Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-4-1
doi:10.36487/ACG_repo/2215_21

Development of mine-derived acid sulfate sediments

DE Windle *Environmental Resources Management, Australia*

TR Weaver *Environmental Resources Management, Australia*

G Race *Environmental Resources Management, Australia*

M Iles *BMT, Australia*

E Fagan *Energy Resources of Australia, Australia*

Abstract

Acid sulfate sediments (ASS) may be present at a mine site due to natural processes but may also develop from mining and water management activities through discharge of impacted groundwater and surface water. This paper outlines conditions under which mine-derived ASS may form and uses that information to develop a conceptual model for ASS in a source-pathway-receptor framework for the Ranger Uranium Mine in the Northern Territory, Australia (the site). The conceptual model was then used to inform the assessment and management of risks associated with potential ASS as the mine site progresses through closure.

Key constituents contributing to ASS formation are waterlogged (anoxic) conditions, elevated sulfate concentrations, and organic carbon. For the site, geographic information system (GIS) spatial mapping was used to develop a conceptual site model that identified areas of potential ASS formation based on:

1. *Groundwater-level data and topographic contours – which were combined to identify areas of shallow (<1 m depth) groundwater since, together with surface water bodies, these represent areas of potential waterlogging.*
2. *The potential waterlogged conditions were overlaid with elevated (>10 mg/L) sulfate concentrations in groundwater and surface water, to identify potential ASS areas.*

The conceptual model identified potential source areas where ASS may form, including a billabong where acidification events had been observed previously (Coonjimba Billabong) and where subsequent sampling confirmed the presence of ASS. As the identified source areas are associated with shallow groundwater and surface water, these can also act as pathways to transport acidification products to downgradient/ downstream receptors if ASS are disturbed or exposed. Identifying these potential source areas for ASS allows the risks associated with their disturbance or exposure to be managed.

Although elevated sulfate concentrations in groundwater or surface water are associated with sulfidic ore or waste rock at many mines, the potential formation of mine-derived ASS is seldom considered and may become particularly relevant as the water balance changes with closure. This assessment approach used existing data to identify and prioritise potential ASS areas for further assessment and management and could be adapted and applied at other mining sites.

Keywords: *acid sulfate sediments, acid sulfate soils, ASS, AASS, PASS, waterlogged, sulfate, groundwater, surface water, conceptual model, Ranger Uranium Mine*

1 Introduction

1.1 Acid sulfate soils

Acid sulfate soils or acid sulfate sediments (collectively known as ASS) are commonly encountered in coastal areas of Australia and are also known to exist naturally in some inland areas, as shown by mapping by the Commonwealth Scientific and Industrial Research Organisation (CSIRO 2011). The mechanism for

ASS formation is well understood and requires the presence of three key components: sulfate, organic matter, and reducing/anoxic conditions. ASS are typically separated into potential ASS (known as PASS) and actual ASS (known as AASS). PASS are those soils or sediments that contain sulfides in a reduced condition that have the potential to generate acid if oxidised. AASS are those soils or sediments that have oxidised to release acid, sulfate and/or metal load.

Disturbance of PASS can result in AASS and associated environmental impacts. Consequently, the identification, assessment and management of both natural and mine-derived ASS can be critical for the protection of human health and the environment in a range of situations, including at mine sites during their operation and as they transition to closure.

1.2 Ranger Uranium Mine

The Ranger Uranium Mine (the site) is located in the Northern Territory in the wet-dry tropics of Australia. Naturally occurring ASS were indicated by CSIRO (2011) mapping in the area, including areas with a 'high probability' of ASS that are located offsite and away from mining impacts. The potential for naturally acidic surface water conditions in an upstream creek is also noted by Hart et al. (1987).

Additionally, the mapping by CSIRO (2011) indicated a 'high probability' of the occurrence of ASS in some areas on site, including the wetland of Coonjimba Billabong and other areas of operational water storage and discharge. ASS in these onsite areas are considered most likely to be mine-derived, including being associated with operational water practices, rather than naturally occurring.

Acidification events have been identified previously at Coonjimba Billabong. Specifically, early in the annual wet season, for several years, acidic water, metals and sulfate were observed in surface water at this location. Although periodic acidification events have been identified that are associated with Coonjimba Billabong, the site includes several other wetland areas and there is the potential that other areas of mine-derived ASS are present. At the site, and many other mines, key constituents for ASS formation are present. Sulfate is present, associated with oxidation of sulfide minerals in mine ore, and organic matter and reducing conditions can naturally co-exist in wetlands due to waterlogging conditions and wetland vegetation.

The site ceased processing ore in January 2021 and is now in a period of rehabilitation and transition to closure. Consequently, the water balance, hydrodynamics and landforms at the site are undergoing significant change, including reduced discharges to Coonjimba Billabong. This introduces the potential for PASS to be exposed (excavated or dried out), with subsequent generation of AASS.

The purpose of this assessment was to map key areas where PASS may be present at the site, based on historical and/or operational activities and information. This informed the development of a preliminary site-wide ASS conceptual model to inform the high-level understanding of ASS formation (source dynamics), potential pathways from ASS source areas to surface water and groundwater receptors, and potentially complete source-pathway-receptor linkages. This information can then be used to guide further sampling and assessment of areas that may contain PASS in terms of their environmental significance and potential to generate AASS, as a result of likely hydrodynamic changes during the transition to closure.

