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Application of a vulnerability assessment framework to assess environmental risks of solutes at Ranger Mine, Northern Territory, Australia

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Abstract

Energy Resources of Australia Ltd (ERA) is planning the closure of Ranger Mine. An ecological vulnerability assessment framework (VAF) was applied to water quality modelling results to understand the potential effects of magnesium (Mg) in mine affected waters on aquatic ecosystem values within the mine site. The VAF assessed three elements: (i) understanding contaminant exposure, which was based on water modelling and species/community (ecological component) distributions; (ii) sensitivity of the ecological component to the contaminant, as determined from laboratory ecotoxicity experiments and field-based studies (monitoring, mesocosm experiments), and (iii) the recovery capacity of the ecological component, based on a review of the traits of ecological components. The VAF was applied to four waterbodies – two billabongs and two seasonal creek sites. The VAF identified that at three of the waterbodies, only the most sensitive algae and invertebrates were predicted to be intermittently affected by Mg, but would recover during periods of low Mg. All other ecological components (including other invertebrates, plants, fish and other vertebrates) at these three waterbodies had low vulnerability. Results for the fourth water body indicated that most ecological components were potentially vulnerable to predicted Mg concentrations. The assessment findings for the fourth water body had low confidence due to knowledge gaps regarding the sensitivity of some ecological components, especially aquatic plants on which most species depend. The VAF findings were applied in conjunction with an environmental risk assessment to identify where closure strategies for contaminant management needed review and inform decisions on whether impacts from those strategies would be as low as reasonably achievable (ALARA).

Keywords: *aquatic ecosystems, water quality, risk*

1 Introduction

1.1 Background and aims

Energy Resources of Australia Ltd (ERA) is planning the closure of Ranger Mine which is surrounded by, but not part of, the culturally and ecologically important Kakadu National Park in the Northern Territory. Water at and leaving the mine site following closure has the potential to impact community values on and off the Ranger Project Area (RPA) if not properly managed. Waters from the closed mine must support protection of the people, ecosystem (biodiversity and ecological processes) and World Heritage and Ramsar values of the surrounds; and impacts on the RPA are as low as reasonably achievable (ALARA). Thus, closure planning requires an understanding of the potential impacts of solutes, such as magnesium (Mg), discharged from the site via groundwater and surface water pathways.

ERA conducts water quality modelling to predict the concentration of Mg and other contaminants in the receiving environments post-closure for the baseline and, if needed, alternative closure strategies. Several types of assessment are conducted to understand the environmental risks associated with the predicted water quality, including risk and vulnerability assessments to understand if impacts are ALARA or if the closure strategy needs to be adjusted (Iles 2019). In the instance that modelling predicts the 99% species protection Water Quality Guideline Value (99% WQGV; Turner et al. 2015) is exceeded, it is important to understand:

- Which ecological components (species, communities, ecosystems) will be exposed?
- Which ecological components are sensitive to Mg?
- If ecological components are likely to be affected, what is their capacity to recover?

A vulnerability assessment framework (VAF) was developed by BMT (2021) to understand the sensitivity and adaptive capacity of the ecological components that underpin the environmental and cultural values (CVs) of the RPA (see Figure 1), and the factors that affect their potential exposure to mine-associated solutes.

