REVIEW OF THE RELEASE OF RADIOACTIVE MATERIAL FROM THE RIO TINTO/QMM MINE MADAGASCAR

by
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March 2019

Commissioned by the Andrew Lees Trust (ALT UK)

www.andrewleestrust.org

Process leading to the review

Background

The Andrew Lees Trust (ALT UK)'s relationship with communities in the south of Madagascar spans almost twenty-five years. The Trust delivered social and environmental education programmes for almost fifteen years and, following it's sustainability strategy, has accompanied and supported local civil society for a further ten years with an emphasis on local ownership and leadership of development.

Since 1995, following the tragic death of its namesake, Andrew Lees, the Trust has also undertaken advocacy and campaigns about the Rio Tinto /QMM mine in Madagascar. Andrew was Director of Campaigns at Friends of the Earth when he went to Madagascar to investigate the Rio Tinto mine and died while filming the imperiled Petriky forest (see www.andrewleestrust.org/andrew). The Trust's advocacy work has included promoting communities' human rights, amplifying their voice, and undertaking research and actions that promote accountability and transparency around the QMM mine.

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. The mine is situated in the Anosy region, where QMM extracts ilmenite and zirsill. Over a projected 40-year project lifetime 6,000 hectares of littoral forest will be dredged to yield approximately 750,000 tons of mineral product per annum.

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, with concomitant questions about the risk of radionuclide enriched waters from the QMM mining basin and mine tailings flooding or seeping into the adjacent rivers and lakes where local people fish, and gather reeds and water for domestic use. Additional questions raised concerned the dispersal of radiation via dust, the management of mine tailings, and other potential pathways e.g. via ingestion, that were not addressed in measurements of the mine by the Malagasy nuclear research institute, INSTN (2012).

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

Studies undertaken

Questions raised about the buffer zone and radioactivity at Rio Tinto's AGM in April 2017[2] led to an invitation from Rio Tinto to Andrew Lees Trust to discuss the issues arising. At a meeting on 19th May 2017, Rio Tinto agreed to two studies:

1) a study of the buffer zone and
2) an independent review of the radioactivity levels of the mine.

At the end of 2017, Rio Tinto contracted a private company to review the buffer zone breach (Ozius). ALT UK decided to commission its own independent study of the buffer breach by mining and hydrogeology expert Dr Steven Emerman, and his report was published in 2018.

In parallel, ALT UK identified and contracted a radioactivity specialist, Dr Stella Swanson of Swanson Environmental Strategies, to undertake an independent radioactivity review.

Associated articles and reports, are available at:
www.andrewleestrust.org/andrew.htm

[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/

Constraints & timing

ALT UK had no funding to undertake its own field studies of radioactivity, so it entered into discussions with Rio Tinto for the release of QMM's data on radioactivity levels around the QMM mine. After more than six months of negotiations to outline the process, including confidentiality considerations, a framework agreement was finalised. Despite the lengthy lead into the process, not all data were delivered by QMM in April 218 as agreed. Some data were not released until August 2018, just ahead of an agreed review of the overall findings and analysis.

Swanson undertook analysis between April-September 2018. Final Report writing and completion of the report was delayed until 2019 due to other commitments. Rio Tinto's Chief Advisor, Radiation Governance and Product Stewardship, reviewed all of Swanson's findings in 2018 and 2019.

The framework agreement established that Rio Tinto could exercise a right to record any differences if it did not agree with Swanson's analysis of the available data or her conclusions. After a final review in March 2019, Rio Tinto's comments were shared with ALT UK and are included as an addendum to this report.

Communications & SDGs

ALT UK is committed to the disclosure of information in recognition of citizens' rights and to promote corporate transparency and accountability. ALT UK cannot be held responsible for how scientific facts and related information are managed by other parties, including local stakeholders, journalists, etc. Ultimately, Rio Tinto/QMM is responsible for managing the impacts of the QMM mine in Madagascar and effectively and responsibly communicating its operational impacts.

The report deals with a sensitive area of environmental hazard. For this reason, in 2017 as part of the framework agreement, the Trust insisted that a communications component be developed to accompany the release of the independent radioactivity review by Swanson. The Trust has provided a six-page document to Rio Tinto with recommendations for a communications process, as well as proposing community level monitoring (e.g., around water quality).

In addition to recommendations to improve QMM's monitoring practices for minimising risks to local people from radiation, the Andrew Lees Trust and Swanson believe this report also highlights two significant opportunities for QMM to meet key **Sustainable Development Goals (SDGs)**:

(1) Safe drinking water sources to be provided to communities most likely to be directly affected by elevated uranium concentrations, with an opportunity for QMM not only to reduce any radiological risk from drinking water, but also to reduce chemical and microbiological risks associated with the consumption of untreated surface water. This requires that Rio Tinto/QMM:

(1) accepts that management of the risk associated with QMM mine-related uranium concentrations in receiving waters is a priority;
(2) develops and implements a monitoring program which is sufficiently rigorous to discriminate between natural background uranium and mine-related uranium concentrations;
(3) manages uranium effluent releases to the receiving environment adaptively, in response to monitoring information; and
(4) demonstrates that it recognizes the multiple benefits of the provision of safe drinking water to nearby communities in accordance with its corporate commitment to management of human rights risks, including risks to water resources and to directing benefits to those affected by mining activities (Rio Tinto 2017 Sustainable Development Report).

(2) Equitable inclusion of local stakeholders and affected communities by developing local staff and community capabilities in communications, social engagement and environmental monitoring skills in order to increase understanding among community members, contribute to informed and inclusive decision making, and provide independent monitoring of the mine's radiation levels over the project lifetime, and beyond.

Thanks

The Andrew Lees Trust (ALT UK) is hugely grateful to Dr Stella Swanson for the time and expertise she has dedicated to this study, with very limited resources from ALT UK to sustain almost two years of exchange, research, and management of the process required to see this report into the public domain.

This report was prepared in accordance with the Contract between Swanson Environmental Strategies Ltd and the Andrew Lees Trust (ALT UK) as well as the Confidentiality Agreement between the Andrew Lees Trust (ALT UK) and QIT Madagascar Minerals S.A. (a member of the Rio Tinto group of companies).

The information, data, analysis, results, recommendations and conclusions in this report:

- *Are subject to the scope, schedule and other constraints and limitations in the above-referenced Agreements;*
- *Represent the professional judgement of Stella Swanson using standards for the preparation of similar reports;*
- *May be based on information which has not been independently verified; and,*
- *Have accuracy limited to the time period and circumstances in which data were collected and processed.*

This report is intended to be read as a whole, and sections thereof should not be read out of context.

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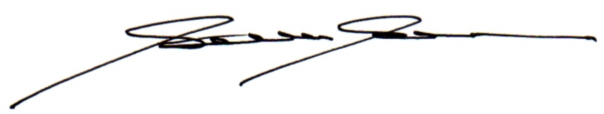
This report is the property of Andrew Lees Trust (ALT UK).

A word about the content of this report

This review involved the exchange and discussion of scientific information and analyses with Frank Harris (Rio Tinto Chief Advisor and Radiation Specialist) with the understanding that the findings and conclusions presented in this report are mine. I gratefully acknowledge Mr. Harris for his assistance regarding the acquisition of monitoring data and supporting information and for professional interaction regarding the analysis of the data, particularly data associated with gamma radiation, radon/thoron, and dust inhalation exposure pathways.



Stella Swanson, Ph.D.

Cover Photograph Courtesy of ALT UK. Aerial View of the QMM Site.

Acknowledgements

I gratefully acknowledge the guidance and assistance of Yvonne Orengo of ALT UK. Yvonne's knowledge of the Anosy region, its people and its environment provided the context required for this review, and her advice and support during the process of assembling, assessing, and reporting on the available information were instrumental to the successful completion of this review.

Exposure pathways graphic: *Alan Hunns*
Report production: *Alan Hunns*

Images of Anosy provided by: *Mbola Mampiray Miandrito; Retsivery; Barry Ferguson; Antonie Kraemer; Andrew Lees Trust.*

Images provided for this study have been sourced from local and international researchers; the people displayed have not been involved in the study and their views are not reflected in its content.

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Contents

Executive Summary

Aims of the Review

This independent review of the release of radioactive material from the QIT Madagascar Minerals S.A. (QMM) Ilmenite Mine was commissioned by the Andrews Lees Trust (ALT UK). This review is subject to a Confidentiality Agreement between ALT UK and QMM (a member of the Rio Tinto group of companies) dated April 12, 2018.

The overall aim was to conduct an independent expert review of all available, relevant information pertaining to the release of naturally occurring radioactive material to the environment due to the activities of the QMM mine Anosy, Southern Madagascar and the subsequent exposure of members of the public. This review does not include consideration of radiation doses to QMM workers.

The Objectives of this review are:

- To review the scientific methods and approach involved in the monitoring and management of the radioactive materials generated by the QMM mine;
- To determine if the levels of naturally occurring radioactive material (NORM) in the environment which result from the operation of the QMM/Rio Tinto mine in Anosy, Southern Madagascar, are within international exposure limits; and
- To determine if the pathways of radionuclides and radioactive by-products are managed to internationally recognized standards for the protection of local citizens.

Caveat: *The review of radioactivity is based on data and information provided by QMM and Rio Tinto, and the study has not been sufficiently resourced nor remitted to undertake separate field studies, measurements, or verification processes on the QMM mine site in Anosy.*

The QMM Mine

The QMM mine is located in the Anosy region near Fort Dauphin on the south-eastern tip of Madagascar. Current mine operations are at the Mandena site. Planned later phases of mining will be at the Ste-Luce and Petriky sites. The mineral sands mined by QMM contain multiple minerals, but the minerals of interest are ilmenite and zirsill. QMM extracts ilmenite (which contains 60% titanium dioxide) and zirsill (which contains zircon).

Mineral sands areas (specifically, monazite sands) within the Anosy region have high natural background levels of radiation. People in the region have always been exposed to these natural levels of radiation in air, soil, water and food. It should be noted that the natural background radiation in the Mandena region is not as elevated as some other high natural background areas in the world

The International Atomic Energy Agency (IAEA) dose limit for the general public is 1 mSv in a year (IAEA 2018). Dose limits are restrictions related to an individual person and apply to the total dose received by that individual from all relevant sources (IAEA 2018). High natural background areas (including areas in the Anosy region) can exceed this dose limit, without consideration of any other sources. Therefore, the dose limit for incremental exposure over and above the natural background present in the Anosy region is 1 mSv/y

People living in the vicinity of the QMM mine can be exposed via several pathways: external gamma radiation; radon inhalation; dust inhalation; and, ingestion of water, food and soil.

Gamma radiation exposure

Mineral sands areas in the Anosy region emit gamma radiation because of the presence of radionuclides such as uranium and thorium. QMM mining activities disturb, redistribute, and in some cases, concentrate, these naturally-occurring radionuclides. Any QMM contribution to gamma exposure would be restricted to the immediate vicinity of the project and the adjacent areas (of the order of one hundred metres). This is because gamma exposure rapidly decreases with distance from the source

Three potential scenarios were considered for gamma exposure: post mining exposure, wood collection at QMM, and transport of material off site.

Dose from gamma exposure to people living on rehabilitated land may be slightly less than that from the natural pre-mining levels because of the placement of monazite sands containing higher levels of radioactivity at depth. However, this is only true if a large area is considered because of the nature of the mining and subsequent reposition of monazite sands, there will be a high variability on a location by location basis.

For wood collection a hypothetical dose of 0.2 mSv/y was estimated based on the assumption that a wood collector would be on the site in unmined areas for 6 hours per day, 3 days a week, every week of the year. The incremental risk of health effects associated with 0.2 mSv/y is very small. However, it is important that people are aware that small incremental gamma exposures can occur if they enter the site. Furthermore, additional incremental doses to a wood collector could result from other exposure pathways such as inhaling dust from the QMM site.

A very conservative model was used for transport of monazite (which contains rare earth oxides) to Port d'Ehoala using assumptions of people being in very close proximity to large transport trucks for relatively long periods of time. An upper maximum of 0.27mSv/y was calculated. This estimate is highly uncertain and far higher than worst-case estimated doses calculated for shipments of similar material in Australia. Specific monitoring of rare earth oxide shipments is required to reduce the uncertainty in these estimates.

Radon exposure

Radon is an inert gas produced by both the uranium and the thorium decay series. The uranium-238 series produces radon-222 with a half-life of 3.8 days. Radon-222 decays to a series of short-lived radionuclide progeny with a maximum half-life of 27 minutes. The thorium-232 series produces radon-220, commonly called thoron, which has a half-life of 55 seconds. Radon-220 decays to a series of short-lived radionuclide progeny with a maximum half-life of 11 hours. The short-lived progeny are the primary issue because, unlike radon-222 and radon-220, which are inert gases that don't interact with tissues in the body, the progeny may attach to the lung or upper respiratory tract.

Radon-220 is the most significant for public exposure because of its 3.8-day half-life compared to the 55 second half-life of radon-222, which is so short that there is insufficient time or it to diffuse out of the mineral sands let alone be transported off-site.

The inhalation of radon gas and its short-lived progeny is not expected to be a significant source of exposure to the public from the QMM operation. This is primarily due to the local weather conditions which provide ample dispersal of the radon gas and prevent its build-up in inhabited areas. QMM-related doses of the order of a few thousandths of a milli-Sievert per year would be the maximum expected in any community.

After mining is completed, the rehabilitated land may become a site of either permanent or temporary residence for local communities; therefore, the potential for exposure to radon should be considered. It is expected that the post-mining burial of the more radioactive material at depth would cause the post-mining radon exposure to be less than that which would have occurred in the natural pre-mining situation. This is because both forms of radon have relatively short half-lives (3.8 days and 55 seconds for Rn222 and Rn220 respectively) and any increase in depth will decrease the amount of radon which can escape to the surface environment.

Consistent placement of minerals containing radioactivity at sufficient depth is required to produce conditions where post-mining radon exposure is not distinguishable from background.

Inhalation of long-lived radionuclides in dust

QMM activities generate dust which may contain enhanced quantities of radionuclides. This dust may be carried via the prevailing wind to the local communities where it can be inhaled. Not all dust in the air can be taken into the lungs. It is the smaller particles (called PM_{10} dust or dust which is smaller than 10 µm in diameter) which are important for this pathway. The longer-lived radionuclides dominate the dose from inhaled dust particles. The potential exposure from shorter lived radionuclides is far less and may be incorporated into the dose from the parent radionuclides. The longer-lived radionuclides important to the consideration of dust inhalation emit gamma, alpha and beta radiation. Inhalation, together with ingestion, is the mechanism for exposure to alpha and beta radiation.

The incremental contribution of QMM operations to dust in nearby communities was estimated using air monitoring data. A conservative approach was used whereby the lowest dust concentration measured at any of the sites was used as the background dust level. The operational component was then calculated based on taking the dust concentrations at the two community sites in the downwind wind direction (Ampasy Nahampoana and Maroamalona) and then subtracting this regional background dust concentration (thereby maximising the operational component).

Estimated yearly doses from dust inhalation were highest for the 1-2-year-old age group. This result reflects breathing rates for this age groups as well as higher dose conversion factors for some of the radionuclides. Estimated doses were consistently higher for Maroamalona than for Ampasy Nahampoana across all age groups. The results should be considered an overestimation of the potential dust-related dose due to the conservative nature of the assumptions used. However, the results do provide a useful indication of the potential significance of the dust pathway.

Estimated doses from inhalation of dust generated by QMM operations are from about 20-40% of the yearly 1 mSv dose limit for the general public. This is a substantial proportion of the allowable incremental dose. Therefore, the application of best practices for effective dust management at the QMM operations is important in order to keep the incremental dose to the public well below the limit. It is equally important to reduce the uncertainty associated with the dose due to dust inhalation by obtaining more monitoring data (see Recommendations section).

Dose conversion factors
convert measured quantities of radiation (e.g. Bq/m³ uranium-238 in a cubic metre of air) to radiation dose to tissues within the body (expressed as mSv/yr). The conversion factors account for the fact that different radionuclides produce different proportions of radiation types (gamma, alpha, beta), which, in turn, deposit different amounts of energy in tissues. Dose conversion factors account for the solubility of individual radionuclides in body tissues. Dose conversion factors also vary with age (e.g. young children versus adults)

Exposure via ingestion

Exposure via ingestion occurs via drinking water, eating food, or accidentally eating soil that is on food or on people’s hands. The people who have the highest potential for receiving QMM-related radiation doses via ingestion would live nearby and obtain a substantial amount of their drinking water and food from adjacent rivers, lakes, fields, and pastures. It is assumed that this applies to all of the settlements in the immediate vicinity of QMM.

Over 75% (or more) of households in the Mandena area rely on surface water bodies for drinking water, including the Mandromondromotra River which receives mine effluent via a wetland immediately adjacent to the river. Lake Ambavarano and Lake Besaroy water quality may be affected by seepage of shallow groundwater from the mine site.

All radionuclide levels in river and lake water samples were well below World Health Organization drinking water guidelines for radiation exposure. However, these measurements were from one sampling event only. Therefore, there is no way of knowing whether these results represent typical conditions. Furthermore, there are several anomalies in the data which indicate that there may be significant problems with the laboratory analysis results.

Because the radionuclide data for water were so limited (and questionable), results of analysis of uranium and thorium as heavy metals were evaluated. With one exception, thorium was not detectable in river water at stations adjacent to QMM effluent discharges. However, uranium was detectable at all Mandromondromotra River stations and all concentrations were above the WHO drinking water quality guideline for chemical toxicity, often by substantial margins (e.g., 50x the guideline near the weir).

Uranium concentrations which are above drinking water quality guidelines are a concern because of the chemical hazard of uranium rather than its radioactivity (which is very low). The contribution to uranium concentrations from QMM operations versus natural background uranium is unknown. However, no matter what the source of uranium in water is, the situation must be addressed in order to protect public health.

Radionuclides which enter the Mandromondromotra River, Ambavarano Lake or Lake Besaroy may not stay in the water column; instead, they may attach to particles in the water and settle on to river or lake sediments. People could then be exposed via direct skin contact or accidental ingestion of sediments (e.g. children playing in shallow water). Radionuclides in sediments can be re-emitted into the water, causing a gradual increase in radioactivity levels (PARC 2013). There are no data for radionuclide concentrations in sediments in the river, nor are there any data for lake sediments.

The direction of groundwater flow from the QMM site is to the south. Therefore, uranium and thorium series radionuclides can be expected to migrate via shallow groundwater south to Lake Ambavarano. QMM groundwater monitoring data for wells located down-gradient from the site are limited, but elevated uranium concentrations were observed. A well located adjacent to the northern shoreline of Lake Ambavarano had uranium concentrations substantially above the WHO drinking water guideline. Water in this well was also very saline, indicating a connection with seawater entering the lake. The salinity level was so high that the water would be unsuitable for drinking. The results indicate a definite need for increased monitoring of groundwater in the area likely to receive shallow groundwater seepage from the QMM site.

Accidental soil ingestion is of most concern for children because children typically ingest more soil via play and are more likely to place their hands in their mouths. QMM did not provide soil monitoring data for off-site areas. Therefore, dose associated with accidental soil ingestion could not be calculated.

It can be assumed that much of the food consumed by people in the area is obtained locally. There are no data on radionuclide concentrations in any food items in the Mandena region. Past estimates of radiation dose from ingestion approached the 1 mSv/y dose limit; however, these estimates are highly uncertain.

Total public radiation dose

Notwithstanding the uncertainty associated with past estimates of total public dose, they are high enough to trigger additional investigation. This review confirmed the potentially significant contribution of the dust inhalation pathway. The contribution of the ingestion pathway requires particular attention in the near future.

Conclusions

Monitoring methods and approach used in monitoring and management of radioactive materials by QMM

As far as can be determined by the information provided by QMM, the methods and approach used in the monitoring and management of radioactive materials by QMM are not sufficient. There are large gaps in the monitoring program, especially regarding the ingestion pathway. In some cases, the quality of the monitoring data is questionable. The quantity of data is often insufficient for understanding spatial or temporal trends.

To the knowledge of the author, there is no over-arching monitoring plan and no explicit connection between the results of environmental monitoring and management of radiation dose to the public. It is recommended that a standard process be used to develop the QMM environmental radiation monitoring plan such as that provided in US EPA (2006).

There were no formal Data Quality Objectives (DQOs) for the monitoring program provided to the author. Data Quality Objectives are highly recommended when monitoring data are relied upon to make decisions about the management of risks. For example, regulatory or industry decisions regarding whether current QMM mitigation measures are effective in maintaining acceptable radionuclide concentrations in the receiving environment must be made with a known degree of confidence in the monitoring information.

There can be no general conclusions drawn regarding total QMM-related incremental radiation dose to the general public because it is unknown whether current dose estimates are, indeed, very conservative or whether in some cases they are not.

Are levels of naturally occurring radioactive materials resulting from the QMM Mine Operation within international exposure limits?

Based upon available information, conservatively estimated incremental doses due to gamma radiation and exposure via dust inhalation due to QMM operations are less than 1 mSv/y and incremental doses from radon exposure are negligible. However, the data supporting these preliminary conclusions are limited. Furthermore, exposure of specific individuals with a combined exposure to gamma radiation on-site (e.g. for wood collection) plus dust inhalation exposure, plus exposure via ingestion may approach or exceed 1 mSv/y.