1.3 Site characteristics

The site experiences well-defined wet (typically November to April) and dry (typically May to October) seasons, although rainfall in October and May is also common. The majority of rainfall occurs during the wet season in the form of tropical monsoons, and the average wet season rainfall is approximately 1,500 mm. Negligible rain falls in the dry season. As a result, strong seasonal influences are seen for groundwater and surface water levels and dissolved sulfate concentrations, which have the potential to influence ASS formation.

The major bedrock geologies of the site are the Nanambu Complex (Archaean-aged gneiss of quartz-feldspar-biotite and granites) and Cahill Formation (Palaeoproterozoic schists of muscovite-biotite-garnet and chlorite/sericite, as well as carbonates of dolomite and magnesite). Weathering and erosion of the natural bedrock geology has also resulted in the presence of alluvial sediments, weathered soils and laterites, and weathered (decomposed or altered) bedrock. Further, waste rock from the mining process and tailings are present and are considered as anthropogenic ‘geologic units’.

The hydrogeology of the site has been conceptualised within a three-zone framework, where each zone comprises multiple geological formations or bedrock types, as follows (from shallowest to deepest):

- Zone 1 (alluvial sediments and lateritic weathered soils) – typically located within or along alluvial channels, these sediments act as a zone where significant groundwater transport can occur (when they have sufficient saturated thickness) and host the watertable (where present), but may go dry during the dry season.
- Zone 2 (weathered bedrock) – varying from highly weathered to weakened and iron-stained bedrock (slightly to moderately weathered), this unit tends to act predominantly as an aquitard, except in specific areas, and most of the groundwater monitoring bores at the site target this zone.
- Zone 3 (unweathered bedrock with fractures and faults) – these units typically have the lowest hydraulic conductivity values and show very limited groundwater movement and transport (i.e. act as aquitards).

Groundwater in Zone 1 and Zone 2 was the focus of this assessment, as these are the zones where groundwater is most likely to discharge to surface water features, such as creeks and billabongs. Groundwater–surface water interactions vary across the site, depending on the local hydrogeologic conditions. The presence of permanent surface water features (such as the billabongs) and artificial surface water management features means there is the potential for recharge of shallow groundwater by standing surface water in some areas.

Although black or grey clay at the base of Coonjimba Billabong has previously been concluded to form a “hydraulic barrier to vertical groundwater movement through much of Coonjimba Billabong” (Esslemont 2016), “the presence of coarser soil implies some potential for connectivity between surface water and groundwater” (Baldwin 2017a). Based on this, although there is the potential for interaction between groundwater and surface water, it may be limited by fine-grained sediments in the base of the billabongs, where present. Seasonal conditions, reflecting variations in groundwater and surface water levels with seasonal rainfall, also influence groundwater–surface water interactions.

The majority of the natural surface water features at the site, excluding Coonjimba Billabong and some others, are naturally ephemeral. They are typically dry during the dry season and only flow during the wet season. Discharge to some surface water features is managed during the wet season, and surface water levels in operational water management features are managed year round as part of site water balance and operations. Some of the operational water features are connected to natural surface waters, while others are not connected. The water quality of the surface water management features at the site varies, with some having high concentrations of sulfate and other salts/metals, and others having lower sulfate concentrations. The quality of water held in each surface water management feature has also varied over time.

2 Methodology

2.1 Premise

In this assessment, we identified where areas with elevated sulfate in groundwater or surface water were co-located with standing water (surface water) or waterlogging (shallow groundwater), thereby indicating the spatial extent where both elevated sulfate and waterlogged conditions were present.

Noting the setting, it was assumed that in these areas there was sufficient organic matter present to enable formation of ASS (i.e. organic matter is not a limiting factor). This assumption was necessitated by the limited organic carbon data available for groundwater, surface water and soil at the site. However, soil sampling (SLR 2018) and sediment sampling (Noller & Hart 1993) have indicated that organic matter would not likely be a limiting factor for the potential formation of ASS in areas where waterlogging of soils and sediments may occur. This is consistent with the understanding that billabongs and wetlands generally have an abundant supply of carbon from decomposing plant material and/or algae (Baldwin 2017a). The presence of this organic matter is assumed to result in sufficiently reducing conditions to form sulfides and PASS, in the presence of sulfate and waterlogged conditions.

A concentration of equal to or greater than 10 mg/L sulfate in groundwater or surface water was adopted for assessment of areas with the potential for ASS formation. This was based on the National Guidance on Acid Sulfate Soils for inland soils (Environment Protection and Heritage Council and Natural Resource Management Ministerial Council 2011), which identifies concentrations of sulfate greater than 10 mg/L in water as an indicator of potential ASS formation for inland aquatic ecosystems. A long-term average concentration in water of less than 10 mg/L is also considered to be a reasonable upper level for sulfate by Baldwin (2017b).

Therefore, the two key constituents that contribute to the potential for ASS that were considered for this site were:

- Potentially waterlogged (anoxic) conditions – based on interpolated groundwater elevations being within 1 m of the ground surface and on areas of standing surface water.
- Elevated sulfate concentrations – based on groundwater or surface water sulfate concentrations ≥10 mg/L.

