C).

(Note that the sites are mislabeled in Fig. 1 of the proposal (Ozius Spatial, 2017) and in Figs. 1 and 3 of the final report (Ozius Spatial, 2018)). The Google Earth images presented by Andrew Lees Trust (Orengo, 2017, see Figs. 2A-B) are equivalent to Site 2 in Ozius Spatial (2017, 2018, see Figs. 4 and 5A). At this Site 2 (see Fig. 5A), Ozius Spatial (2018) documented significant encroachment of the mining infrastructure onto the lake bed itself (below the 0.6-m contour), constituting an even more egregious violation of the buffer zone than had been claimed by Andrew Lees Trust (2017). Ozius Spatial (2018) mentioned the existence of lake gauge data, but did not use or present those data. The final report did not mention any precipitation or piezometric data.

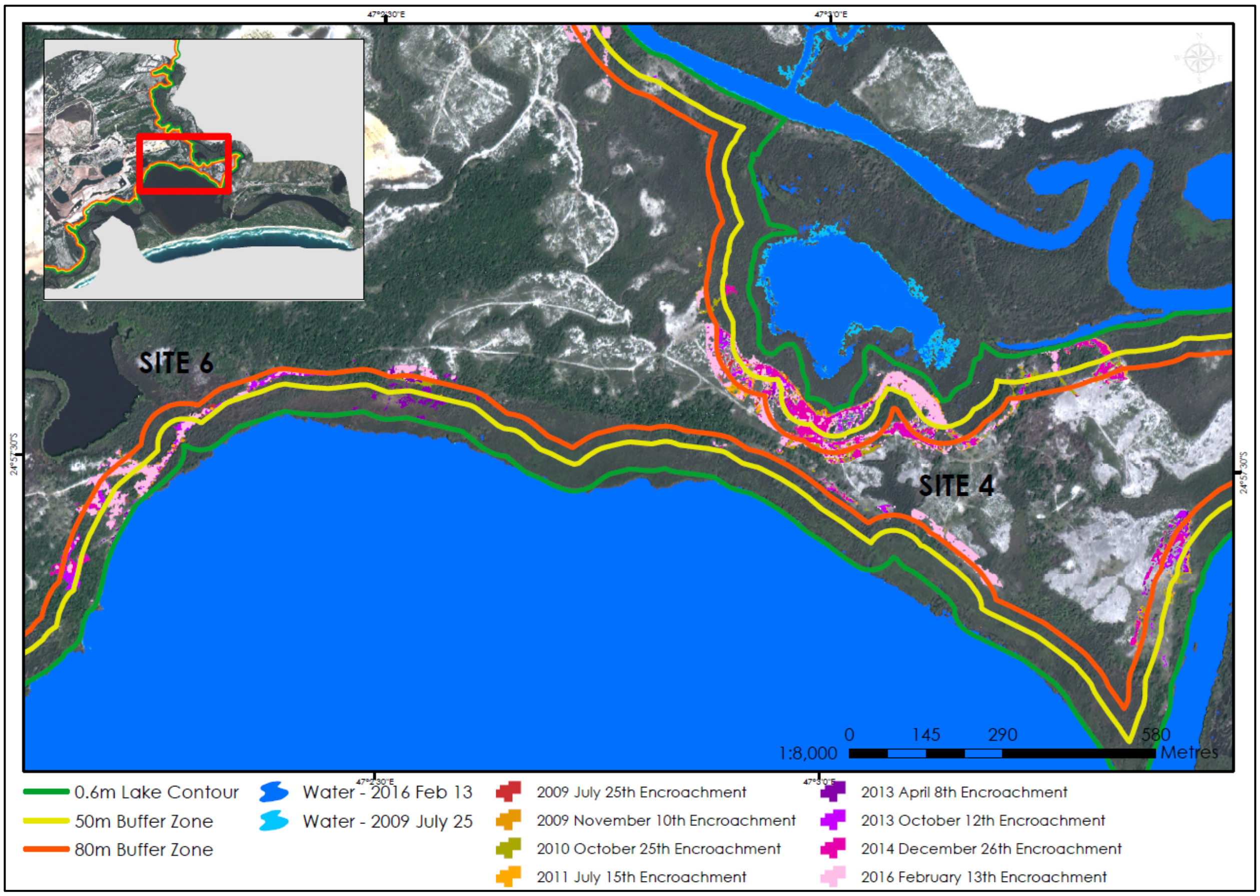

Figure 5B. Using satellite images and a 2012 Lidar survey (Rio Tinto, 2017), Ozius Spatial (2018) documented encroachment into the buffer zone at Site 4 and an additional Site 6 (not requested by Rio Tinto for investigation of compliance) under the assumption that the Ordinary High Water Mark (OHWM) of the lake occurred at 0.6 meters above sea level. According to Rio Tinto (2018), no mining activities have occurred at either Sites 4 or 6. Figure from Ozius Spatial (2018).

Rio Tinto (2018) provided their interpretation of the report by Ozius Spatial (2018) in a one-page memorandum. According to that memorandum, the encroachment at Site 1 was "road access to the meander pump which was allowed per the SEMP [Social and Environmental Management Plan]." Site 2 was "already identified in the SEMP [as an area] where a secondary berm was built and used as secondary protection of the ecosystem and as community access. After that, tails were stacked to provide material to build the berm as specified." The encroachment as Site 3 was due to "access for communities using boats to cross [Lake Besaroy] and using the lagoon system." According to Rio Tinto (2018), the encroachment at Sites 4-6 was irrelevant because no mining activities had yet been conducted at those sites.

The objectives of this study were to answer the following questions:

1) Are the proposal and final report from Ozius Spatial based upon sound hydrologic principles?
2) Did Rio Tinto correctly interpret the final report from Ozius Spatial?
3) Do publicly available elevation data show compliance by Rio Tinto with the legal requirement of an undisturbed buffer zone?
4) Is the design of the "lake protection berm" consistent with generally accepted safety guidelines?

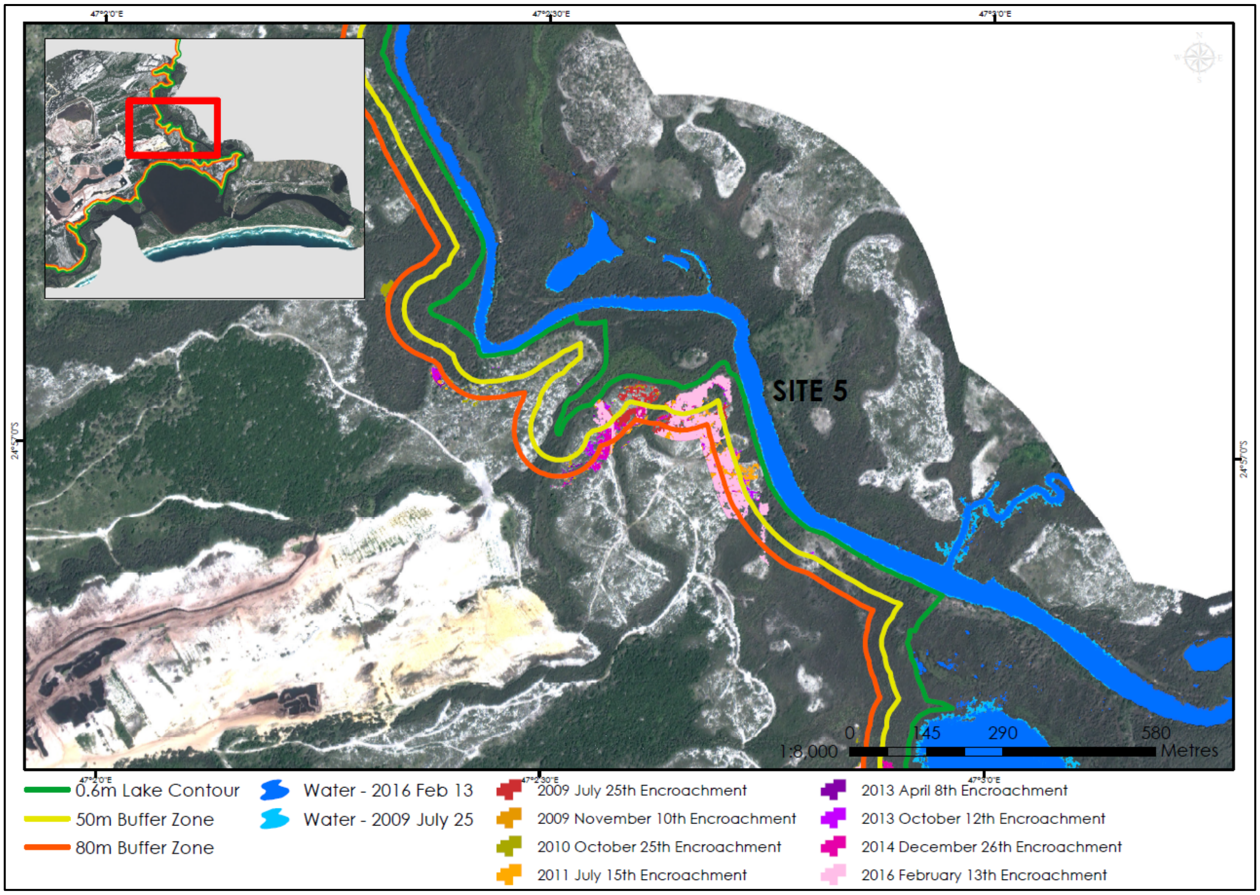

Figure 5C. Using satellite images and a 2012 Lidar survey (Rio Tinto, 2017), Ozius Spatial (2018) documented encroachment into the buffer zone at Site 5 under the assumption that the Ordinary High Water Mark (OHWM) of the lake occurred at 0.6 meters above sea level. According to Rio Tinto (2018), no mining activities have occurred at Site 5. Figure from Ozius Spatial (2018).

Site 1	Epochs 2009 – 2016							
Buffer zone	25-Jul-09	10-Nov-09	25-Oct-10	15-Jul-11	8-Apr-13	12-Oct-13	26-Dec-14	13-Feb-16
BZ_80_100 (m^2)	688	557	351	397	441	663	467	3164
BZ_50_80 (m^2)	1016	653	579	654	474	576	557	1797
BZ_0_50 (m^2)	4687	4266	4169	4551	4604	4534	4225	6377
BZ_<0 (m^2)	0	0	0	0	0	0	361	508

Site 2	Epochs 2009 – 2016							
Buffer zone	25-Jul-09	10-Nov-09	25-Oct-10	15-Jul-11	8-Apr-13	12-Oct-13	26-Dec-14	13-Feb-16
BZ_80_100	1280	954	1161	1975	4917	9411	14631	14476
BZ_50_80	2914	1981	1695	2028	7163	10776	18503	18382
BZ_0_50	0	29	20	13	3573	8635	23158	23086
BZ_<0	0	0	0	0	0	0	10399	10693

Site 3	Epochs 2009 – 2016							
Buffer zone	25-Jul-09	10-Nov-09	25-Oct-10	15-Jul-11	8-Apr-13	12-Oct-13	26-Dec-14	13-Feb-16
BZ_80_100	947	4	514	700	519	440	860	805
BZ_50_80	1253	620	1969	1833	1609	1871	1694	1903
BZ_0_50	4219	2585	3061	2865	342	3458	1465	3945
BZ_<0	0	0	0	0	0	0	1918	2159

Site 4	Epochs 2009 – 2016							
Buffer zone	25-Jul-09	10-Nov-09	25-Oct-10	15-Jul-11	8-Apr-13	12-Oct-13	26-Dec-14	13-Feb-16
BZ_80_100	4243	3089	7740	5457	5757	5455	4520	10506
BZ_50_80	3999	2543	6444	5607	5362	5263	3954	6318
BZ_0_50	6689	3868	6339	6781	5116	6369	6124	6569

Site 5	Epochs 2009 – 2016							
Buffer zone	25-Jul-09	10-Nov-09	25-Oct-10	15-Jul-11	8-Apr-13	12-Oct-13	26-Dec-14	13-Feb-16
BZ_80_100	1537	623	1274	4204	1698	2302	1098	3992
BZ_50_80	4372	1282	920	4276	2337	2731	2297	6117
BZ_0_50	2740	991	1163	1973	975	2620	2170	4072

Figure 6. Using satellite images and a 2012 Lidar survey (Rio Tinto, 2017), Ozius Spatial (2018) documented the spatial extent of encroachment at Sites 1-5 on eight dates in the four categories of BZ_80_100 (80-100 meters from the 0.6-m contour), BZ_50_80 (50-80 meters from the 0.6-m contour), BZ_0_50 (0-50 meters from the 0.6-m contour), and BZ_<0 (below the 0.6-m contour). Encroachment into the lake bed (below the 0.6-m contour) has occurred at all five sites.

Methodology

The proposal and report from Ozius Spatial (2017, 2018) and the interpretation by Rio Tinto were evaluated using documents already mentioned and elementary principles of hydrology. The safety of the "berm" was assessed by comparing the descriptions of the mining basin and dam in documents produced by Rio Tinto (QIT Madagascar Minerals, 2015; Rio Tinto, 2017) with guidelines from the (U.S.) Federal Emergency Management Agency (2013), U.S. Bureau of Reclamation (1987), and U.S. Army Corps of Engineers (USACE, 1991, 2014). Earlier evaluations of the safety of the "berm" and the Ozius Spatial (2017) proposal in both English and French were produced by Emerman (2017, 2018a-b).

The compliance by Rio Tinto with the legal requirement of an undisturbed buffer zone was evaluated by combining Google Earth satellite images with the 30-m elevation data obtained by the Shuttle Radar Topography Mission (NASA, 2018), which was downloaded from Watkins (2018). Measurements and contouring were carried out using ESRI ArcMap 10.6 Spatial Analyst, although the same operations could easily have been done with the free mapping software QGIS (QGIS, 2018). Contouring was done with maximum accuracy and minimum smoothing (see Fig. 7A). Care was taken to ensure that all parts of a Google Earth satellite image were obtained on the same date, the need for which was emphasized by Ozius Spatial (2017, 2018). The satellite elevation data that were used are the most accurate publicly available data at the present time. Higher-resolution Lidar elevation data have been obtained by Rio Tinto (2017), but as mentioned previously, Rio Tinto refuses to release those data.

