Human Health and Environmental Risk Assessment for Closure Planning of the Argyle Diamond Mine Pit Lake

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Abstract

Argyle Diamond Mine (Argyle) is a large open cut and underground mine in Northern Australia preparing for closure with the pit as a water management structure. Water quality will be pH 8-9, with solute concentrations increasing through evaporative concentration. However, poor pit lake habitat quality and restricted access to humans and stock limits exposure to potential receptors.

A risk assessment based on consequence and likelihood, found all risks from the pit lake water to be very low. A risk assessment offers a useful approach to assessing pit lake risk when specific water quality criteria alone may not be appropriate.

Keywords: Mine closure, pit lake, environmental risk assessment, human health, water quality, acid and metalliferous drainage

Introduction

Mine pit lakes are a common feature of open cut mine closures extending below local groundwater levels (Castendyk and Eary 2009). With large water volumes which often contain waters degraded by elevated contaminants of potential concern (COPC), pit lakes can represent a relevant socio-environmental risk at mine closure (McCullough and Lund 2006) and may represent the highest environmental risk closure landform for many mines (Doupé and Lymbery 2005)

Determining acceptable long-term pit lake water quality is a substantial challenge for closure planning because the final lake may not resemble or have intended end use values of a natural lake. Furthermore, some pit lakes take decades to fill with water quality improving or degrading over time, and yet relinquishment decisions need to be made within a much shorter post-closure monitoring period.

Study site

The Argyle Diamond Mine (Argyle) is a large open cut and underground lamproite pipe mine in Northern Australia which is preparing for closure in late 2020. Argyle is located on a State Agreement Mining Lease in the East Kimberley region of Western Australia. It is situated in the headwaters of Smoke and Limestone Creeks, which ultimately drain into Lake Argyle, approximately 35 km to the north-east.

The climate is monsoonal, with potential cyclones and heavy rains during the wet season from November to April, high evaporation rates during dry season months and warm temperatures all year round. The Argyle project area is on a pastoral lease with extensive grazing including access to natural waterways. Long term grazing has led to cattle damage of native vegetation and habitats through direct grazing and associated effects including soil erosion and compaction and weed invasion. These activities are expected to have impacted the suitability and quality of habitats for many native terrestrial vertebrate fauna in particular.

Open pit mining of the Argyle Kimberlite 1 (AK1) pit void commenced in 1985 and was completed in 2013. During open pit mining, waste material was hauled to the waste rock landforms (WRLs), while ore was taken to the processing plant for diamond recovery. The WRLs contain some geological units with the potential to generate acid and metalliferous drainage (AMD) and seepage from the southern WRL has been managed as part of operations since 1999.

The resulting pit void has a maximum depth of approximately 600 m with breakthrough to the underlying block cave in the southern bowl. Following cessation of the underground operations and associated dewatering, the block cave will flood and water will daylight in the base of the open pit within one year. A key closure domain identified as potentially presenting risk at closure was the pit void and associated lake which will form following cessation of dewatering activities.

AK1 Pit lake

A conceptual hydrogeological model was constructed to represent the AK1 Pit Lake including major inflows (predominantly groundwater) and outflows (predominantly evaporation) that form the basis of the design for the water balance model. Pit lake modelling was then undertaken to understand the water levels and water quality that will result in the open pit void for up to 300 y after dewatering and mining ceases (Aquastrat 2020).

Initial modelling predicted that the pit lake would be a terminal evaporative sink. This water balance provided an opportunity for a sustainable and long-term water management approach utilising the pit lake to contain AMD seepage and other mine waters not suitable for release to the environment. As part of Argyle's closure water management strategy, two WRL seepage locations will be directed into the open pit during the dry season and initial drain down of AK1 Tailings Storage Facility (TSF) water will be pumped to the underground leading to the pit lake (fig 1).

Major inflows into the pit lake are from good quality groundwater that mixes with TSF seepage water over the first five years until seepage is less than 15 L/s when discharge to the pit ceases. Groundwater and runoff then dominate pit lake inflows, with only a minor contribution from WRL seepage. Evaporation is the only loss in the (sensu McCullough et al. 2013) pit lake water balance.

Numerical water balance modelling under a median climate regime, predicted a median equilibrium (steady state) pit lake water level with approximately 18 m freeboard below the lowest discharge level, which is the invert point of a waste rock landform seep that will be connected to the underground portal at closure. Groundwater modelling indicated that seepage of the pit lake into regional groundwater, even saline density-driven, was highly unlikely due to low hydrogeological transmissivity around the pit void and the terminal nature of the lake being down-gradient of regional aquifers. Pit lake water balance modelling also indicated that pit lake discharge of water to nearby Limestone Creek was highly unlikely and would only be initiated during extreme storm events concomitantly resulting in extremely high creek flow events.