2.2 Data review

2.2.1 Temporal changes and seasonal variation

As the largest and most reliable surface water and groundwater dataset is available for the site from 2010 onwards, this date range was the focus of the assessment. Key information reviewed for this assessment included water management activities (including changes over time), seasonal rainfall variations, and groundwater and surface water monitoring data (level and quality).

Assessment of temporal influences on water management activities identified that the 2010 dry season appeared to be a time of large-scale change in the surface water management practices at the site, particularly in the vicinity of Coonjimba Creek alignment.

Although there had been isolated observations of low pH (acidic conditions) in Coonjimba Billabong and elsewhere on site previously, conditions during the 2012/13 wet season indicated the lowest pH in surface water from Coonjimba Billabong (4.72) since December 2007. This is understood to reflect drier conditions, as a result of a below-average wet season in 2012/13 and the occurrence of 'patchy' rainfall at the start of the early 2012/13 wet season, resulting in less dilution of acidic waters. Water levels had been unusually low in Coonjimba Billabong since 2012, resulting in sediments that had been permanently wet for several years becoming more exposed to drying, including during the prolonged dry season in 2014 (Esslemont 2016).

A range of changes in water management practices occurred in the 2011 dry season, and there was a general increase in the quality and volume of water that was released from the site through Coonjimba Billabong and other surface water features after 2014. Since then, water management practices have remained relatively similar across the site.

Based on this understanding of key changes in water management, combined with observations of seasonal variation in rainfall, three wet seasons (2010/11, 2015/16 and 2017/18) and three dry seasons (2011, 2016 and 2018) were selected for further assessment. These were selected to capture a range of scenarios and assess variability in the results over time. The 2010/11 wet season was particularly wet (approximately 2,400 mm of rainfall compared to the average of 1,500 mm), sulfate loads reporting to Coonjimba Billabong from the operational surface water features were relatively high, and this represented a time period leading up to the reported acidification events in Coonjimba Billabong around 2012. The 2015/16 wet season was characterised by low rainfall (approximately 1,100 mm of rainfall) and, as it followed another low-rainfall dry season in 2014/15, represented a long dry period. The 2017/18 wet season was characterised by slightly higher than average rainfall (approximately 1,900 mm) and occurred following an average dry season in 2017.

2.2.2 Seasonal influences on sulfate concentrations

Surface water chemistry data were collected more frequently (weekly at some locations) compared to groundwater (typically quarterly to annually). However, surface water quality was often only measured during the wet season, at locations when standing or flowing surface water was present. As such, there were limited surface water quality data for the dry seasons, particularly 2016.

Review of the surface water quality data, including for Coonjimba Billabong, showed that pH typically decreased sharply (became acidic) early in the wet season and then increased (to more neutral conditions) as the wet season progressed. The sulfate concentrations also spiked early on in the wet season, before showing a rapid decline in concentrations. Low pH and high sulfate towards the start of the wet season represent the ‘first flush’ of solutes moving into surface water from the re-wetted sediments that had oxidised over the dry season, with the products of that oxidation then mobilised and diluted by the rainfall.

During the dry season at Coonjimba Billabong, pH generally continued to increase and the sulfate concentrations continued to decrease in surface water; that is, the highest sulfate concentrations in the dry season occur at the start, in the transition from the wet season. This is relatively unusual behaviour for solutes during the dry season, as solutes in several other surface water features at the site tend to increase due to evapoconcentration as the dry season progresses.

