Risk Assessment for Loss of Radionuclides from Mining Basins operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar

by
Steven H. Emerman,
Malach Consulting

Report to Andrew Lees Trust, submitted August 2, 2018
Revision submitted August 21, 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.

Reporting on the violation of an environmental buffer zone by QMM

The following report complements the study by Dr. Emerman on the violation of the environmental buffer zone, entitled: *Evaluation of a Buffer Zone at an Ilmenite Mine operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar.* Report to Andrew Lees Trust, submitted May 27, 2018First, second, third and fourth revisions submitted June 19, July 20, July 26, and August 17, 2018

This additional report was completed in August 2018 in order to address specific questions about rates of seepage and potential overflowing of the dam built by QMM, and to answer related questions from The Andrew Lees Trust.

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

Background

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.

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

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.

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.

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.

Contact details for Dr. Emerman:

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

For further information about The Andrew Lees Trust, please contact:
info@andrewleestrust.org.uk

Risk Assessment for Loss of Radionuclides from Mining Basins operated by Rio Tinto on the Shores of Lakes Besaroy and Ambavarano, Madagascar

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

Report to Andrew Lees Trust, submitted August 2, 2018
Revision submitted August 21, 2018

Explanation of Revision

The revision includes an addendum that answers an additional question from Andrew Lees Trust.

Lightning Summary

Extraction of ilmenite by Rio Tinto along the shores of Lakes Besaroy and Ambavarano, Madagascar, leaves behind radionuclide-enriched tailings within four shallow, unlined mining basins. The annual probabilities of seepage from the basins and of overtopping of dams between the basins and the lakes are 0.18-2.08% and 0.17-0.31%, respectively, which are unacceptably high.

Abstract

Extraction of ilmenite from mineralized sands by Rio Tinto along the shores of Lakes Besaroy and Amabavarano, Madagascar, leaves behind radionuclide-enriched tailings within four shallow (5-15 meters), unlined mining basins. To prevent subsurface transport of radionuclide-enriched water from the mining basins into the lakes, the water level in the basins is maintained 1-2 meters below the lake levels and 2-4 meters below the adjacent topography. To prevent surface transport, a 4-meter-high dam has been built on the buffer zone between the mining basins and the lakes. The objectives of this study were to determine the annual probabilities of seepage from the mining basins and of overtopping of the dams due to extreme precipitation events. Watersheds were determined using the 30-meter elevation data from the Shuttle Radar Topography Mission and surface runoff was predicted using the Soil Conservation Service – Curve Number (SCS-CN) Method. Return periods for annual maximum daily precipitation were calculated using a parabolic fit to 48 years of daily precipitation data. Annual probabilities of seepage from the four mining basins were found to be 0.29-1.22%, 0.51-2.08%, 0.44-1.82%, and 0.18-0.78%, for water level rises of 1-2 meters. Annual probabilities of overtopping were found to be 0.17-0.31%, for water level rises of 6-8 meters. In the event of filling of the basins, all excess water will be spilled into the southwestern basin, so that only the southwestern dam will be overtopped. These annual probabilities are unacceptably high, compared with international safety guidelines that require annual probabilities less than 0.1% for an event resulting in environmental damage and significantly less than 0.01% for an event resulting in the loss of one human life. Rio Tinto has never provided information regarding the closure of the mining basins or the discharge of water that is pumped from the basins to maintain

the water level. If the mining basins are closed simply by filling with sand, radionuclides will be mobilized into the groundwater system and seepage will be a constant occurrence. If radionuclide-enriched water is being discharged into the environment without treatment, then existing safety protocols and infrastructure are completely irrelevant.

Introduction

Rio Tinto is currently operating an ilmenite mine for the manufacture of titanium dioxide on the shores of Lakes Besaroy and Ambavarano in southeastern Madagascar, which are estuaries of the Indian Ocean (see Fig. 1). The ilmenite is extracted from mineralized sands by creating shallow (5 to 15 meter-deep), unlined water-filled basins 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 basins 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.

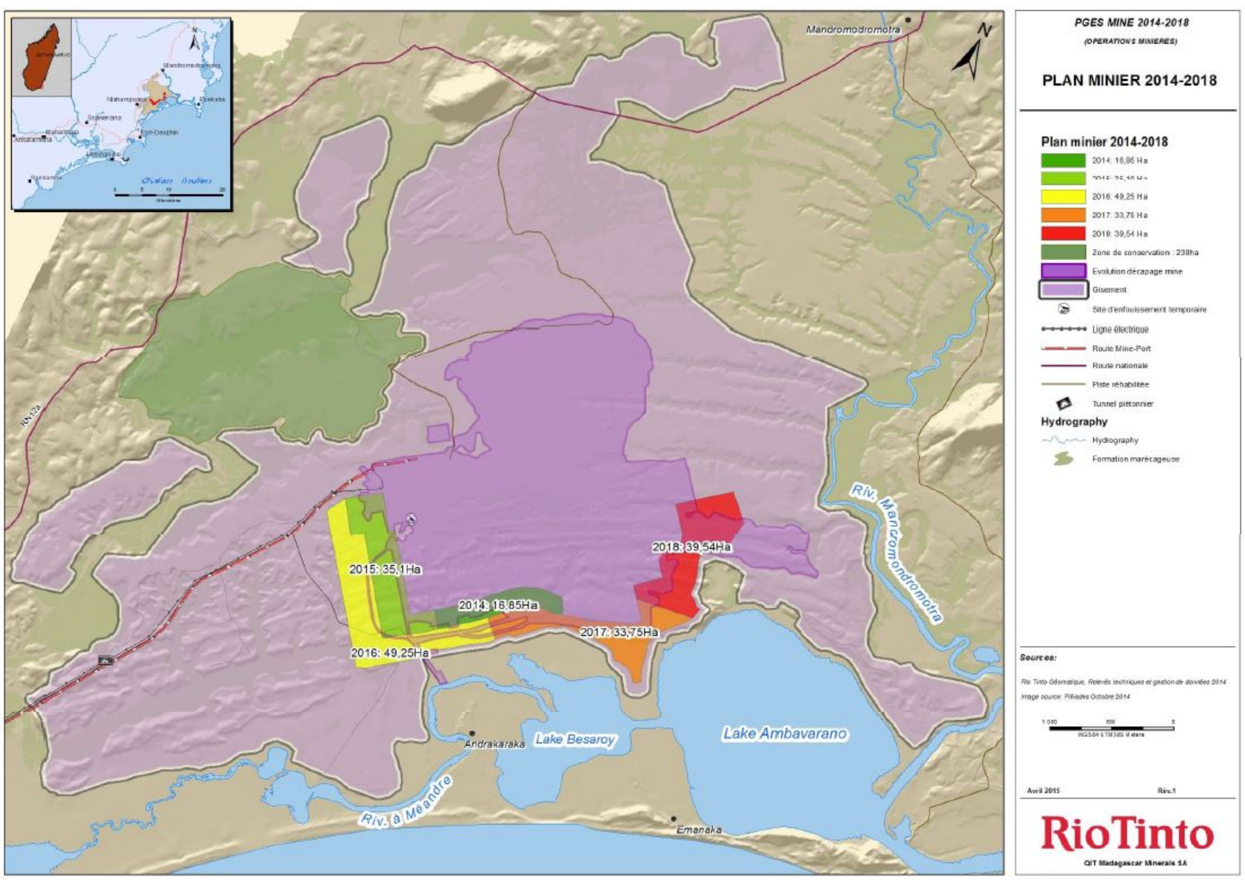

Figure 1. Rio Tinto is currently operating an ilmenite mine along the shores of Lakes Besaroy and Ambavarano in Madagascar. A by-product of the extraction process is the concentration of the radionuclide-enriched minerals monazite and zircon, which would pose a significant threat to aquatic and human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

