5 Key Knowledge Needs Supporting Studies

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Below are key terms that are used in this section.

Key term	Definition
Bioregion	An ecologically and geographically defined area that is smaller than a biogeographical realm but larger than ecoregion or an ecosystem, in the World Wildlife Fund classification scheme.
Becquerels	The Becquerel (Bq) is the SI derived unit of radioactivity. One Becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.
Bininj	Aboriginal (Australian) people of Western Arnhem land in the Northern Territory.
Constituents of Potential Concern	Chemical elements identified by the Supervising Scientist Division as being of potential concern to the receiving environment
Electrical conductivity	Abbreviated to EC. Electrical conductivity is a measure of how well a material accommodates the transport of electric charge.
Gamma Radiation	Ionizing electromagnetic radiation emitted by a radionuclide during radioactive decay
Gray	The Gray (Gy) is a SI derived unit of ionizing radiation dose. One Gray is defined as the adsorption of one joule of radiation energy per kilogram of matter.
Hydrolithologic Unit	A grouping of soil or rock units or zones based on common hydraulic properties.
Georgetown Billabong	The statutory surface water monitoring point for Georgetown Billabong, which is located downstream of Corridor Creek and the Corridor Creek wetland filter.
Groundwater conceptual model	Calibrated numerical groundwater flow model encompassing all hydrogeologic elements governing groundwater flow and transport at the Ranger Mine to provide the foundation for simulating groundwater flow and transport from all mine sources to potential receptors under post-closure conditions.
Land Application Area(s)	Abbreviated to LAA. An area on the RPA used as an evapotranspiration disposal method polished and unpolished pond water from the constructed wetlands filters and, more recently, permeates from the water treatment plants. However, irrigation of unpolished pond water ceased at the end of 2009. The concept of land application is to retain metals and radionuclides in the near-surface soil profile.
Land Disturbance Permit	An ERA permit required prior to undertaking any work on the RPA that may lead to surface disturbance, for example ground breaking, surface disturbance, clearing etc.
Long Lived Alpha Activity	Abbreviated to LLAA. The presence, generally in airborne dust, of any of the alpha emitting radionuclides in uranium ore, except for the short-lived alpha emitting radon decay products.
MBL Zone	A hydrolithologic zone of relatively higher permeability to the south east of Pit 1 identified through testing and pumping of bore MB_L.
Magela Creek downstream	Abbreviated to MG009. MG009 is Ranger downstream statutory or compliance surface water monitoring point. It is located on the Magela Creek,

Key term	Definition
	downstream of Ranger operations.
Magela Creek upstream	Abbreviated to MCUS. MCUS is the upstream statutory surface water monitoring point, location on the RPA.
Mirarr	Mirarr is a patrilineal descent group. Descent groups are often called 'clans' in English and kunmokurrkurr in Kundjeyhmi language. There are several Mirarr clans with each one distinguished by the language they historically spoke (e.g. Mirarr Kundjeyhmi, Mirarr Urningangk, Mirarr Erre). The Mirarr are the Traditional Owners of the land encompassing the RPA.
Minesite Technical Committee (MTC)	A of the Working Arrangements for the Regulation of Uranium Mining in the Northern Territory dated 30 May 2005, is tasked with: Reviewing proposed and existing approvals and decisions under NT legislation Reviewing technical information in relation to Ranger Mine, including monitoring data and environmental performance Collaboratively developing standards for the protection of the environment Developing strategies to address emerging issues The MTC consists of the representatives of the Department of Industry, Tourism and Trade, the Supervising Scientist, ERA and the Northern Land Council. Representatives of the Commonwealth Department of Industry, Science, Energy and Resources may also attend MTC meetings.
Pit 1	The mined out pit of the Ranger #1 orebody, which is used as a tailings repository. Mining in Pit 1 commenced in May 1980 and was completed in December 1994, after recovering 19.78 million tonnes of ore at an average grade of 0.321%.
Pit 3	The mined out pit of the Ranger #3 orebody, which is currently being backfilled with tailings. Open cut mining in Pit 3 commenced in July 1997 and ceased in November 2012.
Plant Available Water	Abbreviated to PAW. The amount of water that can be stored in a soil and be available for growing crops.
Processing	Processing is the mining term to describe all phases of the ore treatment from milling through to the final product packaging of uranium oxide.
Radon decay products or radon progeny	The short-lived radioactive decay products of radon-222. This includes the decay chain up to, but not including lead-210, namely polonium-218 (sometimes called radium A), lead-214 (radium B), bismuth-214 (radium C) an dpolonium-214 (radium C).
Ranger Project Area	Abbreviated to RPA. The Ranger Project Area means the land described in Schedule 2 to the Commonwealth *Aboriginal Land Rights (Northern Territory) Act 1976.*
Reference level	Abbreviated to RL. Denotes a specific elevation relative to mean sea level and is regularly used to identify the height or depth of plan or mine infrastructure – e.g. the height of the TSF or depth of Pit 3.
Retention Pond	A large constructed storage facility that collects runoff and stores pond water for treatment (RP2 & RP6) or release water post-treatment (RP1).