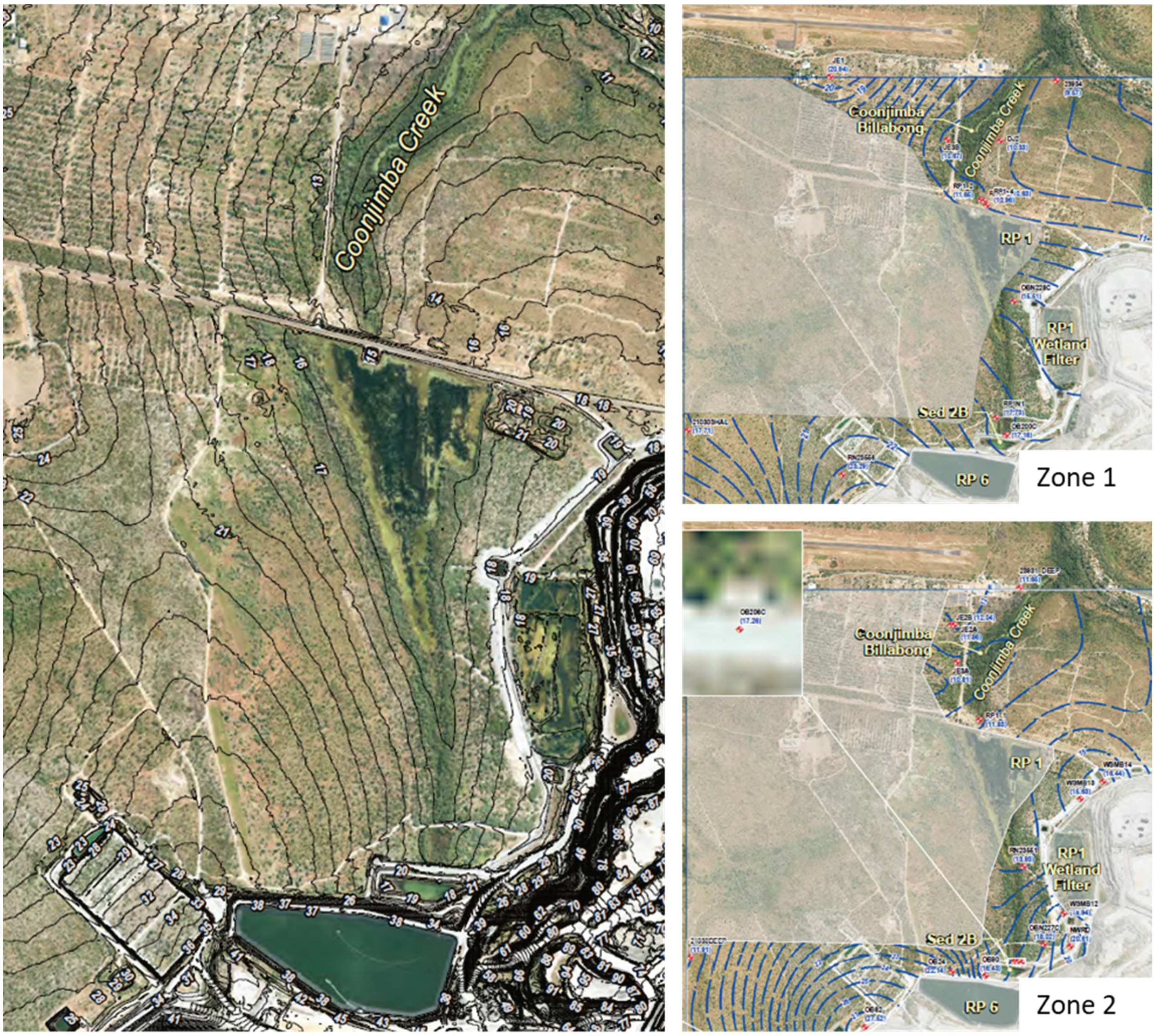
Review of groundwater data since 2010 also identified that, for groundwater from several bores, sulfate concentrations were typically highest at the start of the wet season, similar to the ‘first flush’ observed for surface water, and then show declining concentrations.

Based on this review of concentration trends, the assessment focused on water quality from early in the wet season and early in the dry season as being generally indicative of a worst-case scenario, with the highest sulfate concentrations and higher groundwater elevations. For each wet season and dry season, an individual month was selected for adoption of maximum surface water and groundwater data. Adoption of maximum concentrations, rather than long-term average concentrations, represents a conservative approach.

2.3 Spatial mapping

2.3.1 Topography

A digital elevation model (DEM) based on available LiDAR data for the site was used for the topography elevation component and to infer ground elevations. The DEM was captured in May 2019 and had a vertical spatial accuracy of 0.04 m. Although a 5 m contour interval is shown in Figure 1a, a contour interval of 1 m was interpreted and used for the spatial mapping.



(a) (b)

Figure 1 Topographic contours (mAHD) (a) and groundwater elevation contours (mAHD) – 2015/16 wet season (b)

2.3.2 Groundwater and surface water elevations

Groundwater elevations were adopted to match the date of the groundwater sample, where available. Additional groundwater elevation data were also adopted for locations that did not have groundwater quality data. In general, and as expected, groundwater elevations were typically highest at the end of the wet season (start of the dry season) and lowest at the end of the dry season (start of the wet season).

The kriging function in the geographic information system (GIS) was used to interpolate groundwater elevations (in metres above Australian Height Datum; AHD) from individual bores within catchments. This was undertaken separately for Zone 1 and Zone 2 bores and for each selected month of interest. Contour intervals of 1 m were presented as generated from the data and were not manually adjusted, although the area of contouring was a square set by the maximum extent of the groundwater data to the east, north, south and west for that time period. Contours were truncated at areas of onsite operational features with altered topography, surface water storage, surface water feature and where groundwater elevation data were not available to constrain the contours.

Surface water elevations were available for selected surface water monitoring locations, primarily for the wet seasons, as many of the surface water monitoring locations become dry during the dry season (i.e. are ephemeral). Due to the limited data available, surface water elevations were not adopted in the contouring.

2.3.3 Groundwater and surface water sulfate concentrations

For groundwater, a sulfate concentration from the selected month, or as available from the following one to two months, was adopted. The groundwater sulfate concentrations were considered separately for Zone 1 bores and Zone 2 bores. The GIS kriging function was used to create groundwater sulfate heat maps for each time period, with concentration intervals on a logarithmic scale adopted – that is, <1 mg/L, 1–10 mg/L, >10–100 mg/L, >100–1,000 mg/L and >1,000 mg/L. As for groundwater elevations, the concentration maps were presented as generated from the data and were not manually adjusted, except for constraining the extent of the interpretation in the same way.

Surface water concentration data for sulfate was also adopted. As the surface water concentrations are likely to represent a mix of both groundwater and surface water (including rainfall and runoff inputs) and some surface water monitoring locations are affected by operational inputs, surface water concentrations were not included in the contouring. The highest sulfate concentrations from the selected month were also adopted for surface water. If no surface water data were available, for that month, the next available data within one to two months was selected.