Malagasy law requires that an 80-m undisturbed buffer zone be preserved between the mining operation and the water bodies (Rio Tinto, 2017). The 80-m buffer zone cannot be regarded as a functional barrier to subsurface transport of radionuclides since groundwater will move rapidly through the well-sorted, highly permeable beach sands in the direction of decreasing elevation of the water table (toward the estuaries and river). Therefore, subsurface transport is prevented by maintaining the water level in the mining basin 1-2 meters below the surface of the natural water bodies (QIT Madagascar Minerals, 2015). Under an agreement between Rio Tinto and the National Office of the Environment (ONE), a 30-meter-wide, 4-meter-high earthen dam has been built on top of the undisturbed buffer zone in order to prevent surface transport of radionuclides across the buffer zone (see Fig. 2; QIT Madagascar Minerals, 2015). The dam also serves as a platform for pipes, anchors and mobile equipment supporting the floating dredge plant (Rio Tinto, 2017). According to QIT Madagascar Minerals (2015), the water level in the mining basins is also maintained 3 meters below the adjacent topography, or 7 meters below the top of the dam. The exact value of 3 meters below the topography is inconsistent with the range of 1-2 meters below the lake levels. The water level is more likely to be either 2-3 meters or 3-4 meters below the topography. Since it is not known which is correct, it will be assumed that the water level in the mining basins is maintained 2-4 meters below the adjacent topography, or 6-8 meters below the top of the dam.

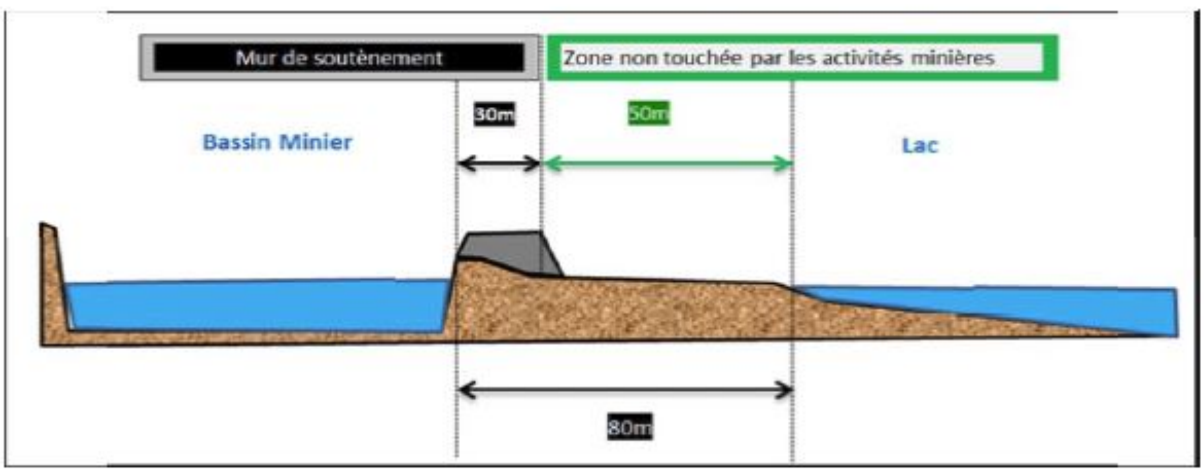

Figure 2. Malagasy law requires that an 80-m undisturbed buffer zone be preserved between the mining operation and the water bodies. The 80-m buffer zone cannot be regarded as a functional barrier to subsurface transport of radionuclides since groundwater will move rapidly through the well-sorted, highly permeable beach sands in the direction of decreasing elevation of the water table (toward the estuaries and river). Therefore, subsurface transport is prevented by maintaining the water level in the mining basin 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 in order to prevent surface water transport across the buffer zone. Diagram from QIT Madagascar Minerals (2015).

The primary threat to the environment and to human health is that an extreme precipitation event, such as a cyclone, will cause the water level in the mining basins to rise higher than the water level in the lakes, resulting in the seepage of radionuclide-enriched water through the well-sorted and highly permeable beach sands, and into the estuaries. Pumping of the mining basins would be useless during a cyclone as there would be no place to which the water could be pumped. An even more extreme precipitation event, such as a cyclone of historic proportions, might cause the water levels in the mining basins to rise higher than the dams, which would destroy the dams, flooding the estuaries with radionuclide-enriched water, and resulting in a major environmental catastrophe.