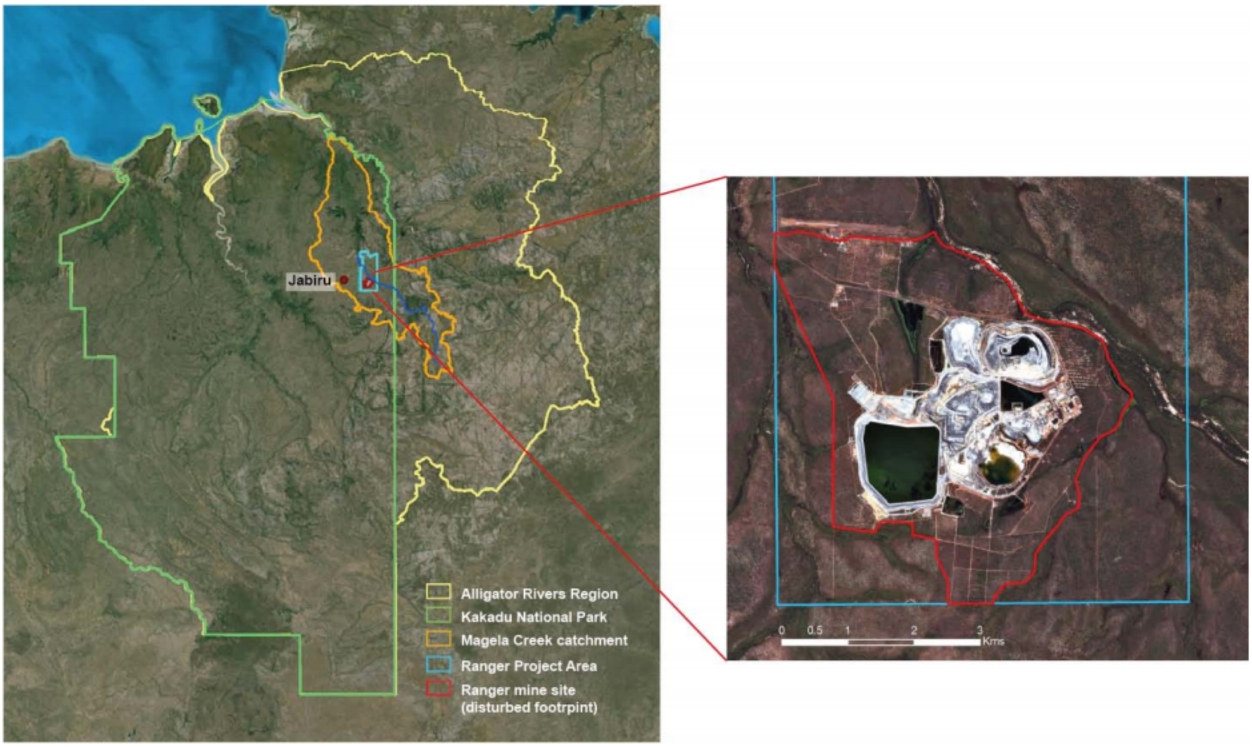

Figure 1 Ranger Project Area and mine site (Bartolo et al. 2013)

Richardson et al. (2019) and BMT (2021) provided an initial vulnerability screening assessment for ecological components known or likely to occur in freshwater lowland environments of the Magela Creek catchment. In lieu of modelling to define Mg exposure, Richardson et al. (2019) and BMT (2021) conservatively assumed that all ecological components would be exposed to Mg concentrations greater than the 99% WQGV.

Once model predictions of Mg concentrations for the baseline closure strategy were available an assessment, Iles & Rissik (2021) identified locations where the frequency or intensity of Mg concentrations above the 99% WQGV posed a medium or higher risk to the aquatic ecosystem. Targeted vulnerability assessments were required for those locations to understand the potential impacts of Mg on aquatic ecosystems in the RPA, to inform decisions on whether impacts are ALARA or if Mg concentrations need to be reduced through additional or alternative contaminant management strategies.

This paper presents the preliminary findings of the targeted vulnerability assessment for medium or higher risk water bodies under the baseline closure strategy. The targeted vulnerability assessment has the following objectives:

1. Identify subject waterbodies.

2. Develop a refined list of ecological components that are specific to the subject waterbodies.
3. Define the exposure context based on a comparison of Mg concentrations predicted in the closure phase and measured in the operational phase.
4. Using a refined VAF decision tree and new information derived from an expert elicitation workshop, assess vulnerability of ecological components at subject waterbodies based on the above.

1.2 Basis for vulnerability assessment

To understand vulnerabilities, there is a need to consider not only sensitivity at the individual organism level, but also how this translates to vulnerability at higher organisation levels – namely the local species population, assemblage, community/habitat and/or ecosystem level – and the capacity of biota to recover. The present study describes the application of an ecological VAF to identify the vulnerabilities of aquatic biodiversity and associated cultural/social values to Mg inputs from Ranger Mine.

Ecological vulnerability assessment fills the knowledge gap that exists between laboratory and field effects experiments on a sub-set of species or assemblages, to understanding risks to higher levels of organisation and/or to other species and species groups (De Lange et al. 2010). Ecological vulnerability assessment considers not only the direct sensitivity of organisms to a stressor, but the potential for indirect flow-on effects through trophic and habitat relationships.