Overall, the highest elevations and sulfate concentrations were adopted for groundwater and surface water as a conservative approach. In some situations, it may be more appropriate to consider seasonal average concentrations, particularly for surface water, but maximum concentrations were adopted to be consistent with the approach for groundwater and to enable comparison to the associated specific surface water levels, where available.

3 Results

3.1 Topography and groundwater elevations

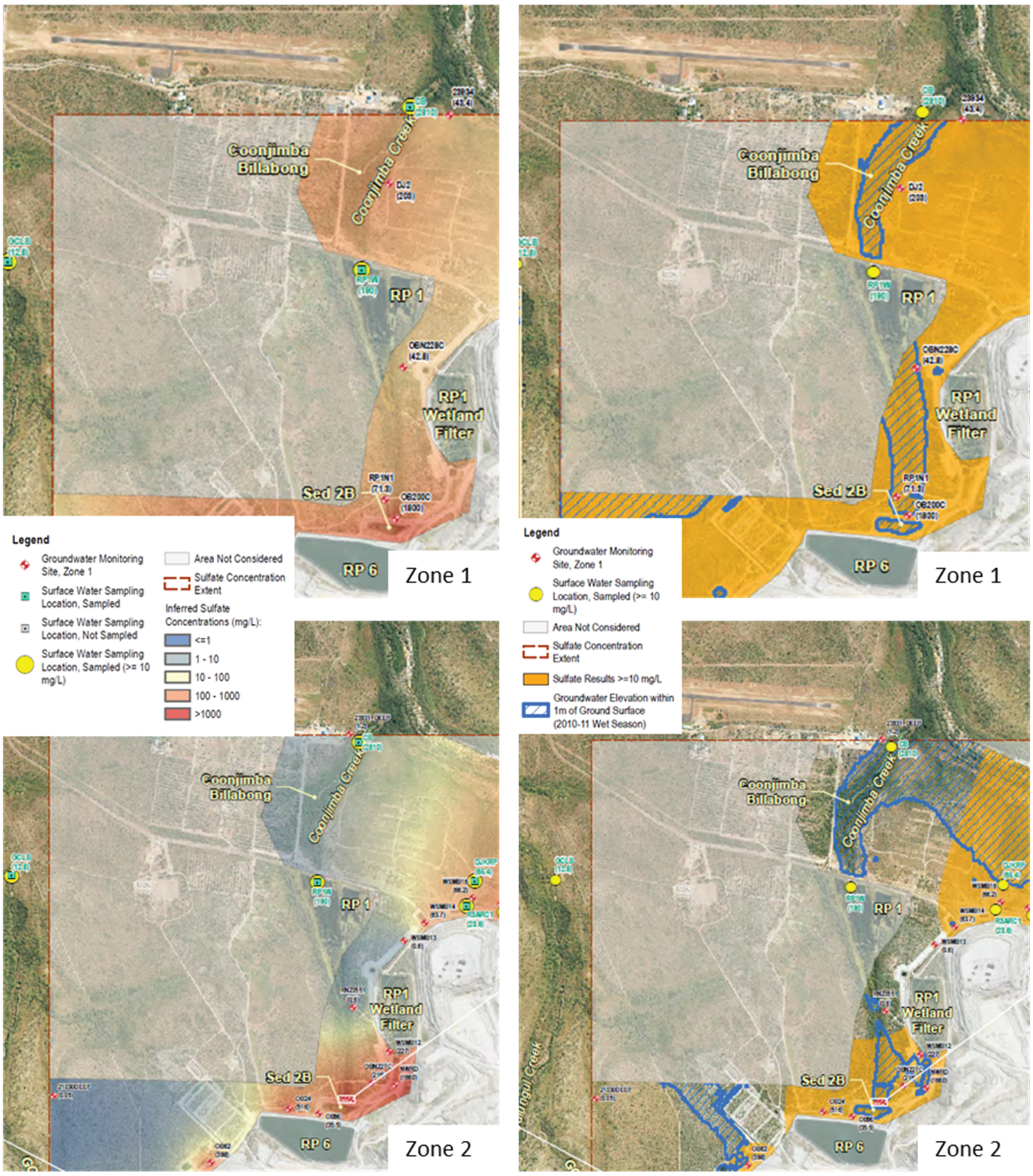
The topography within the site is highly variable and has also changed over time due to mining activities. Excluding the former mine pits, the lowest topography is generally along surface water alignments, including Coonjimba Creek and Billabong (Figure 1a).

Consistent with the topography, groundwater elevation contouring generally showed groundwater flow in both Zone 1 and Zone 2 to be away from the operational higher elevation areas of the site and towards the surrounding surface water features. The groundwater elevations and inferred flow directions were consistent with the conceptual model for groundwater and were consistent for the time periods of interest and for both the wet and dry seasons. Due to limited groundwater data to the west, the groundwater contours were truncated near Coonjimba Billabong (Figure 1b).

3.2 Identification of waterlogging

Areas of waterlogging were identified based on overlay of groundwater contours with topographic data (ground elevations). The data overlay was used to evaluate depth to the watertable and where the watertable may be within close proximity to, or express at, the ground surface. Based on this, areas where the inferred groundwater elevation was within 1 m of the ground surface were identified, with these areas considered to represent potentially waterlogged conditions (Figure 2). Waterlogged areas were identified separately for Zone 1 and Zone 2 and for each time period of interest. As expected, the inferred potential waterlogged conditions were associated primarily with channel alignments and tributaries. Although the extent of potential waterlogged conditions varied, they were, within each zone, generally consistent for the time periods of interest and for both the wet and dry seasons. In areas where groundwater data were not available in the immediate vicinity of the creek alignments for the dates assessed, potentially waterlogged conditions were still considered to be present based on the characteristics elsewhere on site.