No conclusions are possible with respect to incremental doses from ingestion pathways (water, food, accidental ingestion of soil). There is an almost complete lack of information for this pathway. Given the reliance of local people on surface water for drinking water and the use of locally produced foods, the complete lack of relevant monitoring data is unacceptable.

The general conclusion drawn by INSTN that the risk of exposure is "minimal" for members of the public is not consistent with the conservative findings of this report, particularly with respect to lack of any information on the ingestion pathway. Furthermore, the complete lack of any data for the food ingestion pathway prevent general conclusions.

In summary, while the expectation is that incremental doses to the public due to QMM operations will meet international limits, there are insufficient data to come to any confident conclusions in this regard, particularly with respect to ingestion. The dust inhalation pathway may also contribute an important portion of total incremental dose.

Are pathways of radionuclide exposure managed to internationally recognized standards for the protection of local citizens?

It is expected that QMM use "good practices" which have been demonstrated to be effective in reducing radiation exposure at other, relevant mining operations. The author did not receive information which would indicate that QMM consistently is using good practice with respect to control of gamma, dust, or ingestion pathways.

It is impossible to draw any conclusions with respect to the degree to which QMM applies good practice because of the absence of comprehensive monitoring data, particularly with respect to the ingestion exposure pathway. Additional monitoring data are essential in order to inform QMM about where additional mitigation measures are required.

It is imperative that QMM demonstrates that it is managing risk using good practice and in accordance with the 1 mSv/y limit.

Risks from exposure to the chemical hazard of uranium in drinking water must be managed. The uranium concentrations in the Mandromondromotra River are much higher than WHO drinking water guidelines. These elevated concentrations may be due to a combination of natural sources and QMM operations. However, no matter what the source of the uranium, this issue must be addressed in order that the risk associated with uranium toxicity is confirmed and managed. ***There is an opportunity for QMM, through the provision of drinking water sources in communities most likely to be directly affected by elevated uranium concentrations, to not only reduce any radiological risk from drinking water, but also to reduce chemical and microbiological risks associated with the consumption of untreated surface water.***

Recommendations

A series of recommendations for monitoring are presented at the end of this report, on page 54, in order of priority.

Effective communication and community engagement are vital.
It doesn't matter how good a monitoring program is if nobody believes the results.
Characteristics of effective communication are:

- *Trust*
- *Understanding*
- *Credibility*
- *Satisfaction*
- *Cooperation*
- *Agreement*.

The following recommendations apply to QMM's communication and engagement with community members in the Anosy region:

- *A communication and engagement plan which aims to achieve the above 6 characteristics*
- *Retention of risk communication experts with specific experience in communication of radiation risks*
- *Emphasis on clear and accessible communication which is readily available in a variety of forms*
- *Training of front-line QMM staff in communication regarding radiation risk, with particular focus on transparency, empathy, and the building of trust.*
- *Public release of relevant documents such as the INSTN reports*

Introduction

This independent review was commissioned by the Andrew Lees Trust UK.

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The objectives of this review are to review QMM monitoring methods, to determine if levels of radioactive material are within international exposure limits, and to determine if pathways of exposure to radioactive materials are managed to international standards for the protection of local citizens.

The Objectives of this review are:

- *To review the scientific methods and approach involved in the monitoring and management of the radioactive materials generated by the QMM mine.*
- *To determine if the levels of naturally occurring radioactive material (NORM) in the environment which result from the operation of the QMM/Rio Tinto mine in Anosy, Southern Madagascar, are within international exposure limits; and*
- *To determine if the pathways of radionuclides and radioactive by-products are managed to internationally recognized standards for the protection of local citizens.*

There are two outputs of this review:

- A technical report focusing on the above objectives and recommendations for future monitoring and risk management (this report); and,
- A public report in accessible language to increase the publicly available information about NORM released from the QMM mine and to inform stakeholders of any associated risks

The QMM Mine

Mine description

Rio Tinto owns 80% of QMM, with the remaining 20% owned by the Government of Madagascar. Current mine operations are at the Mandena Site.

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QMM extracts ilmenite (which contains titanium) and zirsill (which contains zircon).

The mineral sands mined by QMM contain multiple minerals, but the minerals of interest are ilmenite and zirsill. QMM extracts ilmenite (which contains 60% titanium dioxide) and zirsill (which contains zircon). The ilmenite and zirsill are transported about 15 km to Port d'Ehoala. Ilmenite is shipped to Canada where it is processed and prepared for sale as a pigment agent for whitening of paints, plastics and paper. The smaller quantity of zirsill export is used for production of ceramic tiles, television screens and computer monitors (Hoagland 2013).

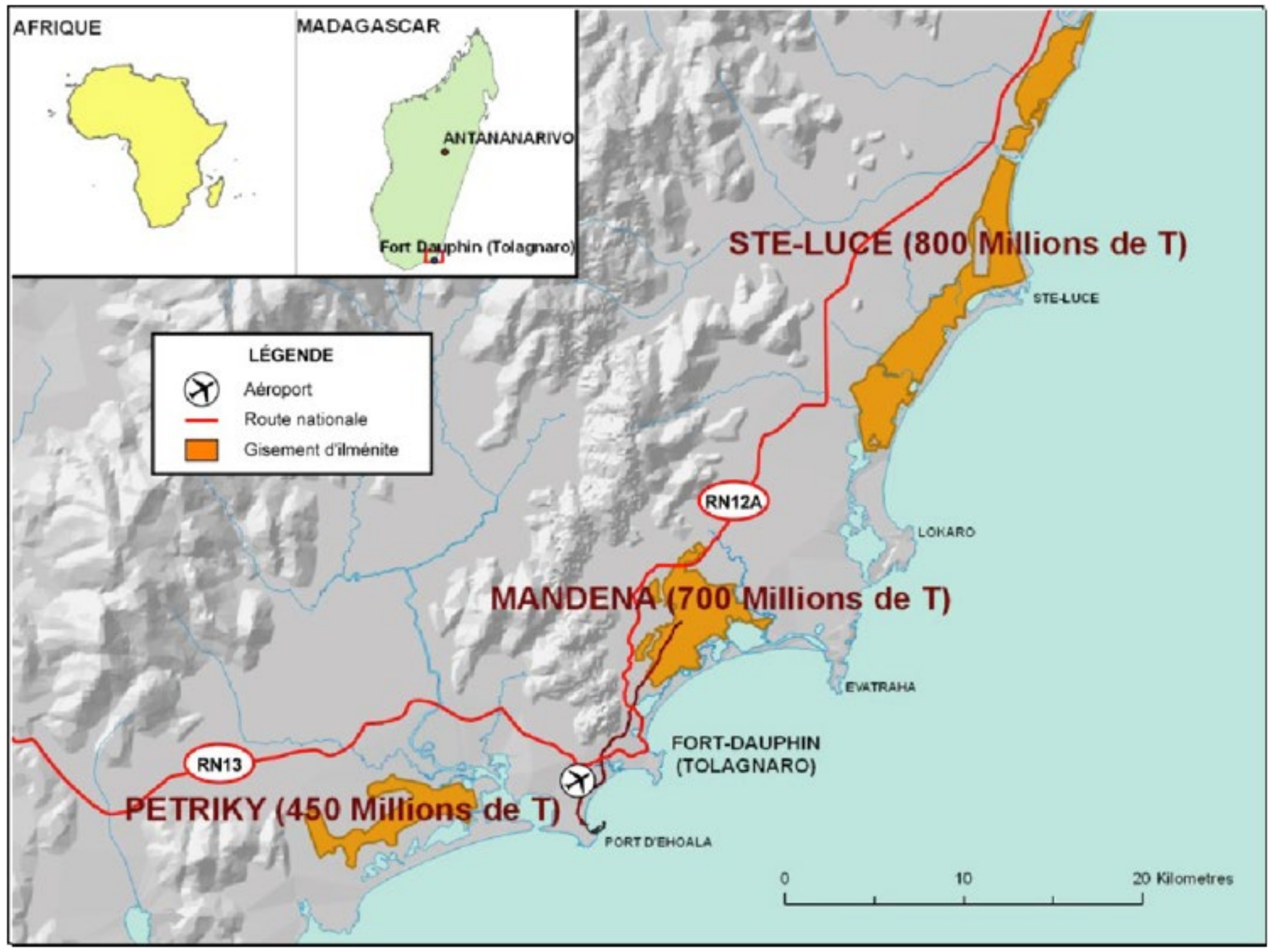


Figure 1. QMM mineral sands mining areas in the Anosy region. Current mine lis at the Mandena Site

Dredged mineral sand is passed through a floating separation plant to remove heavy minerals such as ilmenite (which can be processed to yield titanium dioxide) and zirsill (containing zircon). Lighter materials such as silica are returned to the dredging pond.

QMM uses dredging and a plant which floats on a constructed pond as the first step in separating out the minerals of interest (the wet circuit) (Figure 2). The separation involves mixing dredged sand with water in the plant and then separating the minerals through a series of spirals. The heavy minerals such as ilmenite and zirsill are concentrated near the central column of the spirals while the lighter minerals such as quartz and silica are pushed near the outer edge of the spirals (Rio Tinto 2017 b). Silica sands are returned to the dredging pond or used for construction of discharge canals and other structures (Hoagland 2013).

Ilmenite is removed using electrostatic processing. More separation is then required to remove residual minerals so that zirsill remains. The separation processes remove magnetic minerals such as monazite ('magnetic rejects')

Ilmenite is the only conductive mineral in the concentrate produced by the wet circuit; therefore, it can be separated using electrostatic processing (Rio Tinto 2017b). The remaining non-conductive minerals pass again through a series of spirals to remove magnetic minerals such as monazite (the "magnetic rejects"). One more pass through spirals to remove quartz is followed by more separation to remove residual conductive and magnetic minerals, resulting in zirsill (Rio Tinto 2017b).

The magnetic rejects (monazite) are stored temporarily if the wet plant is closed for maintenance.

QMM extraction process

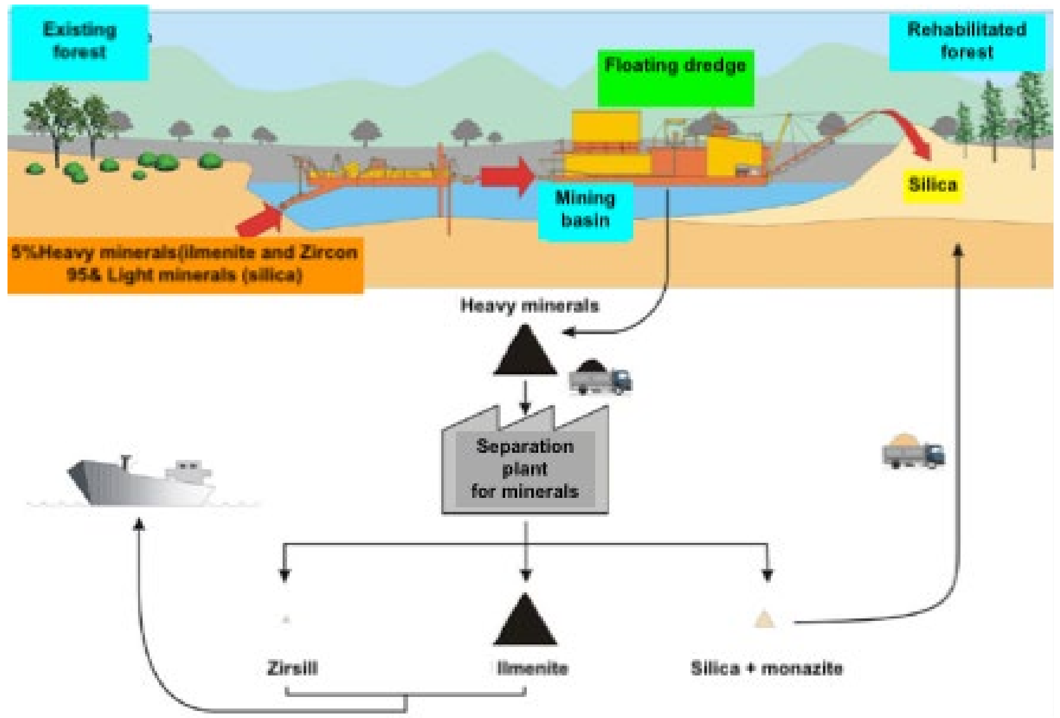


Figure 2. QMM extraction process *(provided by QMM)*

Magnetic rejects are stored temporarily if the wet plant is closed for maintenance. Magnetic rejects are returned to the dredging pond at a depth of about 15m.

The volume of fresh water required for processing of the mineral sands is reduced through recycling.

About 9.4 million litres per year of process effluent is produced.

Process effluent is treated in settling basins prior to discharge to a wetland on the mine site which drains to the Mandromondromotra River.

According to Rio Tinto, of all the sand material mined approximately 5% is sent to the dry plant. After the removal of valuable commodities 1% (of the initial volume mined) is returned to the wet plant for preferential disposal at depth. This returned material is disposed at a depth of 15m below sea level, on top of it the wet plant reject sand is discharged.

The recent initiation of the sale of rare earth oxides (which are found in the monazite 'magnetic rejects') means that surface storage of monazite magnetic rejects occurs on site. Rio Tinto explains that adjacent to the dry plant is a stockpile area. The area is approximately 7.5Ha in size and contains a range of materials such as HMC 86 (Heavy Mineral Concentrate from the wet plant). It is also used as a temporary store for magnetic rejects material but this is a small area approximately 30 metres across and is not a permanent store for this material.

Access to the magnetic rejects stockpile area is restricted; there is definitely no public access to these areas.

The volume of fresh water required for processing is reduced through recycling (QMM 2018). Process effluent is treated in settling basins prior to discharge to a wetland on the mine site. The wetland drains to the Mandromondromotra River. According to a water balance report by QMM (2018), fresh water use at the mine is 300,000 L/yr. The source of the freshwater is not reported in the report but is assumed to be the Méandre River via a pipeline (Hoagland 2013). Total recycled volume of water per year is 13,621,000 L (QMM 2018). About 9,400,000 L/yr of process effluent is produced.

Floating plant at the QMM mine.
(Photo from Rio Tinto website).

Environmental and social setting

The Anosy region is one of the ecologically most diverse regions of Madagascar but is also one of the poorest.

Coastal littoral forests of Anosy are among the most threatened ecosystems of Madagascar.

About 15,000 people live within a few kilometres of the current QMM site.

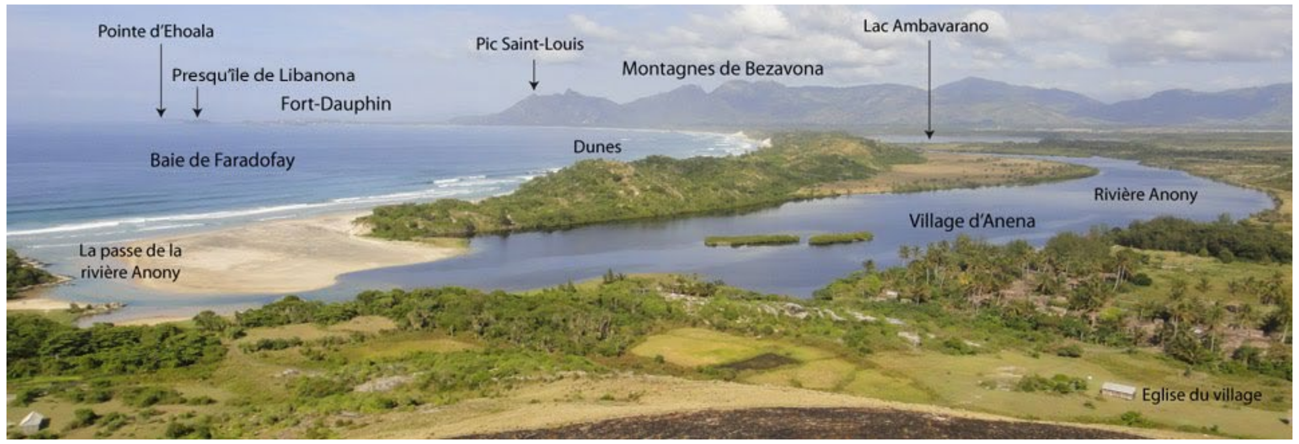
Subsistence agriculture produces rice, vegetables, fruits and other staple foods such as manioc on traditional lands recognized at the community level.

Marine and freshwater fisheries provide food and income. QMM has partnered with local fishing associations to create a more sustainable fishery.

The Anosy region is one of the ecologically most diverse regions of Madagascar but also one of the poorest and most isolated (Vincelette et al. 2008). Per capita income is very low and literacy ranges from 25% to 50%. Environmental zones range from littoral forests along the coastline to humid and transition forest to marshlands and wooded bush. The littoral forests, resting on sandy substrates and already greatly reduced, are among the most threatened ecosystems of Madagascar (Vincelette et al. 2008).

Nine communes, including eight rural and one urban, border QMM's three mining concessions (Rio Tinto 2016). People in these communes are heavily dependent on ecosystem services and the natural resource base for subsistence and income needs.

About 15,000 people live within a few kilometres of the current QMM site in Ampasy Nahampoana and Mandromondromotra (Rio Tinto 2016). About 80% of the population is engaged in subsistence agriculture, including rice, manioc, vegetable, and fruit cultivation (Vincelette et al. 2008, Panos London 2009). Crops are grown on traditional lands recognized at the community level (but rarely through legal tenure) (Panos London 2009). Coastal areas of Anosy are largely populated by fishers and their families. Lobster and prawns are harvested for local and international markets and local people also fish in rivers and lakes for their own consumption. QMM has established a partnership with local fishing associations which includes technical training in sustainable fish practices (Rio Tinto 2017c). The aim is to increase fish yields.



http://www.fort-dauphin.org/tourisme/les-environs-de-fort-dauphin

> Most of the rural population relies on forest resources during times of food shortage as well as for firewood and wood for construction.

> Mandromondromotra and Ampasy Nahampoana have high levels of in-migration with recent in-migration due, in part to prolonged drought in southern Madagascar. The in-migration often results in unequal land access and resource use between long-established residents and recent migrants. Access to land and natural resources within the QMM mining concession is addressed by a social contract (DINA).

Most of the rural population relies on forest resources during times of food shortage, but also year-round for firewood and wood for construction (Rio Tinto 2016). Forests also provide medicinal plants and honey bees Due to its biodiversity and natural beauty, environmental conservation and tourism are promoted in the region, with accompanying employment opportunities and contributions to the economy.

Mandromondromotra and Ampasy Nahampoana have high levels of in-migration (Rio Tinto 2016). Recent in-migration has been due, in part to prolonged drought in southern Madagascar (IOM 2017). The in-migration often results in unequal land access and resource use between long-established residents and recent migrants. Access to land and natural resources within the QMM mining concession is now addressed by a revised social contract (DINA) which defines mutual rights and responsibilities (Rio Tinto 2017c).

Natural background radiation in the Anosy Region

> Mineral (monazite) sands areas within the Anosy region have high natural background levels of radiation.

> Other areas in the world with monazite sands have much higher radiation levels than in Anosy.

> A millisievert (mSv) is a unit of ionizing radiation dose. It is used to represent the biological effects of different forms of radiation on human tissue.

> Global average natural background doses are in the range of 2-4 mSv/y UNSCEAR (2008). The IAEA dose limit is 1 mSv/y above the natural background.

Mineral sands areas (specifically, monazite sands) within the Anosy region have high natural background levels of radiation. People in the region have always been exposed to these natural levels of radiation in air, soil, water and food. The natural background radiation in the Mandena region is not as elevated as some other high natural background areas in the world (Figure3). Other areas in the world with monazite sands which have much higher radiation levels include beaches in the Guarapari area of Brazil where dose rates can be 175 mSv/y or even as high as over 400 mSv/y and levels in coastal areas of Kerala in India where dose rates can be 21 mSv/y or more (UNSCEAR 2000).

The International Atomic Energy Agency (IAEA) dose limit for the general public is 1 mSv in a year above the natural background (IAEA 2018). The global average natural background dose is 2.4 mSv/y and the typical range is from 1.0-13 m Sv/y (UNSCEAR 2008, Table 12, Annex B). The natural background doses in the Anosy region likely exceed the global average when all exposure pathways are taken into account.