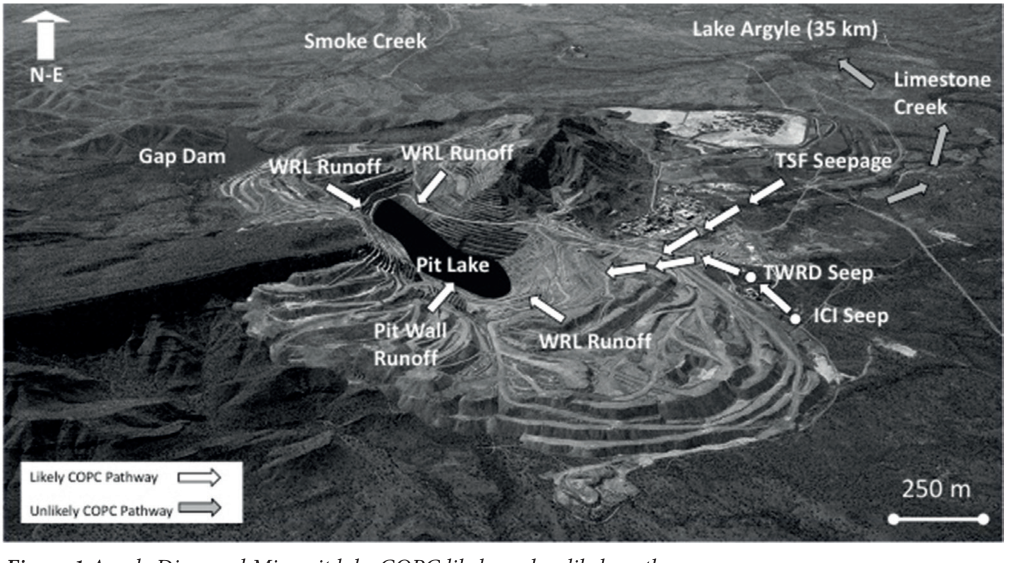

Figure 1 *Argyle Diamond Mine pit lake COPC likely and unlikely pathways.*

Methodology

A Human Health and Environmental Risk Assessment (HHERA) was developed to refine closure planning of the AK1 open cut void and the consequent development of a pit lake therein. Given the interaction of the pit lake with other closure landforms and the need for mine closure planning to be holistic across the project area and greater region, an integrated landform approach was taken across the whole project area. A key objective of this environmental risk assessment was to meet requirements of the Western Australian (DMP & EPA 2015) Guidelines for Preparing Mine Closure Plans for closure risk assessment for pit lakes. The key aspect addressed was consideration of risk to human, native wildlife and stock health primarily from the AK1 pit lake, 150 and 300 years following mine closure (fig 2, left).

Pit lake water balance and quality modelling helped understand COPC sources, trends and concentrations at 300 years following closure. A conceptual Source-Pathway-Receptor (SPR) model linked pit lake water balance and water quality models with fauna and flora studies, and surface and groundwater conceptual models to understand potential COPC transport mechanisms to these receptors. A risk matrix assessed the worst consequence and likelihood of exposure to pit lake water across both spatial and temporal scale following closure planning. Where required, further closure management was used to reduce inherent risks to acceptably low residual levels.

Following international guidance for pit lake closure planning and mine closure risk assessment e.g., APEC (2018); Vandenberg and McCullough (2017), an SPR conceptual modelling approach was undertaken (fig 2, right). As per Commonwealth guidance of (DIIS 2016) *Preventing Acid and Metalliferous Drainage*, all of the SPR model needs to be complete for a risk to be tangible. A workshop of experts and senior staff familiar with Argyle closure planning determined the contaminant hazard sources, pathways and receptors. Risk magnitude was then ascribed in the same workshop from likelihood of a defined consequence occurring. Risk magnitude was further refined from spatio and temporal distribution of the consequence occurring.

The primary intent of the HHERA was to identify:

- the environmental values and their associated human, stock and ecological receptors that need to be protected;
- any further closure management actions planned or required to further mitigate risk; and
- the residual risk to these components, including potential source, pathway and receptors.