Key term	Definition
Sievert	The Sievert is the unit of absorbed radiation dose, taking into account the differing biological effects of different types of radiation.
Tailings dam	Surface dam used to hold tailings and process water at Ranger. Commonly referred to as "tailings storage facility" or "TSF" in other ERA material. The tailings dam is one of currently three tailings storage facilities at Ranger, the others being Pit 1 and Pit 3.
U_3O_8	The most stable form of uranium oxide and the form most commonly found in nature. Uranium oxide concentrate is sometimes loosely referred to as yellowcake. It is khaki in colour and is usually represented by the empirical formula U_3O_8. Uranium is normally sold in this form.
Waste rock	The mineral waste produced in the mine but is stockpiled due to its low grade i.e. material which does not enter the processing plant. For example, 1s waste rock is typically material that has a grade of less than 0.02% U_3O_8; 2s waste rock (or low-grade ore) is typically material that has between 0.02% and 0.12% U_3O_8.
Wetland filter	A constructed biological filter system that is designed for final treatment of release water and is monitored to ensure water quality meets regulatory criteria for disposal.

ABBREVIATIONS & ACRONYMS

Below are abbreviations and acronyms that are used in this section.

Abbreviation/ Acronym	**Description**
AALL	Annual Additional Load Limits
AHD	Australian Height Datum
ALARA	As Low as Reasonably Achievable
ALARP	As Low as Reasonably Practicable
ARR	Alligator Rivers Region
ARRTC	Alligator Rivers Region Technical Committee
ASS	Acid Sulfate Soils
AWBM	Australian Water Balance Model
BDL	Below Detectable Limit
BTV	Background Threshold Value
CCWLF	Corridor Creek Wetland Filter
CDF	Cumulative Distribution Function
CDU	Charles Darwin University
CEC	Cation Exchange Capacity
CM	Conceptual Model
COPC/COPCs	Constituent of Potential Concern/ Constituents of Potential Concern
CPT	Cone Penetration Test
CRE	Conceptual Reference Ecosystem
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CVs	Community Values
DEM	Digital Elevation Model
EC	Electrical Conductivity
ENSO	El Niño Southern Oscillation
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
ER	Environmental Requirements
ERA	Energy Resources of Australia Ltd
ERISS	Environmental Research Institute of the Supervising Scientist
ERM	Environmental Resource Management
ESR	Ecosystem Restoration Rehabilitation Theme
ET	Evapotranspiration
FEPs	Features, Events and Processes
GAC	Gundjeihmi Aboriginal Corporation
GCBR	Georgetown Creek Brockman Road

Abbreviation/ Acronym	Description
GCMBL	Georgetown Creek Mine Bund Leveline
GCT2	Georgetown Creek Tributary 2
GDE	Groundwater Dependent Ecosystem
GTB	Georgetown Billabong
GW	Groundwater
GWT	Groundwater Table Level
HDS	High Density Sludge
HLU	Hydrolithologic Unit
IAEA	International Atomic Energy Agency
ICRE	Initial Conceptual Reference Ecosystem
IOD	Indian Ocean Dipole
ISAM	Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities
ISWWG	Independent Surface Water Working Group
KKNs	Key Knowledge Needs
KNPS	Kakadu Native Plants Pty Ltd
LAA	Land Application Area
LAI	Leaf Area Index
LEM	Landform Elevation Model
MBO	Monosulfidic Black Ooze
MCDS	Magela Creek Downstream
MCP	Mine Closure Plan
MJO	Madden-Julian Oscillation
MTC	Minesite Technical Committee
NAQS	Northern Australia Quarantine Strategy
NESP	National Environmental Science Program
NLC	Northern Land Council
NP	National Park
NT	Northern Territory
OPSIM	Operational Simulation Model
P50, P70, P90	50th percentile, 70th percentile, 90th percentile
PASS	Potential Acid Sulfate Soils
PAW	Plant Available Water
PDF	Probability Distribution Function
PEST	Parameter Estimation Tool

Abbreviation/ Acronym	Description
PFS	Prefeasibility Study
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PPA	Plant Processing Area
PSD	Particle Size Distribution
PTF	Pit Tailing Flux
Pvalue	Probability Value
R3D	Ranger 3 Deeps
Ranger GW UA	Predictive Ranger Groundwater Model with Uncertainty Analysis
RCM	Ranger Conceptual Model
REW	Relative Extractable Water Content
RP1	Retention Pond 1 – also denotes other retention ponds used on site – e.g. RP2, RP3, RP6
RPA	Ranger Project Area
RSWM	Ranger Surface Water Model
SAQP	Sampling Analysis Quality Plan
SBES	Single Beam Echosounder
SBT	Soil Behaviour Type
SERP	Species Establishment Research Program
SPA	Soil-Plant-Atmosphere
SQG-H	Sediment Quality Guideline High Values
SQGV	Sediment Quality Guideline Values
SSB	Supervising Scientist Branch
SW	Surface Water
SWM	Surface Water Model
TAN	Total Ammoniacal Nitrogen
TARP	Trigger Action Response Plan
TLF	Trial Landform
TPM	Total Particulate Metals
TPWC Act	*Territory Parks and Wildlife Conservation Act 1978 (NT)*
TSF	Tailings Storage Facility
TSS	Total Suspended Solids
UA	Uncertainty Analysis
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency

Abbreviation/ Acronym	Description
UTL	Upper Tolerance Limits
VAF	Vulnerability Assessment Framework
WA	Western Australia
WAR	Weak Aqua Regia

5 KEY KNOWLEDGE NEEDS

This chapter provides an overview of the environmental setting of the Ranger Mine and a summary of completed and planned studies that are informing the closure strategy. The chapter provides the context to planning mine closure and a summary of a substantial knowledge base that has been accumulated by Energy Resources of Australia Ltd (ERA) and stakeholders from more than 40 years of monitoring and research investigations of the site and surrounding environment.