Results

Critique of Proposal and Final Report by Ozius Spatial (2017, 2018)

Ozius Spatial (2017) described their proprietary software, Naxia, as a "land management and environmental monitoring solution." Although the proposal referred the reader to a video about Naxia, the video provided very little information about what the software does or how it works. On the other hand, the hydrologic modeling described in the proposal could easily be carried out using well-established algorithms that are available in open-source software such as SWAT (Soil & Water Assessment Tool), which was jointly developed by the USDA (U.S. Department of Agriculture) Agricultural Research Service and Texas A&M University (2018). The SWAT package can calculate surface runoff using either the Green-Ampt or the Curve Number Infiltration Methods and calculates groundwater movement using the MODFLOW code (Texas A&M, 2018). The above well-known methods have been verified through thousands of studies. The use of open-source software would allow any person who was competent in hydrology to verify the calculations and then be either persuaded or not persuaded regarding compliance by Rio Tinto.

The input data that Ozius Spatial (2017) intended to use for their hydrologic modeling did not include evaporation data or any meteorological variables, such as air temperature, water temperature, relative humidity, or wind speed, that could be used to predict evaporation. In fact, there was no mention of evaporation anywhere in the proposal. Presumably, the model was going to assume that evaporation is zero. Evaporation is a significant part of the hydrologic cycle in a tropical climate, so that neglecting evaporation will lead to lake level predictions that are systematically too high. In addition, since the lakes are estuaries that are connected to the Indian

Ocean, the transfer of water between the lakes and ocean must be taken into account. The proposal did not include any mention of the sea surface elevation data that would make those calculations possible.

The time-series modeling approach (a day-to-day prediction of lake levels) that was proposed by Ozius Spatial (2017) could not be carried out without local precipitation data. The proposal stated simply that "Ozius will request the supply of the…data for commencement of the project." Presumably, the data were to be requested from Rio Tinto, since the proposal did not mention any source of governmental or publicly available data. In fact, daily meterological data for the past 45 years, including precipitation, temperature, wind speed and dew point, could be downloaded for the weather station at Taolognaro, only 8.0 kilometers southwest of the Rio Tinto mine, from the web site of the National Climatic Data Center (NOAA-NESDIS-NCDC, 2018).

It is important to recall that the purpose of the proposal was to pass judgement as to whether Rio Tinto has been providing accurate information regarding their compliance with the legally-mandated undisturbed buffer zone. Certainly, Rio Tinto knows whether they have been creating infrastructure on the lakeward side of the buffer zone or filling in the lake or constructing road access on the former lake bed. On that basis, the judgement cannot be based on the presumption that Rio Tinto provides accurate information. If Rio Tinto is capable of providing false information regarding their compliance with legal requirements, then certainly they are capable of providing Ozius Spatial with the input data that would demonstrate their compliance. It would simply be a matter of adjusting rainfall upward so as to predict higher lake levels than actually occurred. In my opinion, carrying out hydrologic modeling using only data provided by Rio Tinto, with no independent verification of those data, would do more harm than good.

The final concern regarding the proposal by Ozius Spatial (2017) is that day-to-day prediction of lake levels is completely irrelevant to the determination of compliance by Rio Tinto with the requirement of an undisturbed buffer zone. Compliance is not based upon the separation between the mining operation and the lake on any particular day, but on the separation between the mining operation and a particular elevation contour that defines the OHWM. Presumably, Ozius Spatial came to the same conclusion because there was no mention of either hydrologic modeling or the necessary input data in their final report (Ozius Spatial, 2018). However, it was important to critique the hydrologic modeling approach in order to prevent a repetition of this type of proposal.

In the end, I am in agreement with both the approach and the conclusions of the final report (Ozius Spatial, 2018) with two caveats. There was no challenge by Ozius Spatial to the assumptions provided to them by Rio Tinto. The first assumption was that the 0.6-m contour is the proper elevation for assessing compliance with the undisturbed buffer zone. The second assumption was that the only areas of interest were the five exceptions, where Rio Tinto was permitted to dredge up to 50 meters from the lake (see Figs. 4, 5A-C). It is mysterious as to why Ozius Spatial (2018) chose to study an additional Site 6 (see Fig. 5B), but no other site. In summary, there is not much wrong with the final report by Ozius Spatial (2018). The problem is with the interpretation of the report by Rio Tinto (2018).

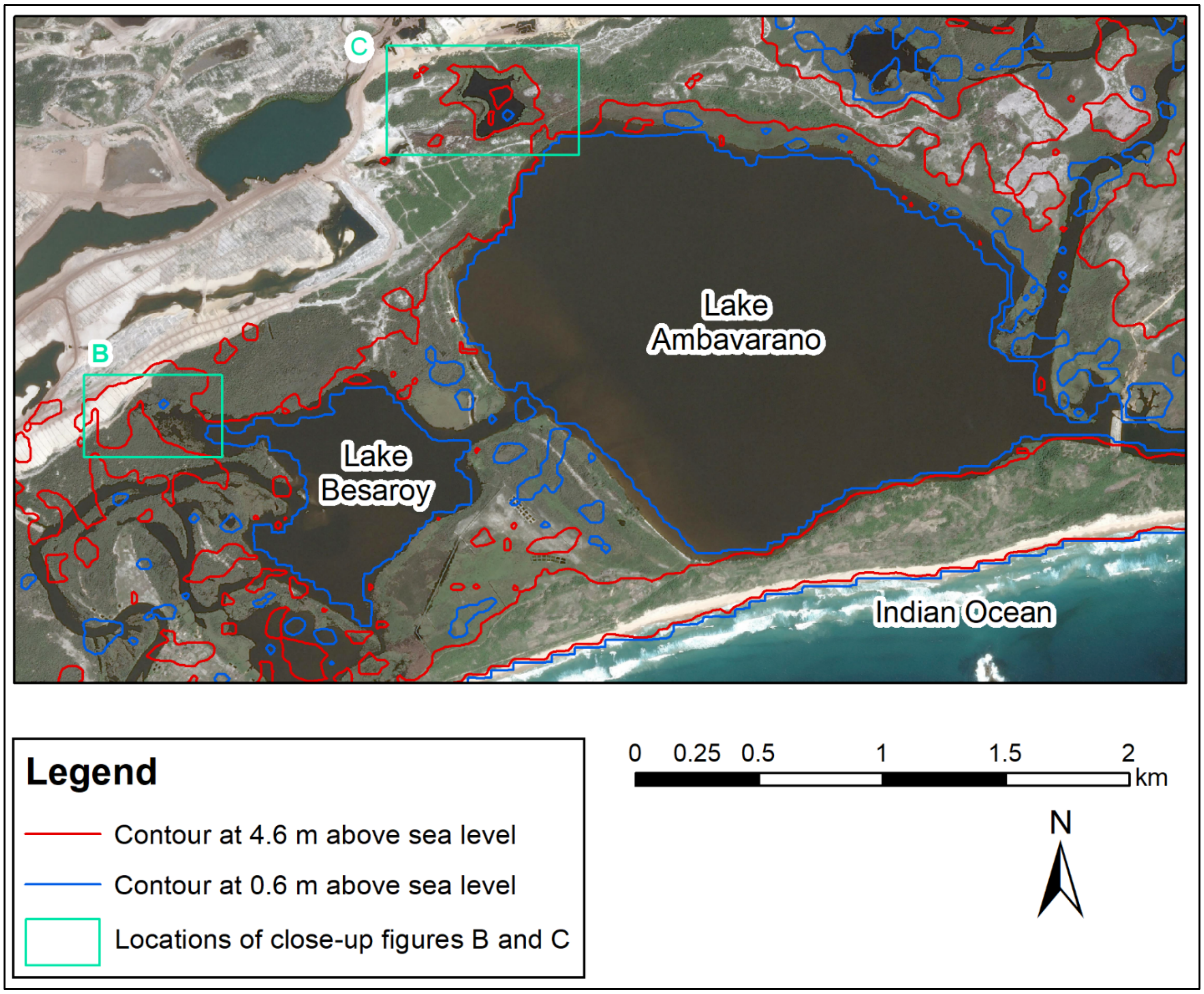

Figure 7A. Compliance of Rio Tinto with a legally-mandated 80-m undisturbed buffer zone from a natural water body was investigated by combining a satellite image from Google Earth dated February 12, 2016, with 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018). Contouring was carried out using ArcMap 10.6 Spatial Analyst with maximum accuracy and minimum smoothing. Although the contouring could be more accurate if results of the higher-resolution 2012 Lidar survey were used, Rio Tinto has repeatedly refused to release those data. The green rectangles are the perimeters of the close-ups shown in Fig. 7B (equivalent to Site 2 of Ozius Spatial (2018, see Figs. 4 and 5A) and the location of the Google Earth images shown by Orengo (2017, see Figs. 2A-B)).

Critique of Interpretation from Ozius Spatial (2018) by Rio Tinto (2018)

The interpretation of the report from Ozius Spatial (2018) by Rio Tinto (2018) was a complete contradiction of their earlier memorandum (Rio Tinto, 2017). Rio Tinto (2018) stated with regard to Site 2 (see Figs. 2A-B, 4, 5A) that a “secondary berm was built and used as secondary protection of the ecosystem.” There was no explanation as to what was meant by a “secondary berm” or “secondary protection.” Rio Tinto (2018) continued with regard to Site 2, “After that, tails were stacked to provide material to build the berm as specified.” There was no explanation as to what was meant by “tails.” Rio Tinto (2018) completely ignored that fact that Ozius Spatial (2018) showed significant encroachment of mining infrastructure below the 0.6-m contour (see Fig. 5A, 6), that is, onto the lake bed itself, as it had been defined by Rio Tinto

(2017). The earlier memorandum explicitly stated that “no mining activities are allowed in the 50 m closest to the water body” (Rio Tinto, 2017).

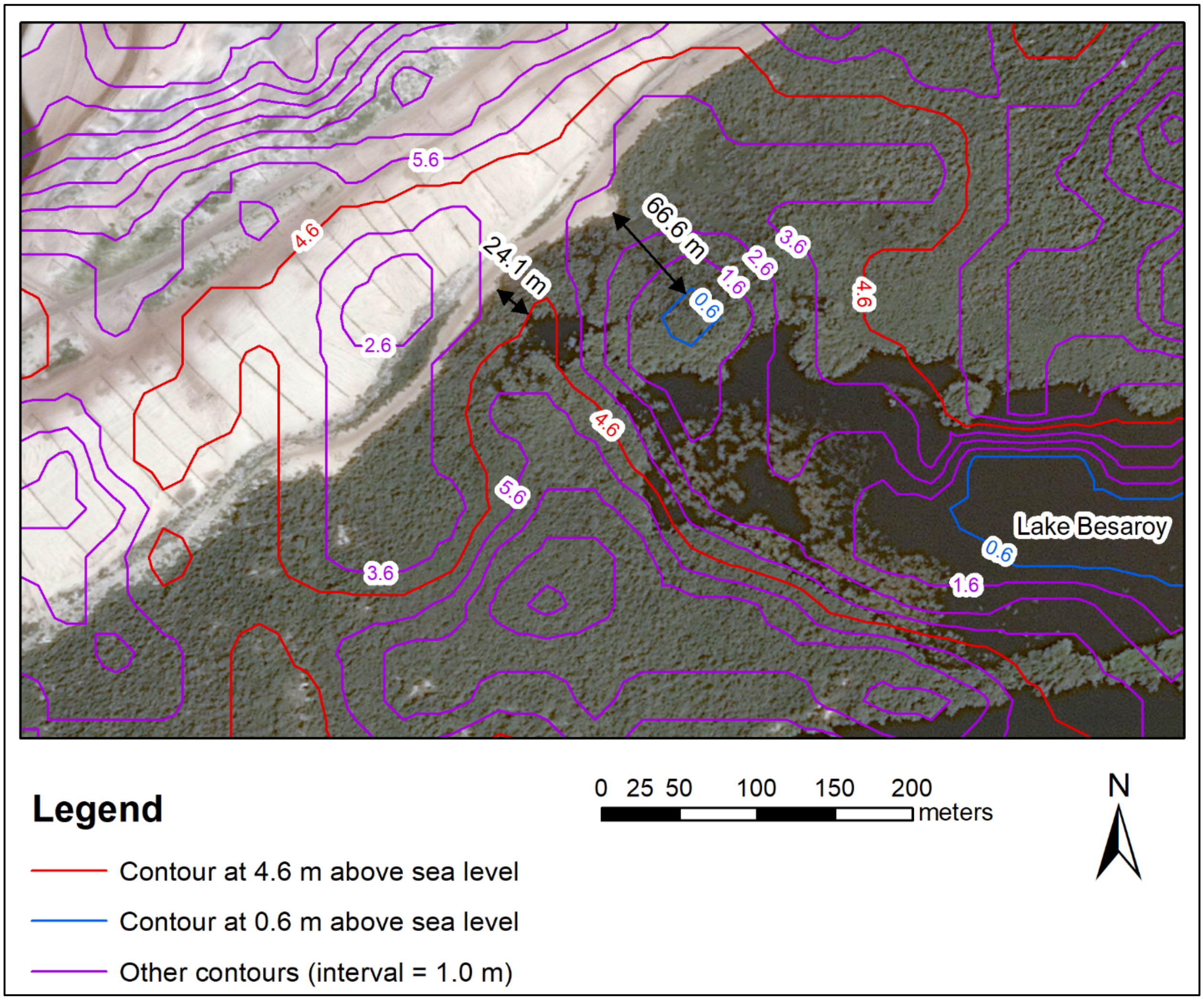

Figure 7B. Rio Tinto has created mining infrastructure within 24.1 meters of a natural water body, in violation of the legally-required 80-m buffer zone. Note that Rio Tinto is out of compliance even taking into account that the National Office of the Environment (ONE) has permitted dredging at this site within 50 meters of a natural water body (see Figs. 4 and 5A). Moreover, the contours indicate that the natural water bodies occur far higher than 0.6 meters above sea level, and that the Ordinary High Water Mark (OHWM) of the lake is closer to 4.6 meters above sea level. Even if the assignment of Rio Tinto (2017) of 0.6 meters above sea level is used as the OHWM, mining infrastructure has been created 66.6 m from the 0.6-m contour. If the 4.6-m contour is used as the OHWM, then a significant amount of mining infrastructure has been built onto the lake bed. Although the contouring could be more accurate if results of the higher-resolution 2012 Lidar survey were used, Rio Tinto has repeatedly refused to release those data. This location is equivalent to Site 2 of Ozius Spatial (2018, see Figs. 4 and 5A) and the location of the Google Earth images shown by Orengo (2017, see Figs. 2A-B)).