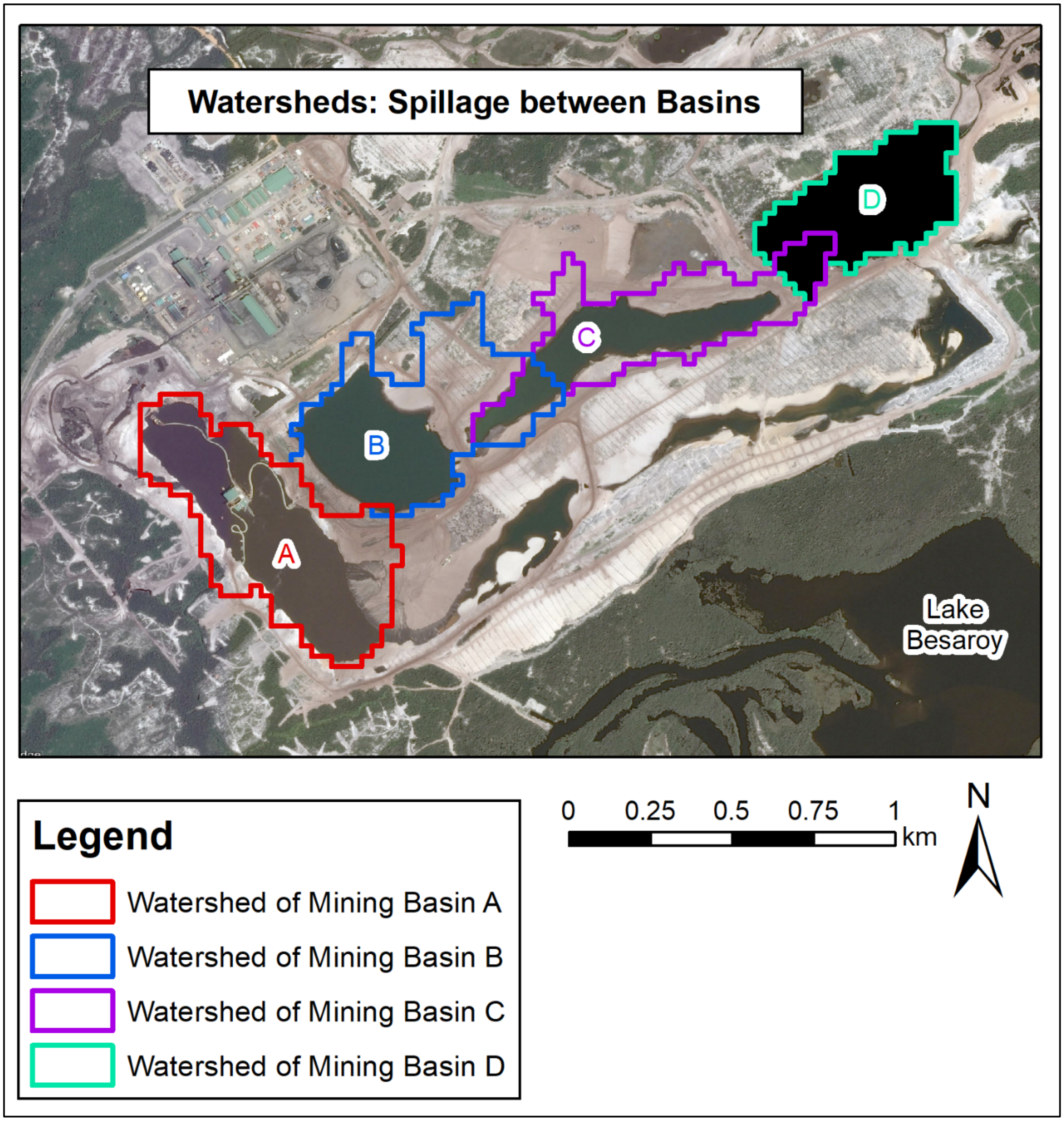

Figure 3a. Watersheds for the four mining basins were determined using 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018) and ArcMap 10.6 Spatial Analyst. Since the satellite elevation data do not resolve any depression of the land surface due to the mining basins, the watershed of each mining basin overlaps the adjacent mining basin to the northeast. In the event of filling of the mining basins, excess water will spill to the southwest to accumulate in Mining Basin A. These are the appropriate watersheds to use to calculate the risk of overtopping the dam between Mining Basin A and Lake Besaroy. Since the lake elevations are 2-4 meters below the adjacent topography and the dam is 4 meters high, overtopping the dam will require a 6 to 8-m rise in the water in Mining Basin A. The satellite image was obtained from Google Earth and is dated February 12, 2016.

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

1) What is the annual probability of seepage (subsurface transport) of radionuclides from the mining basins into the lakes, which would require a 1 to 2-meter rise in the water levels of the basins?
2) What is the annual probability of overtopping of the dam between the mining basins and the lakes by radionuclide-enriched water, which would require a 6 to 8-meter rise in the water levels of the basins?

The objectives were addressed by developing an Annual Maximum Daily Precipitation – Return Period relationship from local meteorological data and by using the Soil Conservation Service – Curve Number (SCS-CN) Method (USDA-NRCS-CED, 1986; Dingman, 2015) to calculate surface runoff.

Previous reports to Andrew Lees Trust by Emerman (2017, 2018a, 2018b, 2018c) in both English and French have questioned the consistency of the design and construction of the dam with generally-accepted safety guidelines. In addition, Emerman (2018c) has documented that the legally-mandated 80-meter undisturbed buffer zone has not been respected by Rio Tinto, and that the mining operation has actually encroached as much as 117 meters onto the bed of the estuary itself. A report that was funded by Rio Tinto determined that the mining operation has encroached by 52 meters onto the bed of the estuary (Ozius Spatial, 2018).

Methods

The analysis was carried out for the four mining basins that are visible in a Google Earth satellite image dated February 12, 2016 (see Figs. 3a and 3b). For this study, the mining basins were labeled as A, B, C and D, starting in the southwest (this terminology is not used by Rio Tinto). In the satellite image, a floating dredge plant is visible in Mining Basin A (see Figs. 3a and 3b). The watershed of each mining basin was determined using 30-meter elevation data from the Shuttle Radar Topography Mission (NASA, 2018), which was downloaded from Watkins (2018), and the Watershed Tool in ArcMap 10.6 Spatial Analyst. Since the satellite elevation data do not resolve any depression of the land surface due to the mining basins, the watershed of each mining basin overlaps the adjacent mining basin to the northeast (see Fig. 3a). In the event of filling of the mining basins, excess water will spill to the southwest to accumulate in Mining Basin A. These unadjusted watersheds are the appropriate watersheds to use to calculate the risk of overtopping the dam between Mining Basin A and Lake Besaroy (see Fig. 3a). Note that the dams between the lakes and Mining Basins B, C and D cannot be overtopped because those mining basins cannot fill higher than the land surface. On the other hand, in order to calculate seepage (which would not involve filling of the mining basins and spillage of water from one basin to another), the watersheds were adjusted to remove overlap (see Fig. 3b, Table 1).