Based on the approach used, uncertainty is associated with the accuracy of the DEM and with the interpolated groundwater elevations at a given location. This uncertainty is greatest in areas with fewer groundwater monitoring bores, which is particularly the case for Zone 1, in part due to its limited extent. The uncertainty is greater for the interpolated groundwater levels compared to the interpolated ground surface (topography) because of the higher accuracy of the contoured topography data. For that reason, the topography often appears to drive the spatial extent of the waterlogged areas.



(a) (b)

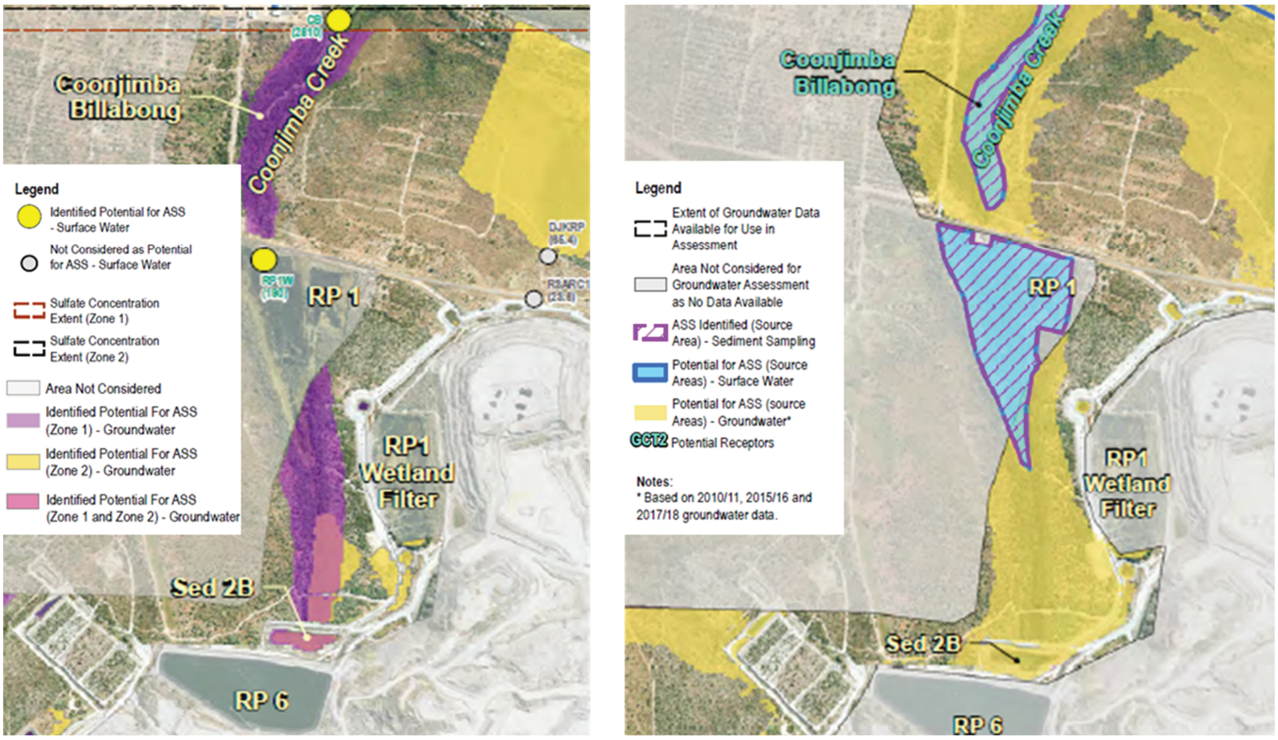
Figure 2 Groundwater and surface water sulfate concentrations: 2015/16 wet season (a) and elevated sulfate (>10 mg/L) and waterlogging (groundwater elevation <1 m bgl) – 2015/16 wet season (b)

3.3 Elevated sulfate concentrations

The interpolated sulfate concentration distributions for groundwater (Figure 2a) were generally consistent for the time periods of interest and for both the wet and dry seasons. Similar trends were apparent for sulfate concentrations in surface water for each year and season assessed, although fluctuations in sulfate concentrations in surface water were greater than for groundwater. This is expected, as surface water is likely to be more affected by variations in rainfall, seasonal effects, and operational water management practices than groundwater.

3.4 Identification of ASS – potential source areas

Areas where both potentially waterlogged conditions and elevated sulfate concentrations in groundwater were co-located were then mapped for both Zone 1 and Zone 2, and areas with surface water sulfate concentrations ≥ 10 mg/L were also identified (Figure 2b). Together, these represent areas with the potential for ASS formation and, as such, are considered to be source areas. Water management features that were not in connection with natural surface waters were not included in this assessment. The identified source areas (potential for ASS) were generally consistent for the time periods of interest and for both the wet and dry seasons. Figure 3a shows an example of the identified source areas for Zone 1 and Zone 2 from the 2015/16 wet season. The results of each dry and wet season were then combined to create a summary of the overall potential source areas for PASS and the receptors (conceptual model) for the site (Figure 3b).