Vulnerability is based on the consideration of following elements (De Lange et al. 2010; Weißhuhn et al. 2018), as shown in Figure 2:

- Level of exposure to stressors –assessed by numerical modelling (not assessed in this paper).
- Sensitivities to stressors, both in terms of direct effects and indirect flow-on effects to habitat and or food resources. This requires consideration of the biological traits of biota, the structural and functional relationships between the organisms, and the abiotic environment.
- Capacity to recover following a perturbation, such as exposure to a contaminant. This is also known as resilience or adaptive capacity.

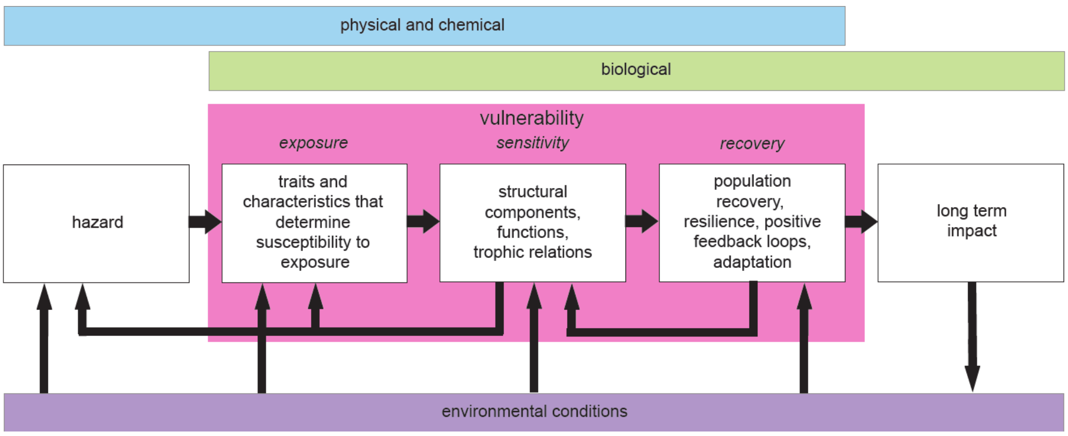

Figure 2 Generalised ecological vulnerability assessment framework of De Lange et al. (2010)

2 Methodology

The present targeted vulnerability assessment builds on the framework and findings of Richardson et al. (2019) and BMT (2021). This involved the following tasks:

- Task 1: Collate and assess exposure information, specifically: (i) predicted Mg concentrations at subject waterbodies during closure (Energy Resources Australia 2021); and (ii) measured Mg concentrations at subject waterbodies during the operational phase (ERA unpublished continuous measurement data).

- Task 2: Identify subject waterbodies to be assessed in the targeted assessment, based on outcomes of Task 1.
- Task 3: Identify ecological components to be assessed. Richardson et al. (2019) and BMT (2021) defined the environmental and community values (ECVs) supported by waterbodies in the RPA and surrounds and underpinning ecological components. This considered planning documents defining ECVs of the RPA and surrounds, especially the Kakadu National Park Ramsar Site Ecological Character Description (BMT WBM 2010) and park management plans. A list of ecological components known or possibly occurring in the subject waterbodies was defined based on a review of habitat preferences and through expert elicitation.
- Task 4: Expert elicitation of context specific ecological information. A workshop was held in Darwin (and remotely) with a group of experts and stakeholders and involved the following:
  - Confirm relevant subject waterbodies based on a review of predicted Mg concentrations.
  - Seek feedback and agree on assessment criteria and data quality criteria.
  - Undertake scoring of geographic range and habitat breadth attributes to derive a refined list of ecological components.
  - Seek feedback and refine vulnerability scores.
  - Identify and confirm key knowledge gaps.
- Task 5: Assess vulnerability scores of ecological components. Ecological trait scores for each ecological component presented in Richardson et al. (2019) were assessed to determine:
  - Ecological responses at the individual organism level. This considered traits describing direct sensitivity to Mg; indirect sensitivity to Mg (dependence on sensitive habitat, dietary breadth and habitat breadth) and avoidance capacity. Based on these traits three potential responses were defined: (i) resist (capacity to persist); (ii) migrate (capacity to move); (iii) perish (for organisms unable to persist in place or move).
  - Ecological responses at the population level. For ecological components with type (i) and (ii) responses at the individual organism level, population resilience was evaluated taking not account recovery modes of components. Recovery potential of ecological components was evaluated using reproduction and dispersal trait scores presented in BMT (2021).
- Task 6: Define vulnerability. For each subject water body, ecological components are rated as high, moderate or low vulnerability (or undefined), using the criteria set out in Table 1.