This section has been structured around the Key Knowledge Needs (KKNs) and associated themes:

- Landform;
- Water and Sediment;
- Health Impact of Radiation and Contaminants;
- Ecosystem Restoration; and
- Cross-theme.

The KKNs outline the relevant knowledge and tools required, primarily through research and monitoring, to ensure:

- the environment and people of the Alligator Rivers Region (ARR) are protected from the impacts of uranium mining; and
- upon reaching end-of-life, uranium mines in the ARR are rehabilitated to the standard required by the Commonwealth and the community.

The KKNs were identified via an ecological risk assessment completed by CSIRO and ERA in collaboration with the Supervising Scientist and other key stakeholders (Pollino *et al.* 2013; Bartolo *et al.* 2013).

The KKNs have been endorsed by the Alligator Rivers Region Technical Committee (ARRTC) and are revised and updated from time to time as research to answer KKNs is completed, and new knowledge needs arise. A formal amendment process, including review by ARRTC and the Ranger Minesite Technical Committee (MTC), has been developed to ensure that any changes to the KKNs are undertaken in consultation with all relevant stakeholders.

The Ranger mine has been the subject of extensive studies and monitoring programs based on the KKNs, which have been presented through various community and stakeholder consultation processes and statutory reports such as annual environment reports, mining management plans, wet season reports and groundwater reports.

A full list and description of the KKNs as published by the Supervising Scientist Branch (SSB) in November 2020 (Supervising Scientist 2020a) within their individual themes is provided in Appendix 5.1. Some KKNs are addressed by ERA, some by the SSB, and others by both. The sections below discuss the KKNs being addressed by ERA and those addressed by both ERA and SSB.

5.1 Landform theme

This section discusses the knowledge base of the physical environment and the Landform themed KKN studies.

5.1.1. Background of physical environment

Historical land use within the Alligator Rivers Region (ARR) has included indigenous occupation, buffalo hunting, missions, pastoral grazing, agriculture, mining exploration, uranium mining and tourism (Levitus, 1995). Contact between the region's Aboriginal people and other cultures increased from around the 17th century and a more permanent non-indigenous presence was evident from the late 1800s (ERA, 2014b).

The Alligator Rivers Region is divided into several land tenures, and encompasses parks, mining and native title lands (Figure 5-1). The Magela catchment is located within the ARR, with the majority of its footprint within the Kakadu National Park, a World Heritage listed area and Ramsar site.

5.1.1.1 Climate

The climate of the Alligator Rivers Region and the Ranger Mine is dominated by a seasonal wet-dry monsoon cycle. The wet season extends from about October through to April in the Northern Territory (BOM, 2019). Active monsoon periods may occur at any time during this period, however the initial monsoon onset, defined by the reversal of the winds, normally occurs in late December around Darwin (BOM, 2019).

The monsoon exhibits inter-annual and intra-seasonal variability and is strongly linked to effects of the El-Niño Southern Oscillation and Madden-Julian Oscillation (Trenberth et al. 2007). Whether it is in El Niño or La Niña can have a significant impact on monsoonal variability (BOM, 2019). La Niña typically means earlier-than-normal monsoon onset, while El Niño is often associated with less than average rainfall during the monsoon season (BOM, 2019). The Madden–Julian Oscillation can be an important influence on the timing of the active and inactive monsoon phases (BOM, 2019).

The tropical cyclone season threatens northern Australia every year during the monsoonal wet season (CSIRO, n.d.). Increased cyclone activity is associated with La Niña years, whilst below normal activity has occurred during El Niño years (Kuleshov & de Hoedt, 2003, Plummer *et al.* 1999). When cyclones and tropical lows are present, the Alligator Rivers Region can experience high winds and rainfall.