(a) (b)

Figure 3 Potential ASS: 2015/16 wet season (a) and summary of preliminary site-wide conceptual model (b)

3.5 Validation using sediment data

In this assessment, soil and sediment sampling data relevant to ASS was not relied on to identify ASS areas, as it was limited across the site. However, soil and sediment data for specific areas of the site were used for validation purposes and as a comparison to the mapping results. PASS that were mapped as part of this assessment had not been confirmed by field testing in all areas (at the time of this assessment), and future determination of AASS will require verification, where applicable.

Specifically, for Coonjimba Billabong, previous testing of sediments from the lower reaches of the billabong in October 2009 identified that ASS are highly likely to be present, and some were activated at the time of sampling (Esslemont & Iles 2015) – that is, both PASS and AASS were identified. In addition, assessment of soils further to the north, “further up the bank, and deeper in the soil profile” was also undertaken at the end of the 2015 dry season (October/November 2015), which “confirmed the presence and extent” of ASS in Coonjimba Billabong (Esslemont 2016).

The mapped areas of PASS in the Coonjimba Creek/Coonjimba Billabong area (from this site-wide GIS analysis) is consistent with the identification of PASS and AASS in Coonjimba Billabong (Esslemont 2016; Esslemont & Iles 2015) based on sample collection and analysis.

4 Discussion

Mechanisms by which PASS in the source areas develop into AASS, and subsequent pathways for the migration of acidification products to identified receptors, will vary with the specific catchment and also with the time of year (e.g. wet season versus dry season).

As indicated by site observations and historic data, surface water quality typically declines at the start of the wet season as solutes in sediments are flushed into surface water and groundwater begins to discharge to surface water as the shallow aquifers wet up. In the case of ASS, oxidation of PASS in the identified source areas to form AASS is most likely to have occurred towards the end of the dry season, particularly where sediments have dried and been exposed to oxygen. This is coupled with enhanced evapoconcentration of solutes, including oxidation products, in exposed soils and sediments at this time.

During the wet season, surface water quality typically improves following the ‘first flush’ with increasing rain, surface water levels, and resultant stream flows. During this period, further oxidation of PASS to form AASS would typically be limited as the sediments are no longer exposed. Seasonal variations in rainfall timing and extent can influence the ‘first-flush’ observations.

Discharge of groundwater with elevated sulfate concentrations (≥ 10 mg/L) to surface water may continue through both wet and dry seasons, depending on specific locations and hydrogeological settings. This may occur particularly in billabongs throughout the year, as they contain standing water during the dry season. Where discharge of this groundwater continues into wet areas that are not flushed and which remain waterlogged, there is the potential for ASS (in the form of PASS) to further develop.

For each of the source areas identified, including Coonjimba Billabong, pending confirmation of the presence of PASS, changes to the water balance and hydrodynamics that result in drying of waterlogged areas and associated oxidation of PASS sediments may lead to the development of AASS. The oxidation of PASS to form AASS results in release of sulfate, acid and potentially metals (dissolved and locally precipitated) to the surrounding environment.

During closure, mechanisms that may lead to drying and subsequent oxidation of PASS, and associated formation of AASS include, but are not limited to, the following:

- Reduction in the amount of water held in surface water features, particularly those that are permanently full and which will be drained as part of closure, allowing currently waterlogged sediments within surface water bodies and downstream surface waters to be exposed to oxidation.
- Reduction in groundwater elevations due to lowering of water levels in site features and cessation or reduction of irrigation at the site, potentially resulting in reduced waterlogging and subsequent exposure of sediments to oxygen in areas of groundwater discharge to surface water features.
- Changes to surface water management features on site, including potential for earthworks and decommissioning of ponds that would expose sediments to oxygen.

Other changes during closure that have the potential to affect the current hydrodynamics, which may therefore change the potential for ASS to develop in the first place, could include:

- Reduction in the amount of water with low sulfate concentrations released from the mine, leading to reduced flushing and dilution through the surface water systems.
- Reduction in the amount of water with higher sulfate concentrations released from the mine, leading to lower sulfate concentrations in surface water systems and/or groundwater.
- Removal or mitigation of potential sources of sulfate, leading to reductions in sulfate concentrations in groundwater.

Additionally, natural seasonal cycles of rainfall influence surface water and groundwater elevations and sulfate concentrations in surface water, and consequently influence the formation of PASS and AASS. Such seasonal variations, as well as longer-term climate change and the potential for drier wet seasons, may also affect PASS and AASS formation in the longer term.

Some areas of the site (e.g. Coonjimba Billabong) may act both as source sediments (location of ASS) and as receptors of acidification products. Additionally, migration of acidification products, including sulfate, to a receptor where the other key constituents (waterlogged conditions and organic matter) are present introduces the potential for ASS development at that receptor and for the receptor to, in turn, become a source of PASS.

In the event of AASS formation, the main pathways for the migration of oxidation and acidification products (acid, dissolved metals and sulfate) from source areas to receptors are likely to be via surface water flow. However, there is the potential for surface water to recharge groundwater, as well as for groundwater to discharge to surface water, depending on the time of year, amount of surface water present and local geology and topography. If recharge to groundwater from surface water were to occur after a drying phase, that would provide a source of acidification products to the shallow groundwater system.