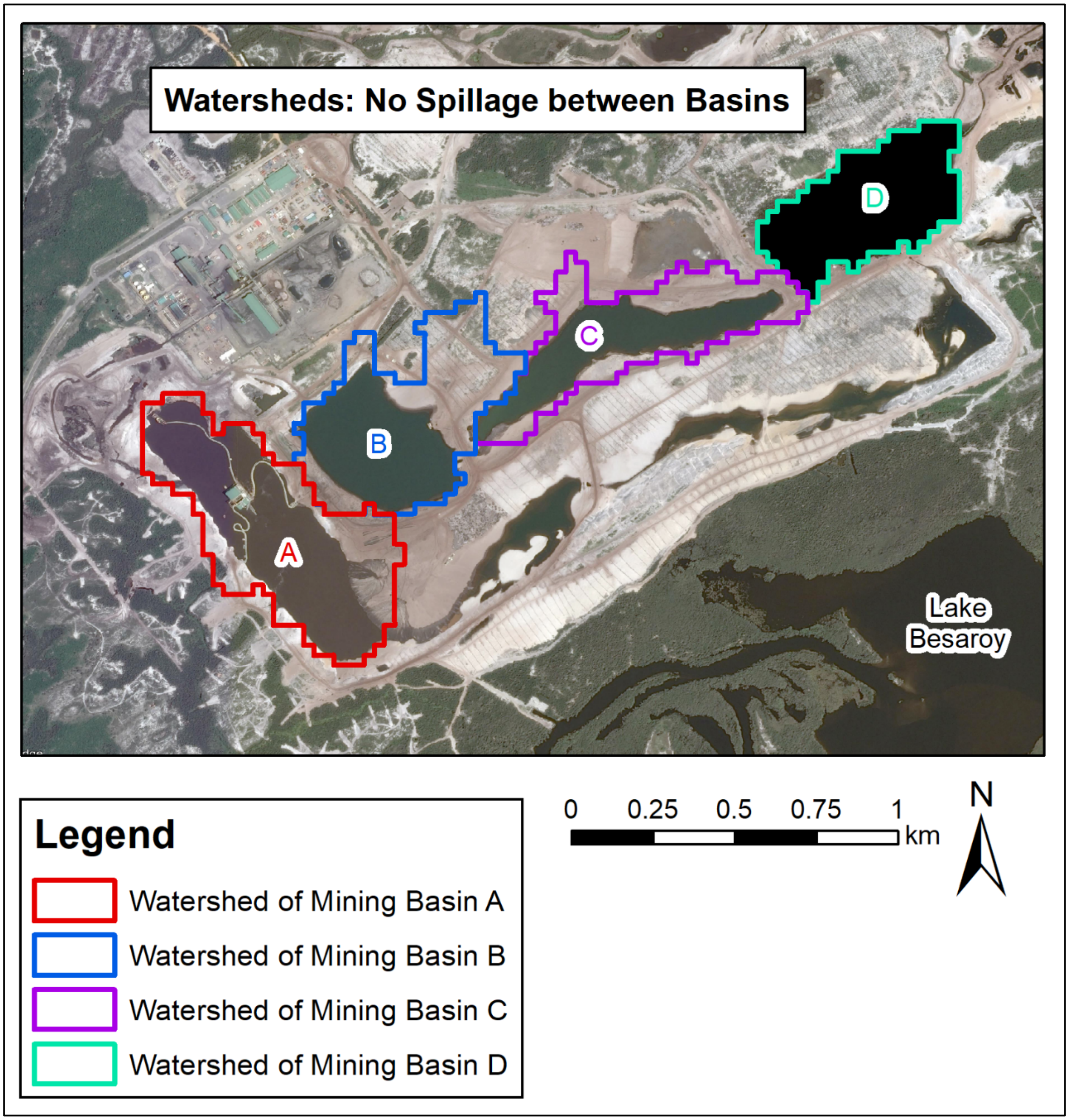

Figure 3b. Watersheds for the four mining basins were determined using 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018) and ArcMap 10.6 Spatial Analyst. Since the satellite elevation data do not resolve any depression of the land surface due to the mining basins, the watersheds were adjusted to remove overlap. These are the appropriate watersheds to use to calculate the risk of seepage between each mining basin and Lake Besaroy. Since the mining basin elevations are maintained 1-2 meters below the level of Lake Besaroy, seepage will occur whenever a storm causes the water level in any basin to rise by 1-2 meters. The satellite image was obtained from Google Earth and is dated February 12, 2016.

The SCS-CN Method calculates surface runoff using the heuristic and empirical relationships (Dingman, 2015)

$$P^* = \frac{(P - S_i)^2}{P - S_i + S_{max}} \tag{1}$$

$$S_i = 0.2 S_{max} \tag{2}$$

$$S_{max} = \frac{1000}{CN} - 10 \tag{3}$$

where P^* is the effective precipitation in inches (precipitation that generates surface runoff or streamflow), P is the total precipitation in inches from a single storm, S_i is the initial abstraction (surface storage that must be satisfied before surface runoff can begin), S_{max} is the maximum retention capacity (maximum amount of precipitation that can fall that does not contribute to surface runoff), and CN is the curve number (which depends upon land use and the hydrologic soil group). For water flowing over the land surface, the curve number was chosen as $CN = 77$ as appropriate for bare soil in Hydrologic Soil Group A (infiltration exceeding 0.30 inches per hour), which should apply to well-sorted beach sands (USDA-NRCS-CED, 1986; Dingman, 2015). For water flowing over the mining basins, which would occur after filling of the basins, the curve number was chosen as $CN = 100$ since no further storage could occur within the basins.

By conservation of mass, the volume of water entering a mining basin is given by

$$P^*(A_W - A_B) + PA_B = A_B \Delta h \tag{4}$$

where A_W is the watershed area (including the area of the basin), A_B is the basin area, and Δh is the rise in the water level of the basin. Eq. (4) could be an underestimate of the volume of water entering a basin because it considers only surface flow and neglects any precipitation that might infiltrate the land surface and then enter the basins through the sides or from the bottom. Any change in the surface area of the basins has been neglected since they have been depicted as having very steep sides (QIT Madagascar Minerals, 2015; see Fig. 2).

Table 1. Annual Probabilities of Seepage from Mining Basins

Water-Level Rise (m)	24-Hour Precipitation[3] (mm)	Return Period[4] (years)	Annual Probability (%)
Mining Basin A Basin Area = 21.9 ha, Watershed Area[1,2] = 32.88 ha			
1.0	693.9	81.9	1.22
1.5	1027.7	189.0	0.53
2.0	1361.2	340.6	0.29
Mining Basin B Basin Area = 13.47 ha, Watershed Area[1,2] = 26.78 ha			
1.0	543.6	48.1	2.08
1.5	796.3	110.0	0.91
2.0	1048.8	197.3	0.51
Mining Basin C Basin Area = 12.12 ha, Watershed Area[1,2] = 22.44 ha			
1.0	577.9	55.0	1.82
1.5	849.1	126.1	0.79
2.0	1119.9	226.5	0.44
Mining Basin D Basin Area = 15.75 ha, Watershed Area[1,2] = 18.65 ha			
1.0	857.8	128.9	0.78
1.5	1280.2	299.6	0.33
2.0	1702.6	541.8	0.18

[1]The watershed area includes the area of the mining basin.
[2]Watersheds were determined based on the 30-m elevation data from the Shuttle Radar Topography Mission (NASA, 2018).
[3]The 24-hour precipitation required to produce a given water-level rise was calculated using the Soil Conservation Service – Curve Number (SCS-CN) Method and assuming $CN = 77$ for bare soil with Hydrologic Soil Group A (USDA-NRCS-CED, 1986).
[4]The return period for exceeding a given 24-hour precipitation event was determined by a parabolic fit to 48 years of daily precipitation data (see Fig. 5).