Table 1 Criteria to define vulnerability ratings for subject waterbodies

Criteria	High	Moderate	Low	Undefined
Capacity for ecological component to 'persist in place' at modelled Mg concentration (organism level) due to direct or indirect (habitat/food) effects	No/limited capacity to persist in the long-term	Mg concentrations may intermittently affect capacity to persist in place	Mg concentrations unlikely to affect capacity to persist in place	High degree of uncertainty due to conflicting information/data deficiency
Recovery potential of the ecological component at the local population (water body) level	Long-term, ongoing exposure prevents full recovery	Contains traits that enable rapid recovery from intermittent exposure	Not relevant	As above

3 Results

3.1 Definition of subject waterbodies

For the baseline closure strategy four waterbodies had modelled Mg concentrations greater than the 99% WQGV causing potential medium or higher risk: Coonjimba Billabong (CB), Georgetown Billabong (GTB), Georgetown Creek (GTCk) and Magela Creek (MCk). Other reporting locations met the 99% WQGV.

3.2 Exposure context

Table 2 summarises the exposure context for each water body, which identifies:

- Relevant sensitive ecological components. BMT (2021) provides Mg sensitivity ratings for each ecological component, which range from A (highest sensitivity) to C (lowest sensitivity). Modelled Mg concentrations were compared to the Mg sensitivity assessment criteria of BMT (2021) to identify ecological components potentially sensitive at the predicted Mg concentration. For example, based on a predicted Mg concentration of 2 mg/L, all ecological components scored as category A (Mg < 3 mg/L) would apply. At a predicted Mg concentration of 200 mg/L, all ecological components scored as category A, B1 and B2 would apply. Refer to Richardson et al. (2019) for categories.
- Trends in modelled Mg based on (i) a comparison to Mg values during the operational phase; and (ii) a summary of intensity, frequency and duration of exposure.

Table 2 Mg exposure at each water body for the baseline closure strategy

Location	Sensitive ecological components at the modelled closure phase Mg	Trends
Coonjimba Billabong (CB)	Direct sensitivity rating of A, B1 and B2 (Mg 10–200 mg/L) Biophysical habitat features (macrophytes, trees) with a direct sensitivity rating of A, B1 or B2	Chronic, long-term exposure during ops and closure phases
Georgetown Billabong (GTB)	Direct sensitivity rating of A and B1 (Mg <3 or 3–10 mg/L) Biophysical habitat features (macrophytes, trees) with a direct sensitivity rating of A or B1	Periodic, short-term exposure Closure median about half operational phase
Georgetown Creek (GTCk)	Direct sensitivity rating of A and B1 (Mg <3 or 3–10 mg/L) Biophysical habitat features (macrophytes, trees) with a direct sensitivity rating of A or B1	Closure phase Mg well below operational phase values
Magela Creek (MCk)	Direct sensitivity rating of A and B1 (Mg <3 or 3–10 mg/L) Biophysical habitat features (macrophytes, trees) with a direct sensitivity rating of A or B1	Closure median 2–5× operational phase

3.3 Definition of ecological components

A refined list of ecological components for creek and billabong habitats in the RPA was determined based on a review of habitat preferences (BMT 2021) and workshop discussions. One ecological component identified by Richardson et al. (2019) and BMT (2021) does not occur in the RPA (Yellow chat) and was removed from the list. Refer to Table 3 for a summary of ecological components assessed.