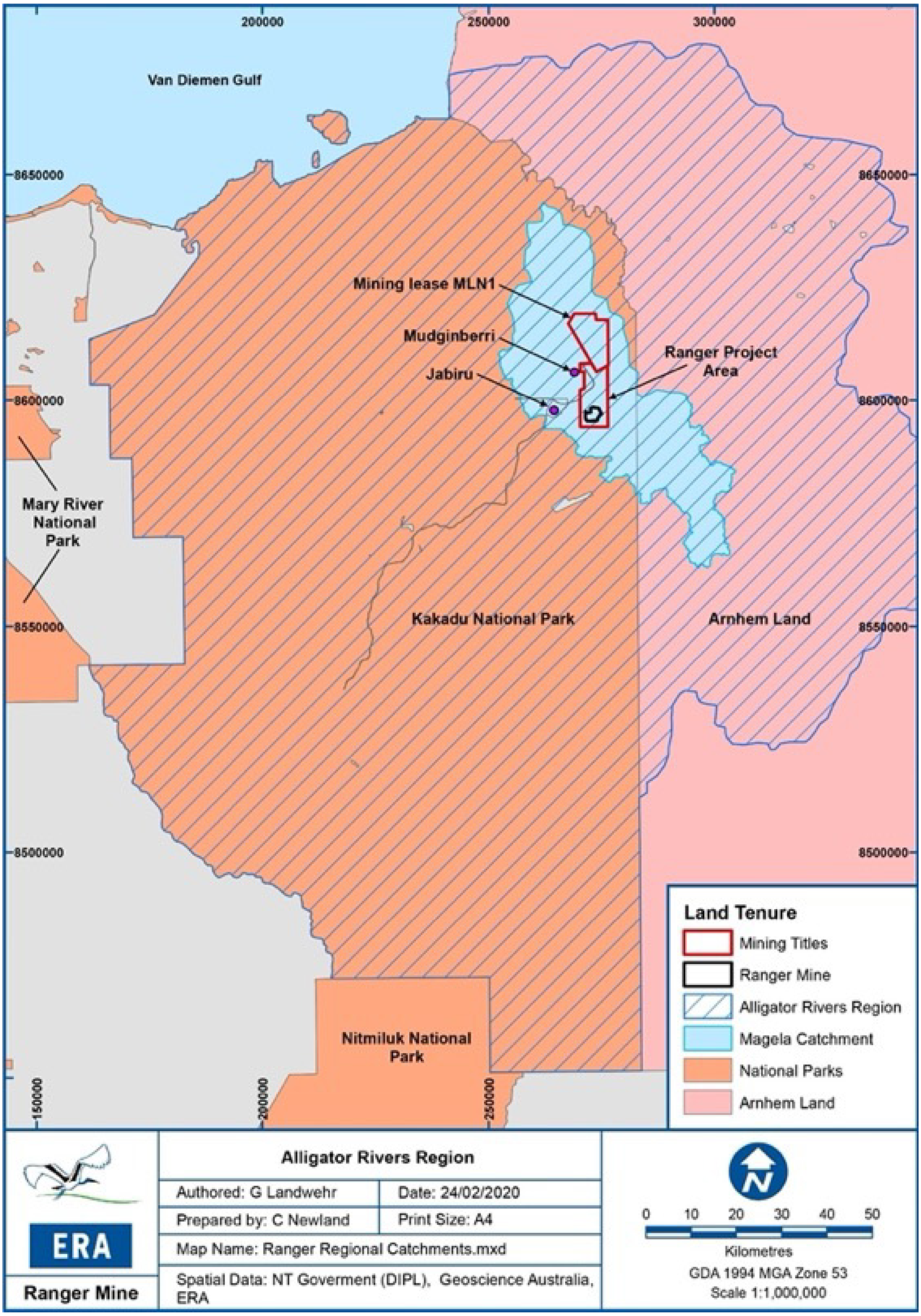


Figure 5-1: Land tenures in the Alligator Rivers Region

The wet season is typically dominated by westerly winds, whilst the dry season is dominated by easterly to south-easterly winds. Seasonal temperatures and rainfalls at Jabiru Airport station 014198 from the Bureau of Meteorology (BOM) between 1971 and 2020 displayed a temperature average of 29.7 °C for the time period 1971 to 2020 with annual rainfall of 1,553.7 mm (Figure 5-2).

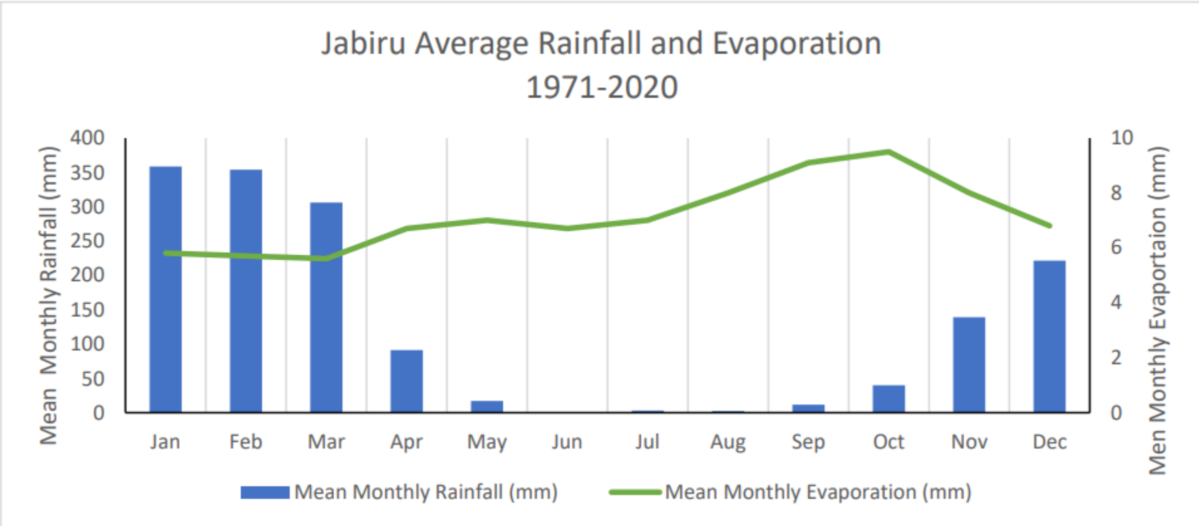


Figure 5-2: Jabiru average rainfall and evaporation 1971 to 2020 (Source: CDM Smith, 2021)

Average climatic conditions at Jabiru Airport are presented in Table 5-1.

The region has a hot climate, with average maximum temperatures typically ranging from just under 32 °C in June and July to approximately 38°C in October (BOM, 2022). Average monthly pan evaporation ranges from 295 mm in October to 160 mm in February (Chiew & Wang, 1999). Annual pan evaporation exceeds rainfall by approximately 1,000 mm. Jabiru Airport hottest annual day recorded was 41°C in October 2021 (BOM, 2022).