Re-evaluation of Compliance with Undisturbed Buffer Zone using Publicly Available Data

Combining a satellite image from Google Earth dated February 12, 2016, with 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018) shows unquestionable mining infrastructure in close proximity to natural water bodies at Rectangles B and C (see Fig.

7A). Rectangle B is equivalent to Site 2 of Ozius Spatial (2017, 2018, see Figs. 4, 5A), which is equivalent to the location of the Google Earth images shown by Andrew Lees Trust (Orengo, 2017, see Figs. 2A-B). Rectangle C is upslope from Site 6 of Ozius Spatial (see Fig. 5B). Numerous spots of disturbed ground are visible between the lakes and the mining operation (see Fig. 7A). As pointed out by Ozius Spatial (2018) and Rio Tinto (2018), it can be difficult to distinguish disturbance from mining activities from disturbance by construction of community access paths, deforestation or forest fires. However, "unquestionable" mining infrastructure is easily distinguished by its continuity with the rest of the mining operation (see Fig. 7A).

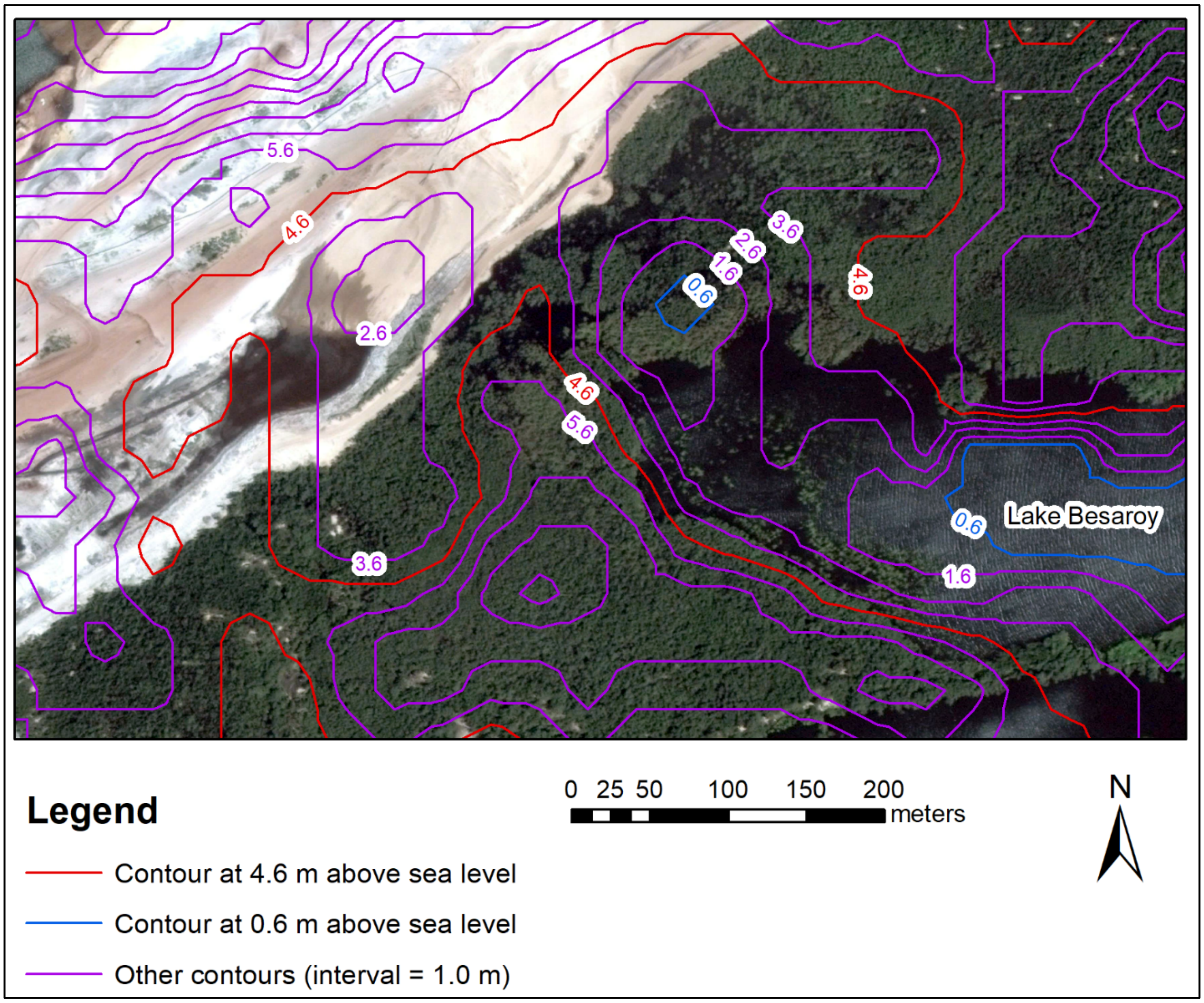

Figure 8. Use of the Google Earth satellite image from December 25, 2014, at the site of Figure 7B (equivalent to Site 2 of Ozius Spatial (2018), see Figs. 4 and 5A), shows that the lake occurs up to the edge of mining infrastructure. This image reinforces the argument that Rio Tinto has constructed mining infrastructure onto the lake bed. This location is equivalent to the location of the Google Earth images shown by Orengo (2017, see Figs. 2A-B).

At Rectangle B (see close-up in Fig. 7B), it can be seen that mining infrastructure has been constructed within 24.1 meters of a natural water body that is clearly an extension of Lake Besaroy. Mining infrastructure also exists within 66.6 meters of the 0.6-m contour, which would be permitted at this site under the agreement between Rio Tinto and ONE (Rio Tinto, 2017) if the 0.6-m contour were accepted as the OHWM of the lake. However, the contours show that the lake rises as high as 4.6 meters above sea level, so that the 4.6-m contour is a better estimate of the OHWM. A significant portion of the mining operation can be found below the 4.6-m contour (see Fig. 7B), indicating that the mining operation has been extended in the southeastern direction by filling in the lake bed. The conclusion that the mining operation is currently situated on the lake bed and has filled in the lake bed is further reinforced by an examination of the site of Rectangle B using an earlier Google Earth satellite image from December 25, 2014 (see Fig. 8). The earlier satellite image shows the water of Lake Besaroy occurring at the very edge of the mining infrastructure and clearly shows the connection between the main body of Lake Besaroy and the ponds to the northwest of Lake Besaroy.

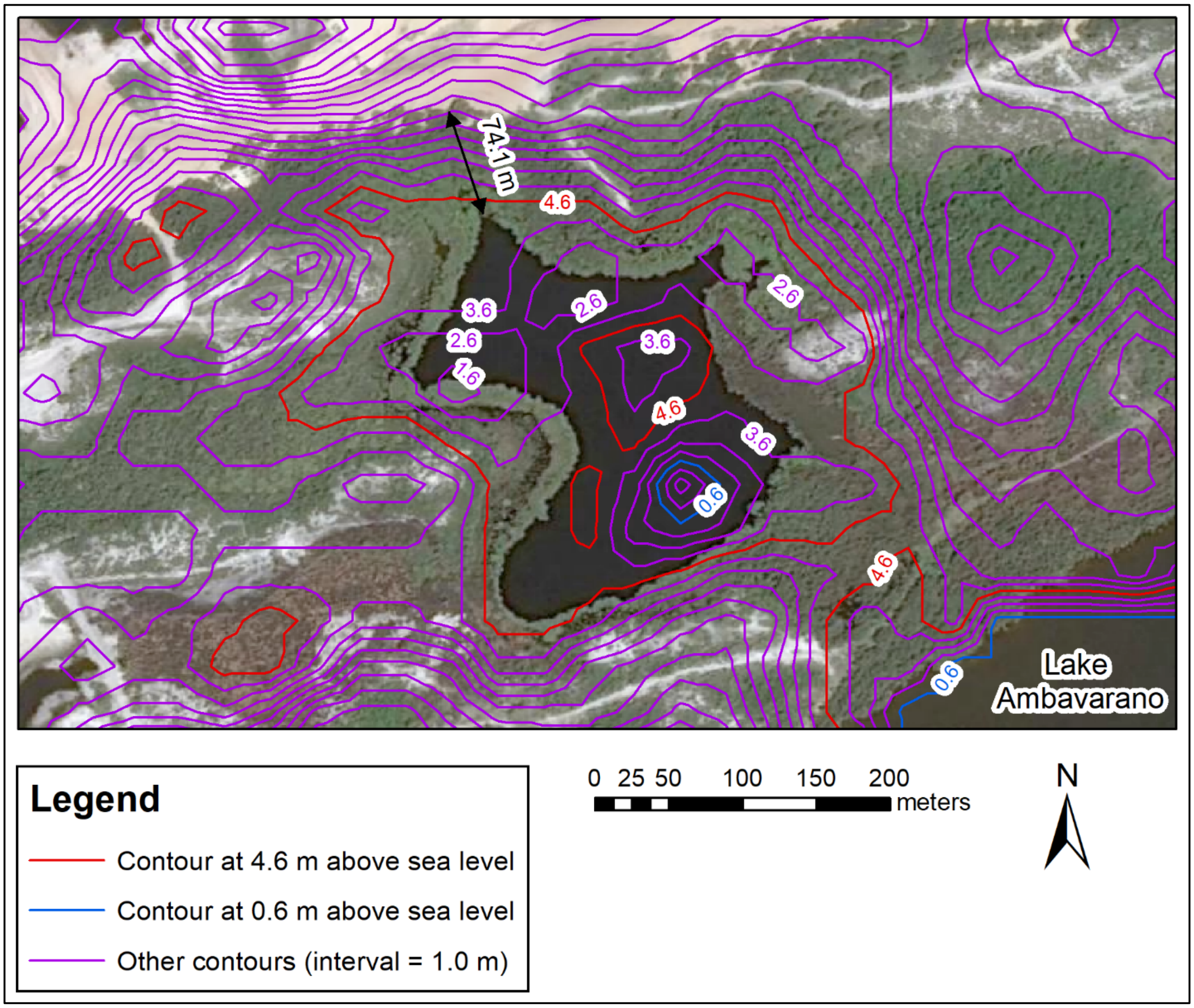

Figure 7C. Rio Tinto has created mining infrastructure within 74.1 meters of a natural water body. Note that this is not one of the sites where the National Office of the Environment (ONE) has permitted dredging within 50 meters of a natural water body (compare Figs. 4, 7A). However, it is not clear from the satellite image whether this mining infrastructure constitutes the “lake protection berm” that would be permitted within 50 meters of a natural water body. The contours indicate that the natural water bodies occur far higher than 0.6 meters above sea level, and that the Ordinary High Water Mark (OHWM) of the lake is closer to 4.6 meters above sea level. Although the contouring could be more accurate if results of the higher-resolution 2012 Lidar survey were used, Rio Tinto has repeatedly refused to release those data.

At Rectangle C (see close-up in Fig. 7C), it can be seen that mining infrastructure has been constructed within 74.1 meters of a natural water body that is clearly an extension of Lake Ambavarano. Note that this is not one of the sites where ONE has permitted dredging within 50 meters of a natural water body (compare Figs. 4 and 5A). However, it is not clear from the satellite image whether this mining infrastructure constitutes the "lake protection berm" that would be permitted within 50 meters of a natural water body. A more important observation is that the 4.6-m contour defines the outer limits of the enclosed pond, which reinforces the previous conclusion that the true OHWM is closer to 4.6 meters above sea level.

Evaluation of Dam Safety

The memorandum from Rio Tinto (2017), states "Berm Design Criteria specified as a Factor of Safety of 1.3 at the 1 in 50 year flood event lake level." The term "berm" refers to the structure depicted in Fig. 3 as "Mur de Soutènement" (usually translated as "retaining wall"). I would refer to this structure as a "dam" since its safety function is to prevent surface spillage from the mining basin into the lake. The statement from the memorandum combines factor of safety with design storm recurrence interval, which are not completely compatible concepts. The design for a 50-year flood event means that, in any given year, there is a 2% probability of failure of the dam due to flooding. The factor of safety of 1.3 means that some dam parameter (such as the undrained shear strength) is 1.3 times as great as the value of the parameter at which failure would occur. Of course, the factor of safety will be calculated differently depending upon the particular parameter or combination of parameters that is assumed to be critical.

A factor of safety of 1.3 does not guarantee that dam failure will not occur due to a 50-year flood event (a flood that has a 2% probability of occurring in any given year). The reason is that the critical parameter used to calculate the factor of safety is not a fixed, precise value. Rather it is simply the mean of a range of values, so that there is always a finite probability that the true factor of safety is actually less than 1.0, which would lead to failure. The factor of safety cannot be converted into a probability of failure (a more meaningful criterion) without knowing the probability distribution of the critical parameter. For example, Hoek (2006) developed a case study in which a factor of safety of 1.22 was equivalent to a probability of failure of 21%. Duncan (2000) created a table that converted factor of safety into probability of failure based upon the coefficient of variation (ratio of standard deviation to mean) of the factor of safety and assuming a lognormal distribution of the factor of safety. The most likely critical parameter is the undrained shear strength, which has a coefficient of variation in the range 13-40% (Kulwahy, 1992; Lacasse and Nadim, 1997; Duncan, 2000). Assuming a typical coefficient of variation of 26.5% (mean of the range) and using the table in Duncan (2000) and a factor of safety of 1.3, leads to a probability of failure of 18.8%. In other words, the dam has been designed so that there is an 18.8% probability that it will fail during a 50-year flood event.

In order to compare the dam design with established guidelines that are based upon probabilities of failure, it is best to convert the dam design criteria into a single probability of failure. Since the probability of a 50-year flood in any given year is 2% and the probability of failure due to that event is 18.8%, the probability of failure in any given year is the product of the two probabilities, or 0.376%. This probability is equivalent to designing the dam for a 270-year flood event (rounded to the nearest decade).

The (U.S.) Federal Emergency Management Agency (FEMA, 2013) classifies dams into three categories based upon hazard potential. High Hazard Potential means "probable loss of life due to dam failure or misoperation." It is clarified that "probable loss of life" refers to "one or more expected" fatalities and that "economic loss, environmental damage or disruption of lifeline facilities may also be probable but are not necessary for this classification." Significant Hazard Potential means "no probable loss of human life but can cause economic loss, environmental damage, or disruption of lifeline facilities due to dam failure or misoperation." Low Hazard Potential means "no probable loss of human life and low economic and/or environmental losses due to dam failure or misoperation."