Background radiation in the world

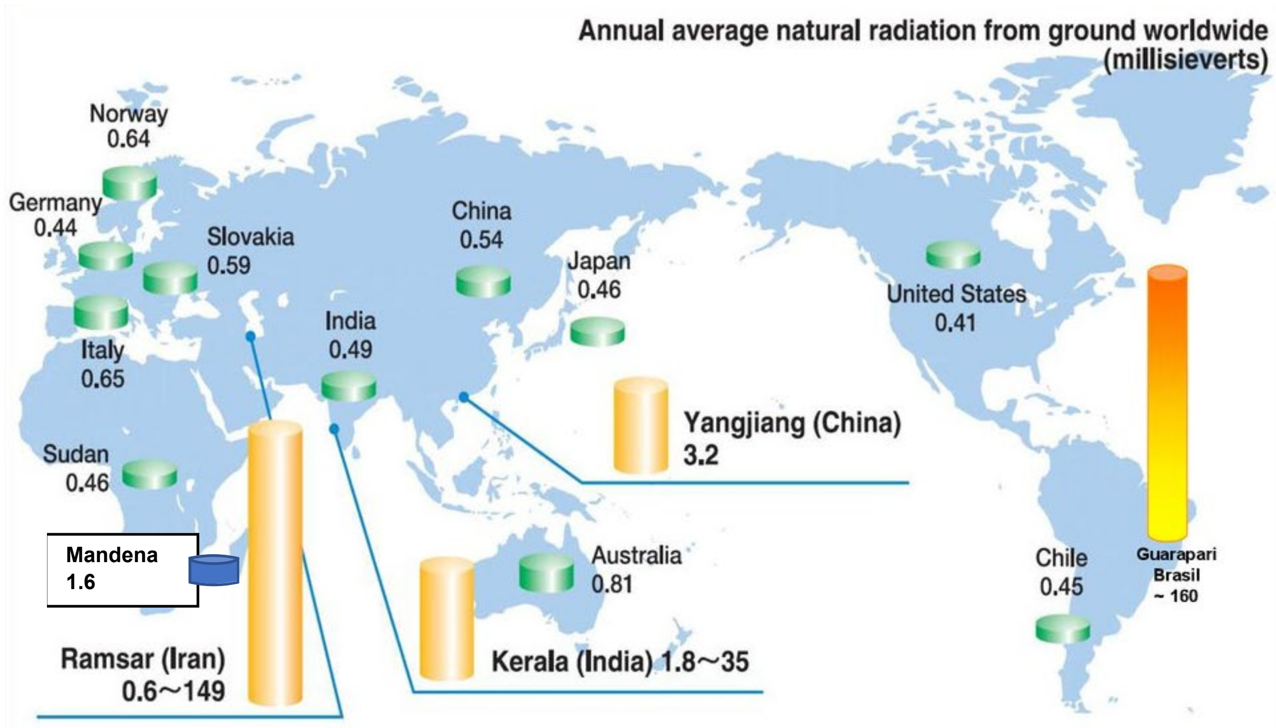


Figure 3. Comparison of yearly average natural radiation emitted from the ground worldwide.

In Figure 3, high natural background areas are shown in yellow/orange. The Mandena region average radiation level is shown in blue. Radiation levels in areas without naturally elevated background are shown in green. (Figure adapted from https://en.ppt-online.org/303224).

Radiation exposure pathways

There are two ways that people can be exposed to radiation: (1) they can be exposed externally to a near-by source of radiation; or, (2) they can be exposed internally by radioactive material that has entered the body through inhalation or ingestion.

External exposure decreases rapidly with distance from the source. The total amount of external exposure depends on how close the person is to the source and how long the person remains near the source. Gamma radiation is the source of external exposure relevant to QMM. Gamma radiation is shown by the yellow arrows on Figure 4. This exposure pathway would apply to people who enter the QMM site; e.g. people gathering wood for charcoal.

Internal exposure occurs when radionuclides enter the body via inhalation, drinking water, eating food, or accidentally ingesting soil. Radon gas (and more importantly, its decay products) can enter the body via inhalation. Radon is shown by the dotted blue arrows on Figure 4. Exposure to radon and its decay products would be applicable to people living close to QMM.

Radionuclides present in soil on the QMM site can be spread via dust. Dust can be inhaled directly by people. It's the very fine particles within dust that are the most concern because they can be taken into the lungs. Radionuclides in dust can be deposited on to soil, water, crops, pastures, fruit trees, and gardens, as shown by the dotted pink lines in Figure 4. Radionuclides deposited on to soil can then be taken up by plants, which are, in turn eaten by people. Radionuclides deposited to water can enter people via drinking water. If food is not washed thoroughly, radionuclides in the dust deposited on food surfaces can be ingested.

Radionuclides in water can enter surface water via discharge of QMM process effluent to the Mandromondromotra River, and from there to Lake Ambavarano, Lake Besaroy, and potentially, even farther to Lake Lanirano. Overland flow after a rain can carry soil particles containing radionuclides from the QMM site to Lake Ambavarano and Lake Besaroy (and adjacent wetlands). Discharge and overland flow are shown by the solid pink lines on Figure 4. Once in the water, radionuclides can be ingested directly via drinking water or water left on food after washing, or they can be ingested via uptake by fish and shellfish which are eaten by people. If water is used for irrigation, radionuclides in the irrigation water can be taken up by crops and garden produce which are , in turn, eaten by people. Cattle and poultry which drink surface water would also take up radionuclides.

Seepage of water from the surface of the QMM site to shallow groundwater can lead to groundwater carrying radionuclides to the river or lakes or to shallow wells used for drinking water. Groundwater seepage pathways are shown by the double pink lines on Figure 4.

Accidental ingestion of soil occurs via soil adhering to food or by hand-to-mouth contact. Children ingest more soil than adults because of play activities and also because they bring their hands to their mouths more frequently. Radionuclides enter soil via dust deposition, irrigation and overland flow.

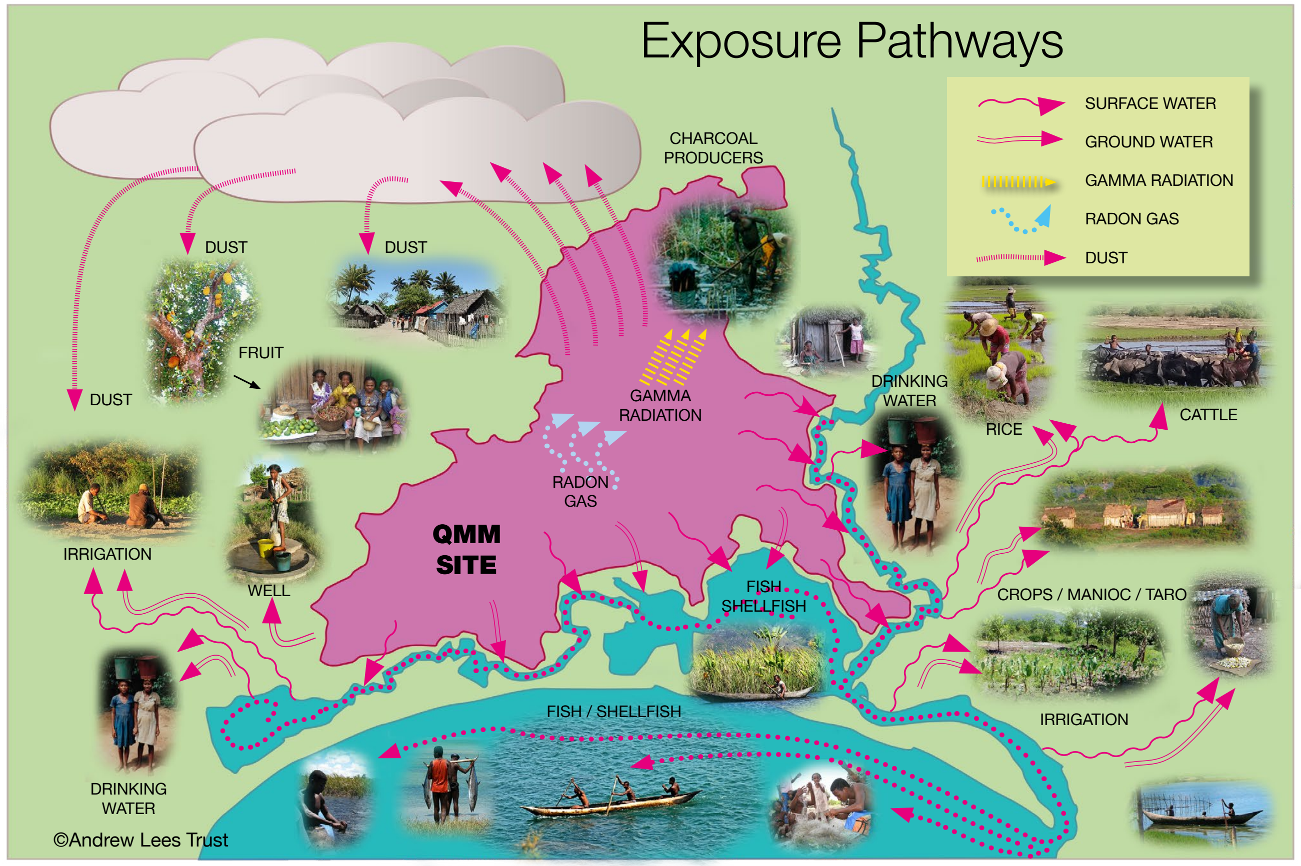


Figure 4. Exposure pathway diagram

Exposure of people near the QMM mine to gamma radiation

The potential for the QMM mining activities to increase exposure to gamma radiation was investigated.

Mineral sands naturally emit gamma radiation. Other natural sources include cosmic radiation and the use of laterite soils for road surfaces.

Gamma radiation is high energy and can penetrate the body from sources outside the body.

Pre-mine gamma radiation dose rates in the Anosy region were higher than the global average natural background gamma exposure.

There is potential for increased exposure of people living near the QMM mine to gamma radiation because of QMM mining activities, which disturb, redistribute, and in some cases, concentrate, naturally-occurring radionuclides. This increased exposure would be addition to exposure which occurs because of the natural presence of mineral sands.

Mineral sands areas in the Anosy region emit gamma radiation because of the presence of radionuclides such as uranium and thorium. Other natural contributions to gamma exposure include cosmic radiation (both solar and extrasolar) and natural emissions from material containing gamma emitting radionuclides such as laterite soils used on road surfaces (Senes 2001). Gamma radiation is high-energy and can penetrate the body when the radiation source is outside the body. Both the uranium and the thorium decay series contribute to gamma exposure. However, due to the higher energy and higher relative intensities of the gamma emissions, the thorium series dominates the potential

More recent gamma dose rates from three locations in the Anosy region show little or no change from baseline gamma dose rates.

Any incremental contribution from the QMM mining activities would be limited to the immediate vicinity because gamma radiation quickly decreases with distance

Two scenarios for increased gamma exposure are wood gathering on the QMM site and people living on the site after mine closure.

Gamma exposure due to transport of rare earth oxides off-site is discussed in a later section of this report.

exposure from gamma radiation.

Baseline (pre-mine) gamma radiation dose rates measured in 2000 were notably higher in much of the study area compared to the (then proposed) mine site and were higher than the global natural background gamma exposure (Figure 5). Median levels in the areas around the proposed QMM mine site were observed to be from 0.16 µSv/h to 0.34 µSv/h (1.4 to 3 mSv/y), assuming a person spends 24 hours a day 365 days a year at the sample site. Median levels at the mine site were only 0.048 µSv/h (0.42 mSv/y.). Globally the natural background gamma exposure is approximately 0.9mSv/y with a range of 0.6-2mSv/y [UNSCEAR 2008 Annex B Table 12]. The lower gamma dose rates on the proposed site may have been because most of the off-site gamma surveys were conducted along roads with laterite soils used on the road surfaces (Senes 2001). Although on average, baseline gamma dose rates were elevated, results across the study area were highly variable, ranging from a low of less than 0.05 mSv/y on the mine site to greater than 42 mSv/y on a beach in the Ehoala area (Senes 2001)

Location	Mean µSv/h	Median µSv/h	Annual median µSv/y
Mangaiky	0.18	0.17	1.6
Mandromondromotra	0.19	0.14	1.4
Ampasy Nahampoana	0.27	0.15	1.5

Table 1. Gamma rates at three locations in the Anosy Region

More recent mean and median gamma dose rates are shown in Table 1 (PARC 2013). These measurements show little or no change from baseline gamma dose rates.

The gamma dose rates in Table 1 show that any QMM contribution to gamma exposure would be restricted to the immediate vicinity of the project and the adjacent areas (of the order of one hundred metres). This is because gamma exposure rapidly decreases with distance from the source and by the time you are hundreds of metres from a gamma emitting source, the operational contribution is negligible in comparison with natural background. Because of this, the potential for gamma exposure to communities is restricted to three primary scenarios: the potential for post mining exposure to local people living on site; members of the public who enter the QMM site for activities such as wood gathering; and, exposure due to transport of rare earth oxides (which contain monazite) to Port d'Ehoala.

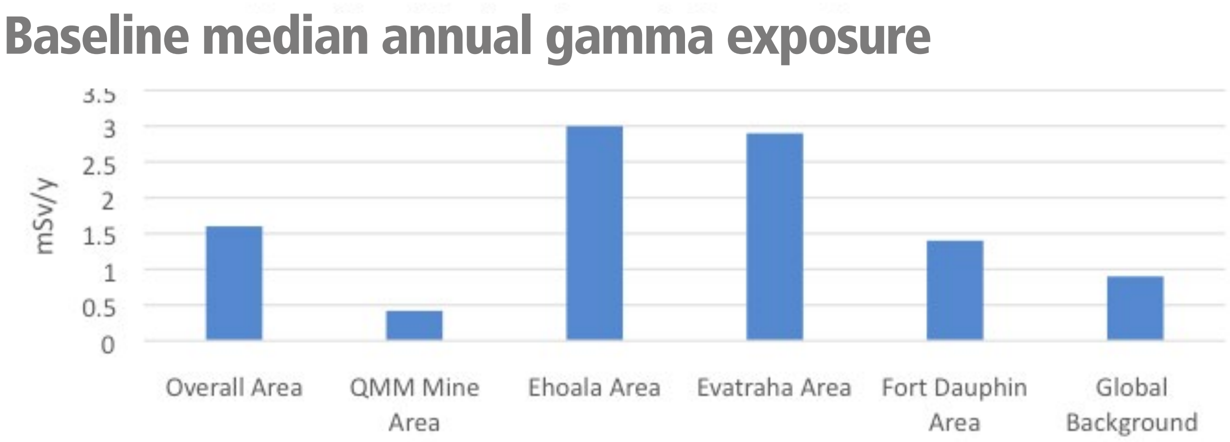


Figure 5. Pre-mining Gamma dose rates in the baseline study area compared to global background (SENES 2001)

Wood gathering on the QMM site

Two scenarios for increased gamma exposure are wood gathering on the QMM site and people living on the site after mine closure.

A conservative exposure scenario for people gathering wood was used to estimate maximum potential gamma exposure.

It was assumed that people spend 6 hours per day on-site over un-mined areas of mineral sands, 3 days a week, every week of the year.

The PARC (2013) median gamma dose rate at Mandromondromotra was used as the background dose.

In general, members of the public from the local communities are discouraged from entering and spending long periods of time on the mine lease because of potential danger due to interaction with mining equipment and to prevent access to mine and process plant workings. However, it is known that local people do come on site for various reasons. People coming to cut down and collect wood for use and/or sale offsite would be the group with the longest potential time on mineralised areas of the site.

To determine the potential QMM-related contribution to total gamma dose, a conservative exposure scenario was developed. Conservative scenarios are designed to produce maximum predicted exposure; e.g., by assuming long time periods spent on-site. It was assumed that members of the public come onto the site in unmined areas and spend six hours of the day, 3 days a week, every week of the year on these areas (to allow time both to reach the site and also importantly to transport the wood to its next destination).Although it is unlikely that any individual would be on site over mineralised areas for this much time, it forms a basis to allow the calculation of a conservative dose for wood collection.

The PARC (2013) median gamma dose rate of 0.14 µSv/h at Mandromondromotra was selected at a suitable background site. This dose rate represents what people would receive if they were not collecting wood on the QMM site.

Gamma data collected by QMM in 2016 for the mine site were used to estimate a dose rate of 0.31 µSv/h to a wood collector. Based on the natural background dose rate of 0.14µSv/h from Mandromondromotra, the incremental gamma dose rate to wood collectors would be 0.16mSv/y. The difference in annual

The estimated incremental gamma dose to people collecting wood on the QMM site was 0.16 mSv/y. Although this is a small amount, other incremental doses from dust inhalation or ingestion should be considered. The limit for incremental exposure of the general public is 1 mSv/y.

doses between staying at home and wood collecting at QMM is shown in Figure 6.

The incremental risk of health effects associated with 0.16 mSv/y is very small. However, it is important that people are aware that small incremental gamma exposures can occur if they enter the site. Furthermore, additional incremental doses to a wood collector could result from inhaling dust from the QMM site, or from ingestion of mineral particles, water and food. The limit for total incremental exposure of the general public is 1 mSv/y.

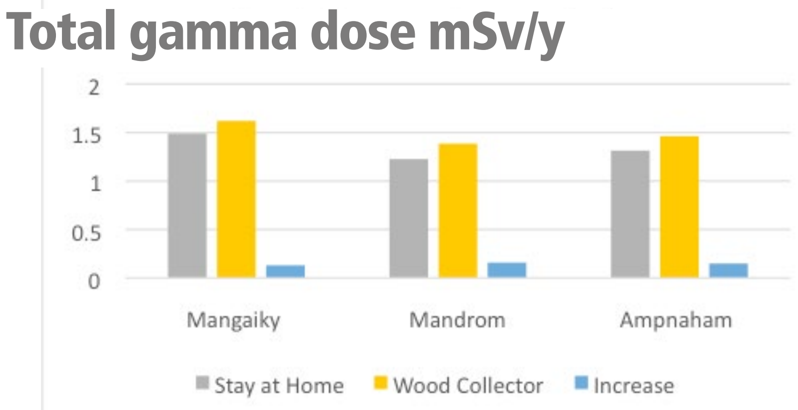


Figure 6. Gamma doses from staying at home vs collecting wood

The results of the INSTN (2017) survey of ambient dose rates on the QMM site as well as in nearby villages, on roads and tracks and the Port d'Ehoala showed that all dose rates outside of the mine site were below the regulatory limit cited by INSTN of 2.5 uSv/h. Measured dose rates ranged from 0.11 to 0.88 μSv/h.

An INSTN (2017) survey of ambient dose rates in nearby villages, on roads and tracks and in the Port of Ehoala showed that all dose rates were below the regulatory limit of 2.5 μSv/h.

INSTN measured dose rates on the QMM site ranged from 0.07 to 72 μSv/h, with the highest doses occurring in areas near magnetic reject (monazite) discharge (INSTN 2017). As noted above, access to magnetic reject stockpiles (which contain rare earth oxides) is restricted and members of the public would not be allowed anywhere near these areas. Furthermore, there are no harvestable trees near the stockpiles.

Post-mining exposure to people living on the site

After mine closure, rehabilitated land may be occupied by local people; therefore, the potential for enhanced gamma exposure post-mining was examined.

After mining is completed, the rehabilitated land may become a site of either permanent or temporary residences for local people; therefore, the potential for exposure should be considered. In the PARC (2013) report, it was identified that there was a potential for the gamma dose rate to be enhanced post mining. This was due to the enhanced levels of radioactivity found in the organic top soil that, as standard practice, is used during rehabilitation.

Post-mining gamma doses may be less than pre-mining doses because of removal or deep burial of minerals which contain the radioactivity.

Mineral sands mining is one of the few forms of mining where it is possible that the post mining dose rate can actually be reduced over that which existed prior to mining commencing, resulting in dose which may be less than the pre-mining natural baseline levels. This is because the minerals which contain the radioactivity are either removed or selectively placed at a deeper depth than existed in nature in the area. As the topsoil previously existed at the location, the removal and subsequent replacement should not adversely affect this reduction process if considered across the site as a whole (although it can be expected that there will be variations across the site).

Pre-mining gamma data collected in 2016 were compared to post-mining data collected in 2018 at 166 sampling locations.

Gamma data measured across the QMM site in 2016 and again in 2018 were analysed to determine if there would be any positive or negative impact on the gamma dose rate post-mining. The 2016 data were from an area before mining occurred. The 2018 data were post-mining. The coordinates of the sampling locations were checked on a location by location basis, and if they were identical, they were included in the analysis. If there was no match then the data were excluded. At each specific location the pre and post mining gamma rates were examined and subtracted from each other. The difference represents the operational contribution to the gamma dose rate at that specific location. Locations which were still under active use (such as two locations in the plant area) and locations which were still undisturbed by mining (under original vegetation) were similarly discarded. This process yielded 166 sampling locations with pre and post mining gamma dose rates.

The post-mining median gamma dose rate showed a decline of 0.11 μSv/h compared to the median pre-mining dose rate. However, gamma data were highly variable across the site.

Much more sampling is required to obtain a more confident indication of the site-wide gamma dose rate post and whether there may be specific areas where post-mine exposure has increased.

Because of the highly variable nature of gamma levels, even additional sampling may not show statistically significant differences between pre- and post-mining.

The post-mining median gamma dose rate was 0.20 μSv/h which is a decline of 0.11 μSv/h from the pre-mining median dose rate of 0.31 μSv/h (Table 2). The gamma data were highly variable across the site, as shown by the high standard deviations in Table 2. Much more sampling is required to obtain a more confident indication of the site wide gamma dose rate post mining and whether there may be specific areas where post mine exposure has increased.

For the sampling points analysed, the annual dose for permanent habitation would decrease from a pre-mining gamma dose of 2.7mSv/y to a post-mining gamma dose of 1.8mSv/y. This is well within the natural variation in the region around QMM.

Because of the highly variable gamma readings, even additional sampling may not produce results which show statistically significant differences between pre and post-mining.

	Mean Dose Rate µSv/h	Std. Dev	Median Dose Rate µSv/h	Annual Mean Dose Rate mSv/y	Annual Median Dose Rate mSv/y
Pre-mining	0.35	0.1	0.31	3.0	2.7
Post-mining	0.25	0.2	0.20	2.2	1.8
Difference	-0.09	N/A	-0.11	-0.81	-0.96

Table 2. Estimated Pre-and post-mining gamma dose rates. Annual dose rates assume permanent occupancy on post-mining land.