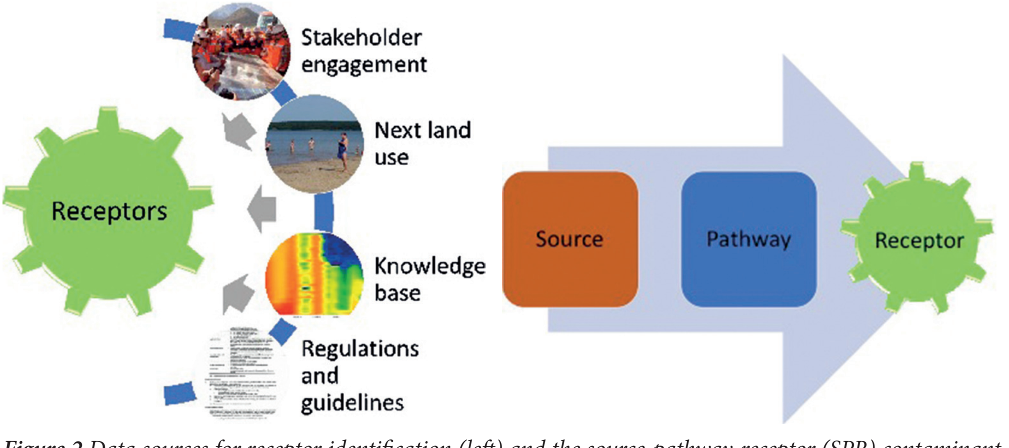

Figure 2 *Data sources for receptor identification (left) and the source-pathway-receptor (SPR) contaminant transfer model (right).*

Risk Assessment

Receptor values

The region surrounding the Argyle lease has agriculture values and is extensively grazed by beef cattle, but also supports ecological and cultural values associated with the land and vegetation, natural waterways and aquatic, terrestrial and bird life. Although the region's environmental values are degraded by grazing, bird life and aquatic ecological functionality and diversity is still high with some conservation listed species likely to be present after closure. Traditional Owners and other people will use the land surrounding the pit lake and therefore may also come into contact with COPC following closure.

Aquatic ecosystem ecotoxicological threshold data was based upon generic guideline values (GVs) relevant to the region (ANZG 2018), or site-specific guideline values (SSGVs) (Warne et al. 2015) developed for Argyle in accordance with Batley et al. (2003). For non-biomagnifying contaminants, SSGV 'Threshold' values were adopted where available.

Drinking water is not the only source of contaminants for terrestrial and semi-terrestrial wildlife. Other sources, typically food, are likely to be more relevant for wildlife, and also need to be considered. Terrestrial and semi-terrestrial wildlife linked to aquatic food chains are at risk from a suite of water-borne contaminants that can bioaccumulate in organisms and biomagnify along the food chain. In these instances, guideline values that protect aquatic species from waterborne contaminants may not convey safety for species that consume aquatic organisms (ANZG 2018). Water quality trigger values of 99% ecosystem protection were chosen for bioaccumulating/bioconcentrating elements risk. This risk was determined through review of ANZG (2018) COPC factsheets and also the primary literature (El-Shenawy et al. 2016).

Water quality guidelines for the protection of aquatic ecosystems were used to screen COPC concentrations. The outcomes of this screening process informed protection of aquatic biota as environmental receptors, but not of waterfowl that might prey upon them as food items. Waterfowl as receptors were screened through considering indirect COPC contact via ingestion of AK1 Pit Lake aquatic biota. These biota may have body burdens of COPC through bioaccumulation and biomagnification (ANZG 2018) and direct contact and ingestion of AK1 Pit Lake COPC as water and sediments. Australasian (ANZECC/ARMCANZ 2000) livestock drinking guidelines were used to screen drinking water specifically for beef cattle. These were complemented by South African livestock drinking guidelines (DWAF 1996). Recreational water quality was determined by a conservative approach of assuming primary contact with ingestion and applying drinking water guidelines (NHMRC/NRMMC 2018).

Results

The HHERA indicated that the AK1 pit lake will present a very low and localized risk (tab. 1). Long-term pit lake water quality would be weakly alkaline but gradually increase in salinity and metalliferous concentrations due to evaporative concentration of tailings and waste rock seepage input and catchment runoff. However, the pit lake is not expected to have similar end use values of natural water bodies for ecological or cultural uses, but instead its primary land use value will be as a water management structure. Furthermore, poor habitat quality meant the lake would not be considered an "attractive nuisance" and restricted access to humans and stock the exposure pathways to potential receptors was limited. The lake is also expected to be hydraulically terminal with very low likelihood of discharge during extreme precipitation events.