Table 3 Preliminary vulnerability ratings

Ecological component	Coonjimba Billabong (CB)	Georgetown Billabong (GTB)	Georgetown Creek (GTCk)	Magela Creek (MCk)
Algae	High vulnerability (long-term effects, likely similar effects to operation phase) Data deficient for attached algae	Moderate vulnerability (potential short-term effects, less than operation phase)	Moderate vulnerability (potential short-term effects, similar to operation phase)	Moderate vulnerability (potential short-term effects, greater than operation phase)
Macrophytes and tubers	Undefined – low to high vulnerability (data deficient, likely similar effects to operation phase)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Riparian trees	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Zooplankton	High vulnerability (long-term effects, likely similar effects to operation phase)	Moderate vulnerability (potential short-term effects, less than operation phase)	Moderate vulnerability (potential short-term effects, similar to operation phase)	Moderate vulnerability (potential short-term effects, greater than operation phase)
Macroinvertebrate assemblages	High vulnerability (long-term effects, likely similar effects to operation phase)	Moderate vulnerability (potential short-term effects, less than operation phase)	Moderate vulnerability (potential short-term effects, similar to operation phase)	Moderate vulnerability (potential short-term effects, greater than operation phase)
Freshwater prawns	High vulnerability (long-term effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Freshwater mussels	High vulnerability (long-term effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Saratoga	High vulnerability (long-term effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Magela hardyhead	High vulnerability (long-term effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)

Ecological component	Coonjimba Billabong (CB)	Georgetown Billabong (GTB)	Georgetown Creek (GTCk)	Magela Creek (MCk)
Other key fish species	N/A	N/A	Low vulnerability (no effects)	Low vulnerability (no effects)
Fish assemblages	High vulnerability (long-term effects, likely similar effects to operation phase)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Frog assemblages	Moderate vulnerability (possible long-term indirect effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Water python and water monitor	High vulnerability (long-term effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
All reptiles except water python and water monitor	Moderate vulnerability (possible long-term indirect effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Birds	Moderate vulnerability (possible long-term indirect effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)
Water rat, water mouse	Moderate vulnerability (possible long-term indirect effects, likely similar effects to operation phase, data deficient)	Low vulnerability (no effects)	Low vulnerability (no effects)	Low vulnerability (no effects)

3.4 Vulnerability assessment Magela Creek, Georgetown Billabong and Georgetown Creek

MCk, GTB and GTCk had similar exposure characteristics and are therefore considered together. Modelling of the baseline closure strategy predicts that these three waterbodies would periodically experience Mg concentrations greater than 99% WQGV, but exposure was predicted to be intermittent and low magnitude.

The following ecological components have known or possible direct sensitivity at the median Mg concentrations predicted to occur at these locations: algae (planktonic and attached), zooplankton (all category A), and creek macroinvertebrates, sandy bed assemblages and Midgley's grunter (*Pingalla midgleyi*) (all category B1). All these groups have high resilience and are expected to recover during periods of lower Mg. These components are considered to have moderate vulnerability.

All other ecological components, including key species, vertebrate and vegetation assemblages, were considered to have low vulnerability at the individual organism level (and by extension local population level).

3.5 Vulnerability assessment for Coonjimba Billabong

Median Mg concentrations at CB for the baseline closure strategy (median 20–40 mg/L) are predicted to be similar or greater than median concentrations recorded during the operational phase (2008–2012: 24 mg/L, 2013–2018: 16 mg/L). Mg is predicted to exceed the 99% WQGV throughout the year, as it also has during the operational phase.

3.5.1 Sensitivity

The following ecological components have known/possible direct sensitivity (categories A, B1, B2) at the Mg concentrations predicted at CB:

- Algae (planktonic, attached).
- Invertebrates (zooplankton, billabong macroinvertebrates, freshwater prawn (*Macrobrachium bullatum*), freshwater mussels).
- Tubers and macrophytes.
- Fish (Magela hardyhead (*Craterocephalus marianae*), saratoga (*Scleropages jardinii*)).
- Reptiles: water python (*Liasis fuscus*) and monitors (*Varanus* spp).

Under the baseline closure strategy there is a high likelihood that the persistent elevated Mg concentrations would have ongoing, direct effects to sensitive phytoplankton and invertebrate species, resulting in long-term changes to community structure relative to reference sites. This is supported by operational phase monitoring results, with high Mg concentrations at CB coinciding with alterations in macroinvertebrate, zooplankton, phytoplankton and fish communities (Humphrey & Chandler 2018; Mooney et al. 2020). The changes observed at CB during the operational phase may be a response to multiple stressors (i.e. Mg and other mine-associated contaminants, acid sulphate soils, low dissolved oxygen concentrations etc.) and to one or more impacting mechanisms (i.e. direct toxicity, impacts to food resources, evasion etc.).