For the sampling points analysed, the annual dose for permanent habitation would decrease from a pre-mining gamma dose of 2.7mSv/y to a post mining gamma dose of 1.8mSv/y (Table 2). Although still on the upper range of natural values globally, it is well within the natural variation in the region around QMM because of the significant natural mineralisation in the region.

The analysis confirmed what would be expected given the disposal of heavier sands at depth. However, this is only true when considering the overall reclaimed area. There will be highly variable gamma dose rates on a location by location basis.

The analysis of the pre-mining and post-mining measurements confirmed what would be expected from theory. Due to the preferential disposal of heavier sands at depth, the gamma dose rate post mining may be reduced from that which existed in the natural pre-mining background. However, this is only true if a large area is considered because due to the nature of the mining and subsequent reposition of reject sands, there will be a high variability on a location by location basis.

Transport of material off-site

In 2018, QMM started shipping rare earth oxides which are used in many important products such as batteries and electric cars. The material is placed in bulka bags and then sealed in shipping containers.

QMM regularly transports its products from the mine site to the port for shipment internationally. Due to the nature of the processing, the majority of the material is not classified as radioactive.

In 2018, QMM started shipping rare earth oxides, which are heavy minerals associated with the waste materials produced after titanium has been removed from the monazite ore. Rare earth elements are used in many important products such as wind turbines, batteries, catalysts and electric cars. They include elements such as scandium and yttrium and are in short supply internationally with domination by China in both production and trade (Haque et al. 2014). Because rare earth elements are found in association with monazite deposits which contain uranium and thorium and their radioactive decay products, shipment can potentially expose the public to radiation.

Rare earth elements are found in association with monazite deposits containing uranium and thorium; therefore, shipment can potentially expose the public to radiation along transportation routes.

Shipments of rare earths are classified as radioactive material and as such are subject to international safety standards and guidelines.

Material containing rare earths is classified as radioactive; therefore, the transport of this material is subject to international safety standards and guidance, including containers, labelling and placarding. According to Rio Tinto, this material is initially sealed in appropriately labelled bulka bags and these in turn are sealed in appropriately placarded 20-foot shipping containers (Class 2012 LSA IIIY). The containers are placed on trucks and driven to the Port d'Ehoala where they are offloaded until loaded onto a ship. The trucks obey normal traffic rules along the route and there are approximately 400 containers per shipment (although this may vary). Detailed information on the shipment of the rare earth oxides was not available at time of writing of this report.

QMM places the rare earth material in sealed, labelled bulka bags which are in turn sealed in shipping containers.

Typical Bulka Bag.

Dose to a hypothetical roadside seller was conservatively estimated as 0.27 mSv/y.

Gamma dose rates at 1 metre from these containers are generally in the 10 - 20 µSv/h range (provided by QMM). A hypothetical roadside seller who is at a stop sign location was assumed to come within a metre of the container for one minute, enough time for half of the trucks with containers to pass by. Therefore, for an entire shipment of 400 containers of rare earth material, they would spend 200 minutes 1 metre away from the containers.

The estimated dose to a roadside seller is extremely conservative. A worst-case scenario of public exposure to rare earth shipments in Australia produced a dose of 0.003 mSv/y.

Based on the above assumptions, the potential exposure would be 0.07 mSv per shipment of 400 containers. Assuming 4 shipments per year then the potential dose to this hypothetical person would be 0.27mSv/y. This estimate is extremely conservative and is far higher than worst-case estimated dose of 0.003 mSv/y to the public from exposure to shipments of similar material in Australia (Calytrix Consulting 2008).

Monitoring of gamma radiation in close proximity to transport trucks containing monazite is required to reduce the uncertainty (and conservatism) of dose estimates to the general public.

Inhalation of radon gas and progeny

Radon is a gas produced in both the uranium and thorium decay series. Radon decays to a series of short-lived progeny, which, when inhaled, may attach to the lung or upper respiratory tract and cause radiation exposure.

Radon-222's half-life of 3.8 days allows time for it to enter the atmosphere and be transported away from the QMM site.

Exposure to radon is very significant globally.
The degree of air ventilation greatly influences radon exposure. Radon exposure is higher in cold climates because of tightly closed houses.

Radon exposure in communities around the QMM mine would be expected to be at the lower end of the global range due to a combination of warm climate and well-ventilated houses.

Highest exposures occur during calm winds but the area of high exposure would be small and in the immediate vicinity of the QMM mine. Higher wind speeds cause mixing which reduces radon concentrations to low levels.

Radon is an inert gas produced by both the uranium and the thorium decay series (Figure 7). The uranium-238 series produces radon-222 with a half-life of 3.8 days. Radon-222 decays to a series of short-lived radionuclide progeny with a maximum half-life of 27 minutes. The thorium-232 series produces radon-220, commonly called thoron, which has a half-life of 55 seconds. Radon-220 decays to a series of short-lived radionuclide progeny with a maximum half-life of 11 hours. The short-lived progeny are the primary issue because, unlike radon-222 and radon-220, which are inert gases that don't interact with tissues in the body, the progeny may attach to the lung or upper respiratory tract. Radon-222 is the most significant for public exposure because of it's 3.8 day half-life compared to the 55 second half-life of radon 220, which is so short that there is insufficient time for it to diffuse out of the mineral sands, let alone be transported off-site.

The average global exposure to radon and progeny is approximately 1.2mSv/y with a range of 0.2-10mSv/y [UNSCEAR 2008 Annex B Table 12].

Radon exposure is heavily dependent on air ventilation. Where ventilation is restricted, such as a tightly closed house or during times of minimal atmospheric dispersion, radon and progeny concentrations increase. Therefore, radon exposure is higher in cold climates.

Radon exposure around the QMM mine would be expected to be at the lower end of the global range due to a combination of the warm climate and living factors (such as natural house ventilation). Thus, despite the relatively large quantities of uranium and thorium bearing material in this region of Madagascar, it is expected that radon doses would be low.

Highest radon exposures occur during calm winds, which is accentuated if there are low-level inversions which "lock" the radon close to the ground. However, these same conditions restrict dispersal and hence the higher concentrations are restricted to the immediate vicinity of QMM. Mixing during higher winds reduces radon concentrations to low levels.

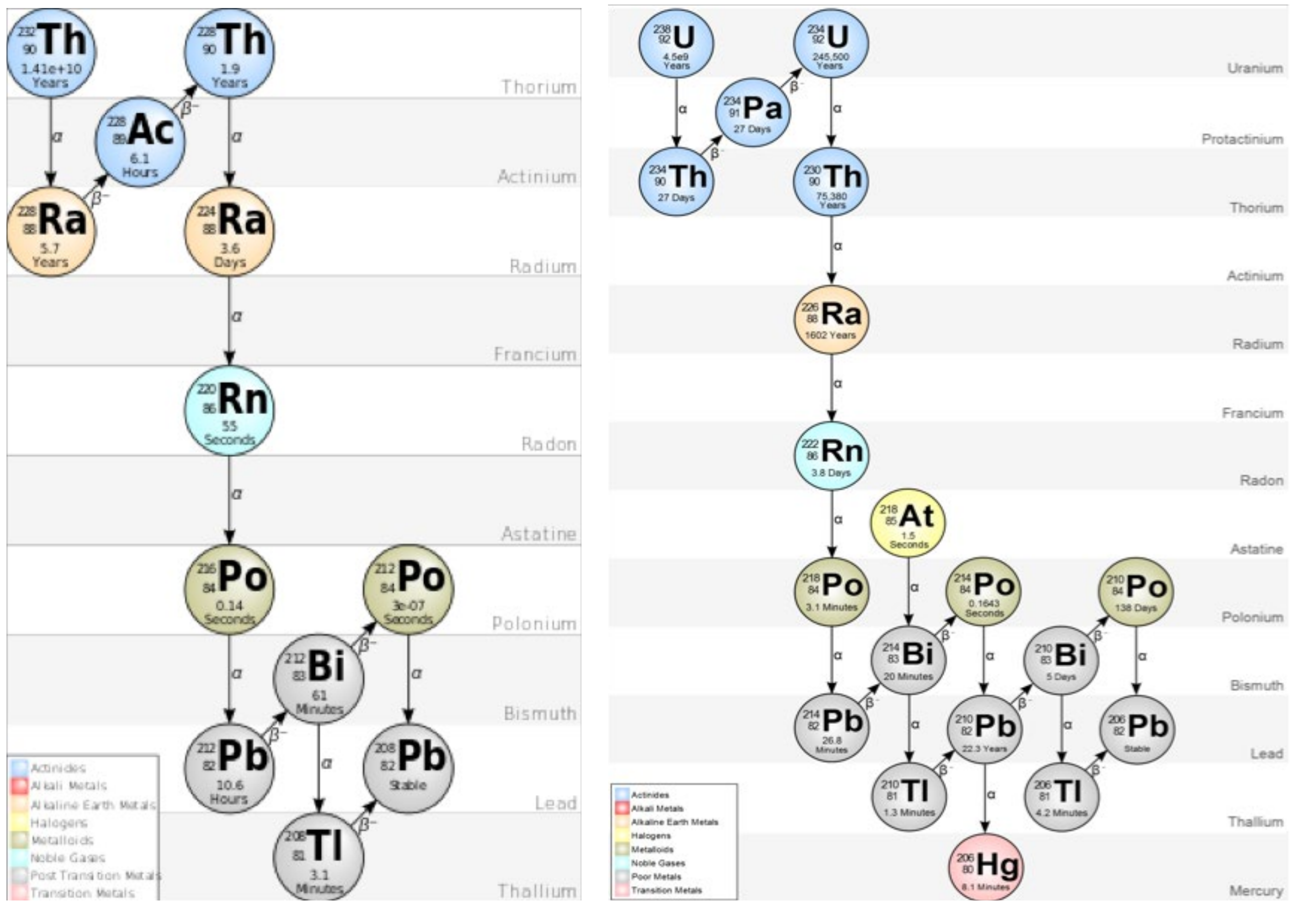


Figure 7. The Thorium and Uranium decay series.
Images modified from https://wikipedia.org/wiki/decay_chain

Radon exposure during mining

Dispersal by wind is a potential exposure pathway for radon to reach near-by communities

Radon dispersal by wind is a potential pathway via which radioactivity may be transported to people living beyond the mine site. Wind data for the QMM site show that the winds almost always come from the north-east to east (Figure 7). Radon Exposure During Mining

Winds are almost always from north-east to east. Moderate to high wind speeds occur in the August-January period.

North and south winds are almost never present. High-speed winds (10-15 m/s) occur mainly in the October-December period. Moderate winds from 5-10 m/s dominate from August-January. Light winds from -0.5-5 m/s are more common from February-July.

Most communities are not located downwind of the dominant wind direction. Moderate-high wind speeds provide ample mixing of radon and prevents build up of both the gas and radon decay products.

The strong dominance of a single wind direction combined with moderate to strong winds means potential radon exposure in near-by communities would be very low. Most communities are not located downwind of the dominant wind direction. Furthermore, moderate-to-high wind speeds provide ample mixing of the radon and prevents the build-up of both the gas and decay products.

This expectation was confirmed by INSTN (2017) radon monitoring data. Radon was less than detection limits in 4 of 6 buildings monitored. An off-site hotel and a QMM employee residence had mean radon concentrations of 70

Given the extremely low predicted radon exposure in near-by communities, detailed radon monitoring is not recommended.

Bq/m³ and 32 Bq/m³, respectively. Both of these results are well below the acceptable limit for the public of 400 Bq/m³. INSTN (2017) stated that the low radon concentrations can be explained by wind mixing and dilution as well as the natural ventilation of local dwellings.

Atmospheric modelling conducted by PARC (2013) and Senes (2001) predicted that the maximum estimated radon exposure to any community was a few thousandths of a milli-Sievert (<0.003mSv/y). Therefore, detailed radon monitoring is not recommended because it is highly unlikely that any monitoring system would be able to discriminate this extremely small additional exposure from the highly variable natural exposure.

Radon exposure post-mining

It is expected that selective placement of minerals which contain radioactivity at depth in the post-mining environment would cause the post-mining radon exposure to be less than that which existed prior to mining.

Consistent and correct placement of minerals containing radioactivity at sufficient depth is required to produce conditions where post-mining radon exposure is not distinguishable from background.

After mining is completed, the rehabilitated land may become a site of either permanent or temporary residence for local communities; therefore, the potential for exposure to radon should be considered.

It is expected that the post-mining burial of the more radioactive material at depth would cause the post-mining radon exposure to be less than that which would have occurred in the natural pre-mining situation. This is because both forms of radon have relatively short half-lives (3.8 days and 55 seconds for Rn222 and Rn220 respectively) and any increase in depth will decrease the amount of radon which can escape to the surface environment.

Consistent placement of minerals containing radioactivity at sufficient depth is required to produce conditions where post-mining radon exposure is not distinguishable from background.

Inhalation of long-lived radionuclides in airborne dust

Dust containing radionuclides can be carried via the wind to local communities.
The smaller particles in dust (less than 10 µm in diameter) can be taken into the lungs.

QMM activities generate dust which may contain enhanced quantities of radionuclides. This dust may be carried via the prevailing wind to the local communities where it can be inhaled. Not all dust in the air can be taken into the lungs. It is the smaller particles (called PM_{10} dust or dust which is smaller than 10 µm in diameter) which are important for this pathway.

Longer-lived radionuclides in the uranium and thorium decay series dominate the dose from inhaled dust particles. These radionuclides emit gamma, alpha and beta radiation.

The longer-lived radionuclides dominate the dose from inhaled dust particles. The potential exposure from shorter lived radionuclides is far less and may be incorporated into the dose from the parent radionuclides. The important long-lived radionuclides in the uranium series are uranium-238 (U238) uranium-234 (U234), thorium-230 (Th230), radium -226 (Ra226), lead-210 (Pb210) and polonium-210 (Po210) (Figure 5). The important long-lived radionuclides in the thorium series are thorium-232 (Th232), radium-228 (Ra228), thorium-228 (Th228) and radium-224 (Ra224) (Figure 5).

The longer-lived radionuclides important to the consideration of dust inhalation emit gamma, alpha and beta radiation.

Inhalation and ingestion are the two prime the mechanisms for exposure to alpha and beta radiation.

Inhalation and ingestion are the two primary mechanisms for exposure to alpha and beta radiation. Alpha radiation consists of particles made up of two protons and neutrons which are ejected as a radionuclide decays. Alpha radiation can be stopped by a piece of paper or the dead outer layer of the skin. Thus, alpha radiation outside of the body does not present a radiation hazard. However, when alpha radiation is taken into the body, the energy of the radiation is completely absorbed into bodily tissues, creating an internal hazard (CNSC 2012). In the case of inhalation, this hazard is primarily to lung and upper respiratory tract tissue.

Alpha radiation outside of the body does not present a radiation hazard because it can be stopped by a piece of paper. However, when taken into the body, it poses a hazard.

Beta radiation consists of charged particles that are ejected from the nucleus of a radionuclide as it decays. Most beta radiation can be stopped by small amounts of shielding, such as sheets of plastic, glass, or metal. Some beta radiation can penetrate the outer layer of skin; however, it is very limited in its ability to penetrate to deeper tissues in the body (CNSC 2012). However, when beta radiation is inhaled or ingested, its energy is absorbed by tissues in the body.

Beta radiation can penetrate the outer layer of skin, but it is only when inhaled or ingested that deeper tissues can be affected

The key to understanding the potential impact from dust inhalation on communities surrounding QMM is an understanding of the atmospheric dispersal pathway and in particular the wind speeds and directions. Figure 8 shows the

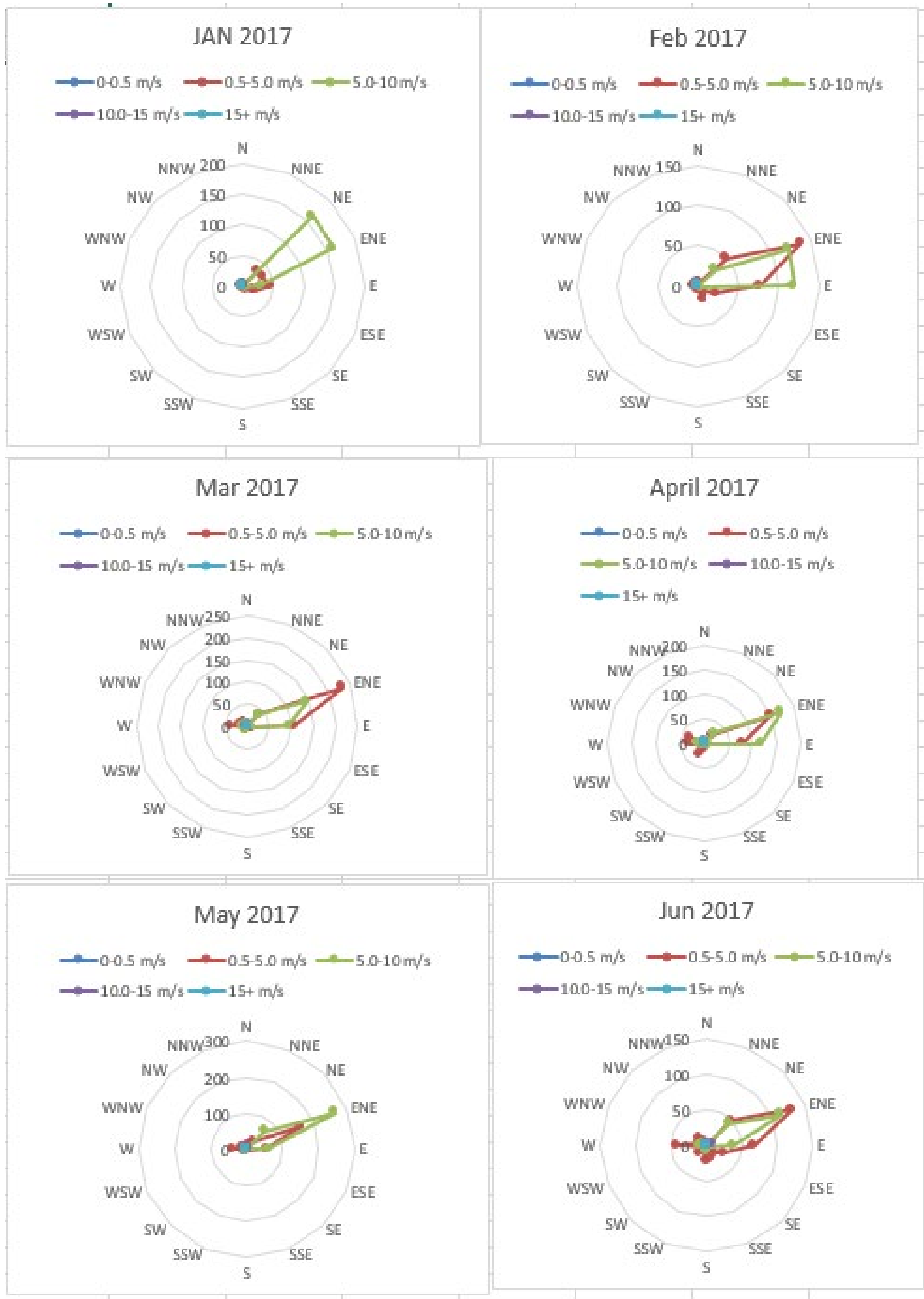
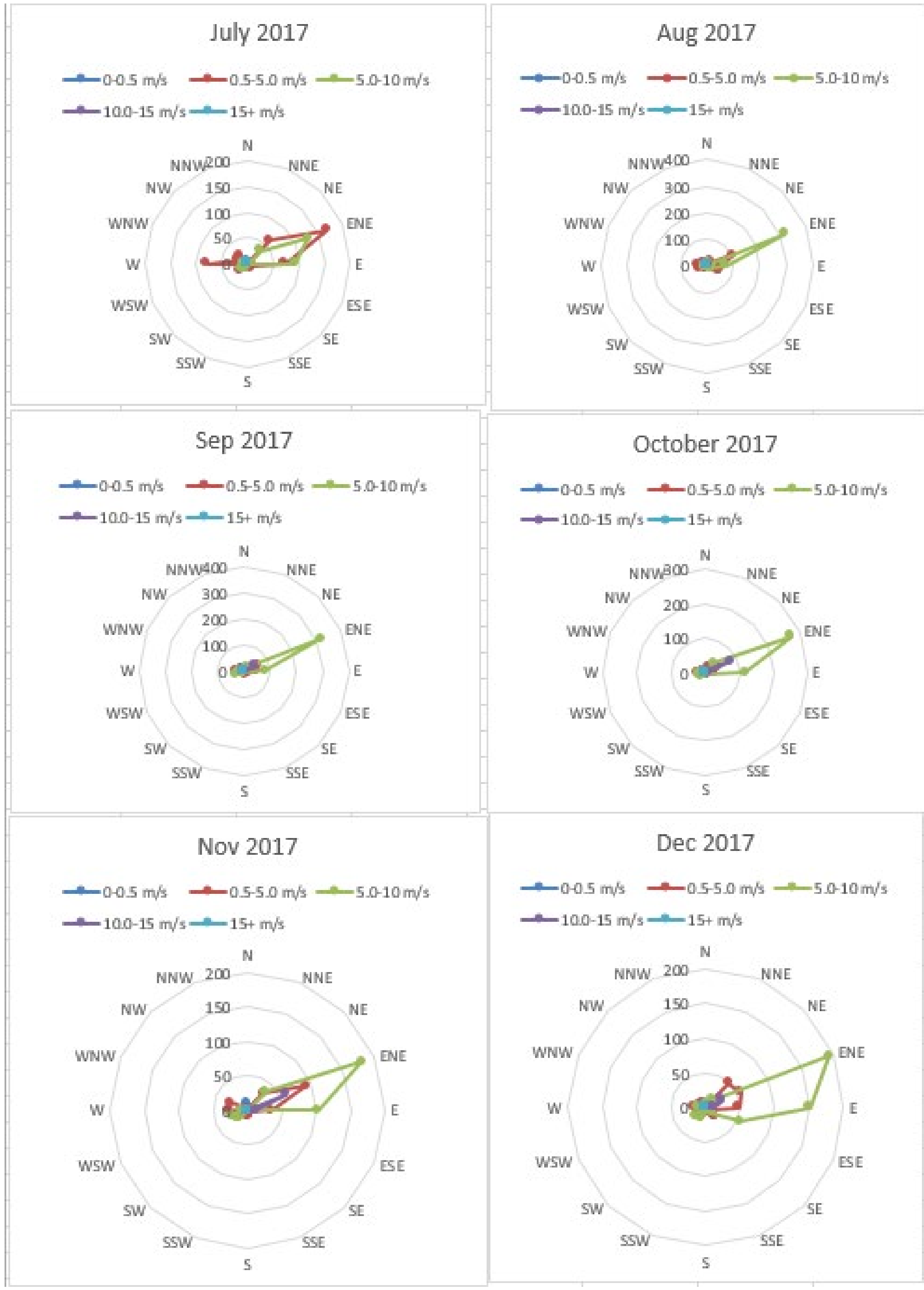


Figure 8. Month by month wind roses for the QMM site in 2017



month by month wind roses for QMM in 2017.
The wind roses are remarkably consistent with winds almost always being from the north east to east. Winds in the northerly and southerly directions are almost never present. High-speed winds (10-15 m/s) occur mainly in the October-December period. Moderate winds from 5-10 m/s dominate from August-January. Light winds from -0.5-5 m/s are more common from February-July. The highly consistent wind directions mean that communities which are not southwest or west of QMM would receive negligible dust originating from the site. Only two settlements have the potential to be significantly impacted by the QMM operation: Ampasy Nahampoana and Maroamalona. Other locations are well off the predominant wind direction.