Each of the hazard potential classifications corresponds to an inflow design flood (FEMA, 2013). A dam with Low Hazard Potential should be designed for a 100-year flood (flood with an exceedance probability of 1% in a given year) or "a smaller flood justified by rationale." A dam with Significant Hazard Potential should be designed for a 1000-year flood (flood with an exceedance probability of 0.1% in a given year). However, a dam whose failure is expected to result in loss of at least one life (High Hazard Potential) should be designed for the Probable Maximum Flood (PMF), which is defined as "the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study." The magnitude of the PMF is normally derived from the Probable Maximum Precipitation (PMP), which is defined as "the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year." The magnitudes of PMP have been determined for much of the United States (NWS-HDSC, 2017), but I am not aware of any estimation of PMP for Madagascar. The procedures for determination of the PMP have been described by the World Meteorological Organization (WMO, 2009). It is worth noting that, according to the U.S. Army Corps of Engineers, "the PMF does not incorporate a specific exceedance probability, but is generally thought to be well beyond the 10,000 year recurrence interval" (USACE-HCE, 2003).

The concept that the Probable Maximum Flood is the basis for design of a dam whose failure could result in the loss of at least one life is widely accepted throughout the U.S. federal government. For example, according to the U.S. Bureau of Reclamation (USBR), "the PMF is used for design and construction organizations as a basis for design in those cases where the failure of the dam from overtopping would cause loss of life or widespread property damage downstream" (USBR, 1987). The USBR guideline is even stricter than the FEMA guideline as it includes extensive property damage as a basis for design using the PMF. The USBR guidelines continue to state that "for a minor structure with significant storage where it is permissible to anticipate failure within the useful life of the project, a flood in the range of a 1 in 50 chance to 1 in 200 chance of being equaled or exceeded may be used as the IDF [Inflow Design Flood]." The above guideline roughly corresponds to the guideline for dams with Low Hazard Potential recommended by FEMA (2013).

On the other hand, the safety guidelines for dams designed by the U.S. Army Corps of Engineers are, in some cases, even stricter than those recommended by FEMA (2013). For all dams designed or maintained by the U.S. Army Corps of Engineers, "APF [Annual Probability of Failure] ≥ 1 in 10,000 (0.0001) Per Year. Annual probability of failure in this range is unacceptable except in extraordinary circumstances" (USACE, 2014). The U.S. Army Corps of Engineers has four categories of dam safety standards, similar to the three hazard potentials of the Federal Emergency Management Agency. The strictest "Standard 1 applies to the design of dams capable of placing human life at risk or causing a catastrophe, should they fail" (USACE, 1991). For this standard, "structural designs will be such that the dam will safely pass an IDF [Inflow Design Flood] computed from probable maximum precipitation (PMP) occurring over the watershed above the dam site." For the third strictest Standard 3 dams, "the base safety standard will be met when a dam failure related to hydraulic capacity will result in no measurable increase in population at risk and a negligible increase in property damages over that which would have occurred if the dam had not failed." For standard 3 dams, "one-half of the PMF [Probable Maximum Flood] is the minimum acceptable IDF [Inflow Design Flood]."

By this point, it should be clear that the safety criterion (ability to withstand a 270-year storm event) used by Rio Tinto to construct a dam to store radionuclides is not even remotely close to the dam safety guidelines recommended by U.S. federal agencies. The introduction of radionuclides into food and water supply would certainly constitute a threat to human life. On that basis, the dam should be designed to withstand the Probable Maximum Flood, which is a significantly rarer event than even a 10,000-year storm. According to the guidelines set by FEMA (2013), the safety criterion used by Rio Tinto would be acceptable only if the consequences of dam failure were "low economic and/or environmental losses." In other words, the safety criterion used by Rio Tinto is similar to the criterion that would be used for the design of storm drains at a shopping mall parking lot (Nathanson and Schneider, 2014).

A more disturbing issue is that there is no apparent connection between the dam safety criteria set forth in the memorandum from Rio Tinto (2017) and the description of the dam in QIT Madagascar Minerals (2015). The twin criteria of a factor safety of 1.3 for a 50-year storm are not mentioned anywhere in QIT Madagascar Minerals (2015) nor are any dam safety criteria mentioned anywhere in that document. Without any further information, a reader of QIT Madagascar Minerals (2015) is led to believe that the dam was not designed to meet any safety criteria, but was simply "designed" by piling up sand with a bulldozer.

Discussion

It is telling that this study and the study by Ozius Spatial (2018) have arrived at the same conclusion, that the mining operation has been extended onto the bed of Lake Besaroy, using two independent data sets, the proprietary Lidar survey used by Ozius Spatial (2018) and the publicly available Shuttle Radar Topography Mission data used by this study. The only significant difference in methodology is that Ozius Spatial (2018) accepted the assumption that the 0.6-m contour constitutes the OHWM, while this study has re-opened the question of the true elevation of the OHWM. A comparison of contour maps created using the satellite elevation data (see Figs. 7A-C, 8) with those created using the Lidar elevation data (see Figs. 5A-C) suggest that there is some sort of systematic vertical offset between the two data sets. Ozius Spatial (2018) did point out that "unfortunately [the] Lidar signal is affected significantly in wet vegetated areas such as marshlands." Of course, none of this can be rigorously tested without access to the Lidar survey data.

The report by Ozius Spatial (2018) did suggest that the 0.6-m contour might not be the true OHWM, although this suggestion was not used in any of their analyses. According to their report, "In some areas, the water level in the epochs analyzed were up to 20 meters from the 0.6-m level. In other areas, the 0.6-m water level was > 100 meters from the water level mapped" (Ozius Spatial, 2018). The report continued, "the gauge data provided indicated that the water level at the gauge locations exceeds 0.6 meters" (Ozius Spatial, 2018). The lake gauge data are included among the data sets that Rio Tinto refuses to release. Such data could potentially be used to argue that the lake level was unusually high when it could be seen at the very edge of the mining operation (see Fig. 8). On the other hand, such a conclusion is unlikely in light of the statement from the report that, “Based on the gauge data supplied by QMM, it appears the satellite capture times utilized in this project…were generally halfway between high and low tide on the respective capture dates” (Ozius Spatial, 2018).

With regard to the safety of the earthen dam, it should be noted that a more likely event than overtopping or collapse of the earthen dam is seepage of water containing dissolved radionuclides from the mining basin to the lake or river (see Fig. 3). Since the buffer zone is almost certainly composed of highly permeable, well-sorted beach sands, any rise in the water level in the mining basin above the lake or river level would result in significant seepage. This seepage would be completely unaffected by the existence of a dam on top of the buffer zone. Seepage would be a more likely event because the water level would have to rise only 1-2 meters for seepage to occur. (The rise in the water level necessary for seepage to occur is based upon information provided by QIT Madagascar Minerals (2015). However, this is open to question based upon the discrepancy in the OHWM that has been discussed throughout this study.) On the other hand, since the water level in the mining basin is 3 meters below the adjacent topography and the dam is 4 meters high, the water level would have to rise 7 meters to overtop the dam and perhaps 4 meters to have a significant impact on the structural integrity of the earthen dam.

On the above basis, a possible future objective might be to address the question: Will the water level in the basin rise 1-2 meters following a PMP (Probable Maximum Precipitation) storm event in the watershed of the mining basin? The PMP criterion is appropriate due to the significant impact on the environment and human health that would occur following the introduction of dissolved radionuclides into the lakes or river. This question could be answered using local meteorological data available from the National Climatic Data Center (NOAA-NESDIS-NCDC, 2018), procedures for estimating the PMP based on historic precipitation data and a knowledge of storm patterns as described by the World Meteorological Organization (WMO, 2009), and a rainfall-runoff model, such as the SCS Runoff Curve Number Method (USDA-NRCS-CED, 1986). The same procedures could be used to project rises in water level due to storm events with various recurrence intervals, such as the 100-year storm and the 1000-year storm. I would be happy to carry out these calculations if this were of interest to the Andrew Lees Trust.

Based on the results of this study, it cannot be overemphasized that the design of this ilmenite mine along the shores of Lakes Besaroy and Ambavarano is fundamentally flawed. According to Rio Tinto (2017), the agreement with ONE that permitted Rio Tinto to carry out dredging at Site 2 (as denoted by Ozius Spatial (2017, 2018)) within 50 meters from a natural water body, but no closer, was reached in 2014. However, Ozius Spatial (2018) showed that, by the beginning of 2014, the mining operation had already encroached to the edge of the lake bed (defined as the 0.6-m contour by Rio Tinto (2017)). By the end of 2014, the mining operation had advanced 52 meters onto the lake bed (see Fig. 9). The memorandum from Rio Tinto (2017) also stated, “The impact of complying with the 80-m buffer zone would be 1) a 9% loss of reserves; 2) a non-optimal life of mine plan [in that] the higher grade and lowest cost ore to the northeast would only be accessible at the end of the mine life.” It is disconcerting to bring financial considerations into play in a memorandum devoted to safety, environmental protection, and compliance with environmental law. Presumably, the financial considerations were the only justification for the need to construct a dam on top of the 80-m buffer zone and the five exceptions where dredging was permitted within the 80-m buffer zone, since no other justification has ever been given. If Rio Tinto could not comply with an 80-m undisturbed buffer zone and still make a reasonable profit, then surely there is no way that they could operate a profitable mine after being required to move their mining operation out of the lake bed and restore the lake bed to its former condition.

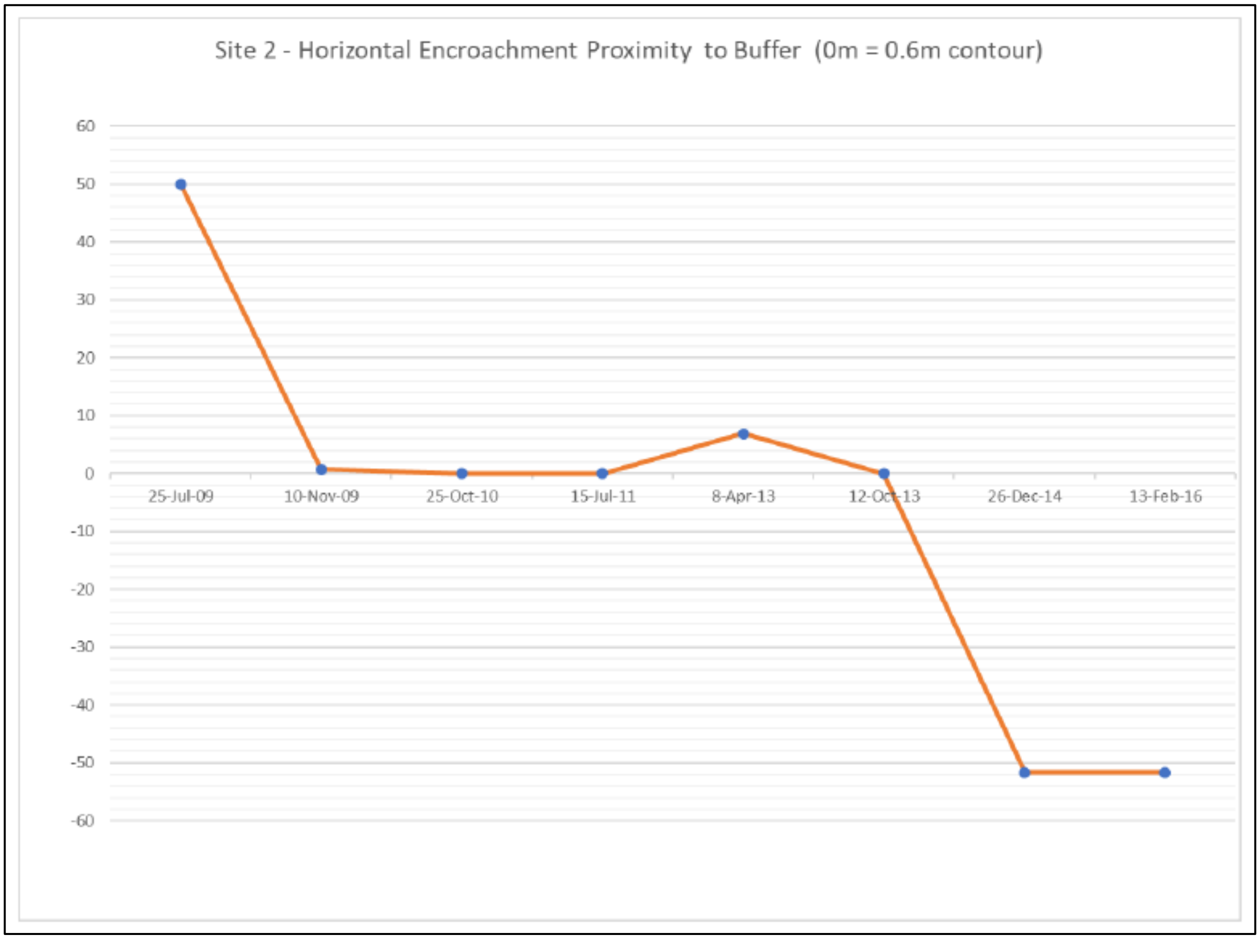

Figure 9. In 2014, Rio Tinto reached an agreement with the National Office of the Environment (ONE), according to which Rio Tinto was permitted to carry out dredging at Site 2 (as denoted by Ozius Spatial (2017, 2018)) within 50 meters from a natural water body, but no closer. However, by the beginning of 2014, the mining operation had already encroached to the edge of the lake bed (defined as the 0.6-m contour by Rio Tinto (2017)). By the end of 2014, the mining operation had advanced 52 meters onto the lake bed.

Conclusions

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

1) Using Lidar elevation data provided by Rio Tinto and the assumption by Rio Tinto that the 0.6-m contour is the Ordinary High Water Mark (OHWM) of the estuaries Lakes Besaroy and Ambavarano, Ozius Spatial documented that the mining operation has encroached upon the bed of Lake Besaroy, in violation of environmental law in Madagascar.
2) Rio Tinto falsely claimed that this encroachment was permitted under their agreement with the National Office of the Environment (ONE).
3) Using publicly available 30-m elevation data from the Shuttle Radar Topography Mission, this study confirmed that the mining operation has encroached upon the bed of Lake Besaroy.
4) The satellite elevation data indicate that the OHWM is closer to 4.6 meters above sea level.