There is a low degree of certainty regarding sensitivities of attached algae, tubers/macrophytes, the two key fish species, freshwater prawn (*Macrobrachium bullatum*) and the two key reptile species to Mg levels predicted to occur at CB. In this regard:

- There is no available information regarding the sensitives of attached algae. It has been conservatively assumed that they have similar sensitivities to phytoplankton.
- The sensitivity ratings for all other groups are inferred from habitat information, which may not be representative of actual sensitivities.

3.5.2 Capacity to evade

Ecological components with no/low capacity to persist at elevated Mg concentrations (see above) would either perish or move from the sub-optimal habitat which could form under the baseline closure strategy, as follows:

- Ecological components with low motility (low capacity to evade) and low capacity to persist are vulnerable at the individual organism level. This group is composed of Mg sensitive algae and invertebrate species, and Mg sensitive tubers/macrophytes (if present; see above regarding uncertainties with macrophyte sensitivities).
- Ecological components that are mobile (moderate to high capacity to evade) and low capacity to persist have lower vulnerability at the individual organism level. This includes:
  - Fish – recent studies of Magela catchment fish communities demonstrate that Mg concentrations up to 11 mg/L do not elicit an avoidance response (Crook et al. 2021). The response of CB fish assemblages to Mg values recorded during mine operation are more than 11 mg/L, and therefore cannot be defined at this location.
  - Other vertebrate species – all other vertebrate species have high mobility, but their degree of site fidelity varies among species. Further work is required to determine current patterns in habitat usage of CB by semi-aquatic vertebrate species.

For all mobile species, any Mg avoidance response would result in reduced species richness at CB.

3.5.3 Recovery and potential population level effects

All ecological components with known or potential Mg sensitivity have high reproduction/recruitment rates, generally short-lived and a short age at breeding. These biological traits allow aquatic species to rapidly recover following periodic disturbance, such as seasonal drying of billabongs, extreme weather events etc. This is a requirement for living in dynamic, seasonal wetland environments. However, modelling of the baseline closure strategy predicts that Mg values at CB would continue to be well above the 99% WQGV. Therefore, ecological components at CB would be subject to chronic, long-term Mg exposure, as has been the case for over a decade during mine operations (BMT 2021). Species that are resilient to Mg (and other stressors) would be expected to persist, whereas sensitive species (such as some algae and invertebrates) would not, as is the case at present. It should be noted that the assessment does not consider the capacity of biota to acclimate to changes in environmental conditions.

A systematic assessment of this ecosystem is required to assess its ecological character, functions, and potential long-term trajectory.

3.6 Implications for closure planning

Four water bodies were assessed to have potential medium or higher ecological risks from Mg concentrations under the modelled baseline closure strategy. Consideration of the adaptive capacity of the key ecological components at those sites showed the ecosystem has low vulnerability at three of the sites and moderate to high vulnerability at the CB site. Alternative management strategies for contaminants entering Magela Creek have been developed by ERA to reduce the concentrations of other contaminants, which has the effect of lowering Mg concentrations in the creek even further.

Alternative approaches to managing the contamination sources in the Coonjimba catchment are being assessed by ERA. The alternative closure strategies that are developed will be assessed for ecological risk and vulnerability to inform the decisions on which strategy results in impacts that are ALARA.

4 Conclusion

The VAF provides an understanding of the vulnerability of ecological components underpinning ECVs, which is important for determining the potential mine impacts from different proposed closure strategies on waters in the RPA, and how such onsite changes could indirectly affect adjacent receiving environments. As such, this information helps to refine the closure strategy and understand if potential impacts on the RPA are ALARA.

Further research priorities to better understand and define vulnerability are as follows:

- Dynamics of aquatic macrophytes and attached algae in billabongs.
- Structural characteristics and inventory of aquatic macrophyte assemblages.
- Structural characteristics and dynamics of attached algae assemblages.
- Inventory and assessment of macroinvertebrates (especially prawns, mussels) and fish species in billabongs to improve Mg sensitivity ratings.

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Figures that have been reproduced (without modification) from other sources have been referenced accordingly.

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