Understanding wind speeds and directions is key to understanding the potential impact on near-by communities from dust inhalation.

Winds are almost always from the north-east to east. North or south winds almost never occur. The highly consistent wind directions mean that communities which are not southwest or west of QMM would receive negligible dust originating from the site.

Dust on the QMM Site During High Winds (PARC 2013).

Determination of QMM operational contribution to dust

The incremental contribution of QMM operations to dust in nearby communities was estimated using air monitoring data. QMM performs PM_{10} dust monitoring on a rotational basis in the communities. PM_{10} is used as an estimate of the proportion of dust which will be inhaled by a person (dust greater than 10 µm generally does not enter the more sensitive areas of the respiratory system). The monitoring instrument used by QMM measures the airborne dust concentration every 5 minutes and generally operates at each community site for approximately 6 to 7 hours.

The dust concentrations recorded in 2017 are displayed in Figure 9 (no monitoring data were available for October 2017). The first six bars show the raw dust concentrations measured at each of the community locations. However, the proportion of the dust which is background versus the proportion which is due to QMM operations is difficult to determine.

A conservative approach was used whereby the lowest dust concentration measured at any of the sites was used as the background dust level. The operational component was then calculated based on taking the dust concentrations at the two community sites in the downwind wind direction (Ampasy Nahampoana and Maroamalona) and then subtracting this regional background dust concentration (thereby maximising the operational component). This is likely to be an overestimation of the operational component but in the absence of simultaneous upwind and downwind monitoring is the best possible estimate. The background dust level (minimum of all sites) and the QMM related dust concentrations are displayed in Figure 9 as the final three bars (IOC stands for incremental operational contribution). Measurements in the two downwind communities were not made in all months; therefore, incremental QMM contributions could not be estimated for March or October.

Ampasy Nahampoana and Maroamalona are the only settlements which have the potential to be significantly impacted by dust from the QMM site.

The incremental contribution of QMM operations to dust in nearby communities was estimated using QMM air monitoring data.

Incremental contributions to dust by QMM operations in the two downwind communities of Ampasy Nahampoana and Maroamalona were estimated by subtracting the conservatively assumed regional background dust concentration from measured dust concentrations. Figure 9 shows the incremental QMM contribution to dust for months where dust was measured in these two communities (the bars corresponding with Maroamalona (INC) and Ampasy Nahampoana (INC)).

Measured dust concentrations from 2017 were used. The proportion of the dust which is background versus the proportion which is due to QMM was estimated by assuming that the lowest dust concentration measured at any of the sites was the background dust level. This is a conservative assumption.

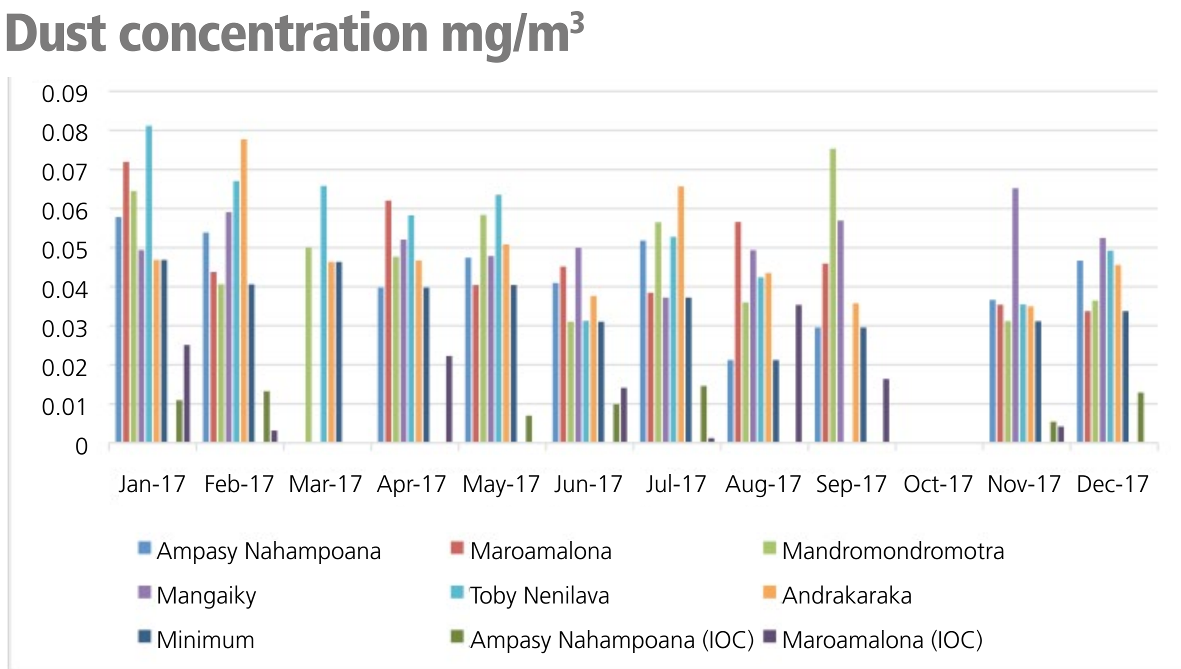


Figure 9. Dust Concentrations at communities in 2017 and the calculated operational increment at the two downwind communities of Ampasy Nahampoana and Maroamalona

Calculation of radiological doses associated with dust

Once the incremental contribution of QMM operations to dust was estimated, the amount of radioactivity in the dust had to be determined. Ideally, this would be calculated from direct measurement of the radioactivity in the dust but this information was unfortunately not available. Therefore, a conservative approach was used. It was assumed that all the operational dust has the same radionuclide concentration as the Heavy Mineral Concentrate (HMC) which is the feed material for the dry plant at QMM. This is likely be a substantial overestimation of the actual radionuclide concentration but does enable the calculation of the expected maximum potential dose from QMM. Using this HMC radionuclide activity, it was possible for the operational-related airborne radioactivity concentration to be estimated.

Once the incremental contribution of QMM operations to dust was estimated, the amount of radioactivity in the dust had to be determined.

Unfortunately, there are no available data on radioactivity in dust. Therefore, it was conservatively assumed that all operational dust has the same radionuclide concentration as the Heavy Mineral Concentrate feed material for the dry plant at QMM.

It can be assumed that all the long-lived decay products have the same concentrations as the parent U238 and Th232 radionuclides.

Yearly doses for different age groups living in the two downwind communities were calculated using dose conversion factors (DCFs) provided by IAEA (2014).

The highest DCF (corresponding with high solubility) was used for all radionuclides even though the QMM material is unlikely to be highly soluble.

Estimated yearly doses were highest for the 1-2-year-old age group and were consistently higher for Maroamalona across all age groups.

The results in Table 3 are likely overestimates because of the conservative assumptions used in the calculations. However, the results indicate the potential significance of the dust inhalation pathway.

Estimated doses are from about 20-40% of the 1 mSv/y dose limit for the general public. This indicates that dust management on the QMM site is important in order to minimize public exposure and keep the incremental dose well below the limit.

Because the material has not been subject to any chemical modification, it can be assumed that all the long-lived decay products have the same concentrations as the head of the series (U238 and Th232 for the uranium and thorium series respectively).

Inhaled radionuclides may be metabolised differently by people in different age groups. The International Atomic Energy Agency (IAEA 2014), in their Basic Safety Standards (GSR3) provide Dose Conversion Factors (DCF) for inhalation for different age ranges. These DCFs vary according to the solubility of the individual radionuclide, with higher DCFs for more soluble radionuclides. For the purposes of this dose estimation, the highest DCF was used for all the radionuclides. This adds another layer of conservatism given the low potential solubility for the QMM material. It was assumed that people are at the downwind locations for 24 hours a day, 365 days in the year.

Estimated yearly doses were highest for the 1-2-year-old age group (Table 3). This result reflects breathing rates for this age groups as well as higher dose conversion factors for some of the radionuclides. Estimated doses were consistently higher for Maroamalona across all age groups.

The results provided in Table 3 should be considered an overestimation of the potential dust-related dose due to the conservative nature of the assumptions used. The results are similar to the PARC (2013) estimated doses from dust inhalation in the same two communities, with the exception of estimates for 1-year-olds where the PARC estimates were considerably lower. Thus, the PARC estimates and the estimates produced for this report reflect similar conservative assumptions.

Estimated doses from inhalation of dust generated by QMM operations are from about 20-40% of the yearly 1 mSv dose limit for the general public. This is a substantial proportion of the allowable incremental dose. Therefore, effective dust management at the QMM operations is important in order to keep the incremental dose to the public well below the limit, in accordance with the As Low as Reasonably Achievable (ALARA) principle.

Downwind Location	Age Group (y)					
	1	1-2	2-7	7-12	12-17	17
Ampasy Nahampoana	0.17	0.23	0.19	0.17	0.18	0.08
Maroamalona	0.28	0.38	0.32	0.28	0.30	0.13

Table 3. Estimated yearly dose (MSV) from exposure to dust generated by QMM operations at downwind locations.

Exposure via ingestion

Exposure via ingestion occurs via drinking water, eating food, or accidentally eating soil that is on food or on people's hands.

The people who have the highest potential for receiving QMM-related radiation doses via ingestion would live nearby and obtain a substantial amount of their drinking water and food from adjacent rivers, lakes, fields, and pastures.

It will be important to continue to monitor and evaluate radiation exposure in communities in the Petriky and St. Luce areas into the future because the people who potentially receive the highest incremental doses due to mining will change with time

People living downwind of the QMM mine have the greatest potential for exposure to enhanced radiation in soils caused by dust deposition. Ampasy Nahampoana and Maroamalona are the communities which would potentially receive the most mine-related dust deposited on soils.

It is assumed that the communities of Mandromondromotra, Maroamalona, Andrakaraka, Emanaka, Andranokana and Ampasy Nahampoana use the Mandromondromotra River, the Méandre River and Lake Ambavarano and Lake Besaroy for water and fishing.

Exposure via ingestion occurs via drinking water, eating food, or accidentally eating soil that is on food or on people's hands. As explained above, the area around QMM has high natural background levels of radiation because of the presence of monazite sands. People in the region have always been exposed to these natural levels of radiation in soil, water, and food.

The people who have the highest potential for receiving QMM-related radiation doses via ingestion would live nearby and obtain a substantial amount of their drinking water and food from adjacent rivers, lakes, fields, and pastures. It is assumed that this applies to all of the settlements in the immediate vicinity of QMM.

This analysis focuses on the Mandena region because current mining is occurring within this region. The mine plan is to extend mining to the Petriky and St. Luce areas. Therefore, it will be important to continue to monitor and evaluate radiation exposure in communities in the Petriky and St. Luce areas into the future because the people who potentially receive the highest incremental doses due to mining will change with time.

People living downwind of the QMM mine have the greatest potential for exposure to enhanced radiation in soils caused by dust deposition. Northeast or east winds are by far the dominant winds in the region (Figure 8). Currently, mine activities which generate dust occur at the south/south-west side of the site. Based on this information, Ampasy Nahampoana and Maroamalona are the communities which would potentially receive the most mine-related dust deposited on soils at this stage of mining by QMM. Andranokana might also receive mine-related dust during northeast winds. Andrakaraka and Emanaka are south and south-east of the current location of dust-generating mine activities and north winds are very rare; therefore, these two communities are unlikely to receive significant dust deposition on to soils, at least at the present time.

It is assumed that the communities of Mandromondromotra, Maroamalona, Andrakaraka, Emanaka, Andranokana and Ampasy Nahampoana use the Mandromondromotra River, the Méandre River and Lake Ambavarano and Lake Besaroy for drinking water, livestock water, irrigation water for crops, bathing, and fishing. The extent of use would depend the proximity of each community to these rivers or lakes and the location of surface ponds or wells in or near the communities.

Mine effluent discharges to the Mandromondromotra River via a wetland on the QMM site.

Groundwater seepage may release radionuclides to Lake Ambavarano and Lake Besaroy.

The Méandre River may receive radionuclides via dust deposition.

According to available information, only one-quarter of all households in the Mandena area were reported to have access to potable drinking water. Review of more recent QMM reports did not yield any information regarding whether there has been an increase in the availability of potable water in the area.

For this review, it was assumed that people obtain their drinking water from rivers, lakes, or ponds.

Discharges and seepage from the QMM site are sources of radionuclides to the Mandromondromotra River, Lake Ambavarano and Lake Besaroy.

The water flow path during the mining process ends with three effluent release points. From there, water follows natural drainage patterns through a wetland area to the Mandromondromotra River

Water that is determined to be of too poor quality to discharge is directed to the dredging pond (BASMIN)

The Mandromondromotra River receives mine effluent discharges via a wetland on the QMM site. Radionuclides may be released to Lake Ambavarano and Lake Besaroy via groundwater seepage originating from the mine site. The Méandre River may receive radionuclides via dust deposition.

Drinking water

Only one quarter (26% overall) of all households in the Mandena area were reported to have access to potable drinking water in 2009 (ATW 2009). For the purposes of this analysis, it was assumed that people would obtain all of their water for domestic use from untreated surface water bodies. This assumption is supported by the findings of Community Development Plans. For example, 80% of households in Mandromondromotra did not have drinking water and the 9 water fountains in the community were all non-functional (Mandromondromotra PCD 2003a). Ampasy Nahampoana residents were reported to use river water or ponds for drinking water built in Hovatraha and Ambaniala (Hai-Tsingo Consultants 2008). QMM is assisting in providing clean water to some villages in the region; e.g., water fountains in Andranara and Ilafitsinanana, but not at the villages potentially most directly affected by the uranium issue, notably Ampasy Nahampoana and Mandromondromotra

Water flow paths on the mine site and QMM water quality sites

The surface water flow path during the mining process is as follows (Hoagland 2013):

- Water is sourced from onsite storage basins (Paddocks) and transported to the Mineral Separation Facility (MSP)
- From the MSP, water is either recycled or it flows to a collector canal system for treatment in a "biodiversity control pond" (settling pond)
- Water is discharged depending on quality past effluent release points WMC 603, WMC 703, WMC 803.
- The water then follows natural drainage patterns through a wetland area to the Mandromondromotra River.

Water that is determined to be of too poor quality to discharge is directed to the dredging pond (BASMIN).

Water quality in the river adjacent to the QMM site is of particular interest because of the overland discharges from the QMM water release points WMC 603,703 and 803. Water quality monitoring sites S42, S43 and S44 on the Mandromondromotra River are the closest monitoring sites to these release points (Figure 10).

Water quality monitoring sites S42, S43 and S44 on the Mandromondromotra River (Figure 8) are the closest monitoring sites to the QMM effluent release points.

Lake Ambavarano water quality may be affected by water entering the lake from the Mandromondromotra River and shallow groundwater seepage from the mine site via the wetland areas immediately to the north of the lake.

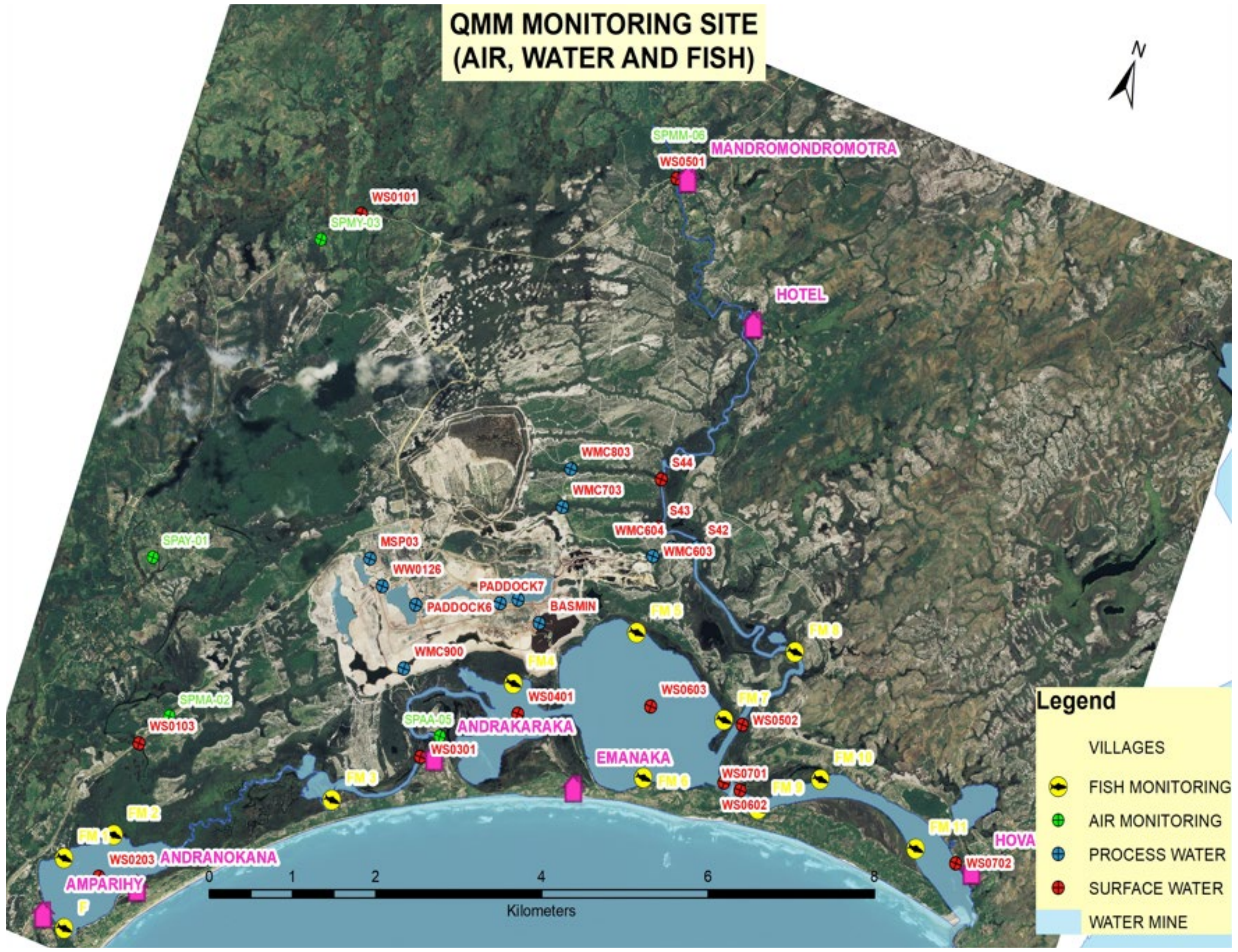
There is only one QMM water quality monitoring station in Lake Ambavarano and Lake Besaroy. Therefore, there are insufficient data to evaluate effects on water quality from surface water or groundwater entering the lakes.

Lake Ambavarano water quality may be affected by water entering the lake from the Mandromondromotra River. Water quality in both Lake Ambavarano and Lake Besaroy may be affected by shallow groundwater seepage from the mine site since isotopic groundwater signatures show a connection between the upper water table and surface water (INSTN 2017). Furthermore, the direction of groundwater flow is south (INSTN 2017). There is only one water quality sampling site in each lake (Sites WSO401 and WS0601). Therefore, there are insufficient water quality data to determine whether there might be detectable effects of groundwater seepage or whether water quality at the mouth of the Mandromondromotra River differs from water quality in the Lake Ambavarano. Note that Figure 10 mistakenly labels the location WS0601 as WS0603.