Table 5-1: Statistical climate data for Jabiru Airport from June 2021 to June 2022 (BOM, 2022)

Parameter	**Value**	**Month**
Mean maximum temperature	38.7ºC	October 2021
Mean minimum temperature	17.1 ºC	July 2022
Mean Maximum relative humidity	96 %	February 2022
Mean minimum relative humidity	21.9%	August 2021
Maximum average daily evaporation*	9.5 mm	October
Minimum average daily evaporation*	5.6 mm	March
Annual average daily evaporation*	7.2 mm	
Annual evaporation*	2,628 mm	
Mean annual rainfall	1,554 mm	

Parameter	Value	lonth
Maximum average daily evapotranspiration	8.7 mm	;eptember 2021
Minimum average daily evapotranspiration	0.7 mm	)ecember 2021
Annual evapotranspiration	2354.7 mm	

Source BOM 2019b

**these values are averages from data available between 1973-1990 only*

5.1.1.2 Topography

The Ranger Mine lies on plains to the north of the Mount Brockman Massif, an outlier of the Arnhem Land Plateau. The plains are generally flat with numerous swamps rarely more than 45 m above sea level.

South and east of the Ranger Mine, the Arnhem Land Plateau escarpment rises to between 200 and 300 m above sea level (Figure 5-3). Approximately 3.5 km south of Ranger Mine is Mount Brockman, rising 170 m above the plain (Figure 5-3 and Figure 5-4).

The Ranger Mine is influenced by four land surfaces to varying degrees:

The Mount Brockman Massif – This is a quartz sandstone outlier located to the south of the mine. Its steep escarpment and skeletal soils forms part of the watershed of the Magela and Gulungul creek systems. It's resistance to erosion and low soil moisture retaining capacity readily accumulates large volumes of localised rainfall in the surface drainage networks causing rapid flood responses in creeks and drainage lines. Water infiltrates joints and fissures, contributing to groundwater recharge and the formation of springs and swamps, some of which continue to discharge well into the dry season many months after the last rainfall.

The Koolpinyah Surface - corresponding to the plains on which the Ranger Mine is located, it is characterised by level, rolling or dissected lowlands. The surface is deeply weathered bedrock partly overlain by Late Tertiary to Recent sediments derived from the erosion of Cretaceous, Middle Proterozoic and Lower Proterozoic formations. These are mantled by ferruginous soils and ferricrete crusts.

Alluvial plains - formed by the flow of numerous rivers across the Koolpinyah Surface. The Magela and Gulungul Creeks flow northerly from the Mount Brockman Massif dissecting the Ranger Project Area (RPA). Alluvial materials have been deposited by the creek systems forming the flat Magela floodplains to the northwest. Coarse, sandy Late Tertiary and Quaternary alluvial deposits cover part of the plains. These occupy channels of diverted streams and anabranches.

Coastal plains - extending north of the Koolpinyah Surface are flat, poorly drained and penetrate far inland along the broader river valleys.