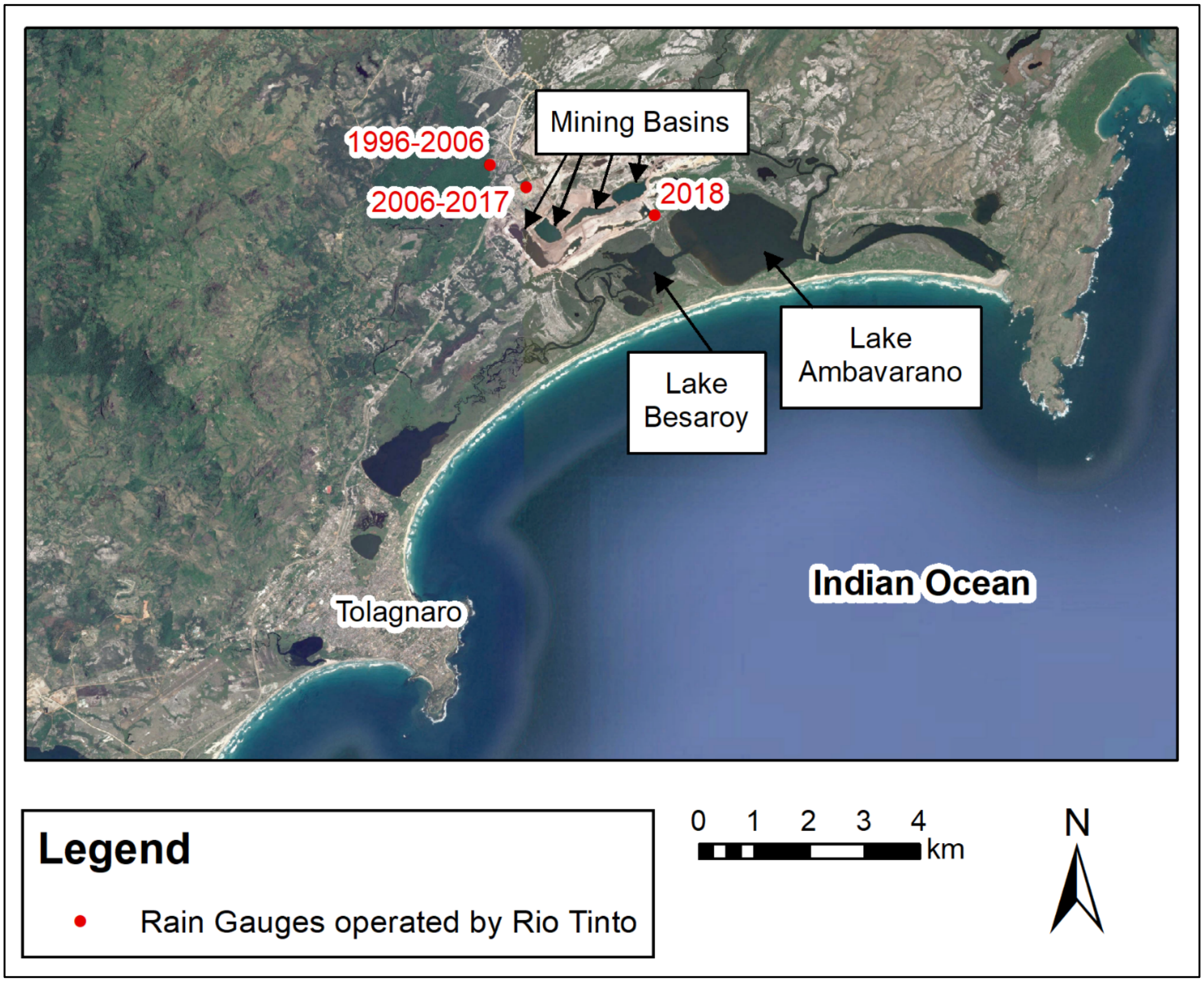

Figure 4. Although Rio Tinto operates a rain gauge in the vicinity of the mining basins, they measure only monthly precipitation and the record goes back to only 1996. Moreover, the rain gauge has been moved three times since 1996. Therefore, the 24-hour-precipitation – return period relationship for the mining basins was determined using the daily precipitation data from the weather station at Tolagnaro, which is 8 kilometers to the southwest, and which has data going back to 1973. The satellite image was obtained from Google Earth and is dated February 12, 2016.

Determining the value of P, the 24-hour precipitation event that would result in a rise in water level equal to a given Δh, then involves the simultaneous solution of Eqs. (1)-(4). For calculating the values of P that would be relevant for seepage (rises of water level of Δh = 1-2 meters), the values of A_W were the areas that were adjusted to remove overlap (see Fig. 3b, Table 1). In addition, the curve number was set at $CN = 77$ because no water would be flowing across the mining basins since the basins would not be filled. On the other hand, for calculating the values of P that would be relevant for overtopping the dam at Mining Basin A (rises of water level of Δh = 6-8 meters), the value of A_{W} was the sum of the areas of the adjusted watersheds, or the total watershed that would export surface water to Mining Basin A (see Figs. 3a and 3b; Table 1). The relevant value of CN was then the composite CN that was weighted according to the fractions of the total watershed that were land ($CN = 77$) and water ($CN = 100$), resulting in $CN = 91$ (USDA-NRCS-CED, 1986; Dingman, 2015).

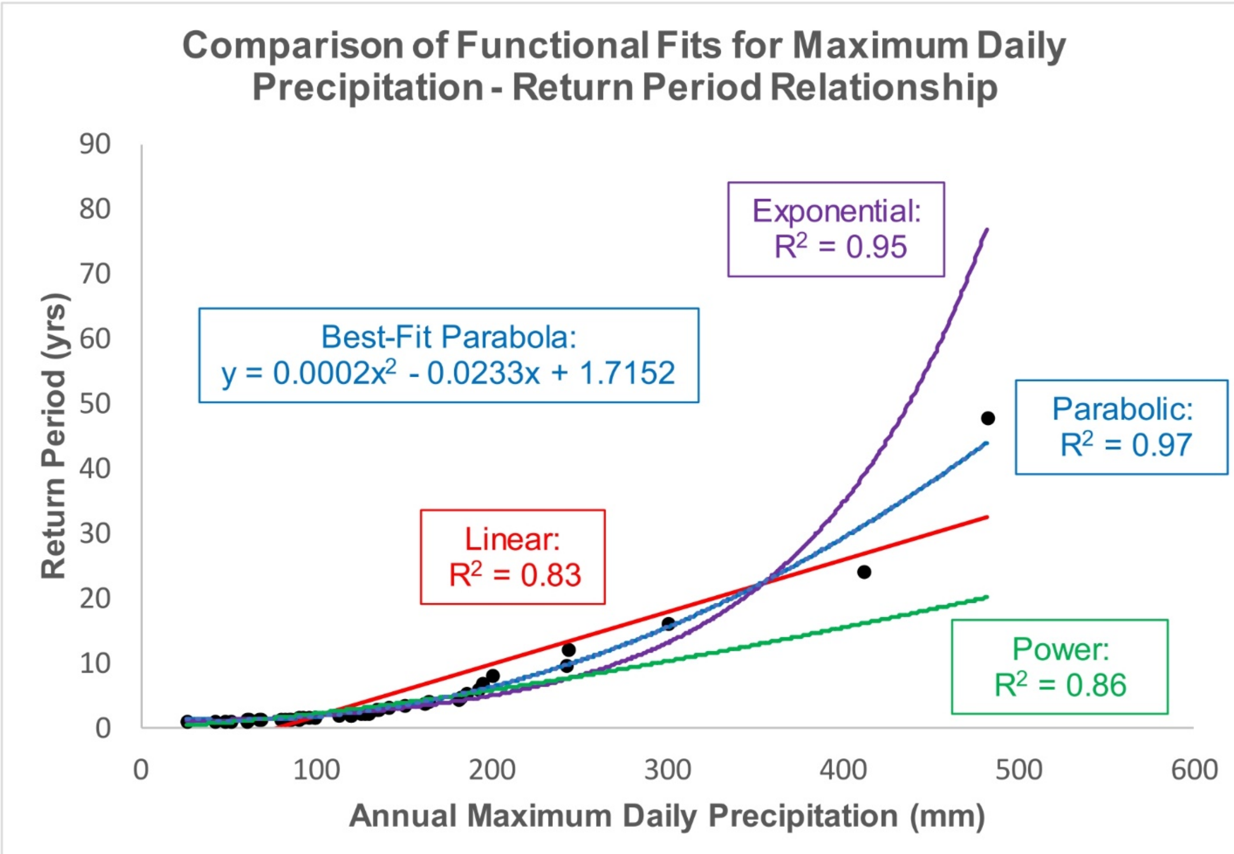

Figure 5. Out of the common functional fits, the best fit to the Annual Maximum Daily Precipitation – Return Period relationship for Tolagnaro is a parabola, which accounts for 97% of the variation in the return period. The parabolic fit is especially good at the upper range of annual maximum daily precipitations, at which the return period would be greatly overestimated by an exponential fit and greatly underestimated by linear and power fits.

The final step was to determine the return period, or annual probability of exceedance, corresponding to each calculated 24-hour precipitation event. Although precipitation data going back to 1996 was supplied by Rio Tinto, only monthly precipitation was measured, and the rain gauge has been moved three times (see Fig. 4). Therefore, the daily precipitation data from the weather station at Tolagnaro, 8 kilometers to the southwest of the mine (see Fig. 4) was used to calculate the Annual Maximum Daily Precipitation – Return Period relationship. These data go back to 1973 and were downloaded from the web site of the National Climatic Data Center (NOAA-NESDIS-NCDC, 2018). The chief source of uncertainty in the use of these data is the number of missing days with no observations, especially prior to the mid-1990s (see Table A1). However, the entire dataset was used, primarily because some years with many missing days still recorded some days with significant daily precipitation events (see, for example, 1981 in Table A1).