Monitoring results for Radionuclides in surface water

Radionuclide levels in process water samples on the QMM site were higher than in river or lake water samples; however, all levels in river and lake water were well below World Health Organization (WHO) drinking water guidelines for

Figure 10. Location of QMM monitoring sites *(Figure providedby QMM)*



Radionuclide levels in process water samples on the QMM site were higher than in river or lake water samples; however, all levels in river and lake water were well below World Health Organization (WHO) drinking water guidelines (Table 4).

The data in Table 4 are from one sampling event only. The time of year of the sampling was not available. Therefore, there is no way of knowing what sort of conditions are represented by the data; e.g. water flow rates and volume, season of the year, mine production rate, proximity of dredging ponds to the river or the two lakes, etc.

There are insufficient data to explain striking differences in the relative levels of U238 and U234 versus thorium isotopes and Ra226 in river and lake water samples. No such differences would be expected.

Alpha and beta results do not correspond with the type of water or the levels of radionuclides. There may be significant problems in the gross alpha and beta analyses which should be investigated.

The acidic pH levels in Table 4 may, in part, reflect that the pH in the wetland on the QMM site is acidic. Drainage from the wetland area to the river may contribute to maintaining an acidic pH in the river, at least until farther downstream. The pH may influence radionuclide concentrations in water.

Process Water				Upstream of QMM		Downstream of QMM Discharges		
	BASMIN	Paddock 3	WMC603	WMC1000	WS0501 Mandromondromotra River	S44 Mandromondromotra River	WS0601 Lac Ambavarano	WHO Drinking Water Guideline
Radionuclide	Mining Basin	Mine Pond	Discharge Point	Wetland	Upstream of QMM	First receiving point	Mid-lake	mBq/L
	mBq/L	mBq/L	mBq/L	mBq/L	mBq/L	mBq/L	mBq/L	
U238	200	590	170	480	150	270	150	10000
U234	650	1800	680	1470	480	790	490	1000
Sum of U238 & U234	850	2390	850	1950	630	1060	640	
Th230	130	680	34	17	30	30	17	1000
Ra226	480	230	52	3	4	12	9	1000
Th232	100	9	32	10	8	6	10	1000
Th228	580	230	70	15	13	4	5	1000
alpha	2500	-75	410	-120	-43	-110	580	
beta	6300	350	755	330	306	300	3400	
pH	3.8-4.6	3.2-4.0	2.8-3.3	3-4	4.7-6.5	4.2-5.5	6.7	

Table 4. Radionuclide measurements in process water on the QMM site and in river and lake water. *(Data provided by QMM)*

radiation (Table 4). The data in Table 4 were provided by QMM. Apparently, the data in Table 4 are from one sampling event only. The time of year of the sampling was not available. Therefore, there is no way of knowing what sort of conditions are represented by the data. For example, water flow rates and volume in the Mandromondromotra River will vary seasonally and water flow and volume can greatly affect the concentration of radionuclides and other water quality parameters such as metals. Mine production rate can also affect water quality via the volume of process effluent discharged. The proximity of dredging ponds to the river or lakes may also be an important factor with respect to the potential for shallow groundwater transport to the river or the two lakes.

There is a striking difference in the relative levels of U-238 and U-234 versus Th isotopes and Ra-226 in river and lake water samples (Table 4). There was no such striking difference in process waters, with the exception of Th-232. The reasons for this are unknown. Measurements of pH at the S44 site show that it was somewhat less acidic (4.2-5.5) than in process waters, where pH ranged from 2.8-4.6. However, the differences in pH are not sufficient to explain the higher relative concentrations of U-238 and U-232 in the river and lake samples relative to the process water samples. Furthermore, pH data are from a different QMM monitoring program.

The acidic pH levels in Table 4 may, in part, reflect that the pH in the wetland on the QMM site is acidic (INSTN 2017). Drainage from the wetland area to the river may contribute to maintaining an acidic pH in the river, at least until farther downstream.

The pH of the river water may influence the concentrations of radionuclides. Other parameters such as salinity and dissolved oxygen also play a role. For example, low pH and high salinity

The radionuclide data are too limited to support detailed interpretation and analysis.

Future monitoring of radionuclides in surface water should include supporting information on the physical and chemical properties of the water which can affect the total versus dissolved concentrations. Furthermore, data on both filtered and unfiltered samples would assist the evaluation of exposure of people to radionuclides in poorly filtered drinking water.

Uranium and thorium data in mg/L obtained using ICP analysis (i.e., measured as metals and not as radionuclides) were reviewed because radionuclide data for surface water were so limited.

There were insufficient data to evaluate spatial patterns in thorium or uranium concentrations in river or lake water.

The lack of corresponding process water samples taken on the same dates as receiving environment samples prevented any confident interpretation of correspondence between process water and surface water thorium and uranium levels.

have been correlated with high Ra226 and low Th in water in a monazite area (Lauria and Godoy 2002). Radium226 concentrations can be high in near neutral to alkaline (pH>6) conditions and anoxic waters, or in acidic (pH<6) and anoxic waters (Szabo et al. 2012). Herczeg et al. (1988) observed that the redox state of waters significantly affects uranium and Ra226 concentrations with low uranium concentrations and much higher Ra226 concentrations in reducing (low oxygen) conditions.

The radionuclide data are too limited to support detailed interpretation and analysis. A key limitation is that the alpha and beta results do not correspond with the type of water (process versus receiving water) or the levels of individual radionuclides. The gross alpha should be approximately the same as the sum of U238 and U234, yet there is no similarity. This suggests some significant problems in the gross alpha and beta analyses which should be investigated.

INSTN water samples taken from 12 locations, including a location in the Mandromondromotra River, did not have detectable U238 and Th232 activities (INSTN 2017). The INSTN report concluded that radionuclides do not dissolve easily in receiving waters. Given the low specific activity of both U238 and Th232, it is not surprising results were less than detection limits. However, this does not mean that uranium and thorium were not present in the water, as evidenced by ICP analyses discussed below.

Future monitoring of radionuclides in process water, river water and lake water should include supporting information on physical and chemical properties of the water which affect the degree to which radionuclides would be found in the dissolved form. This supporting information includes: water flow in m^3/s (for river samples), water depth (for lake samples), pH, redox potential (Eh), dissolved oxygen, salinity, total dissolved solids, iron, manganese, and total suspended solids. Both filtered and unfiltered samples should be analysed in order to evaluate the influence of particulates in the water on the partitioning of radionuclides in the dissolved phase. Furthermore, data on both filtered and unfiltered samples would assist in the interpretation of exposure of people drinking surface water which may not be filtered, or which is poorly filtered.

Other measurements of Uranium and Thorium in surface water

Upstream river flow data are valuable for interpreting water quality; however, flow data did not show the expected relationships with water quality parameters such as total suspended solids.

With one exception, thorium was not detectable in river water at stations adjacent to QMM effluent discharges (via the wetland). However, thorium was well above detection limits farther downstream.

Uranium was detectable in river water at stations adacent to QMM discharges as well as farther downstream. All detectable concentrations were above the WHO drinking water quality guideline.

Because the radionuclide data for river and lake water were so limited and because the gross alpha and beta measurements were unreliable, data on uranium and thorium concentrations in mg/L as obtained using ICP methodology were reviewed. The data were from the QMM monitoring program sites in the Mandromondromotra River, Lake Ambavarano and Lake Besaroy (Figure 10).

There were insufficient data to evaluate spatial patterns in thorium or uranium concentrations in river or lake water. Furthermore, the dates of process water sampling from the QMM site seldom, if ever, corresponded to the dates of water sampling in the Mandromondromotra River or in the lakes. Lake sampling was very infrequent (only one sample for Lake Besaroy).

River flow is an important determinant of river water quality. River flow data are collected at a hydrometric station located near the upstream water quality station WS0501; however, no flow data were provided by QMM for any of the downstream stations. Upstream water flow data are not consistently related to water quality at WS0501 (Appendix Table 1). For example, it would be expected that higher flow would correspond with higher total suspended solids (TSS); however, one of the lowest flows was recorded on the same day as one of the highest TSS measurements.

Thorium concentrations at the site upstream of QMM were all less than analytical detection limits. Thorium was above detection limits at sites S42, S43 and S44 in the Mandromondromotra River downstream of QMM discharges on July 6, 2016. There were no corresponding process water samples taken on or near this date. Without flow and TSS data for this date and site, it is not possible to determine whether this one event was related to higher levels in process water, higher flows and/or higher TSS. All other thorium measurements at S42, S43 and S44 were less than detection. Thorium concentrations were well above the detection limit upstream and downstream of the weir and in Lake Besaroy (one sampling occasion each). There is insufficient information regarding the possible mine-related sources (notably seepage) to allow evaluation of the source of thorium at these sites.

Uranium concentrations at the site upstream of QMM were less than analytical detection limits, with the exception of one measurement in March, 2017 (0.136 mg/L) (Table 5). Unfortunately, there are no supporting data for pH, conductivity, total dissolved solids (TDS) or dissolved

There were no consistent patterns in thorium or uranium concentrations with respect to date, pH, conductivity, TDS or concentrations in process water.

Radiation dose via drinking river or lake water cannot reliably be estimated because of the lack of data and/or the questionable nature of the data (e.g. gross alpha and beta).

Uranium concentrations in the Mandromondromotra River are a concern because of the chemical toxicity of uranium, not its radioactivity.

Because there is already a high natural background of uranium and thorium in the area, it is important to understand the incremental effect of QMM process water discharges.

There were insufficient uranium and thorium data on specific sampling dates to allow for evaluation of QMM incremental contributions.

Conductivity, salinity and TDS data show that there is a process water "signature" in the river.

oxygen for this date and concentrations of other metals were not unusual; therefore, the possible explanation for this one occurrence at the upstream site is unclear. There were several occurrences of detectable uranium concentrations at sites S42, S43 and S44 downstream of QMM discharge points, with no particular pattern with respect to sample date, pH, conductivity, TDS, or concentrations in the process water at or near the date of sampling the river water.

There were also detectable uranium concentrations farther downstream on several sampling dates - at the entrance to Lake Ambavarano, and above and below the weir (Appendix Table 1).

Radiation dose from uranium and thorium via the drinking water pathway cannot reliably be estimated because of the lack of data and/or the questionable nature of the data (e.g. gross alpha and beta).

All detectable uranium concentrations in the Mandromondromotra River as well as at the weir were above the WHO drinking water quality guideline for chemical toxicity of 0.03 mg/L (Appendix Table 1). The contribution of natural uranium versus QMM sources is unknown. No matter what the sources of uranium are, the concentrations which are above drinking water quality guidelines are of concern because of the chemical hazard of uranium rather than its radioactivity (which is very low). The kidney is the organ that is most susceptible to the effects of uranium (Health Canada 2018).

Sources of Uranium and Thorium in surface water

It is important to evaluate the incremental effect of QMM process water discharges on water quality. There were insufficient uranium and thorium data on specific sampling dates to allow a full comparison between process water discharge concentrations and receiving water concentrations. However, there were sufficient conductivity, salinity and Total Dissolved Solids (TDS) data for sites S42, S43 and S44 in the Mandromondromotra River. A comparison of these three parameters in process water and river water shows similar patterns (Figure 11).

This confirms that there is a process water "signature" in the river in response to the discharges. INSTN (2017) noted that river water passing through the village of Mandromondromotra had physical characteristics such as pH that were close to surface waters in the rehabilitation zone on-site suggesting a relation between the two waters.

There are a number of requirements which must be met in order to develop a more confident assessment of the incremental contribution of QMM operations to radionuclide

ID	Date Ech	pH	Cond	Salinity	Oxygène dissous	TDS	Fe	Pb	Ti	Th	Ca	U	TSS
Process Water													
S42	2015-06-02	4.55	207	0.10	4.03	103	0.058	0.009	<0,004	< 0,045	2.037	< 0,642	3.32
S42	2015-08-26	4.87	156	0.07	4.11	78	0.221	< 0,008	<0,004	< 0,045	0.531	< 0,642	9.24
S42	2016-03-15	4.38	65	0.03	4.06	33	0.314	< 0,005	<0,003	< 0,009	0.832	< 0,047	2.20
S42	2016-06-27	3.53	348	0.17	4.39	183	0.228	0.058	<0,003	0.035	25.016	0.798	<0,001
S42	2017-03-16						0.767	0.035	0.004	< 0,009	20.462	0.579	0.40
S42	2017-06-21	4.93	79	0.04	6.6	55	0.089	0.009	<0,003	< 0,009	2.403	< 0,047	2.00
S42	2017-09-13						0.049	0.016	<0,003	< 0,009	3.688	0.391	4
S42	2018-04-11	4.55	129	0.06	7.03	81	0.170	< 0,005	<0,003	< 0,009	1.222	< 0,047	7.2
S43	2015-08-12	4.23	182	0.08	4.38	91	0.053	< 0,008	<0,004	< 0,045	1.223	< 0,642	4.49
S43	2016-01-20	5.92	73	0.03	3.54	36	0.362	< 0,008	<0,004	< 0,045	0.797	< 0,642	3.60
S43	2017-03-16						0.116	< 0,005	<0,003	< 0,009	0.602	0.058	1.60
S43	2017-09-13						0.066	0.009	<0,003	0.032	0.846	0.320	6
S44	2015-08-12	4.46	174	0.08	4.40	87	0.149	< 0,008	<0,004	< 0,045	1.159	< 0,642	5.71
S44	2016-01-20	5.83	68	0.03	3.42	34	0.635	< 0,008	<0,004	< 0,045	0.617	< 0,642	2.40
S44	2017-03-16						0.715	0.014	0.015	< 0,009	5.453	0.184	4.00
S44	2017-09-13						0.153	0.017	<0,003	0.058	0.626	0.325	1
Receiving Environment													
S42	2015-06-04	4.51	227	0.11	4.00	113	0.095	< 0,008	<0,004	< 0,045	2.107	< 0,642	4.47
S42	2015-08-28	4.50	163	0.08	4.32	81	0.196	0.009	0.004	< 0,045	0.791	< 0,642	5.00
S42	2016-03-24	4.90	70	0.03	4.02	35	0.218	< 0,005	0.003	< 0,009	0.612	< 0,047	6.47
S42	2016-06-30	4.60	80	0.04	4.51	41	0.075	< 0,005	<0,003	< 0,009	0.992	< 0,047	5.00
S42	2017-03-22						0.296	0.033	<0,003	< 0,009	4.961	0.261	4.00
S42	2017-06-23	4.60	60	0.03	5.28	42	0.094	< 0,005	<0,003	< 0,009	1.370	< 0,047	3.50
S42	2017-09-20	5.25	139	0.07	6.81	93	0.115	0.012	<0,003	< 0,009	1.171	0.055	5.00
S42	2018-04-18	4.77	84	0.04	5.28	55	0.194	< 0,005	<0,003	< 0,009	1.027	< 0,047	3.60
S43	2015-08-28	4.55	163	0.08	4.12	81	0.190	< 0,008	0.004	< 0,045	0.669	< 0,642	4.35
S43	2016-01-27	4.61	69	0.03	2.61	35	0.310	0.029	0.005	< 0,045	0.830	< 0,642	3.00
S43	2017-03-22						0.234	0.027	<0,003	< 0,009	0.978	0.173	4.67
S43	2017-09-20	5.49	75	0.04	6.95	50	0.097	< 0,005	<0,003	< 0,009	1.577	0.067	2.00
S44	2015-08-28	4.60	162	0.08	3.86	81	0.216	< 0,008	0.005	< 0,045	0.642	< 0,642	3.15
S44	2016-01-27	4.52	65	0.03	2.85	35	0.152	0.022	<0,004	< 0,045	0.826	< 0,642	6.90
S44	2017-03-22						0.342	0.025	0.006	< 0,009	1.061	0.145	6.00
S44	2017-09-20	5.60	67	0.03	6.76	45	0.098	0.013	<0,003	< 0,009	7.021	0.187	1.00

Table 5. Process water versus receiving environment (Mandromondromotra River) water quality on similar sampling days. All units are mg/L except conductivity (µS/cm) and salinity (PSU parts per thousand). *Data provided by QMM.*

concentrations in the Mandromondromotra River.

Process water and river water samples should be taken on the same date and should always be accompanied by supporting data.

Process water and river water samples should be taken on the same day. Supporting data should always accompany measurements of radionuclides, including pH, conductivity, dissolved oxygen, TDS, and TSS. River flow data should continue to be collected at the upstream hydrometric station; however, additional flow data from downstream locations would be very helpful.

Exposure via sediments

Exposure via river or lake sediments is a potential pathway but there are no data for radionuclides in sediments.

Radionuclides which enter the Mandromondromotra River, Ambavarano Lake or Lake Besaroy may not stay in the water column; instead, they may attach to particles in the water and settle on to river or lake sediments. People could then be exposed via direct skin contact or accidental ingestion of sediments (e.g. children playing in shallow water). Radionuclides in sediments can be re-emitted into the water, causing a gradual increase in radioactivity levels (PARC 2013). There are no data for radionuclide concentrations in sediments in the river, nor are there any data for lake sediments.

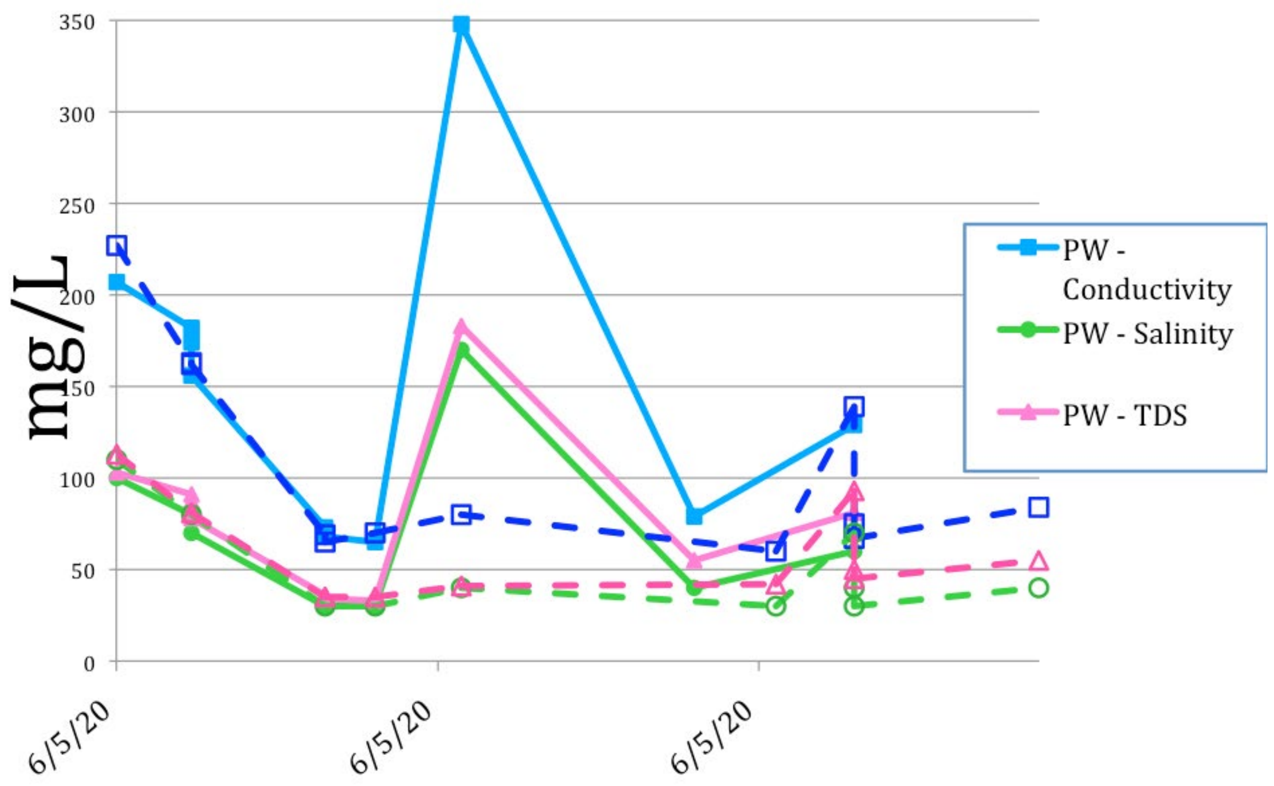


Figure 11. Process water (PW) versus receiving Eenvironment (RE) water quality for three indicators of process water in the Mandromondromotra River. Dotted lines are river samples at stations S42, S43 and S44. *Data provided by QMM.*

Uranium and Thorium in groundwater

Groundwater flow direction from the site is to the south; therefore, uranium and thorium series radionuclides can be expected to migrate via shallow groundwater to Lac Ambavarano.

The INSTN (2017) study of isotopic signatures in groundwater indicated that there are two groundwater systems – shallow and deep. There are direct connections between river water and shallow groundwater and recharge of shallow groundwater is from local precipitation. Deep groundwater recharge is from precipitation over a wider geographic area and there was no connection with local surface waters. The INSTN (2017) report stated that the direction of groundwater flow from the site is to the south. Therefore, uranium and thorium series radionuclides can be expected to migrate via shallow groundwater south to Lake Ambavarano.