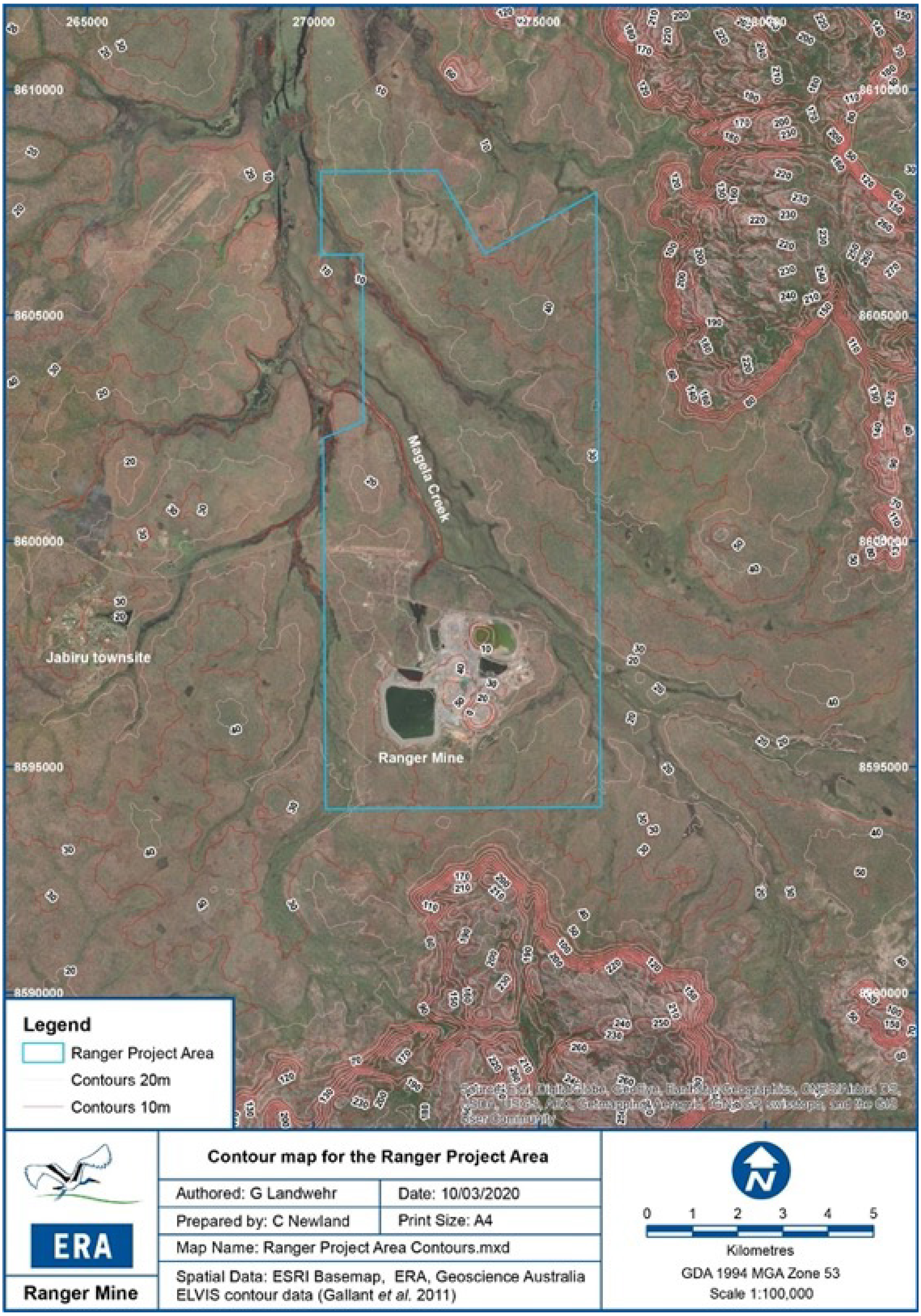


Figure 5-3: Contour map of the RPA and surrounds

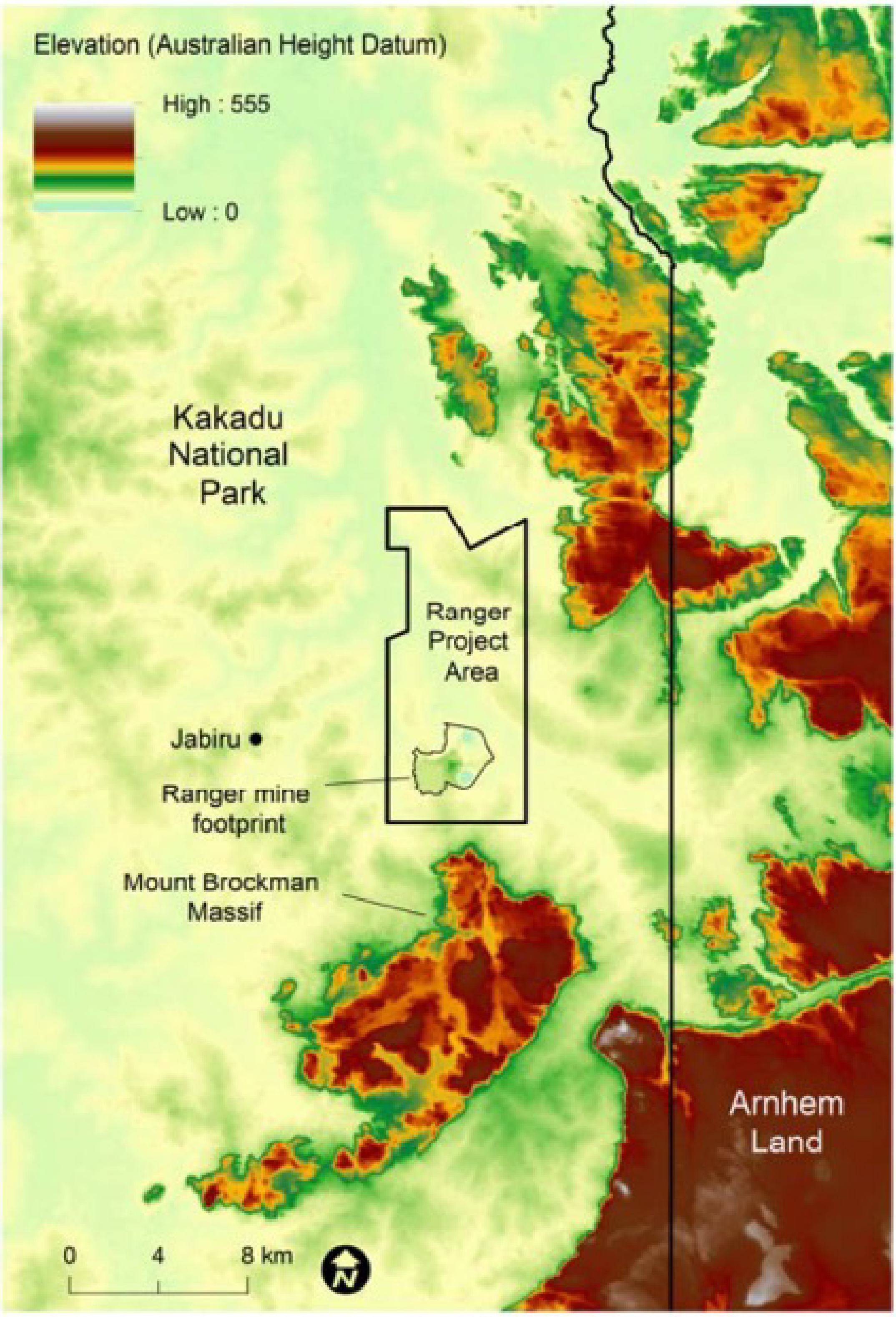


Figure 5-4: Elevation of RPA and the surrounding region

5.1.1.3 Soils

The type (class) and distribution of soils across the land surfaces of the RPA are influenced by geology, topographic position and seasonal changes to the amount of moisture in the ground (Story *et al.* 1969, Chartres *et al.* 1991 and Hollingsworth *et al.* 2005). The four main geomorphic units have associated soil types, which in turn influence vegetation assemblages.

Colour variation in the soils is primarily a product of differential drainage and the resulting mineralogy of the component iron oxyhydroxides. Stony layers within the soil profile may represent the boundary between residual and non-residual (e.g. transported) materials.