5 Conclusion

Groundwater elevations and sulfate concentrations, along with surface water sulfate concentrations and previous sediment sampling results, were used to assess areas of potential ASS formation at the site, and to identify potential receptors in the event PASS are able to oxidise to form AASS. This has allowed development of this preliminary site-wide ASS conceptual model to inform closure; this paper focuses on mine-derived ASS in the Coonjimba Billabong area.

Sulfate concentrations in surface and groundwater at the site indicate that sulfate is potentially supplied from a number of operational areas and water management features. In several areas of the site, sulfate concentrations ≥ 10 mg/L in groundwater occur together with shallow groundwater (potential waterlogged conditions), or sulfate concentrations in surface water drainage lines and surface water bodies are ≥ 10 mg/L. In these areas, there is the potential for ASS to form. These areas have conservatively been considered to represent PASS or potential source areas, noting that the maximum, rather than the long-term average, sulfate concentration in groundwater or surface water has been considered.

It is assumed that sufficient organic matter is present in the environment to support the potential for ASS to form where sufficient sulfate and potential waterlogged conditions are present. However, there is a lack of data to confirm whether sufficiently reducing conditions persist to allow PASS formation, with the exception of limited sediment sampling conducted at specific areas of the site.

The approach presented here indicated a PASS source area along the Coonjimba Creek/Coonjimba Billabong alignment. Observed acidification events in Coonjimba Billabong were consistent with formation of AASS. Historic sediment sampling also identified the presence of both PASS and AASS along that alignment.

Comparison of data for three wet seasons and three dry seasons from 2010 to 2018 did not identify significant difference in the distribution of the potential source areas over time, other than those attributed to differences in data availability.

In Coonjimba Billabong, and elsewhere across the site, natural (including climate variations and changes) as well as mine closure–driven changes to the hydrodynamics have the potential to dry out these areas and/or expose PASS that may have formed. This would result in the potential for oxidation and release of acidification products including sulfate, acid and potentially dissolved metals to the surrounding environment as a result of the formation of AASS. AASS and its products have previously been identified at Coonjimba Billabong, including in 2015/16 and 2017/18.

In the event of AASS formation, the location of the source areas generally associated with surface water bodies means that surface water movements, and potentially shallow groundwater, could act as a pathway for transport of acidification products to receptors. However, potential pathways for the migration of AASS acidification products from PASS source areas to identified receptors will vary with the specific catchment, and also with the time of year. The main surface water receptors at the site, including Coonjimba Creek and Coonjimba Billabong, have the potential to be exposed to and impacted by oxidation of PASS to form AASS.

Uncertainties with this assessment are associated with the accuracy of the DEM-derived topographic surface, as well as the spatial distribution and interpolation of groundwater elevation and sulfate concentration data, particularly in areas with fewer groundwater monitoring bores. Uncertainties were also associated with variations in sulfate concentrations over time, particularly with respect to surface water. The maximum sulfate concentration was considered in order to provide a conservative assessment.

This site-wide approach to identifying areas of likely PASS formation allows targeted investigation and sampling, and planning to evaluate impacts of likely future changes in hydrodynamics as closure progresses, informing remediation and/or management measures, both under current conditions and during closure.

Acknowledgement

The authors wish to acknowledge Energy Resources of Australia Ltd who funded this assessment, particularly Elmarie Fagan, Michelle Iles, David Staggs and Sarah Reid.

References

Baldwin, DS 2017a, *Understanding Acid Sulfate Soils in Coonjimba Billabong*, prepared for the Supervising Scientist Branch, the Department of Environment and Energy by Rivers and Wetlands, May 2017.

Baldwin, DS 2017b, *Review of Supervising Scientist Branch Rehabilitation Standard for Sulfate,* prepared for the Supervising Scientist Branch, the Department of Environment and Energy by Rivers and Wetlands, August 2017.

CSIRO 2011, *Australian Soil Resource Information System (ASRIS)*, viewed 16 December 2019, http://www.asris.csiro.au/mapping/viewer.htm

Environment Protection and Heritage Council and Natural Resource Management Ministerial Council 2011, *National Guidance on Acid Sulfate Soils: National Guidance for the Management of Acid Sulfate Soils in Inland Aquatic Ecosystems 2011*, Canberra.

Esslemont, G & Iles, M 2015, *Coonjimba Billabong Water Quality Assessment and Stage 1 Assessment of Acid Sulfate Soils,* Energy Resources of Australia Ltd.

Esslemont, G 2016, *Coonjimba Billabong Stage 2 Assessment of Acid Sulfate Soil*, Energy Resources of Australia Ltd.

Hart, BT, Ottaway, EM & Noller, BN 1987, 'Magela Creek System, Northern Australia I. 1982-83 wet-season water quality', *Australian Journal of Marine and Freshwater Research*, vol. 38, pp. 261–288.

Noller, BN & Hart, BT 1993, 'Uranium in sediments from the Magela Creek catchment, northern territory, Australia', *Environmental Technology*, vol. 14, no. 7, pp. 649–656.

SLR 2018, *Contaminated Soil Investigation, Land Application Areas, Ranger Uranium Mine*, report dated July 2018.