QMM groundwater monitoring data for wells located down-gradient from the site are limited, but elevated uranium concentrations were observed (Table 6). Results from 2017 show that two wells located at the southern boundary of the site (wells 46 and 51) had elevated uranium concentrations, although well 46 concentrations were much higher than in well 51. Thorium was detectable in well 46

Water quality data for groundwater wells located downgradient from the QMM site were available for 2017. Two wells were located on the southern edge of the QMM site. One well (Well 5) was located off-site immediately adjacent to the northern shoreline of Lake Ambavarano.

All samples from Well 5 had uranium concentrations substantially above the WHO drinking water quality guideline of 0.03 mg/L. Uranium concentrations in the two on-site wells were also elevated.

The data in Table 6 indicate that groundwater in areas downgradient of QMM should not be used as a drinking water source.

Water from Well 5 was very saline which indicates connections with seawater. It is possible that all shallow groundwater in the area between QMM and Lake Ambavarano is affected by salinity, making the water unsuitable for drinking in any case.

The limited groundwater data available for downgradient wells indicate a need for increased monitoring. Even if most groundwater is too saline to drink, additional understanding of potential groundwater seepage to Lake Ambavarano is required.

Well ID	Sample Date	Conductivity µS/m	Salinity o/oo	Uranium mg/L	Thorium mg/L
5	17/3/2017	3777	1.99	0.85	<0.009
5	16/6/2017	3504	1.85	0.67	<0.009
5	15/9/2017	3803	2.01	1.04	0.415
46	15/9/2017	n/a	n/a	1.40	0.956
51	17/3/2017	149	0.07	0.13	<0.009

Table 6. Groundwater quality in monitoring wells downgradient from the QMM site. *Data supplied by QMM.*

but not well 51. Well 5 adjacent to the shoreline of Lake Ambavarano had uranium concentrations substantially above the WHO drinking water guideline of 0.03 mg/L. Thorium was detectable on one occasion in Well 5.

The data in Table 6 indicate that groundwater in areas downgradient of QMM should not be used as a drinking water source. INSTN (2017) has already stated that because of the connection between the upper water table and surface water, groundwater in the upper water table south of the QMM site is not exploitable for human use.

Water from Well 5 was very saline, showing that there are also connections between seawater entering Lake Ambavarano and shallow groundwater along the shoreline. It is possible that all shallow groundwater in the area between QMM and Lake Ambavarano is affected by salinity, making the water unsuitable for drinking in any case. However, the water may be used for bathing, washing clothes, and washing food.

The results indicate a definite need for increased monitoring of groundwater in the area likely to receive shallow groundwater seepage from the QMM site. Even if most or all groundwater is unsuitable for drinking because of high salinity, monitoring wells along the shoreline of Lake Ambavarano are needed to indicate the potential degree and spatial extent of migration of radionuclides to the lake. The PARC (2013) report on the ingestion pathway also called for routine monitoring of groundwater samples because of the potential migration of radionuclides to Lake Ambavarano.

Accidental soil ingestion

Children typically ingest more soil than adults. People living traditional rural lifestyles have higher soil ingestion.

QMM did not provide soil monitoring data. Soil collected from the QMM site by INSTN contained a wide range of thorium and uranium concentrations, including some very high levels, reflecting the variable presence of monazite sands on site.

Because there were no off-site soil sample results available, radiation dose resulting from people ingesting soil could not be calculated.

Radiation dose from soil ingestion will depend upon age. Children typically ingest more soil than adults because of their tendency to play on the floor indoors and on the ground outdoors and their tendency to place objects in their mouths or place their hands in their mouths (EPA 2017). However, adults also ingest soil or dust particles that adhere to food, cigarettes or their hands. People living traditional rural lifestyles typically have higher soil ingestion (EPA 2017).

QMM did not provide soil monitoring data. Soil samples taken from the QMM site contained 70 to 94,892 Bq/kg thorium activity and <17 to 4,522 Bq/kg uranium activity (INSTN 2017). Chemical concentrations ranged from 17 to 23,390 mg/kg thorium and from <1.4 to 366 mg/kg uranium (INSTN 2017). The high variability of measurements of both radioactivity and concentrations in soil across the site reflected the variability in the surface presence of monazite sands as well as proximity to site features such as rare earth oxide stockpiles.

INSTN (2017) used the site soil data in calculations of dose to workers. However, there were no off-site soil samples; therefore, dose resulting from people living in vicinity of QMM ingesting soil could not be calculated.

Ingestion of food

People living in the Mandena region typically consume 1-2 meals per day. The diet is based on rice, greens, fish and shellfish. Manioc, sweet potato and maize are additional starches. Market garden vegetables, chickens and cattle are primarily for sale.

It can be assumed that much of the food consumed by people living near QMM is obtained locally.

There are no data on radionuclide concentrations in any food items in the Mandena area. Therefore, radiation dose from ingestion of food cannot reliably be estimated.

Information on food consumption was provided by ALT UK, supplemented by information in Community Development Plans for Mandromondromotra (PCD 2003a) and Ampasy Nahampoana (PCD 2003b). People living in the Mandena region typically consume 1-2 meals per day, depending upon access to land and other income-generating activity. Three meals a day is relatively rare. The diet is based on rice, greens, fish (freshwater and ocean fish) and shellfish (crabs, crevettes and lobster). Additional starches in the diet are manioc/cassava, maize and sweet potato. Vegetables include omatoes, cabbage, onions and carrots, but market garden vegetables are grown mostly for sale. Fruit is grown or foraged and includes mango, lychee, papaya, jackfruit, pineapple, corrisol, wild strawberry, and passion fruit. Chickens and cattle are raised to be sold. They may occasionally be consumed during special occasions such as funerals.

It can be assumed that much of the food consumed is obtained locally, with the exception of rice and items such as cooking oil. Some rice is grown in the area; e.g., about 80ha of rice is grown near Mandromondromotra (PCD 2003a).

Growing crops in the Anosy region. *Panos London.*

Previous estimates of radiation dose from ingestion approached the 1 mSv/y dose limit (PARC 2013). Drinking water and consumption of fish were the largest contributors to dose.

The PARC (2013) estimates were based on a one-time only analysis of gross alpha and beta activity in water combined with numerous assumptions which were unsupported by applicable regional data.

However, the proportion of local rice versus rice from other locations has not been studied (at least not to the knowledge of the author).

There are no data on radionuclide concentrations in any food items in the Mandena region. Therefore, radiation dose from ingestion of food cannot reliably be estimated.

Estimates of radiation dose from ingestion approached the 1 mSv/y dose limit in a study by PARC (2013). Highest doses from ingestion were to the 15-year-old age group and the highest contributors to dose were from drinking water and eating fish and beef.

The PARC (2013) dose estimates were based on a one-time only analysis of gross alpha and beta activity in water from the Mandromondromotra River, combined with questionable assumptions of secular equilibrium between parent uranium and thorium and daughter radionuclides such as radium226 and polonium 210. PARC's assumptions regarding types and amounts of food consumed by local people are also questionable; e.g., local people seldom consume beef because any beef produced is used a source of income. Radionuclide concentration factors from water/soil/sediment to food items used by PARC in the calculation of dose greatly influence the final dose estimates. It is not known whether the concentration factors used by PARC are applicable to the geochemical and biological conditions typical of the Anosy region. Because of all of the above issues with respect to the PARC dose estimates, the results are very uncertain.

Total public radiation dose

Estimates of total public radiation dose are high enough to trigger additional investigation. In particular, the contribution to total dose from the inhalation and ingestion pathways requires attention.

According to PARC (2013), long-lived radionuclides in dust are the major contributor in the inhalation pathway and has the highest potential impact on the public outside the QMM site. PARC estimated that ingestion pathway impact is related to the areas of water use by the public. Total annual dose estimates for people living in Mandromondromotra, Andrakaraka and Ampasy Nahampoana were all less than 1 mSv and a hypothetical maximum dose was about 0.9 mSv.

Notwithstanding the uncertainty associated with the PARC (2013) estimates, they are high enough to trigger additional investigation. This review confirmed the potentially significant contribution of the dust inhalation pathway. The contribution of the ingestion and pathways requires particular attention in future monitoring.

Conclusions

Monitoring methods and approach used in monitoring and management of radioactive materials by QMM

Monitoring methods and approaches used by QMM are not sufficient.

The author was not provided with an over-arching monitoring plan with specific goals regarding radioactive releases from QMM and subsequent risk to people living in the area.

There were no formal Data Quality Objectives provided to the author. These DQOs would establish the minimum monitoring effort required to answer the Key Monitoring Questions within a specified margin of error.

No general conclusions can be drawn regarding total incremental radiation dose to the general public because it is unknown whether current dose estimates are, indeed, very conservative or whether in some cases they are not.

With the exception of gamma measurements on site and airborne dust in communities, monitoring does not appear to be conducted according to a standard schedule.

As far as can be determined by the information provided by QMM, the methods and approach used in the monitoring and management of radioactive materials by QMM are not sufficient. There are large gaps in the monitoring program, especially regarding the ingestion pathway. In some cases, the quality of the monitoring data is questionable. The quantity of data is often insufficient for understanding spatial or temporal trends.

To the knowledge of the author, there is no over-arching monitoring plan and no explicit connection between the results of environmental monitoring and management of radiation dose to the public. It is recommended that a standard process be used to develop the QMM monitoring plan such as that provided in US EPA (2006). The process includes the articulation of Key Questions. Key Questions help focus monitoring and should be as specific as possible; e.g. "Are radionuclide concentrations in surface water immediately downstream of effluent discharge points significantly above background levels?".

There were no formal Data Quality Objectives (DQOs) for the monitoring program provided to the author. Data Quality Objectives are highly recommended when monitoring data are relied upon to make decisions about the management of risks. For example, regulatory or industry decisions regarding whether current QMM mitigation measures are effective in maintaining acceptable radionuclide concentrations in the receiving environment must be made with a known degree of confidence in the monitoring information. DQOs would establish the minimum monitoring effort required of QMM in order to answer the Key Questions and confirm QMM's incremental contribution to radiation exposure of local people within a specified, acceptable margin of error. (US EPA 2006).

There can be no general conclusions drawn regarding total incremental radiation dose to the general public because of the lack of sufficient monitoring data, especially for the ingestion pathway. Therefore, it is unknown whether current dose estimates are, indeed, very conservative or whether in some cases they are not.

Monitoring sites are not sampled consistently – especially sites which are in the receiving environment. Supporting information necessary for interpretation of radionuclide data is not always collected.

The IAEA dose limit of 1 mSv/y is to be used as the incremental limit above natural levels observed near QMM. Thus, it is necessary to estimate the incremental dose within an acceptable margin of error.

Based upon available information, conservatively estimated incremental doses due to gamma radiation and exposure via dust inhalation due to QMM operations are less than 1 mSv/y. Incremental contribution to dose via radon exposure is expected to be negligible.

Exposure of specific individuals with a combined exposure to gamma radiation on-site (e.g. for wood collection) plus dust inhalation exposure, plus exposure via ingestion may approach or exceed 1 mSv/y.

No conclusions are possible with respect to incremental doses from ingestion of water, food and soil.

Given the reliance of local people on surface water for drinking water and the use of locally produced foods, the complete lack of monitoring data for radionuclides in water and food is unacceptable.

With the exception of some specific measurements (e.g. gamma measurements on-site and airborne dust in communities), monitoring does not appear to be conducted according to a standardized schedule. Sites which are sampled are not consistent from sample period to sample period.

Supporting information necessary for understanding measured radionuclide concentrations is not always collected. This makes interpretation of results very difficult, since parameters such as pH, salinity, and dissolved oxygen can greatly influence the concentrations of radionuclides. Laboratory analysis results indicate problems with methods; e.g. alpha and beta measurements. Accredited laboratories with recognized quality assurance/quality control programs should be used.

Are levels of naturally occurring radioactive materials resulting from the QMM mine operation within international exposure limits?

The IAEA radiation dose limit of 1 mSv/y is to be used as the incremental limit above natural levels observed near QMM. Thus, it is necessary to estimate the incremental dose within an acceptable margin of error.

Based upon available information, conservatively estimated incremental doses due to gamma radiation and exposure via dust inhalation due to QMM operations are less than 1 mSv/y and incremental doses from radon exposure are negligible. However, the data supporting these preliminary conclusions are limited. Exposure of specific individuals with a combined exposure to gamma radiation on-site (e.g. for wood collection) plus dust inhalation exposure, plus exposure via ingestion may approach or exceed 1 mSv/y. This may be unlikely; however, at present, there are insufficient data to rule out this possibility.

No conclusions are possible with respect to incremental doses from ingestion pathways (water, food, accidental ingestion of soil). There is an almost complete lack of information for this pathway. Given the reliance of local people on surface water for drinking water and the use of locally produced foods, the complete lack of relevant monitoring data is unacceptable.

The INSTN (2017) concludes that in general, the risk of exposure, whether through external exposure to gamma radiation or through ingestion or inhalation, is "minimal" for people who live off-site or who travel through the site. This conclusion is not supported by sufficient data or analysis.

In summary, while the expectation is that incremental doses to the public due to QMM operations will meet international limits, there are insufficient data to come to any confident conclusions in this regard.

It is expected that QMM use "good practices" which have been demonstrated to be effective in reducing radiation exposure at other, relevant mining operations.

The author did not receive information which would indicate that QMM consistently is using good practice with respect to control of gamma, dust, or ingestion pathways. Additional monitoring data are essential in order to inform QMM about where additional measures are required.

It is impossible to draw any conclusions with respect to the degree to which QMM applies good practice because of the absence of comprehensive monitoring data, particularly with respect to the ingestion exposure pathway.

It is imperative that QMM demonstrates that it is managing risk using good practice and in accordance with the 1 mSv/y limit.

Risks from exposure to the chemical hazard of uranium in drinking water must also be managed.

Most of the INSTN (2017) sampling sites were from the QMM site and the report focussed on worker exposure. While this focus is understandable, the general conclusion drawn for members of the public is not consistent with the conservative findings of this report, particularly with respect to ingestion and dust inhalation. Furthermore, the complete lack of any data for the food ingestion pathway prevent general conclusions.

In summary, while the expectation is that incremental doses to the public due to QMM operations will meet international limits, there are insufficient data to come to any confident conclusions in this regard.

Are pathways of radionuclide exposure managed to internationally recognized standards for the protection of local citizens?

It is expected that QMM use "good practices" which have been demonstrated to be effective in reducing radiation exposure at other, relevant mining operations. The author did not receive information which would indicate that QMM consistently is using good practice with respect to control of gamma, dust, or ingestion pathways.

It is impossible to draw any conclusions with respect to the degree to which QMM applies good practice because of the absence of comprehensive monitoring data, particularly with respect to the ingestion exposure pathway. Additional monitoring data are essential in order to inform QMM about where additional mitigation measures are required.

It is imperative that QMM demonstrates that it is managing risk using good practice and in accordance with the 1 mSv/y limit.

Risks from exposure to the chemical hazard of uranium in drinking water must be managed. The uranium concentrations in the Mandromondromotra River are much higher than WHO drinking water guidelines. These elevated concentrations may be due to a combination of natural sources and QMM operations. However, no matter what the source of the uranium, this issue must be addressed in order that the risk associated with uranium toxicity is confirmed and managed.

There is the opportunity for QMM, through the provision of safe drinking water in communities most likely to be affected by elevated uranium concentrations, to not only reduce any radiological risk from drinking water, but also to reduce chemical and microbiological risks associated with the consumption of untreated surface water. The provision of safe drinking water can be done in collaboration with public sector bodies or international agencies such as Water Aid.

Recommendations

The following recommendations are made in order of priority. Priority was determined by the potential significance of each of the exposure pathways, together with the uncertainty associated with each pathway caused by the lack of data.

General recommendations are presented which apply to all monitoring conducted by QMM.

Ingestion pathway

- **Recommendation Ingestion 1**: Water and sediment from surface water bodies (rivers, lakes, ponds) commonly used for drinking water and bathing should be collected in the wet and dry seasons for at least 3 years and analysed for: U238, U234, Th230, Ra226, Th232, Th228, Pb210, Po210, and alpha and beta activity. Supporting data should include pH, conductivity, TSS, TDS, and (if applicable) water flow. Monitoring frequency may be reduced if there is sufficient confidence in and understanding of the data after 3 years.
- **Recommendation Ingestion 2**: Water and sediment from Lake Ambavarano and Lake Besaroy should be collected from several locations, particularly locations near the buffer zone and likely groundwater inflow areas and analysed for U238, U234, Th230, Ra226, Th232, Th228, Pb210, Po210, and alpha and beta activity. Collection and analysis should be conducted at periods of high and low lake levels for 3 years. Monitoring frequency may be reduced if there is sufficient confidence in and understanding of the data after 3 years.
- **Recommendation Ingestion 3**: Uranium in drinking water sources (surface and groundwater) should be monitored twice per month, with additional monitoring, evaluation and oversight by appropriate local and national agencies. If regular exceedance of WHO drinking water guidelines is confirmed, appropriate management measures should be taken in the near future, even if the QMM-related incremental contribution to uranium concentrations remains uncertain. Priority monitoring stations should be located in a series of upstream-to-downstream locations in the Mandromondromotra River, including the area of the weir. NOTE: risks associated with ingestion of untreated surface water are by no means limited to uranium. Much higher risks are likely to be associated with bacteria, viruses, and parasites as well as nitrates/nitrites. Access to safe drinking water appears to be an ongoing issue in the region. QMM could address this issue in its Communities and Social Performance plans, over and above what it has already done with respect to the provision of safe drinking water by providing safe water sources in communities closest to QMM, including Mandromondromotra and Ampasy Nahampoana.
- **Recommendation Ingestion 4**: Dietary surveys should be conducted to confirm the food items, amounts consumed per day, and food sources in communities in the immediate vicinity of the QMM site, including Mandromondromotra and Ampasy Nahampoana. This information can be used to update information contained in the PCD reports for these two communities. Dietary surveys should be updated every 5 years.
- **Recommendation Ingestion 5**: A typical "food basket" of food items commonly eaten by local people should be assembled and analysed for U238, U234, Th230, Ra226, Th232, Th228, Pb210, Po210, and alpha and beta activity. These food items would include (but not necessarily be limited to) rice, manioc, freshwater fish, marine fish, shellfish, greens, and fruits. All food items must be acquired locally. The contents of the "food basket" should be determined through consultation with community members. The collection and analysis should be undertaken as soon as is practical. Further monitoring may be indicated depending upon results of the first round of analysis as well as the results of the updated dietary survey.
- **Recommendation: Ingestion 6**: Soil samples from Mandromondromotra and Ampasy Nahampoana should be collected and analysed for U238, U234, Th230, Ra226, Th232, Th228, Pb210, Po210, and alpha and beta activity. These samples should be taken from villages, fields, pastures and tracks/roadways according to standard soil sampling protocols. Soil samples should be collected in the wet and dry seasons. Further monitoring may be indicated after the first year of sampling depending upon results.

Dust inhalation pathway

- **Recommendation Dust 1**: Continuous PM_{10} sampling upwind and downwind of the operation is required to improve the accuracy of the estimation of doses at downwind locations (Ampasy Nahampoana and Maroamalona) and improved discrimination of background versus QMM-related dust.
- **Recommendation Dust 2**: Collection of periodic medium to large volume samples of airborne dust at upwind and downwind locations (Ampasy Nahampoana and Maroamalona) and submitting them for determination of radionuclide content would greatly improve the accuracy of the determination of public dose via the dust inhalation pathway. Dust sampling would take place during times when the wind was blowing from the direction of QMM. Analyses could include the chemical analysis of U and Th, radionuclide determination by gamma spectroscopy and/or by the use of gross alpha counting). The radionuclide data would be combined with PM_{10} data from the same dates. This monitoring should be conducted for 1-2 years and then evaluated. Monitoring frequency may be reduced if there is sufficient confidence in and understanding of the data after 1-2 years.
- **Recommendation Dust 3**: Dust deposition to crops and surface water bodies used as drinking water sources should be modelled using data from recommendations 1 and 2 above, plus weather data. Predictions should be verified by monitoring.

Gamma exposure pathway

- **Recommendation Gamma 1**: Gamma monitoring should continue at set locations pre and post mining to confirm that gamma exposure rates post rehabilitation are similar to or below pre-mining levels. Supporting information on the presence and depth of mineral sands pre and post-mining should be collected.
- **Recommendation Gamma 2**: The wood collector exposure scenario should be substantiated. This will require well-planned interactions in the communities which include common language explanations of why information on wood collection activities in being sought.
- **Recommendation Gamma 3**: If and when there are additional shipments of rare earth concentrate, time series gamma monitoring should be undertaken at major intersections and other areas where trucks may be stopped to directly measure the potential exposure to a member of the public being at this location. The measurements should be for at least six truck transits and be at the location as close as possible to the truck that a person could reasonably be expected to be for an extended period.

Radon exposure

- **Recommendation Radon1**: Although not expected to be a significant exposure pathway, periodic monitoring of radon concentrations in the community should be undertaken. This can consist of the low-cost use of passive radon monitoring devices (track etch cups) which can be left in a community location for periods of 3 months at a time.
- **Recommendation Radon 2**: Consistent placement of minerals containing radioactivity at sufficient depth is required to produce conditions where post-mining radon exposure is not distinguishable from background. Therefore, operational plans should include explicit requirements for the management and placement of radioactive minerals.