Soils are non-saline and non-sodic and can be gravelly, with clasts of quartz, ferricrete and ferruginised rock. Kaolinitic minerals are common and illite, together with minor chlorite, can be inherited from underlying Cahill Formation schists (see also 5.1.1.4). The cation exchange capacity (CEC) is generally moderate to low in the near-surface horizons and there are low levels of organic materials and nutrients. Table 5-2 provides a brief description of the soil characteristics associated with the Ranger Mine, which are also depicted in Figure 5-5.

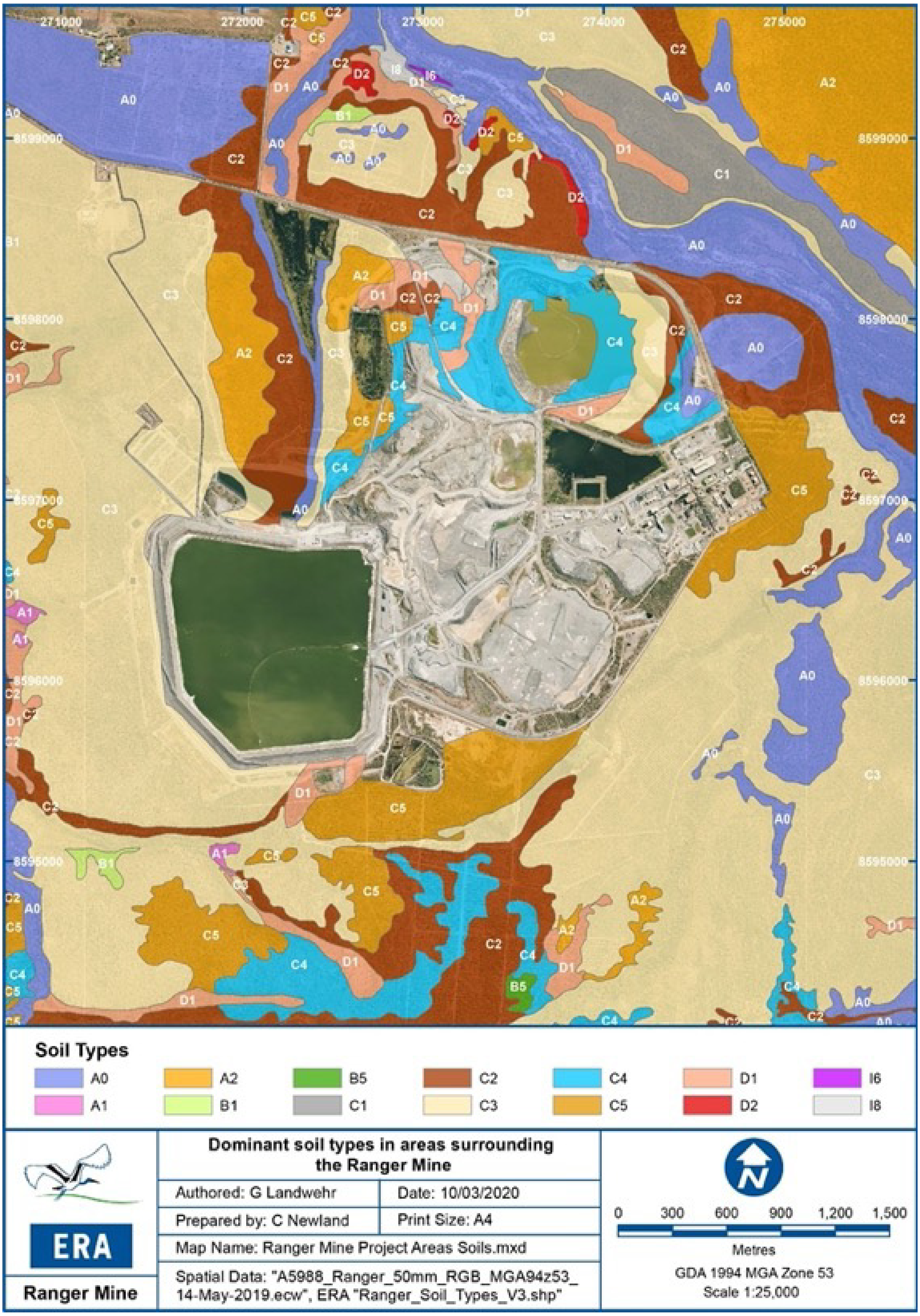


Figure 5-5: Dominant soil types in areas surrounding the Ranger Mine

Table 5-2: Key to soil characteristics locations around the Ranger Mine shown in Figure 5-5