5) The stated safety criteria for the dam that separates the mining basin from the rest of the lake of a factor of safety of 1.3 in a 50-year storm event is probably equivalent to the single safety criterion of a 270-year storm event.
6) By contrast, the (U.S.) Federal Emergency Management Agency recommends that, if the failure of a dam would be expected to result in the loss of at least one human life, the dam should be designed to accommodate the Probable Maximum Flood (PMF), which is significantly rarer than even a 10,000-year storm.
7) It is not clear from the documents provided by Rio Tinto that the dam was designed to meet any safety criteria.
8) Seepage through the buffer zone is a more likely event than either overtopping or collapse of the dam.

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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 and has 66 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in assessing the environmental impacts of mining for both mining companies and environmental organizations.

References

Duncan, J.M., 2000. Factors of safety and reliability in geotechnical engineering. Journal of Geotechnical and Geoenvironmental Engineering, vol. 126, pp. 307-316. Available online at: http://geo.cv.nctu.edu.tw/prob/download/Factors%20of%20Safety%20and%20Reliability%20in%20Geotechnical%20Engineering.pdf

Emerman, S.H., 2018a. Evaluation of a proposal for assessing compliance with a legally-mandated natural barrier at an ilmenite mine operated by Rio Tinto on the shores of Lakes Besaroy and Ambavarano, Madagascar, Report to Andrew Lees Trust, 6 p.

Emerman, S.H., 2018b. Évaluation des dangers d'un bassin minier et d'un barrage dans une mine d'ilménite exploitée par Rio Tinto sur les rives des Lacs Besaroy et Ambavarano, Madagascar, Report to Andrew Lees Trust, 9 p.

Emerman, S.H., 2017. Hazard assessment of a mining basin and dam at an ilmenite mine operated by Rio Tinto on the shores of Lakes Besaroy and Ambavarano, Madagascar, Report to Andrew Lees Trust, 8 p.

FEMA (Federal Emergency Management Agency), 2013. Selecting and Accommodating Inflow Design Floods for Dams: FEMA-94, 38 p. Available online at: https://www.fema.gov/media-library-data/1386108128706-02191a433d6a703f8dbdd68cde574a0a/Selecting_and_Accommodating_Inflow_Design_Floods_for_Dams.PDF

Hoek, E., 2006. Practical Rock Engineering, 341 p. Available online at: https://www.rocscience.com/documents/hoek/corner/Practical-Rock-Engineering-Full-Text.pdf

Kulwahy, F.H., 1992. On the evaluation of soil properties. American Society of Civil Engineers Special Publication No. 31, pp. 95-115.

Lacasse, S. and F. Nadim, 1997. Uncertainties in characterizing soil properties. Norwegian Geotechnical Institute Publication No. 201, pp. 49-75.

Nathanson, J.A. and R.A. Schneider, R.A., 2014. Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control, 6th ed. Pearson, 456 p.

NASA (National Aeronautics and Space Administration), 2018. Shuttle Radar Topography Mission: The Mission to Map the World. Available online at: https://www2.jpl.nasa.gov/srtm/

NOAA-NESDIS-NCDC (National Oceanic and Atmospheric Administration – National Environmental Satellite, Data, and Information Service – National Climatic Data Center), 2018. NNDC Climate Data Online. Available online at: https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD

NWS-HDSC (National Weather Service – Hydrometeorological Design Studies Center, 2017. Current NWS Probable Maximum Precipitation (PMP) Documents. Available online at: http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html

Orengo, Y., 2017. Tall tales and tailings – the truth about Rio Tinto's rare earth mine in Madagascar. The Ecologist, April 3, 2017. Available online at: https://theecologist.org/2017/apr/03/tall-tales-and-tailings-truth-about-rio-tintos-rare-earth-mine-madagascar

Ozius Spatial, 2017. OS1718133 QMM Waterbody Buffer Zone Analysis, December 5, 2017, 22 p.

Ozius Spatial, 2018. OS1718133 QMM Waterbody Buffer Zone Analysis, March 29, 2018, 34 p.

QIT Madagascar Minerals, S.A., 2015. Chapitre 4 : Description des Activités et des Infrastructures Associées à l'extraction et à la Séparation des Sables Minéralises du Secteur Minier de Mandena. PGES – Mine – Phase Opération (2014-2018), 18 p.

QGIS, 2018. QGIS: A Free and Open Source Geographic Information System. Available online at: https://qgis.org/en/site/

Randriantseheno, H.F., A. Raoelina, J.L.R. Zafimanjato, and N.B. Razatovo, 2015. Radiation dose assessment in installation operating mineralized heavy sand in Madagascar. NORM VII: International Symposium on Naturally Occurring Radioactive Material, Beijing, China, 22-26 April 2013, pp. 101-106.

Rio Tinto, 2017. Update QMM Mining Boundary with Water-bodies. Memorandum from P. de Kock to P. Harvey, October 3, 2017, 4 p.

Rio Tinto, 2018a. Memorandum. April 3, 2018, 1 p.

Texas A&M University, 2018. SWAT: Soil & Water Assessment Tool. Available online at: http://swat.tamu.edu/

USACE (U.S. Army Corps of Engineers), 1991. Inflow Design Floods for Dams and Reservoirs. Engineer Regulation ER 1110-8-2(FR), 10 p. Available online at: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-8-2_FR.pdf

USACE (U.S. Army Corps of Engineers), 2014. Safety of Dams – Policy and Procedures. Engineer Regulation ER 1110-2-1156, 528 p. Available online at:

http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-1156.pdf
USACE-HEC (U.S. Army Corps of Engineers– Hydrologic Engineering Center), 2003. Application of Paleohydrology to Corps Flood Frequency Analysis. RD-47, 34 p. Available online at: http://www.hec.usace.army.mil/publications/ResearchDocuments/RD-47.pdf
USBR (U.S. Bureau of Reclamation), 1987. Design of Small Dams, 3rd ed. Water Resources Technical Publication, U.S. Department of the Interior, 904 p. Available online at: https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/SmallDams.pdf
USDA-NRCS-CED (U.S. Department of Agriculture – Natural Resources Conservation Service – Conservation Engineering Division), 1986. Urban Hydrology for Small Watersheds. Technical Release TR-55, 164 p. Available online at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf
WMO (World Meteorological Organization), 2009. Manual on Estimation of Probable Maximum Precipitation. WMO-No. 1045, 257 p. Available online at: http://www.wmo.int/pages/prog/hwrp/publications/PMP/WMO%201045%20en.pdf
Watkins, D., 2018. 30-Meter SRTM Tile Downloader. Available online at: http://dwtkns.com/srtm30m/

First Addendum

In this addendum, quotes from the cover letter (Rio Tinto, 2018b) and the response by Rio Tinto (2018c) are given in bold italics followed by my responses.

"The crux, as you will see, is the source and quality of the base data. The technical team's view is that the different interpretations have their roots in the underlying data sources" (Rio Tinto, 2018b.)

The above statement says the exact opposite of what was reported by both this study and the study by Ozius Spatial (2018). Ozius Spatial (2018) used Lidar data provided by Rio Tinto to show that the mining operation had not only violated the 50-m buffer at Site 2, but had encroached 52 meters onto the bed of the lake itself (see Figs, 5A, 6 and 9). The study by Ozius Spatial (2018) explicitly stated "[Site] 2 experienced encroachment below the 0.6 meter contour line and it appears this encroachment occurred sometime after 12th October 2013 but before 26th December 2014." This study used publicly available satellite elevation data to reach the same conclusion, namely that Rio Tinto is carrying out ilmenite mining in the bed of the estuary. There are no differences between the interpretations by this study and the study by Ozius Spatial (2018), despite their use of different data sources.

"Google Earth imagery is used as the basis for the arguments given in Dr. Emerman's report, however Google Earth imagery is not photogrammetrically accurate. It is therefore not unusual to have tens of meters difference between the imagery and georegistered locations, particularly in rural areas" (Rio Tinto, 2018c).

This statement about the positional accuracy of Google Earth is both incorrect and irrelevant. The disclaimer by Google (2009) states, "Our imagery varies from sub-meter resolution in major cities to 15 meter resolution for most of the earth's surface…Since our database is constantly being updated, we cannot state a specific resolution for any geographic region." The disclaimer by Google Earth should be regarded as quite conservative. Recent academic studies have shown the positional accuracy of Google Earth to be 2.64 meters in the Big Bend region of Texas (USA) (Benker et al., 2011), 1.59 meters in Khartoum State of Sudan (Mohammed et al., 2013), 2.18 meters in Riyadh, Saudi Arabia (Farah and Algarni, 2014), and close to 1 meter in Rome (Pulighe et al., 2015). Therefore, it is not correct to state that an inaccuracy of "tens of meters" is "not unusual" (Rio Tinto, 2018c).

The statement about the positional accuracy of Google Earth imagery is irrelevant because Google does not own satellites, just as Rio Tinto and Ozius Spatial do not own satellites. Google Earth is a computer program for seamless integration of governmental and commercial satellite imagery and aerial photography. Ozius Spatial (2018) does not state the source of their satellite imagery, but this study and the study by Ozius Spatial (2018) seem to be using the same satellite image (compare Figs. 5A-C with Figs. 7A-C). Rio Tinto (2018b) seems to be saying that satellite images cannot be trusted, which is surprising considering that they paid $58,150 to Ozius Spatial to carry out an analysis of satellite imagery (Ozius Spatial, 2017).

"Radar-based topographical maps can also be an inaccurate source of geographical data, picking up tree canopies rather than the true ground level (for example). For this reason, Rio Tinto QMM use laser surveying technology, to ensure measurement accuracy" (Rio Tinto, 2018c).

This point is irrelevant because the only elevations that matter are the elevations of the mining operation and the natural water bodies, both of which are devoid of trees (see Figs. 7B-C, and 8).

"Regarding the berm mentioned in our report:

a) The dredge pond is generally operated at an elevation below the neighboring lakes and below the natural topography" (Rio Tinto, 2018c).

This statement is quite disturbing because seepage of water enriched in radionuclides from the mining basin (referred to as the "dredge pond" in the above quote) to the lake will occur whenever the water elevation in the mining basin exceeds the water level in the lake. According to QIT Madagascar Minerals (2015), "[Le contrôle critique est] maintenir le niveau du basin entre 1 m à 2 m en dessous du niveau du lac [The critical control is to maintain the water level of the basin between 1 meter and 2 meters below the level of the lake]." According to Rio Tinto (2017), "The dredge pond elevation will be maintained at -1 masl [meters above sea level]." The previous statements implied that the water level in the mining basin is <u>always</u> maintained 1-2 meters below the elevation of the lake surface. The current statement (Rio Tinto, 2018c) implies that it is only "generally" true that the water level in the mining basin is below the elevation of the lake surface.

I would like to add that I continue to object to the use of the English word "berm" (Rio Tinto 2017, 2018c) or the French phrase "mur de soutènement [retaining wall]" (QIT Madagascar Minerals, 2015). The safety function of the structure is to prevent the transfer of water enriched in radionuclides from the mining basin to the lake (see Fig. 3). Therefore, it should be referred to as "dam" in English or "barrage" in French.

"b) The dredge pond is much smaller in volume than the neighboring lakes" (Rio Tinto, 2018c).

I assume that the point of this statement is that the overtopping of the dam (see Fig. 3) by a flood from the mining basin will have no environmental consequence to the lake because the radionuclide-enriched water from the mining basin will be diluted by the greater volume of water in the lake. First, this statement cannot be evaluated without knowing the concentration of radionuclides in the mining basin and Rio Tinto has never released this information. Second and more important, the statement assumes that mixing between the waters of the mining basin and the lake will be instantaneous and complete. In fact, estuaries with narrow connections to the ocean, such as Lakes Besaroy and Ambavarano (see Figs. 1, 4 and 7A) tend to exhibit a significant halocline and to be very poorly mixed (Pinet, 1992). Therefore, the total volume of the lakes is irrelevant to the contamination that would occur following overtopping of the dam.

"c) The dredge pond is temporarily mining adjacent to the lakes (approximately three years). Therefore the design criteria of a long life civil dam are not applicable" (Rio Tinto, 2018c).

Safety guidelines for civil or mining infrastructure are equivalent to acceptable annual probabilities of infrastructure failure, which are based upon the consequences of failure. According to the (U.S.) Federal Emergency Management Agency (FEMA, 2013), if the consequence of dam failure would be the probable loss of only a single human life, the dam should be designed to withstand the Probable Maximum Flood (PMF). The PMF is significantly rarer than even a 10,000-year flood (USACE-HEC, 2003), which has an annual probability of occurrence of 0.01%. Similar safety guidelines are found among the regulatory agencies of all of the developed countries. The expected lifetime of a dam is irrelevant either to the annual probability of failure of a dam or to the consequences of that failure.

This study determined that the annual probability of failure of the dam that separates the mining basin from the lake is 0.376%. Even that seemingly low probability was based upon the assertion by Rio Tinto (2017) that the dam was designed with a factor of safety of 1.3 in a 50-year flood, which has not been substantiated by any document from Rio Tinto. Note that if a dam has a three-year lifetime and an annual probability of failure of 0.376%, then the probability of failure sometime within the dam lifetime is 1.1%. Any reasonable person would regard a 1.1% probability of a major environmental catastrophe with significant loss of life to be an unacceptable risk.

Additional References

Benker, S.C., R.P. Langford, and T.L. Pavlis, 2011. Positional accuracy of the Google Earth terrain model derived from stratigraphic unconformities in the Big Bend region, Texas, USA. Geocarto International, vol. 26, pp. 291-303.

Farah, A. and D. Algarni, 2014. Positional accuracy assessment of Google Earth in Riyadh. Artificial Satellites, vol. 49, pp. 101-106.

Google, 2009. Google Earth Help Forum. Available online at: https://productforums.google.com/forum/?hl=en#!category-topic/earth/imagery--data--layers/6-4HUc-bWqk

Mohammed, N.Z., A. Ghazi, and H.E. Mustafa, 2013. Positional accuracy testing of Google Earth. International Journal of Multidisciplinary Sciences and Engineering, vol. 4, pp. 6-9. Available online at: http://www.ijmse.org/Volume4/Issue6/paper2.pdf

Pinet, R, 1992. Oceanography, an Introduction to the Planet Oceanus. West Publishing Company, 571 p.

Pulighe, G., V. Baiocchi, and F. Lupia, 2015. Horizontal accuracy assessment of very high resolution Google Earth images in the city of Rome, Italy. International Journal of Digital Earth, vol. 9, pp. 342-362.

Rio Tinto, 2018b. E-mail from Peter Harvey to Yvonne Orengo, June 7, 2018.