Each year was assigned a ranking number M with the years ranked in order from the year with the highest daily precipitation ($M = 1$) to the lowest daily precipitation ($M = 48$). The return period for each precipitation event was calculated as (Watson and Burkett, 1995)

$$T = \frac{n+1}{M} \tag{5}$$

where *T* is the return period in years and *n* is the number of years ($n = 48$). Out of the common functional fits (Watson and Burnett, 1995), the best fit to the Annual Maximum Daily Precipitation – Return Period relationship for Tolagnaro was the parabola

$$T = 0.0002P^2 - 0.0233P + 1.7152 \quad (6)$$

where *P* is 24-hour precipitation in millimeters. Eq. (6) accounts for 97% of the variation in the return period (see Fig. 5). The parabolic fit is especially good at the upper range of annual maximum daily precipitations, at which the return period would be greatly overestimated by an exponential fit and greatly underestimated by linear and power fits (see Fig. 5). The return periods were converted into annual probabilities using

$$AP = \frac{100}{T} \quad (7)$$

where *AP* is the annual probability as a percentage that a given 24-hour precipitation event will be equaled or exceeded.

Results

The annual probabilities of seepage were found to be 0.29-1.22%, 0.51-2.08%, 0.44-1.82%, and 0.18-0.78% for Mining Basins A, B, C and D, respectively, where the lower probability corresponds to a water-level rise of 2 meters and the higher probability corresponds to a water-level rise of 1 meter (see Table 1). Taking $\Delta h = 1.5$ meters as a mean required water-level rise results in annual probabilities of seepage of 0.53%, 0.91%, 0.79% and 0.33% for Mining Basins A, B, C, and D, respectively (see Table 1). The mining basin at greatest risk of seepage is Mining Basin B, due to its relatively large watershed to the northeast (see Fig. 3b). The annual probabilities of overtopping the dam between Mining Basin A and Lake Besaroy were found to be 0.17, 0.23, and 0.31%, corresponding to water-level rises of 8, 7, and 6 meters, respectively (see Table 2). These probabilities would be considerably lower if there were not a hydraulic connection among the mining basins, which causes all of the excess water to accumulate in Mining Basin A (see Fig. 3a). Although the 24-hour precipitation amounts resulting in water-level rises of 6,7 and 8 meters (corresponding to return periods of 323, 443 and 582 years, respectively) might seem unrealistically high (see Table 2), for comparison, in 1966, Tropical Cyclone Denise dropped 1825 mm of rain in 24 hours on Réunion, an island 680 kilometers to the east of Madagascar (Arizona State University, 2018).

The above annual probabilities of major environmental damage are unacceptably high. Although different governmental bodies have different safety guidelines, the safety guidelines followed by the U.S. federal government are well-regarded internationally and will be used for comparison in the absence of equivalent safety guidelines in effect in Madagascar. It is appropriate to consider safety guidelines for dams, since the safety function of a dam is to prevent the movement of water from one location to another. These guidelines for dams should be regarded as absolute minima, since most dams are not intended to prevent the movement of water enriched in radionuclides or other contaminants.

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.”

Table 2. Annual Probabilities of Overtopping Dam at Mining Basin A[1]

Water-Level Rise (m)	24-Hour Precipitation[2] (mm)	Return Period[3] (years)	Annual Probability (%)
6.0	1327.4	323.2	0.31
7.0	1544.8	443.0	0.23
8.0	1762.3	581.8	0.17

[1]Overtopping of the dam was considered only at Mining Basin A because all other mining basins spill excess water into Mining Basin A.
[2]The 24-hour precipitation required to produce a given water-level rise was calculated using the Soil Conservation Service – Curve Number (SCS-CN) Method. A composite *CN* for the watershed of Mining Basin A was calculated assuming *CN* = 100 for the other mining basins and *CN* = 77 for bare soil with Hydrologic Soil Group A (USDA-NRCS-CED, 1986).
[3]The return period for exceeding a given 24-hour precipitation event was determined by a parabolic fit to 48 years of daily precipitation data (see Fig. 5).

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]."

The possibility of seepage of radionuclides from the mining basins into the estuaries would certainly result in environmental damage and economic loss (due to the impact on fish), and should, at least, be placed into the category of Significant Hazard Potential according to the classification system of FEMA (2013). Therefore, the annual probabilities of seepage should not exceed 0.1% as an absolute minimum (compare with annual probabilities in Table 1). On the other hand, the overtopping and consequent destruction of the dam would represent a major environmental catastrophe and would certainly result in the loss of at least one human life, corresponding to High Hazard Potential in the system of FEMA (2013). As mentioned above, the return period for this environmental catastrophe ought to be well beyond 10,000 years (USACE-HCE, 2003), corresponding to an annual probability that is significantly less than 0.01%. By this standard, the annual probabilities of overtopping the dam are at least two to three orders of magnitude too high (see Table 2).

Discussion

There are three disturbing issues that have not yet been discussed. The first, is that, although annual probabilities of seepage are unacceptably high even if water levels in the mining basins are maintained 1-2 meters below the lake levels, Rio Tinto has rapidly retreated from even this safety protocol. The protocol of maintaining the water levels 1-2 meters below the lake levels was stated by QIT Madagascar Minerals (2015). However, a 2017 memorandum from Rio Tinto stated that "The dredge pond [mining basin] elevation will be maintained at -1 masl [meters above sea level]" and then stated that "The Ordinary High Water Mark along Lake Ambavarano and the Meandre River is at an elevation of 0.6 masl" (Rio Tinto, 2017) for a water-level difference of 1.6 meters. This was followed by a 2018 memorandum that was a response to Emerman (2018c), which stated, “The dredge pond is generally operated at an elevation below the neighboring lakes and below the natural topography” (Rio Tinto, 2018). The current position of Rio Tinto seems to be that it is only “generally” true that the water level in the mining basin is below the elevation of the lake surface. This implies that sometimes the water levels in the mining basins are higher than the lake levels and that there is no longer any commitment to maintain the water levels in the basins at any specified depth below the water levels in the lakes. Note that seepage of radionuclides, which was regarded above as an event with at least Significant Hazard Potential (FEMA, 2013) will occur whenever the water level in the mining basins rises above the lake levels and will be quite rapid due to the high hydraulic conductivity of well-sorted beach sands.

In a response to concerns expressed by Emerman (2018c) regarding the safety of the dam, Rio Tinto (2018) responded, “The dredge pond is temporarily mining adjacent to the lakes (approximately three years).” The second disturbing issue is that no document issued by Rio Tinto has ever provided a plan for closure of the mining basins, although Andrew Lees Trust has asked Rio Tinto to provide such a plan. If the mining basins are simply filled in with sand, the water table will rise close to the surface, which will mobilize all of the radionuclides (except those that are sorbed onto sediment) into the groundwater system. The result will be that the seepage of radionuclides from the former mining basin into the estuaries will be a constant occurrence, as opposed to only an occurrence with an unacceptably high annual probability. It is, in fact, shocking that no document from Rio Tinto has mentioned the need for a natural or synthetic liner that would confine the radionuclides.