Low likelihood high rainfall events would commensurately dilute COPCs in AK1 Pit Lake discharge to relatively low concentrations and resulting low environmental consequence. Pit lake discharge was therefore also very low risk to downstream water quality. However, due to the terminal evapoconcentrating nature of the pit lake water quality, risks from poor quality pit lake water are likely to exist for a very long time. Predominant contaminant pathways were direct contact and drinking of pit lake water and biomagnification from aquatic biota of the pit lake. Transport pathway effectiveness was reduced through a number of factors which are expected to limit biotic

***Table 1** Summary of potential AK1 pit lake receptors, pathway and residual risk rating.*

Receptor	Pathway	Residual risk rating
Terrestrial native wildlife	May attempt to forage.	Very low
	Direct consumption of pit lake aquatic biota, especially flying invertebrates with aquatic life stages and amphibians.	Very low
Bats	Native terrestrial animal water consumption low but may still be attracted.	Very low
	Direct consumption of pit lake aquatic biota, especially flying invertebrates with aquatic life stages and amphibians.	Very low
Regional birdlife	May use habitat for predator avoidance. May attempt to forage.	Very low
	Direct consumption of pit lake aquatic biota, especially flying invertebrates with aquatic life stages and amphibians.	Very low
Livestock	Direct consumption of pit lake water.	Very low
Humans	People may be attracted to the pit lake for swimming.	Very low

processes including: limited opportunities for organic matter and nutrients to accumulate in the lake, lack of vegetated littoral margins and riparian zones, low nutrient status and water quality issues associated with elevated concentrations of some metals, including salinity.

Waterfowl, ghost bats, terrestrial native wildlife and humans were identified as the most sensitive receptors; particularly through potential bioaccumulation and biomagnification via a food chain with foundations in pit lake aquatic biota. However, both waterfowl and bats were not expected to spend substantial time foraging the low food biomass of the pit lake ecosystem due to steep shaded sides and deep waters, little vegetation and low nutrient and productivity status.

The environmental risk of biomagnification through bushtucker hunting and fishing by Indigenous land users intentionally within the pit lake was not considered of high consequence, and the frequency low and thus of low risk. Risk to both waterfowl and human ingestion of pit lake biota was also inherently assessed as low, due to the presence of nearby Gap Dam as a more productive and diverse water body and therefore preferred alternative aquatic habitat for native wildlife and as a hunting/fishing resource.

Stock risk was considered very low due to very limited access to the steep sided pit lake void and poor climbing ability of cattle as well as poor grazing habitat within the pit lake catchment. Stock risk was further mitigated by the presence of alternative stock watering points and preferential grazing outside of the pit void. Although COPC concentrations will be elevated with water quality deteriorating over many years, COPCs will not be at concentrations to impact human health e.g. from skin absorption or accidental ingestion of water during swimming.

Conclusions

In conclusion, the Argyle pit lake water quality is likely to present a minor risk to key environmental receptors of birdlife, terrestrial wildlife bats, livestock and human ingestion in particular. Furthermore, closure planning risk mitigation activities are expected to reduce these risks to very low and acceptable levels. Consequently, risk to wildlife and humans from the presence of the AK1 pit lake containing elevated solute concentrations is not of material significance. Although environmental risks are low, various closure features and management activities may further reduce inherent risk. These management activities included:

- construction of an engineered abandonment bund to reduce human and animal access;
- deliberate avoidance of revegetation and other habitat creation measures within the pit void catchment; and,
- Stakeholder engagement and pit void perimeter warning signage was also expected to further mitigate human health risk.

Rather than a simple check box exercise, pit lake closure planning should be based upon risk assessments to potential receptors of wildlife, humans and other relevant end uses, including local community health risk. In line with contemporary pit lake closure planning advice, we recommend a HHERA (or equivalent) be undertaken for all mine closures where pit lakes present as a key final landform, but that explicit consideration is given to developing clear pit lake and associated catchment end use values and closure objectives with stakeholders prior.

Post-closure pit lake water level and quality monitoring data are recommended to validate and calibrate pit lake modelling that underpins risk assessments. These data provided validation and associated assurance that the pit lake is on predicted trajectories for both water balance and quality, whereby there can be confidence that closure risk is appropriately determined for relinquishment and into the future.

Further, pit lake closure planning should be undertaken with a holistic approach that considers risk and interactions between other landforms. These synergisms and efficiencies will frequently realize better pit lake, and overall, mine closure outcomes (Vandenberg and McCullough 2017).

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