Rio Tinto, 2018c. Initial response to the Andrew Lees Trust report into the buffer zone at the QIT Madagascar Minerals operation received on the 30th May, 2018, titled "Evaluation of a Buffer Zone at an Ilmenite Mine operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar" by Dr. Steven H. Emerman, Malach Consulting, 1 p.

Second Addendum

After the original report and the first addendum were written, Rio Tinto released the data from the 2012 Lidar survey, which they had used to determine the elevation of the lakes (Rio Tinto, 2017) and which Ozius Spatial (2018) used to evaluate violation of the legally-mandated buffer zone. The objectives of this second addendum are to address the following questions:

1) Does the Lidar dataset have adequate spatial coverage for evaluating violation of the buffer zone?
2) Is there a vertical offset between the Lidar dataset and the 30-m satellite elevation data obtained from the Shuttle Radar Topography Mission (NASA, 2018)?

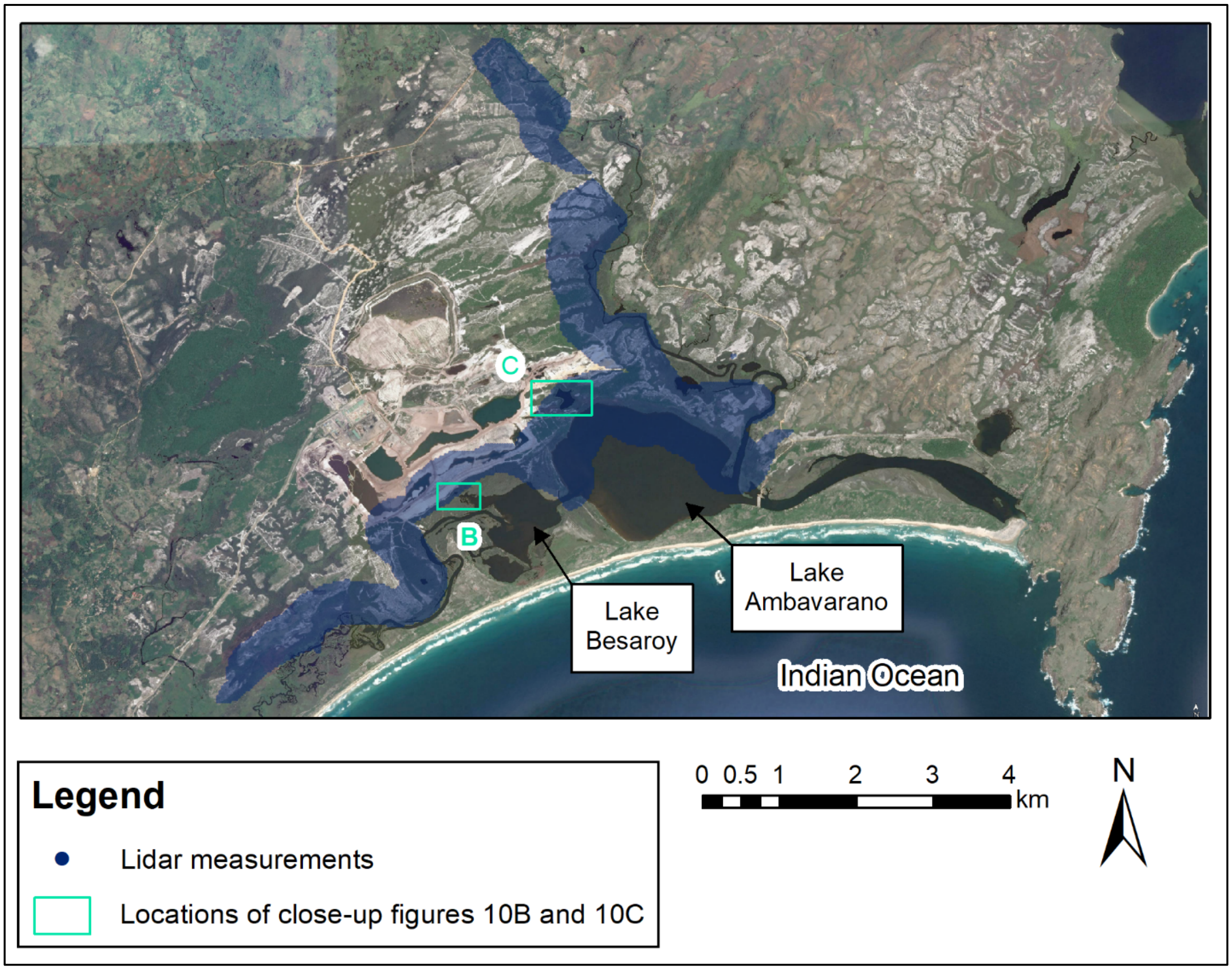

Figure 10A. In 2012 Rio Tinto carried out 8.5 million Lidar elevation measurements, which formed the basis for their determination that the elevations of Lake Besaroy and Ambavarano were 0.6 meters above sea level. Since none of the measurements covered Lake Besaroy, the Lidar survey could not be used to determine its elevation. The green rectangles are the perimeters of the close-ups shown in Figs. 10B and 10C (equivalent to Figs. 7B and 7C with the addition of the locations of the Lidar measurements).

Before addressing the objectives, it should be emphasized that, at this point, these are strictly academic questions without consequences for human or environmental health. First, this study and the study by Ozius Spatial (2018) have already independently used both the satellite data and the Lidar data, respectively, to document that, not only has Rio Tinto violated the 80-m buffer zone, but that they are carrying out mining operations within the bed of the estuary. Second, in order to document violation of the buffer zone, it is not necessary to know the absolute elevation of the lakes, but only the relative differences between the lake elevation and every other elevation (such as the elevation of the seaward edge of the mining operation). Third, although Rio Tinto has finally released the Lidar data after many refusals, as of this writing, they have still refused to release any of the methodology that was followed in the collection and processing of the Lidar data. On that basis, it would be quite far-fetched for anyone to claim that the Lidar data was "right" and the satellite data was "wrong." The methodology involved in the development of the 30-m satellite elevation data has, of course, been exhaustively documented (NASA, 2018).

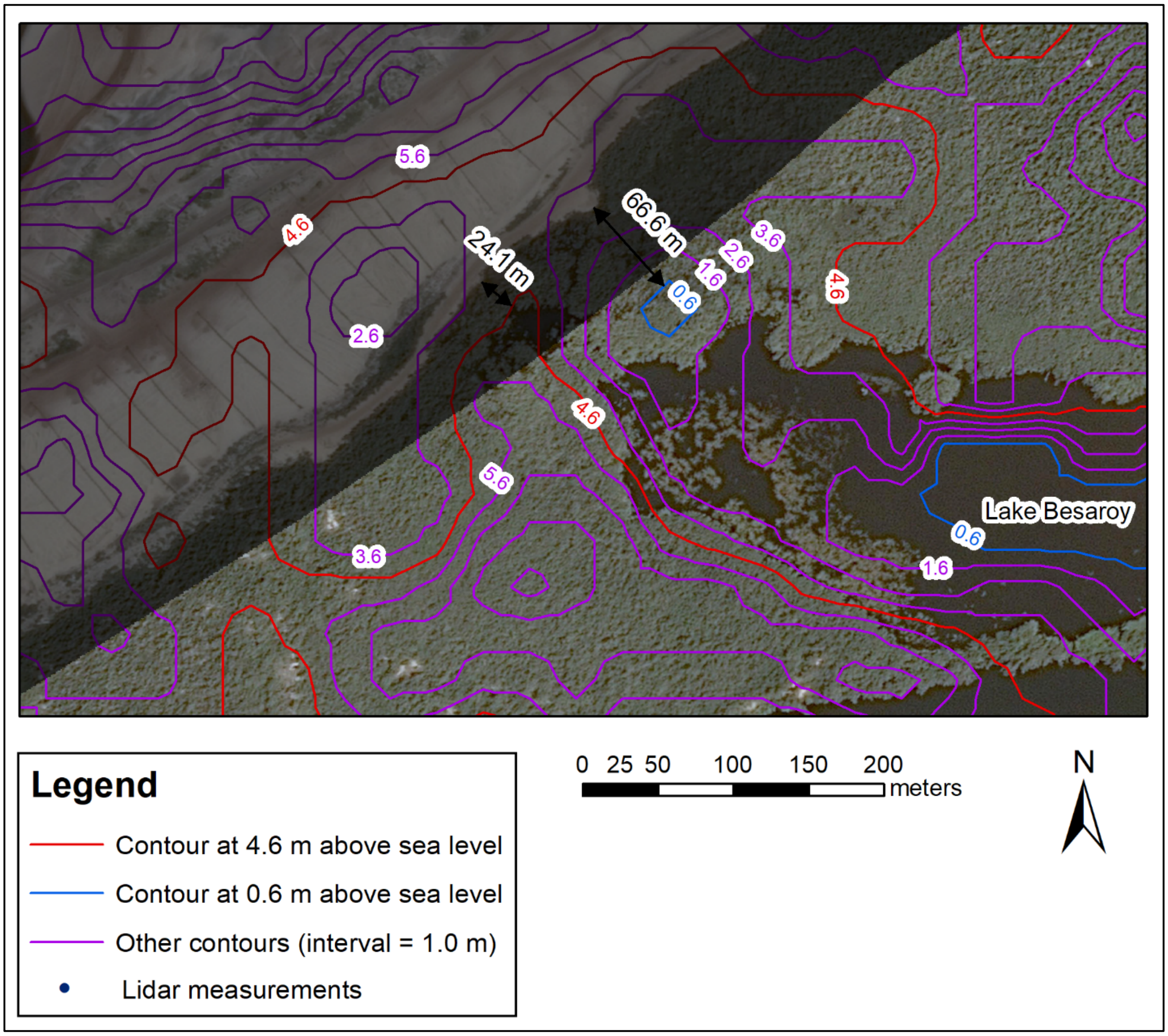

Figure 10B. The Lidar survey carried out by Rio Tinto in 2012 covers the region of encroachment at Site 2 of Ozius Spatial (2018, see Figs. 4 and 5A) and validates the use of that data set by Ozius Spatial (2018). This figure is identical to Fig. 7B with the addition of the locations of the Lidar measurements. The contours are based upon the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018). Contouring was carried out using ArcMap 10.6 Spatial Analyst with maximum accuracy and minimum smoothing.

The objectives were addressed by mapping the spatial extent of the Lidar measurements, and also by mapping the Lidar measurements onto the existing maps that were used to document violation of the buffer zone (see Figs. 7B and 7C). For comparison with the satellite data, the Lidar measurements were averaged over the same 30-m pixels that were used in the satellite data. The mean Lidar-derived elevation of each pixel was then rounded to the nearest meter for consistency with the satellite data. All mapping operations were carried out using ESRI ArcMap v. 10.6. A linear regression line was created that predicted the satellite elevations from the Lidar elevations averaged over the 30-m pixels. The statistical significance of the correlation was assessed using the F-test.

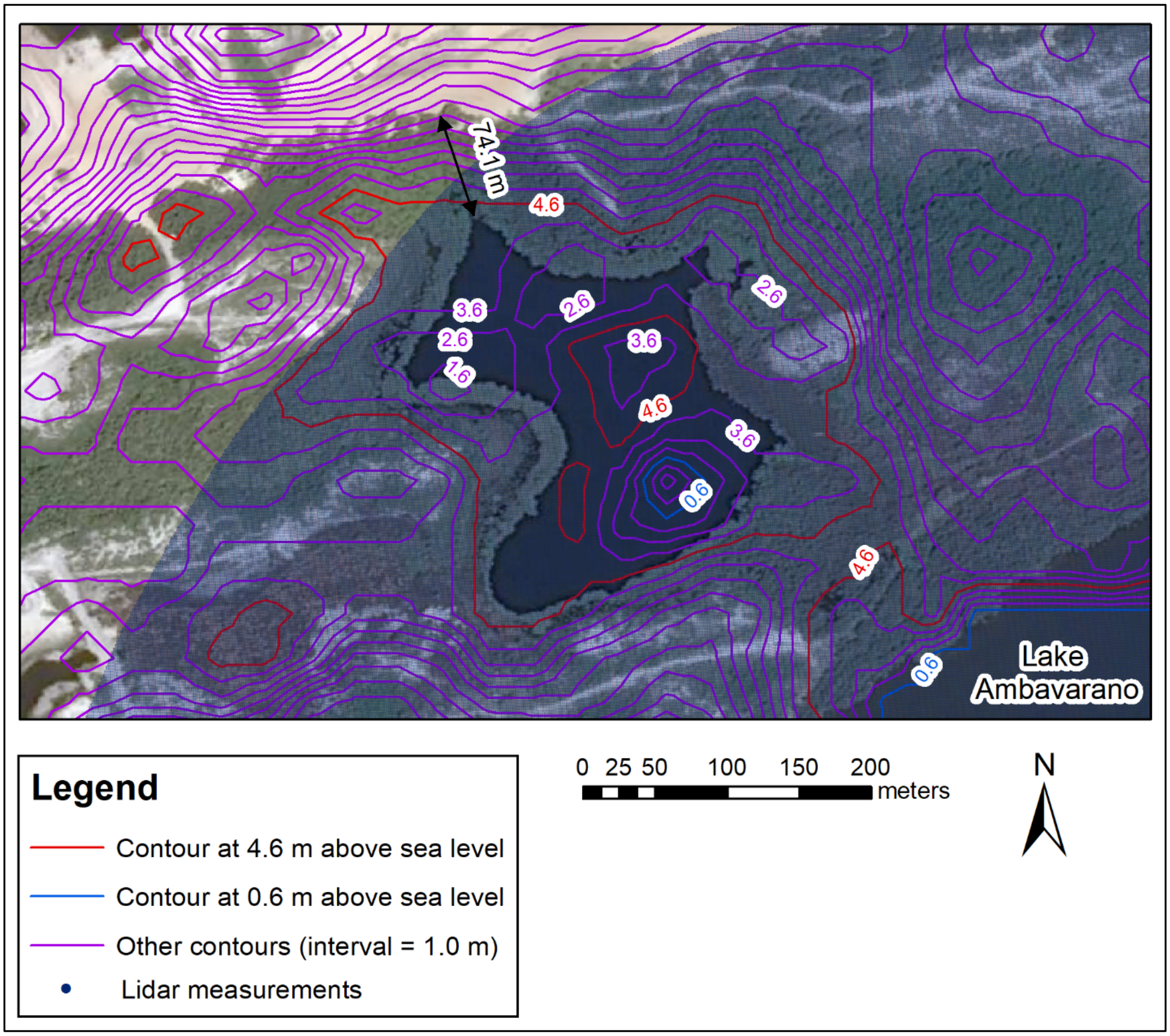

Figure 10C. The Lidar survey carried out by Rio Tinto in 2012 does not show sufficient coverage in the vicinity of Rectangle C (see Fig. 10A). On that basis, the satellite elevation data should be used to investigate encroachment in this region. This figure is identical to Fig. 7C with the addition of the locations of the Lidar measurements. The contours are based upon the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018). Contouring was carried out using ArcMap 10.6 Spatial Analyst with maximum accuracy and minimum smoothing.