The 2017 memorandum from Rio Tinto refers to a “Trigger Action Response Plan that actively monitors the dredge pond [mining basin] level, the water level in the lake and the weather. Actions include dewatering of the dredge pond” (Rio Tinto, 2017). Along the same lines, the regular maintenance of the water levels in the mining basins below the water levels in the lakes must involve dewatering, which presumably is carried out by pumping. This maintenance of the water levels in the mining basins below the lake levels must be ongoing because the water table in the vicinity of the mining basin must naturally be higher than the estuaries. No document from Rio Tinto has ever clarified where the radionuclide-enriched basin water is discharged and how or whether it is treated, although Andrew Lees Trust has requested answers to these questions. If the radionuclide-enriched water from the mining basins is being routinely discharged into the environment without treatment, then current safety protocols and infrastructure for confining radionuclides to the mining basin are completely irrelevant.

Conclusions

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

1) The annual probabilities of seepage of radionuclides from the four mining basins are 0.29-1.22%, 0.51-2.08%, 0.44-1.82%, and 0.18-0.78%, where the lower probability corresponds to a water-level rise of 2 meters and the higher probability corresponds to a water-level rise of 1 meter.
2) The annual probabilities of overtopping the dam with radionuclide-enriched water are 0.17, 0.23, and 0.31%, corresponding to water-level rises of 8, 7, and 6 meters, respectively.
3) The above annual probabilities are unacceptably high, compared with international safety guidelines that require annual probabilities less than 0.1% for an event resulting in

environmental damage and significantly less than 0.01% for an event resulting in the loss of one human life.

4) If the mining basins are closed simply by filling in with sand, radionuclides will be mobilized into the groundwater system and seepage into the estuaries will be a constant occurrence.
5) If the mining basins are being dewatered by discharging radionuclide-enriched water into the environment without treatment, then current safety protocols and infrastructure for confining radionuclides to the mining basin are completely irrelevant.

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 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

Arizona State University, 2018. World Meteorological Organization Global Weather & Climate Extremes Archive. Available online at: https://wmo.asu.edu/content/world-meteorological-organization-global-weather-climate-extremes-archive

Dingman, S.L., 2015. Physical hydrology, 3rd ed: Long Grove, Illinois, Waveland Press, 643 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.

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., 2018c. Evaluation of a buffer zone at an ilmenite mine operated by Rio Tinto on the shores of Lakes Besaroy and Ambavarano, Madagascar: Report to Andrew Lees Trust, 34 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

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
Ozius Spatial, 2018. OS1718133 QMM waterbody buffer zone analysis, March 29, 2018: Report to Rio Tinto, 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.
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, 2018. 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.
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
Watkins, D., 2018. 30-Meter SRTM Tile Downloader. Available online at: http://dwtkns.com/srtm30m/
Watson, I. and A.D. Burnett, 1995. Hydrology—an environmental approach: Boca Raton, Florida, CRC Press, 702 p.
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

Appendix

Table A1. Annual Maximum Daily Precipitation at Tolagnaro, Madagascar[1]

Year	Days of Record	Maximum Daily Precipitation (mm)
1973	55	59.9
1974	76	199.9
1975	145	25.9
1976	180	51.1
1977	275	59.9
1978	335	130.0
1979	288	80.0
1980	270	41.9
1981	252	300.0
1982	301	130.0
1983	306	68.1
1984	295	85.1
1985	325	119.1
1986	277	89.9
1987	327	48.0
1988	347	130.0
1989	300	130.0
1990	221	119.9
1991	227	150.1
1992	270	99.1
1993	303	61.0
1994	341	412.0
1995	350	182.1
1996	336	482.1
1997	311	192.0
1998	345	134.9
1999	342	95.0
2000	342	134.1
2001	354	141.0
2002	364	127.0
2003	361	89.9
2004	365	242.1
2005	365	181.1
2006	363	99.1
2007	362	84.1
2008	366	185.9
2009	365	91.9
2010	365	82.0
2011	365	194.1
2012	366	125.0
2013	364	164.1

2014	365	243.1
2015	344	119.9
2016	366	67.1
2017	345	113.0
2018[2]	206	162.1

[1]Daily precipitation data downloaded from NOAA-NESDIS-NCDC (2018).
[2]Data were downloaded on July 25, 2018.

Addendum

The objective of this addendum is to answer the following additional question from Andrew Lees Trust: What is the best estimate of the rate of dewatering of the mining basins? The objective was addressed by assuming a steady-state flow of groundwater from the natural water bodies to the mining basins (see Fig. 6). Under the assumption of steady-state conditions, the rate of mining basin dewatering must be equal to the discharge of groundwater into the mining basins. The steady-state assumption is probably valid for estimating the time-averaged rate of mining basin dewatering over periods longer than a year (covering both wet and dry seasons).

The steady-state discharge of groundwater is given by Darcy's Law (Fetter, 2001)

$$Q = Kdw\frac{\Delta h}{L} \tag{8}$$

where Q is discharge, K is hydraulic conductivity, d is the depth of the mining basins, w is the perimeter of the mining basins projected perpendicular to the groundwater flow direction (see Fig. 6), Δh is the difference in water level between the mining basins and the natural water bodies, and L is the length of the groundwater flow path. The depth of the mining basins is in the range 5-10 meters and the water-level difference is in the range 1-2 meters (QIT Madagascar Minerals, 2015). The length of the groundwater flow path for each mining basin was estimated by drawing a straight line from the midpoint of the perimeter of the mining basin facing the natural water bodies (southeastern segment of perimeter) to the nearest river or lake (see Fig. 6). The effective length of the groundwater flow path for discharge into all four mining basins was then calculated as the weighted mean of the flow lengths for each mining basin, weighted according to the perimeter of each mining basin perpendicular to the flow path. The effective projected perimeter, w, was calculated as the sum of the projected perimeters for all four mining basins.

The assumption of this calculation is that all four mining basins are being dewatered simultaneously. When a mining basin has been created and the extraction of ilmenite has begun, the mining basin is a source of radionuclide-enriched water. That basin must then be continuously dewatered to prevent the subsurface transport of radionuclide-enriched water from the mining basin to the river or lakes, even if the basin is not being actively mined at a particular time. (Note that the satellite image from February 12, 2016 shows the floating dredge plant only in the southwestern mining basin, although the other three mining basins appear to be fully operational (see Fig. 6)).

The greatest source of uncertainty in the estimation of the rate of dewatering of the mining basins is the hydraulic conductivity of the beach sands on the seaward side of the mining basins. This value of hydraulic conductivity is actually known by Rio Tinto. A study by Schlumberger Water Services (2007) that was funded by Rio Tinto wrote, "Field data and modelling demonstrated anisotropy in the sand deposit with horizontal conductivity about 1000 times the vertical hydraulic conductivity." Without having access to these data, it will be assumed that hydraulic conductivity is in the range 10^{-3}-10^{-1} cm/s, which is appropriate for well-sorted sands (Fetter, 2001). The best estimate for hydraulic conductivity is probably 10^{-2} cm/s, since the geometric mean tends to be the best estimate for the expected value for data that range over orders of magnitude. In fact, Clapp and Hornberger (1978) give 1.76×10^{-2} cm/s as the expected saturated hydraulic conductivity for sandy soils, based on an analysis of 1845 soils.

Note that the anisotropy measured by Schlumberger Water Services (2007) reinforces the one-dimensional (horizontal) flow that is assumed in Eq. (8).