General recommendations

- Identify and retain qualified laboratories which have sufficient and acceptable assurance/quality control programs, proven capability in the analysis of the full range of environmental materials (dust, soils, water, food items) and acceptable turn-around times for analysis.
- The entire monitoring program should be reviewed every 3-5 years and adjusted according to the results (and level of confidence in those results).
- During the period when the search for laboratories is taking place, completely revise the QMM monitoring program.
  - Start with formal establishment of QMM Management Objectives with respect to radioactive emissions from QMM operations
    - E.g. Manage dust generation in order to ensure that radiation dose rates related to inhalation of dust from the mine site meet international requirements for the protection of workers and for the protection of the general public.
    - E.g. Manage discharges to surface water and groundwater from the QMM site in order that incremental dose rates related to ingestion pathways linked to water meet international requirements for the protection of the general public
  - Identify the key uncertainties where information about important aspects controlling radiation doses is imperfect or lacking (see above specific recommendations).
  - Design the monitoring program to meet Data Quality Objectives which explicitly identify the level of confidence required in the data (i.e., acceptable level of error)
  - Include a standard suite of regular monitoring data analyses, including a standard template for reporting to regulatory authorities, QMM management, and the public.
  - Develop monitoring "triggers" which are to be used to trigger management/ mitigation actions (e.g. if dust inhalation doses exceed a trigger level in nearby communities, additional dust control would be implemented)
- Once a credible and comprehensive monitoring program is in place, apply the ALARA principle to establishing monitoring triggers and implementing management practices to control exposure of the general public to radiation.

Recommendations for communication

Effective communication and engagement with local community members is vital. Radiation exposure is a sensitive topic known to create fear and uncertainty in members of the public. Unintended consequences of poor communication about radiation exposure can include people eliminating certain foods from their diet (e.g. locally caught fish) even though monitoring shows that eating fish is safe (and very good for health).

There have already been communications to the public by QMM, public officials, and non-government organizations regarding radiation exposure due to QMM operations. These communications have resulted in some people being concerned or upset, leading to a situation described by Covello and Milligan (2010) where trust, empathy, and clear and accessible communication which answers the questions people have are required.

"A good risk communication programme will ensure that factual information is provided quickly, through an authoritative, accessible source with a clear, understandable message. Research has shown that organisations with strong relationships with key stakeholders will benefit from those relationships…" (Lang et al. 2001).

Marra (1998 in Lang et al. 2001) presents six characteristics of effective communication and management of relationships with communities:

- Trust
- Understanding
- Credibility
- Satisfaction
- Cooperation
- Agreement

The following recommendations apply to QMM's communication and engagement with community members in the Anosy region:

- A communication and engagement plan which aims to achieve the above 6 characteristics
- Retention of risk communication experts with specific experience in communication of radiation risks
- Emphasis on clear and accessible communication which is readily available in a variety of forms
- Training of front-line QMM staff in communication regarding radiation risk, with particular focus on transparency, empathy, and the building of trust.
- Public release of relevant documents such as the INSTN reports

Communication and engagement with respect to the issue of radiation exposure requires more than science. The public's concern and stress are caused, in part by a science-centred approach. Science alone cannot deal with the issues of trust, cooperation and mutual benefit that often underlie the public's lack of faith in information that is solely based on "objective facts" (Swanson et al. 2017). Finding common ground with respect to acceptable risk from QMM-related radiation exposure will require: (1) communication which is not dominated by scientists, engineers and regulators; (2) precautionary approaches when uncertainty is high and cannot be reduced in a timely manner; and, (3) the resolution of value conflict and the assurance of fair treatment of concerns to achieve socially acceptable outcomes (Swanson et al. 2017).

Addendum Rio Tinto/QMM Response to the independent radioactivity review by Swanson

Findings	*Response/Comments*
Monitoring methods and approach are used in monitoring and management of radioactive materials by QMM	
Methods and approach used in the monitoring and management of radioactive materials by QMM is not sufficient.	The programme adopted by QMM has been based on a baseline assessment pre-operational study (web link) and a number of other scientific studies (web link) looking at the potential impacts on the environment and surrounding communities. The programme has been formally approved by the national regulator, and the regulator conducts periodic review missions to assess QMM's performance (web link). QMM is always seeking to improve its monitoring performance and as such is open to considering potential improvements identified in the report. The recommendations of the report will be considered in detail and any alterations in the monitoring requirements will be discussed with the national regulator. QMM acknowledges that the region has a high natural background radiation level that existed prior to the commencement of mining, and that fully understanding the impacts of mining is scientifically challenging.
The author was not provided with an over-arching monitoring plan with specific goals regarding radioactive releases from QMM and subsequent risk to people living in the area.	A pre-mining radiation study conducted in 2001 stated that the most important source of exposure, amongst the public radiation pathways, is the external gamma radiation from soils containing elevated concentrations of thorium. It also stated that measuring of offsite incremental effects from the mining activities will likely be difficult since the variability in baseline radioactivity is large. The radiation baseline completed in 2014 also stated that generally the exposure risk by contamination, ingestion or inhalation, is minimal for people outside the operational areas. The monitoring developed by QMM has therefore been essentially focused on employee exposures. However, as mentioned above, we performed technical and scientific studies which include community exposure in 2001, 2009, 2012, 2014, and 2017 (web link). A new public radiation exposure study is in plan for 2019 as part of a regular assessment process. The scope of work is currently in development based on recommendations of previous studies (the findings of the report will be considered as well) as part of this review. In particular, the identified need for more monitoring data for the assessment of the ingestion pathways will be a priority for additional work. All alterations in the process will have to be approved by the regulator.

Findings	*Response/Comments*
Monitoring methods and approach are used in monitoring and management of radioactive materials by QMM	
There was no formal Data Quality Objectives provided to the author. These DQOS would establish the minimum monitoring effort required to answer the Key Monitoring Questions within margin of error.	As part of regular reviews of public radiation exposure, the basis for the desired outcomes and objectives of the monitoring will be undertaken. This will include revision of the potential exposure pathways (including ingestion pathway).
No general conclusions can be drawn regarding total incremental radiation dose to the general public because it is unknown whether current dose estimates are, indeed, very conservative or whether in some cases they are not.	QMM acknowledges the findings of different reports for the gamma, dust and radon pathways and that they, even using conservative approaches, are unlikely to exceed the relevant public dose limits. QMM also acknowledges the need for more information around the ingestion pathway and this is included in the 2019 review of public radiation exposure.
With the exception of gamma measurements on site and airborne dust in communities, monitoring does not appear to be conducted according to a standard schedule.	As a result of the initial baseline studies and other scientific reports, QMM has focused its environmental monitoring efforts on the gamma and airborne dust pathways. This is based on the belief that these will be the major quantifiable exposure pathways for communities. This monitoring is undertaken with the approval of the national regulator and follows a set monitoring schedule. For the ingestion pathway, a combination of the inherent difficulty in determining the QMM related impacts and the need for specialist radionuclide analysis which is only available in external laboratories, has meant that monitoring of this pathway requires additional work. In 2018, QMM had meetings with a number of international laboratories (South Africa, Australia) seeking to undertake these specialist analyses. Final laboratory arrangements are underway (including transport, customs and quarantine concerns, particularly where animal and plant biota requires analysis).
Monitoring sites are not sampled consistently – especially sites which are in the receiving environment. Supporting information necessary for interpretation of radionuclide data is not always collected.	We will address this issue in future studies to ensure results are directly comparable. This includes the means of sample collection and preservation, the types of physical and chemical data collected during sampling, and the chemical analysis which is performed at the site laboratory.

Findings	Response/Comments
Are levels of naturally occurring radioactive materials resulting from the QMM Mine operation within international limits?	
The IAEA dose limit of 1 mSv/y is to be used as the incremental limit above natural levels observed near QMM. Thus, it is necessary to estimate incremental dose within an acceptable margin error.	The region surrounding QMM is naturally high in radiation (web link to baseline study) and the separation of the QMM incremental impacts is an essential component of verifying compliance with international dose limits. For the gamma, airborne dust and radon pathways, QMM believes that the operation can scientifically show compliance and this is acknowledged in the report. Separation of QMM incremental exposure to the ingestion pathway is scientifically more challenging. Previous scientific reports have modelled this pathway and have identified the uncertainty around this pathway. Although the expectation is that the ingestion pathway is unlikely to exceed the IAEA dose limit, further monitoring is needed to confirm this in a quantifiable form. QMM is currently conducting a 2019 public radiation exposure study.
Based upon available information, conservatively estimated doses due to gamma radiation and exposure via dust inhalation due to QMM operations are less than 1mSv/y. Incremental contribution to dose via radon exposure is expected to be negligible.	This is the information that QMM has been using to inform its monitoring program, based on conclusions from 2001, 2014 and 2017 reports. For the gamma, airborne dust and radon pathways, QMM believes that the operation can scientifically show compliance and this is acknowledged in the report.
Exposure of specific individuals with a combined exposure to gamma radiation on-site (e.g. for wood collection) plus dust inhalation exposure, plus exposure via ingestion may approach or exceed 1 mSv/y	For the gamma, airborne dust and radon pathways, QMM believes that the operation can scientifically show compliance and this is acknowledged in the report. Separation of the QMM incremental exposure to the ingestion pathway is scientifically more challenging. Previous scientific reports have modelled this pathway and have identified the uncertainty around this pathway. Although the expectation is that the ingestion pathway is unlikely to exceed the dose limit, further monitoring is needed to confirm this in a quantifiable form. QMM is currently conducting a 2019 public radiation exposure study.

Findings	Response/Comments
Are levels of naturally occurring radioactive materials resulting from the QMM Mine operation within international limits?	
No conclusions are possible with respect to incremental doses from ingestion of water, food and soil.	Separation of the QMM incremental exposure to the ingestion pathway is scientifically more challenging. Previous scientific reports have modelled this pathway and have identified the uncertainty around this pathway. Although the expectation is that the ingestion pathway is unlikely to exceed the dose limit, further monitoring is needed to confirm this in a quantifiable form. QMM is currently planning a 2019 public radiation exposure study.
Given the reliance of local people on surface water for drinking water and the use of locally produced foods, the complete lack of monitoring data in water and food is unacceptable.	Current environmental monitoring has focused on the exposure pathways where the incremental contribution from QMM can quantitatively be measured. QMM acknowledges that there is historically missing information for the ingestion pathway. Given that this approach is approved by the national regulator and the expectation is that the ingestion pathway is unlikely to exceed the dose limit, QMM does not agree with the term "unacceptable". Rather QMM believes that a more constructive and appropriate finding would be: *Given the reliance of local people on surface water for drinking water and the use of locally produced foods, it is recommended that QMM assess the need to gather more data with regards to community exposure.*
In summary while the expectation is that incremental doses to the public due to QMM operations will meet international limits, there are insufficient data to come to any confident conclusions in this regards.	QMM, based on the baseline study and subsequent scientific reports and monitoring, agrees with this finding. The aim of the 2019 study will be to close these gaps and improve understanding. The end result will be to quantifiably verify QMM's compliance with international limits for all potential exposure pathways.

Findings	*Response/Comments*
Are pathways of radionuclide exposure managed to internationally recognized standards for the protection of local citizens?	
It is expected that QMM use "good practices" which have been demonstrated to be effective in reducing radiation exposure at other, relevant mining operations.	QMM currently operates the mine in a similar manner to other mineral sands operations globally. Continual review of the operational methods is undertaken to ensure it remains abreast of good practices in use internationally. This is part of QMM's commitment to continuous improvement for environmental performance.
The author did not receive information which would indicate that QMM consistently is using good practices with respect to control of gamma, dust, or ingestion pathways. Additional monitoring data are essential in order to inform QMM about where additional measures are required.	QMM has conducted regular off-site radiation monitoring since the start of mining. The frequency and scope of these studies were determined by the limited exposure (according to the studies). Potential improvements have been identified and QMM will address this in future monitoring to ensure that any additional risk is identified and controlled. Aspects that relate to the naturally occurring radiation will be addressed in partnership with the regulator.
It is impossible to draw any conclusions with respect to the degree to which QMM applies good practice because of the absence of comprehensive monitoring data, particularly with respect to the ingestion exposure pathway.	
It is imperative that QMM demonstrates that it is managing risk using good practice and in accordance with the 1 mSv/y limit.	

Findings	*Response/Comments*
Are pathways of radionuclide exposure managed to internationally recognized standards for the protection of local citizens?	
Risks from exposure to the chemical hazard of uranium in drinking water must also be managed. The uranium concentration in the MMM river are much higher than WHO drinking water guidelines. These elevated concentrations may be due to a combination of natural sources and QMM operations. However, no matter what the source of the uranium is this issue must be addressed in order that the risk associated with uranium toxicity is confirmed and managed.	As was determined before the commencement of mining (web link baseline study) the area surrounding QMM has naturally elevated levels of radiation. This is a result of the surrounding geological conditions and this leads to naturally enhanced levels of uranium in drinking water. This is not a QMM related impact and is an aspect of the water used by local communities before the commencement of construction or operations at QMM. Due to the vital need for access to water for local communities, care must be taken when comparing to conservative guidelines such as the WHO Drinking Water Guidelines. In fact, in the WHO Drinking Water Guidelines, it specifically states : *Where supplies exceed 30 µg/l, it is important that precipitate action be avoided. Consideration should first be given to exposure from all sources and the availability of alternative safe sources.*

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Appendix 1 Water quality by receiving environment site

Site	Sample date	pH	Conduct -ivity µSm/cm	Diss Oxygen mg/L	Salinity PSU o/oo	TDS Mg/L	Fe mg/L	Pb mg/L	Ti mg/L	Th mg/L	U mg/L	TSS mg/L	Flow
WS0501	6/4/2015	5.46	140	5.18	0.07	69	0.234	0.010	<0,004	< 0,045	< 0,642	1.60	1.64
WS0501	8/20/2015	4.74	162	3.65	0.08	81	0.444	0.019	0.009	< 0,045	< 0,642	4.63	n/a
WS0501	10/22/2015	5.29	164	3.84	0.08	82	0.710	< 0,008	<0,004	< 0,045	< 0,642	1.00	0.61
WS0501	3/23/2016	4.63	67	3.38	0.03	34	0.067	0.011	<0,003	< 0,009	< 0,047	15.40	0.45
WS0501	3/23/2017				0.03		0.307	< 0,005	0.013	< 0,009	0.136	2.67	2.49
WS0501	6/22/2017				0.05		0.091	< 0,005	<0,003	< 0,009	< 0,047	0.50	0.37
WS0501	9/21/2017	6.48	55	7.05	0.04	37	0.206	< 0,005	<0,003	< 0,009	< 0,047	2.00	n/a
WS0501	4/17/2018	6.08	61	7.88	0.03	41	0.292	< 0,005	<0,003	< 0,009	< 0,047	2.00	n/a
S44	8/28/2015	4.60	162	3.86	0.08	81	0.216	< 0,008	0.005	< 0,045	< 0,642	3.15	
S44	1/27/2016	4.52	65	2.85	0.03	35	0.152	0.022	<0,004	< 0,045	< 0,642	6.90	
S44	3/24/2016	4.76	60	3.90	0.03	30	0.082	< 0,005	<0,003	< 0,009	0.056	3.87	
S44	6/30/2016	4.32	62	3.60	0.03	32	0.128	< 0,005	<0,003	< 0,009	< 0,047	<0,001	
S44	7/6/2016	4.17	72	3.79	0.03	36	0.322	0.089	0.021	0.062	0.422	2.90	
S44	3/22/2017						0.342	0.025	0.006	< 0,009	0.145	6.00	
S44	6/23/2017	5.26	52	5.36	0.02	36	0.146	< 0,005	<0,003	< 0,009	< 0,047	2.00	
S44	9/20/2017	5.60	67	6.76	0.03	45	0.098	0.013	<0,003	< 0,009	0.187	1.00	
S44	4/18/2018	5.54	56	5.79	0.02	36	0.436	< 0,005	<0,003	< 0,009	< 0,047	1.20	
S43	8/28/2015	4.55	163	4.12	0.08	81	0.190	< 0,008	0.004	< 0,045	< 0,642	4.35	
S43	1/27/2016	4.61	69	2.61	0.03	35	0.310	0.029	0.005	< 0,045	< 0,642	3.00	
S43	3/24/2016	4.83	62	3.86	0.03	31	0.152	0.012	0.003	< 0,009	0.053	3.87	
S43	6/30/2016	3.96	68	3.62	0.03	35	0.031	< 0,005	<0,003	< 0,009	< 0,047	2.00	
S43	7/6/2016	4.06	74	4.15	0.03	37	0.210	0.088	0.020	0.075	0.386	4.90	
S43	3/22/2017						0.234	0.027	<0,003	< 0,009	0.173	4.67	
S43	6/23/2017	4.59	59	5.42	0.03	41	0.065	0.008	<0,003	< 0,009	< 0,047	2.50	
S43	9/20/2017	5.49	75	6.95	0.04	50	0.097	< 0,005	<0,003	< 0,009	0.067	2.00	
S43	4/18/2018	5.36	60	5.52	0.03	39	0.216	< 0,005	<0,003	< 0,009	< 0,047	0.40	
S42	6/4/2015	4.51	227	4.00	0.11	113	0.095	< 0,008	<0,004	< 0,045	< 0,642	4.47	
S42	8/28/2015	4.50	163	4.32	0.08	81	0.196	0.009	0.004	< 0,045	< 0,642	5.00	

Site	Sample date	pH	Conduc-tivity µSm/cm	Diss Oxygen mg/L	Salinity PSU o/oo	TDS Mg/L	Fe mg/L	Pb mg/L	Ti mg/L	Th mg/L	U mg/L	TSS mg/L	Flow
S42	3/24/2016	4.90	70	4.02	0.03	35	0.218	< 0,005	0.003	< 0,009	< 0,047	6.47	
S42	6/30/2016	4.60	80	4.51	0.04	41	0.075	< 0,005	<0,003	< 0,009	< 0,047	5.00	
S42	7/6/2016	4.08	74	4.51	0.03	37	0.257	0.106	0.020	0.041	0.419	6.80	
S42	3/22/2017						0.296	0.033	<0,003	< 0,009	0.261	4.00	
S42	6/23/2017	4.60	60	5.28	0.03	42	0.094	< 0,005	<0,003	< 0,009	< 0,047	3.50	
S42	9/20/2017	5.25	139	6.81	0.07	93	0.115	0.012	<0,003	< 0,009	0.055	5.00	
S42	4/18/2018	4.77	84	5.28	0.04	55	0.194	< 0,005	<0,003	< 0,009	< 0,047	3.60	
WS0502	6/4/2015	4.49	210	3.83	0.10	105	0.050	0.009	<0,004	< 0,045	< 0,642	5.27	
WS0502	6/23/2017	4.57	97	5.91	0.05	67	0.062	< 0,005	<0,003	< 0,009	0.067	1.50	
WS0502	4/18/2018	4.8	89	6.01	0.04	58	0.055	< 0,005	<0,003	< 0,009	< 0,047	3.20	
WS0701	6/4/2015	6.15	1138	4.92	0.57	569	0.149	0.043	<0,004	< 0,045	< 0,642	2.07	
WS0701	6/23/2017	8.45	3161	6.80	1.72	2131	0.184	0.063	<0,003	< 0,009	0.319	3.50	
WS0701	9/21/2017	6.86	2691	7.77	1.43	1797	0.130	0.111	0.003	< 0,009	0.559	13.00	
WS0701	4/18/2018	6.75	6898	6.94	3.75	4.459	0.107	0.277	0.013	0.141	1.073	3.20	
WS0602	6/23/2017	7.23	144	6.67	0.07	98	0.155	< 0,005	<0,003	< 0,009	< 0,047	5.00	
WS0602	9/21/2017	6.80	1864	7.77	0.98	1256	0.110	0.075	<0,003	0.068	0.403	5.00	
WS0602	4/18/2018	6.31	89	7.16	0.04	58	0.251	< 0,005	<0,003	< 0,009	< 0,047	4.40	
WS0702	3/23/2017											2.67	
WS0702	6/23/2017						0.172	0.107	<0,003	< 0,009	0.542	3.50	
WS0702	9/21/2017	6.67	7230	7.67	4.12	4853	0.129	0.224	0.011	< 0,009	1.132	13.00	
WS0702	4/18/2018	7.03	12903	6.69	7.39	8.373	0.085	0.398	0.020	0.220	1.574	3.20	
WS0603	3/22/2017											2.00	
WS0603	3/23/2017											6.00	
WS0603	4/18/2018	6.7	89	7.85	0.04	57	0.412	< 0,005	<0,003	< 0,009	< 0,047	5.20	
WS0401	10/22/2015	6.45	1650	5.01	0.83	825	0.059	0.060	<0,004	0.069	< 0,642	1.00	
WS0401	3/22/2017											2.67	
WS0401	4/18/2018	6.46	72	7.45	0.03	47	0.329	< 0,005	<0,003	< 0,009	< 0,047	4.80	
WS0301	10/22/2015	6.09	898	4.96	0.44	449	0.098	0.040	<0,004	< 0,045	< 0,642	1.00	
WS0301	3/23/2017											2.67	
WS0301	4/18/2018	6.33	73	6.79	0.03	47	0.433	< 0,005	<0,003	< 0,009	< 0,047	4.80	
WS0203	3/23/2017											5.33	
WS0203	4/18/2018	6.76	62	8.28	0.03	4	0.356	< 0,005	<0,003	< 0,009	< 0,047	3.20	