The nearly 8.5 million Lidar measurements covered nearly 9.5 km^2, and were assembled into 10,543 30-m pixels (see Fig. 10A). Although these measurements were used to determine the elevation of Lakes Besaroy and Ambavarano (Rio Tinto, 2017), no data were collected over Lake Besaroy (see Figs. 10A and 10B). The spatial extent of the Lidar measurements is just barely adequate to cover the encroachment in Rectangle B (equivalent to Site 2 of Ozius Spatial (2018); see Fig. 10B). On the other hand, the spatial extent of the Lidar measurements is insufficient to document the encroachment at Rectangle C (see Fig. 10C), and this location was not examined by Ozius Spatial (2018).

The best-fit regression line that predicted the satellite elevations from the Lidar elevations had an intercept of 4.26 meters with a 95% confidence interval of 4.14-4.37 meters (see Fig. 11). This vertical offset is consistent with the determination by Rio Tinto (2017) that the estuaries have an elevation of 0.6 meters above sea level and the determination by this study that the estuaries have an elevation of 4.6 meters above sea level, equivalent to a 4-m vertical offset. (Recall that the resolution of the satellite data is only 1 meter.) The source of the vertical offset cannot be determined without knowing how the Lidar data were calibrated. It is possible that the Lidar data were never calibrated because, as mentioned above, only relative elevations are needed to document compliance with a buffer zone.

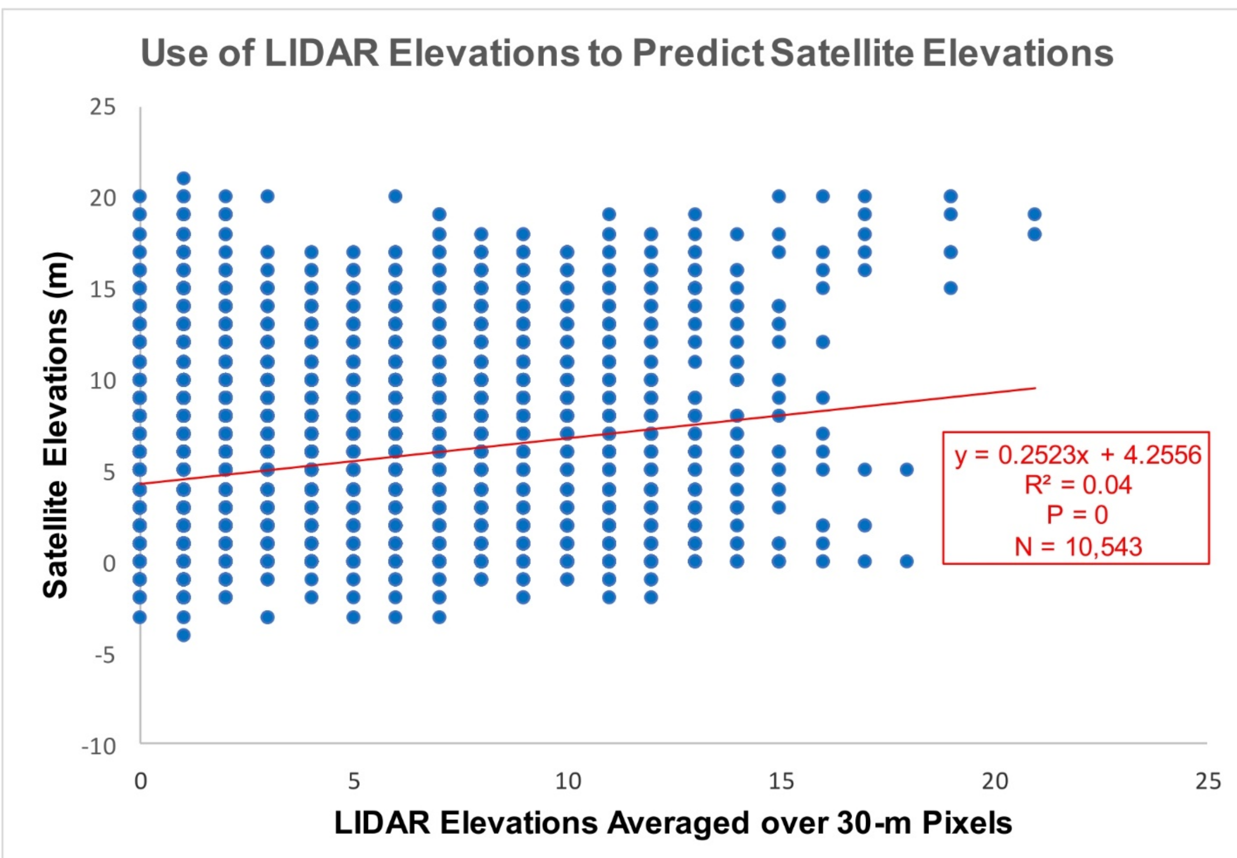

Figure 11. The ability of the Lidar measurements carried out by Rio Tinto to predict the elevations from the Shuttle Radar Topography Mission (NASA, 2018) was tested by averaging the Lidar measurements over the same 30-m pixels as were used by the satellite data. The averages were also rounded to the nearest meter for consistency with the satellite data. The variation in the Lidar data predicts only 4% of the variation in the satellite data, although the prediction is statistically significant (P = 0). The intercept of the best-fit regression line implies a vertical offset of 4.3 meters between the two data sets.

The source of the considerable scatter in the plot of satellite elevation vs. Lidar elevation is more difficult to explain (see Fig. 11). The correlation is certainly statistically significant (P = 0), although the variation in the Lidar data explains only 4% of the variation in the satellite data. It is not possible to explore this question any further without knowing the methodology behind the Lidar data. The most important pieces of missing information are the locations of the control points, how the control points were used to process the data, and how the position of the aircraft was determined.

The conclusions of this addendum can be summarized as follows:

1) The spatial extent of the Lidar data is adequate to document violation of the buffer zone in Rectangle B (equivalent to Site 2 of Ozius Spatial (2018)), but not in Rectangle C (not examined by Ozius Spatial (2018)).
2) There is a 4-meter vertical offset between the Lidar data and the satellite data, which is probably an artifact of the way in which the Lidar data were calibrated.

Third Addendum

The objectives of the third addendum are to address the following additional questions from Andrew Lees Trust:

1) Based upon the satellite elevation data, what is the extent of the encroachment of the mining operation onto the bed of Lake Besaroy?
2) How much additional area for mining was created by building the 30-m-wide dam onto the 80-m buffer zone, as opposed to outside of the buffer zone?

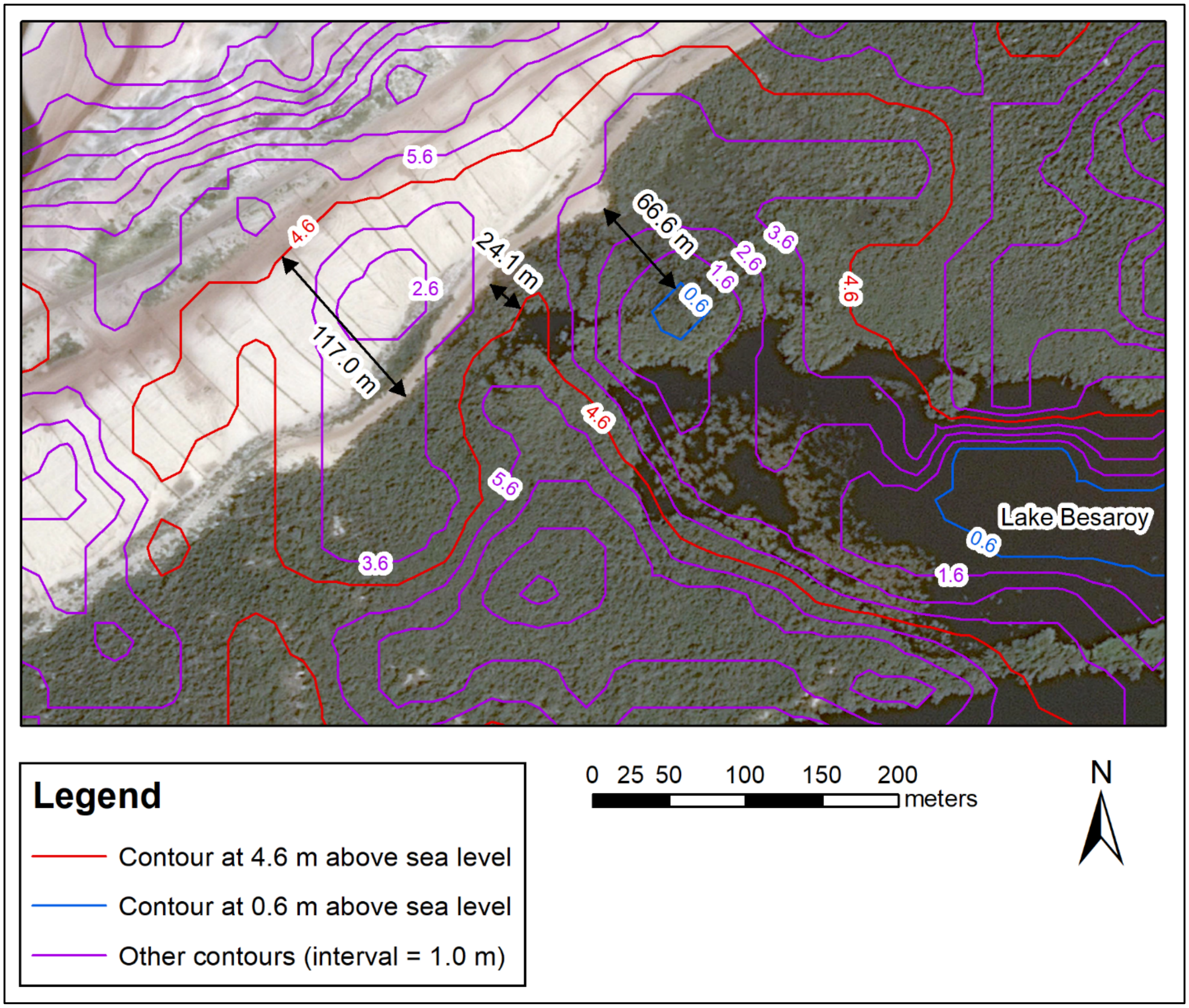

Figure 12. Since visible water of Lake Besaroy occurs at 4.6 meters above sea level, all of the mining operation that occurs below the 4.6-m contour should be regarded as taking place within the bed of the lake. On that basis, the mining operation has encroached 117 meters onto the bed of Lake Besaroy. This figure is identical to Fig. 7B with the addition of a double arrow to indicate the distance of the edge of the mining operation to the 4.6-m contour. The contours are based upon the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018). Contouring was carried out using ArcMap 10.6 Spatial Analyst with maximum accuracy and minimum smoothing.

The first question was addressed by measuring the perpendicular distance from the 4.6-m contour to the seaward edge of the mining operation to be 117.0 meters (see Fig. 12). Note that since visible water of Lake Besaroy occurs at 4.6 meters above sea level, all of the mining operation that occurs below the 4.6-m contour should be regarded as taking place within the bed of the lake (see Fig. 12). This estimate of the extent of encroachment onto the lake bed is reasonably close to the estimate of 52 meters at the same site by Ozius Spatial (2018; see Fig. 9), especially considering the questionable quality of the Lidar data (see discussion in second addendum).

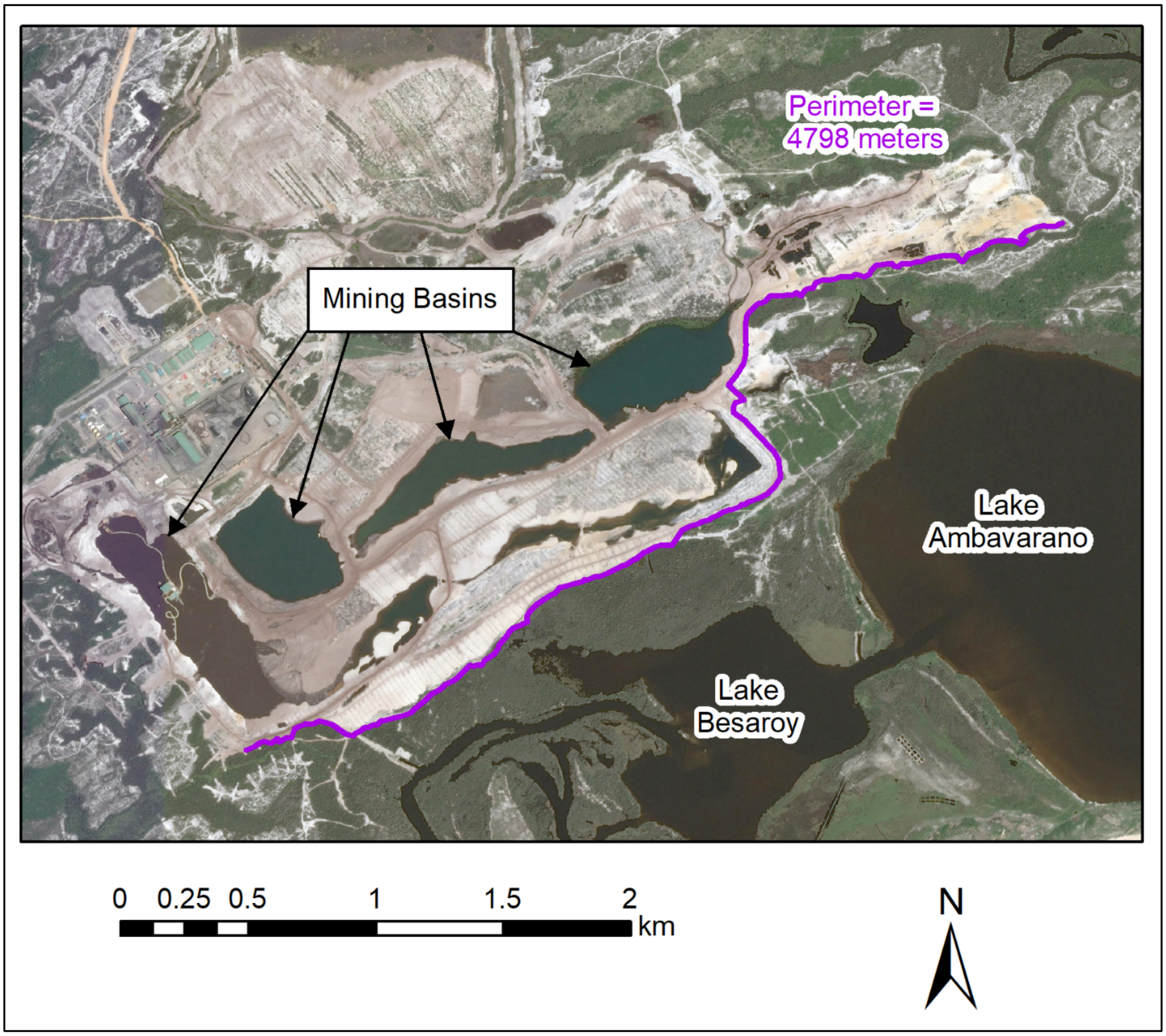

Figure 13. Based on a satellite image from Google Earth dated February 12, 2016, the seaward perimeter of the mining operation was 4798 meters. The additional area for mining that was created by building the 30-m-wide dam onto the 80-m buffer zone could be approximated by multiplying the perimeter by 30 meters, yielding 14.4 hectares. For comparison, the average area of the four mining basins is 15.8 hectares, so that the additional area is roughly equal to an additional mining basin.