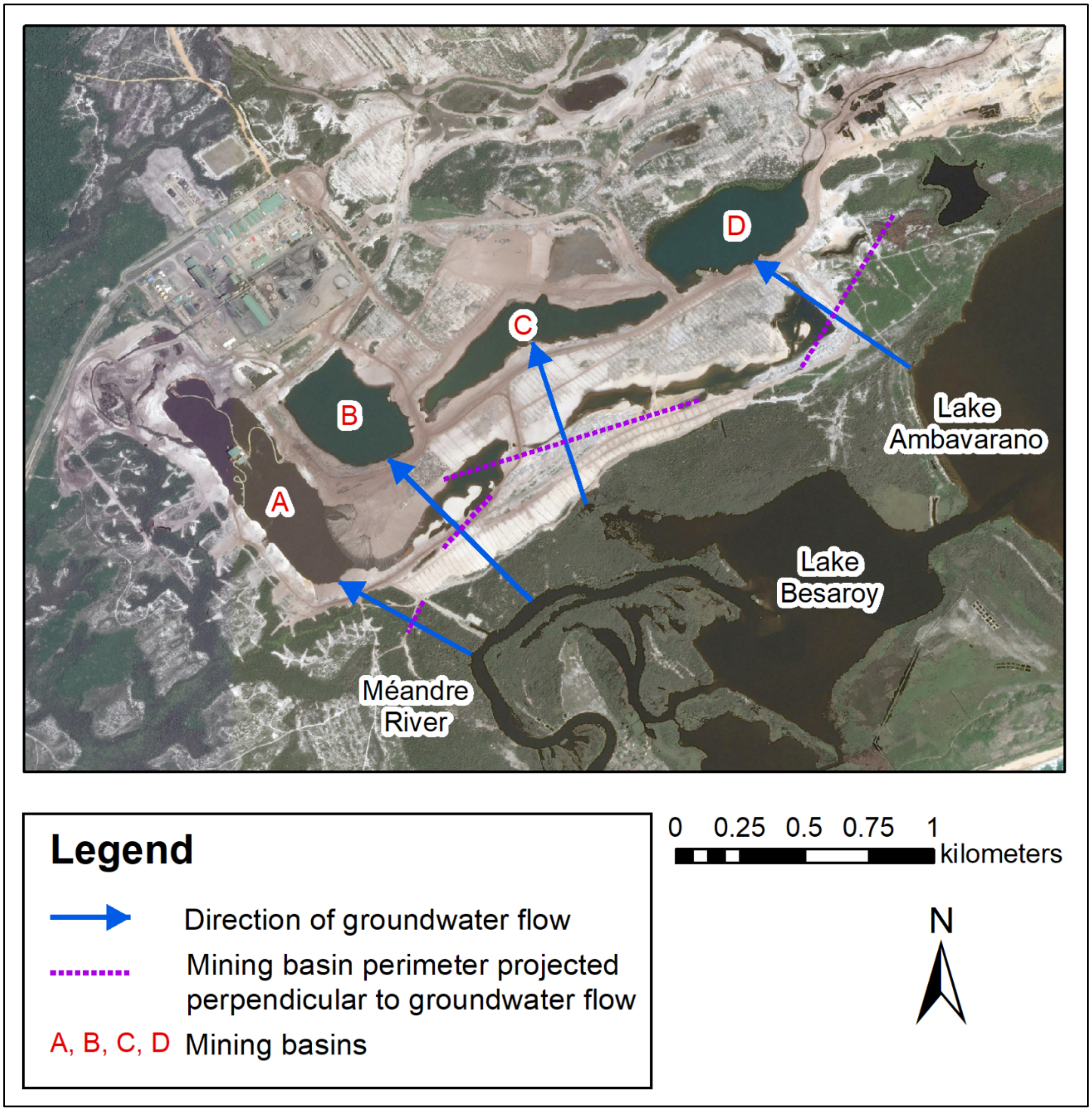

Figure 6. Maintaining the water level in the mining basins 1-2 m below the water level of the river and lakes results in continuous groundwater flow from the natural water bodies to the mining basins. The groundwater flow paths were drawn from the midpoint of the perimeter of the mining basin facing the natural water bodies (southeastern segment of perimeter) to the nearest river or lake. The cross-section for groundwater flow was drawn as the perimeter of each mining basin projected onto a horizontal line perpendicular to the groundwater flow path. The satellite image was obtained from Google Earth and is dated February 12, 2016.

Based on the preceding range of values, estimates of the rate of mining basin dewatering range from 465 m^3/yr to 279,192 m^3/yr with a best estimate (d = 10 m, Δh = 1.5 m, $K = 10^{-1}$

cm/s) of 13,960 m^3/yr. Due to the uncertainty in hydraulic conductivity, only one significant digit is appropriate, so that the best estimate should be stated as 15,000 m^3/yr with a range of 500-300,000 m^3/yr. For comparison, the mean area of a mining basin is 15.81 hectares (see Table 1). Taking a mean depth of 10 meters, the mean volume of a mining basin is 1.581×10^6 m^3. Therefore, the best estimate of the rate of mining basin dewatering is equivalent to removing 0.9% of the volume of a mining basin each year, and the maximum estimate is equivalent to removing 17.7% of the volume of a mining basin each year.

Table 3. Estimates of Mining Basin Dewatering Rates[1]

Low Hydraulic Conductivity (K = 0.001 cm/s)		
Mining Basin Depth (m)	Water-Level Difference[2] (m)	Dewatering Rate (m^3/yr)
5	1	465
5	1.5	698
5	2	931
10	1	931
10	1.5	1396
10	2	1861
15	1	1396
15	1.5	2094
15	2	2792
Moderate Hydraulic Conductivity (K = 0.01 cm/s)		
5	1	4653
5	1.5	6980
5	2	9306
10	1	9306
10	1.5	13,960
10	2	18,613
15	1	13,960
15	1.5	20,939
15	2	27,919
High Hydraulic Conductivity (K = 0.1 cm/s)		
5	1	46,532
5	1.5	69,798
5	2	93,064
10	1	93,064
10	1.5	139,596
10	2	186,128
15	1	139,596
15	1.5	209,394
15	2	279,192

[1]Dewatering rates were estimated using Darcy's Law with a groundwater flow length of 671 m and a total perimeter perpendicular to the flow path of 198 m. The groundwater flow length was calculated as the weighted mean of the flow lengths of each mining basin, weighted according to the perimeter of each mining basin perpendicular to the flow path.
[2]Depression of water level in mining basins below water levels of river and lakes.

According to the best estimate for the rate of mining basin dewatering, the dewatering equipment (pumps and pipes) should be a significant part of the mining infrastructure, which is typical for most mines of any kind. On that basis, it is disconcerting that Rio Tinto has provided no information as to the discharge points of the radionuclide-enriched water that is being removed from the mining basins. Without any further information, it should be assumed that the excess radionuclide-enriched water is simply being discharged directly into the river or lakes. As mentioned previously, if this is the practice of Rio Tinto, then all of their protocols and infrastructure for protection of the environment are completely irrelevant.

Additional References

Clapp, R.B. and G.M. Hornberger, 1978. Empirical equations for some soil hydraulic properties: Water Resources Research, v. 14, pp. 601-604.

Fetter, C.W., 2001. Applied hydrogeology, 4th ed.: Upper Saddle River, New Jersey, Prentice Hall, 598 p.

Schlumberger Water Services, 2007. Case study—mine water supply study—Rio Tinto – QIT Madagascar Minerals Ltd. (QMM), 2 p. Available online at: https://www.slb.com/resources/customsitemaps/casestudysitetree.aspx.