The second question was addressed by tracing the perimeter of the mining operation to be 4798 meters based on the satellite image from Google Earth dated February 12, 2016 (see Fig. 13). The additional area for mining that was created by building the 30-m-wide dam onto the 80-m buffer zone could be approximated by multiplying the perimeter by 30 meters, yielding 14.4 hectares. For comparison, the average area of the four mining basins is 15.8 hectares (see Fig. 13), so that the additional area is roughly equal to an additional mining basin.

Fourth Addendum

The fourth addendum was written in response to a request from Andrew Lees Trust to create a single map that shows the conclusions of both this study and the study by Ozius Spatial (2018). The salient conclusions will be reviewed before explaining how the map was created.

The objective of both studies was to determine whether the mining operation carried out by Rio Tinto had encroached upon the 50-meter buffer zone with a natural water body that was agreed upon between Rio Tinto and ONE (National Office of the Environment). The conclusion of the study by Ozius Spatial (2018), which was funded by Rio Tinto, was that, not only had the mining operation encroached upon the buffer zone, but it had advanced 52 meters onto the bed of the estuary of Lake Besaroy (see Figs. 5A, 6 and 9). The conclusion of this study was that, not only had the mining operation encroached upon the buffer zone, but it had advanced 117 meters onto the bed of the estuary (see Fig. 12).

The source of the discrepancy between the two studies lies in the different data sets and assumptions used by the studies. Ozius Spatial (2018) based their conclusions upon the Lidar data that were provided by Rio Tinto and the assumption by Rio Tinto that the elevation (Ordinary High Water Mark) of Lake Besaroy is 0.6 meters above sea level. That assumption has not been justified by any document from Rio Tinto. Although Rio Tinto claimed that the lake elevation was determined by the Lidar survey (Rio Tinto, 2017), no Lidar measurements were made over Lake Besaroy (see Fig. 10A). Moreover, no document from Rio Tinto has ever explained how the Lidar data were calibrated, or how relative elevation differences were converted into absolute elevations above sea level. The conclusions of this study were based upon the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018). In this study, the lake elevation was not assumed, but was determined by the elevation of the visible water connected to Lake Besaroy (see Figs. 7B and 7C). It is worth repeating that both studies were in full agreement in documenting violation of the entire buffer zone by the mining operation.

The method of contouring the satellite elevation data has already been explained, so only the Lidar data will be addressed. Before contouring the Lidar data, it was necessary to create a raster of the point measurements (aggregation of the point measurements into pixels). The resulting contours can differ slightly depending upon how the raster is created. Since the method of contouring was not explained in Ozius Spatial (2018), the raster was created with pixels identical to the 30-m pixels used by the satellite elevation data. Contouring was then carried out using ArcMap 10.6.1 Spatial Analyst with maximum accuracy and minimum smoothing. This method of contouring exactly reproduced the 52 meters of encroachment onto the estuary bed (see Fig. 14A) that was deduced by Ozius Spatial (2018). The resulting map clearly shows that the 50-m buffer zone has been completely occupied by the mining operation, no matter which data set and assumptions have been used (see Fig. 14A).

Replacing the satellite image dated February 12, 2016, in Fig. 14A with the satellite image obtained from Google Earth dated November 1, 2009, shows the amount of littoral forest that was destroyed by the mine expansion from 2009 to 2016 (see Fig. 14B). In 2009 Rio Tinto was still avoiding carrying out mining operations within the 50-m buffer zone, according to their determination of the lake level. On the other hand, note the visible water of Lake Besaroy between the trees within the 4.6-m contour that determines the lake level based on the satellite elevation data (see Fig. 14B). According to the satellite elevation data (not available in 2009), the mining operation was already at the edge of the lake in 2009.

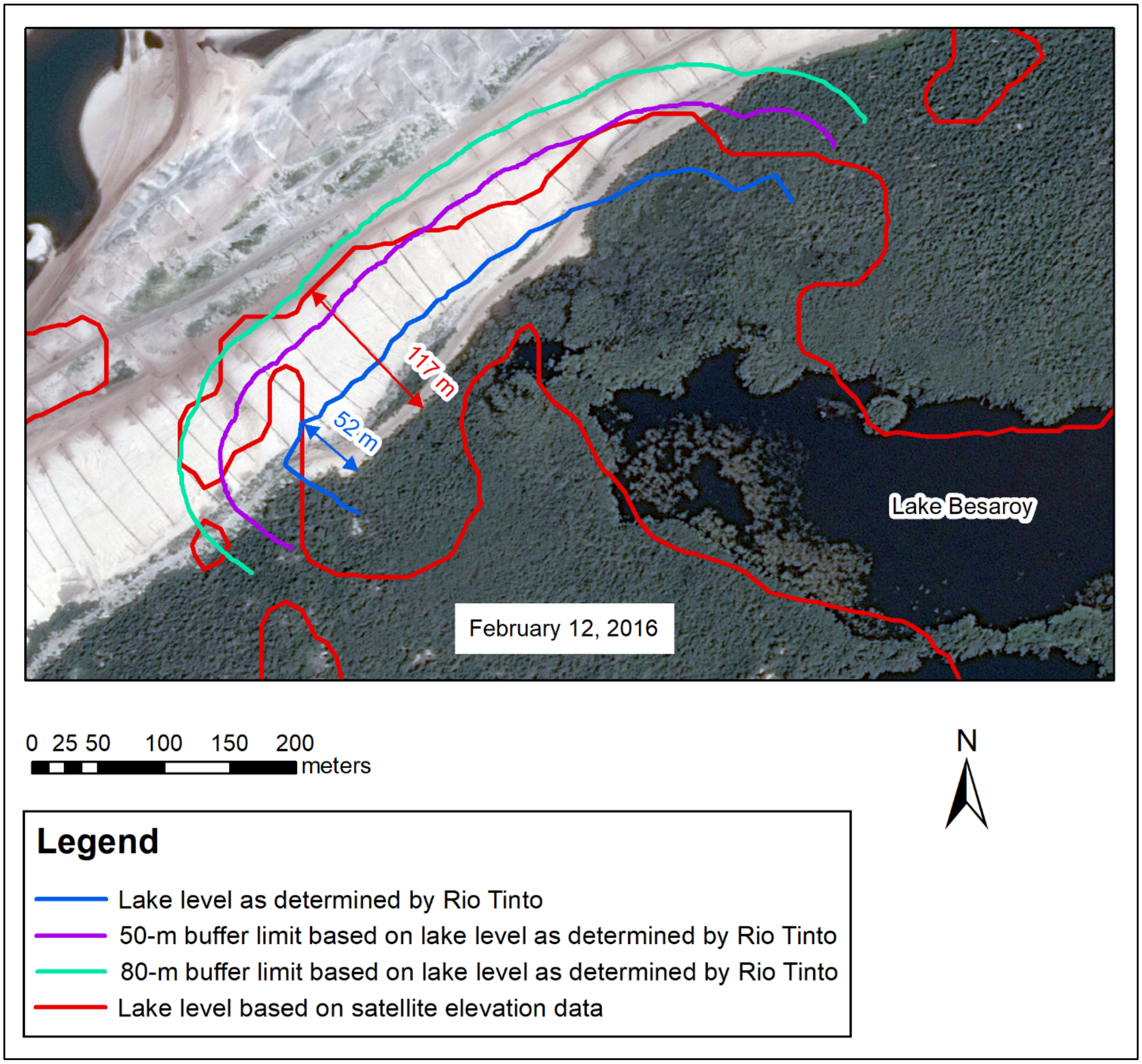

Figure 14A. Based upon the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018), the mining operation has encroached 117 meters upon the bed of the estuary. Based upon the Lidar data provided by Rio Tinto and an elevation of Lake Besaroy that was assumed by Rio Tinto, the mining operation has encroached 52 meters upon the bed of the estuary. Both data sets clearly demonstrate violation of the 50-m buffer (purple contour) that was agreed upon between Rio Tinto and ONE (National Office of the Environment). Contouring was carried out using ArcMap 10.6.1 Spatial Analyst with maximum accuracy and minimum smoothing. Prior to contouring, the Lidar data were aggregated into the same 30-meter pixels as the satellite elevation data. The satellite image was obtained from Google Earth and is dated February 12, 2016.

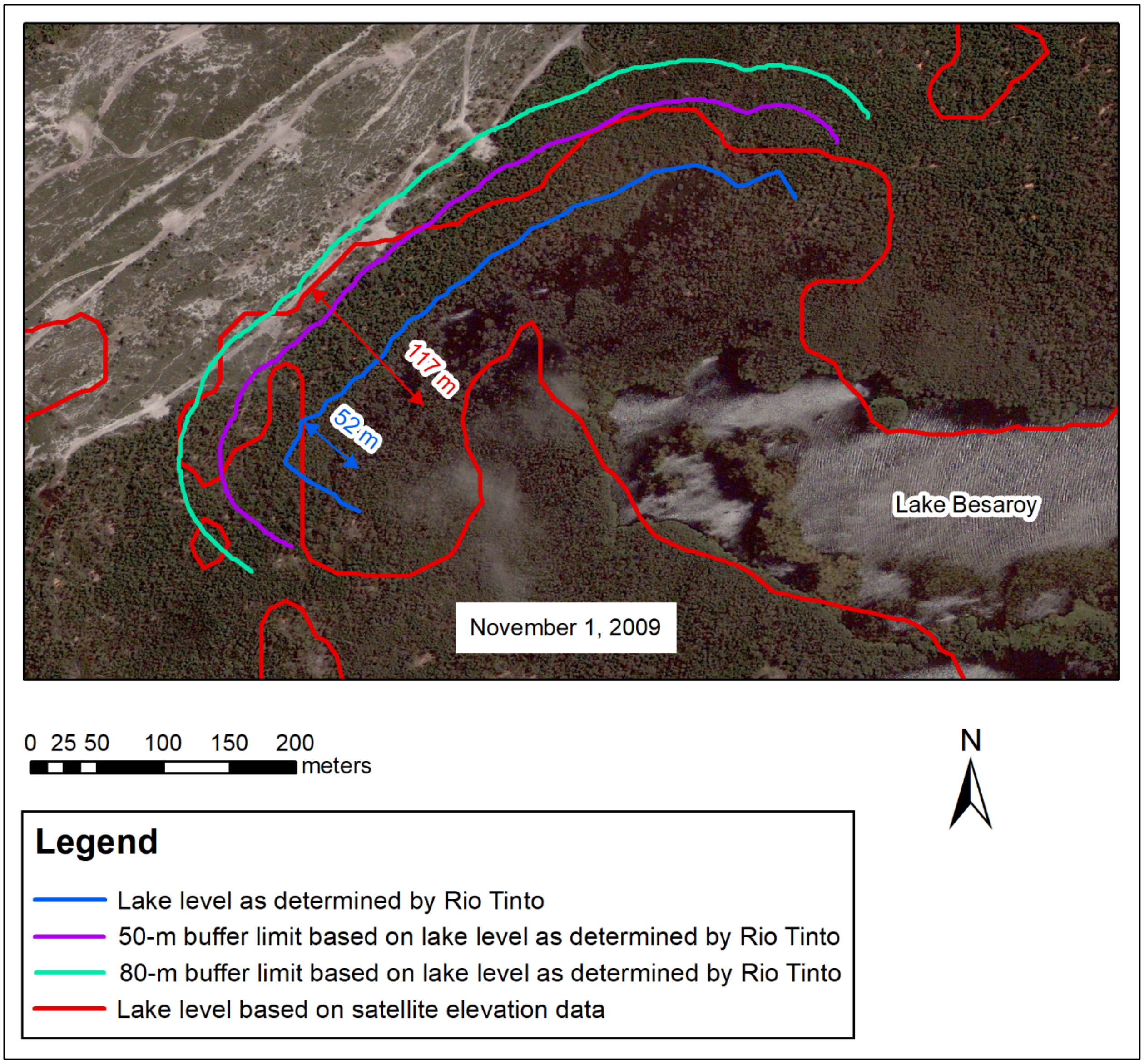

Figure 14B. Replacing the satellite image dated February 12, 2016, in Fig. 14A with the satellite image obtained from Google Earth dated November 1, 2009, shows the amount of littoral forest that was destroyed by the mine expansion from 2009 to 2016. In 2009 Rio Tinto was still avoiding carrying out mining operations within the 50-m buffer zone, according to their determination of the lake level. Note the visible water of Lake Besaroy between the trees within the 4.6-m contour that determines the lake level, based on the 30-m pixels from the Shuttle Radar Topography Mission (NASA, 2018). Contouring was carried out using ArcMap 10.6.1 Spatial Analyst with maximum accuracy and minimum smoothing. Prior to contouring, the Lidar data were aggregated into the same 30-m pixels as the satellite elevation data.