Map unit (Hollingsworth, 1999)	Map unit description
A0	Organic horizon, sand/loamy surface.
A1	Deep pale brown, yellow and yellowish brown sands, sand/loamy sand surface and generally non-mottled single grained and sandy throughout. Variations include: light yellowish brown and dark brown; and yellow brown, yellow and faint red brown mottles.
A2	Deep yellowish brown to very pale brown; highly permeable, generally non-coherent sand, bottoming onto ferruginous and quartz gravel and stone. Profiles may vary: depths may extend from 100 cm; *in situ* gravels may occur within the lower horizons and the firm clay clod nodules may become hard; 10-15 mm, prominent, red mottles.
B1	Deep brownish yellow to yellowish brown massive gravel-free earthy sands with minor mottles common at depth. Profile variations include different degrees of mottles at depth, and on rare occasions, overlie a buried zone.
B5	Shallow, gravelly, brown to yellowish brown, massive, earthy sands. Variations may have light brownish yellow and minor light grey horizons at depth, textures may not be heavier than loamy sands.
C1	Moderately deep to deep yellowish brown to light yellowish brown, sandy earths with no gravel present. No profiles bottom onto laterite pavement and gravel pans. Profiles may be deeper, lighter in chroma and increasing in texture to sandy light clay.
C2	Moderately deep to deep sandy loams over a gravel pan.
C3	Moderately deep to deep, dark yellowish brown to yellowish brown, sandy earths with gravel throughout, bottoming onto ferruginous gravel.
C4	Shallow yellowish brown to brownish yellow sandy earths bottoming onto dense ferruginous gravel and stone. Mottles may occur. Variations include distinct, grey and prominent, red mottles in B-horizon.
C5	Shallow brown to yellowish brown gravelly sandy earths over a ferruginous and quartz gravel pan. Variations include colours to yellowish brown; depth varying to 30 cm; and gravel contents ranging between 5% and 50% within the profile.
D1	Deep light brownish grey to grey loamy earths, massive.
D2	Deep to moderately deep yellowish brown to pale brown gravel-free loamy earths over a gravel/stone hardpan. Variations include textures to coarse sandy clay at depth; colours from pale brown to grey; and mottles where sites are ponded.
I6	Deep profiles of grey to brown sands and earthy sands over a generally mottled light grey to pale brown clay and sandy clays.
I8	Profiles are very dark grey to greyish brown loamy earths and sandy earths over a brown to pale brown earthy sand, with mottles common. Considerable variation was found with all soil characteristics.

Field investigations of soil hydraulic conductivity (Table 5-3) have identified that individual soil horizons range from very permeable, due to naturally occurring piping, to impervious. The A and B horizons typically support a shallow, unconfined surface aquifer that overlays a low conductivity C horizon (Hollingsworth, 1999). This unit is underlain by an impervious unfractured bedrock D horizon. The unconfined aquifer is observed to recharge both the A and B horizons during the wet season, to the point where water expresses as baseflow in lower areas of the topography and drainage lines. During the dry season, the upper A and B soil horizons can be entirely dry down to the confining C horizon.

Hydraulic conductivities in the A and B horizons can range from 0.01 to 10 m/day (Chartres *et al.* 1991), whilst the range of hydraulic conductivities of underlying confining C and D horizons are indicative of low transmissive hydrolithologic units (HLUs) (INTERA 2016).

Table 5-3: Soil hydraulic conductivity

Horizon	Hydraulic conductivity, K
Alluvial sands and 'A' horizon	10 to 1 m/day
Bleached zone 'B' horizons	1 to 0.1 m/day
Saprolite 'B' horizon	2 to 0.01 m/day
Fractured rock 'C' horizon	0.1 to 0.001 m/day
Unfractured rock 'D' horizon	0.05 to 0.001 m/day

Depending on vegetation cover and the presence or absence of a surface rock lag, erosion is highly seasonal and is dominated by sheet erosion in the wet season. At the beginning of the wet season, understorey cover can be sparse due to preceding dry season conditions and vegetation loss due to fire. The variability of vegetation cover contributes to the impact of rain splash erosion. Where grasses and leaf litter remain, these assist in protecting the soil from early wet season rain splash erosion. However, as rainfall intensifies with the development of monsoonal troughs, other erosion processes become dominant including floods, sheet flow runoff, high winds and cyclones. Overland sheet flow, and gully erosion by streams increase and are particularly severe in areas where vegetation is disturbed. Further detail on these erosion processes are provided in Table 5-4.

Table 5-4: Typical erosion susceptibility of soils

Soil type	Erosion potential
Deep siliceous sands lacking structure	Vulnerable to rain splash and overland flow erosion but are less vulnerable if covered by vegetation
Red earths well drained with good structure	Characteristic of areas with minimal erosion
Yellow earths less well drained than the red earths	More erodible, particularly if dispersive
Duplex soils with texture contrast and massive impermeable B horizons which form aquicludes	Most erodible, very vulnerable to slope wash and gully type erosion, due to dispersive

Soil type	Erosion potential
when saturated, weakly structured topsoils	nature
Alluvial soils	Generally, recipients of other soils but prone to erosion along breaks of slope
Shallow skeletal soils	Protected by surface layer of gravel but, if this is disturbed, erosion can be rapid

5.1.1.4 Geology and mineralisation

The Ranger uranium deposits are located in the East Alligator region of the Paleoproterozoic Pine Creek Inlier. Mineralisation is contained in chlorite-altered metasediments of the Lower Cahill Formation (age approximately 1,870 million years) which overlie an older basement complex of Archaean granitoid gneisses and schists known as the Nanambu Complex (age approximately 2,470 million years). Unconformably overlying rocks of both the Lower Cahill Formation and the Nanambu Complex are sandstones and conglomerates of the Kombolgie Sandstone (age approximately 1,650 million years) which forms part of the Katherine River Group of the McArthur Basin.

Uranium mineralisation occurs within a northerly trending and gently easterly-dipping belt of Lower Cahill metasediments, directly east of the Nanambu Complex (Figure 5-6). The Lower Cahill Formation has been informally subdivided into three units. All uranium ore occurs in chlorite schists referred to as the Upper Mine Sequence schists. These overlie a sedimentary sequence dominated by carbonates and dolomites (Lower Mine Sequence) and are themselves overlain by mica schists with local horizons of amphibolite (Hanging Wall Schists), as shown in Figure 5-6.

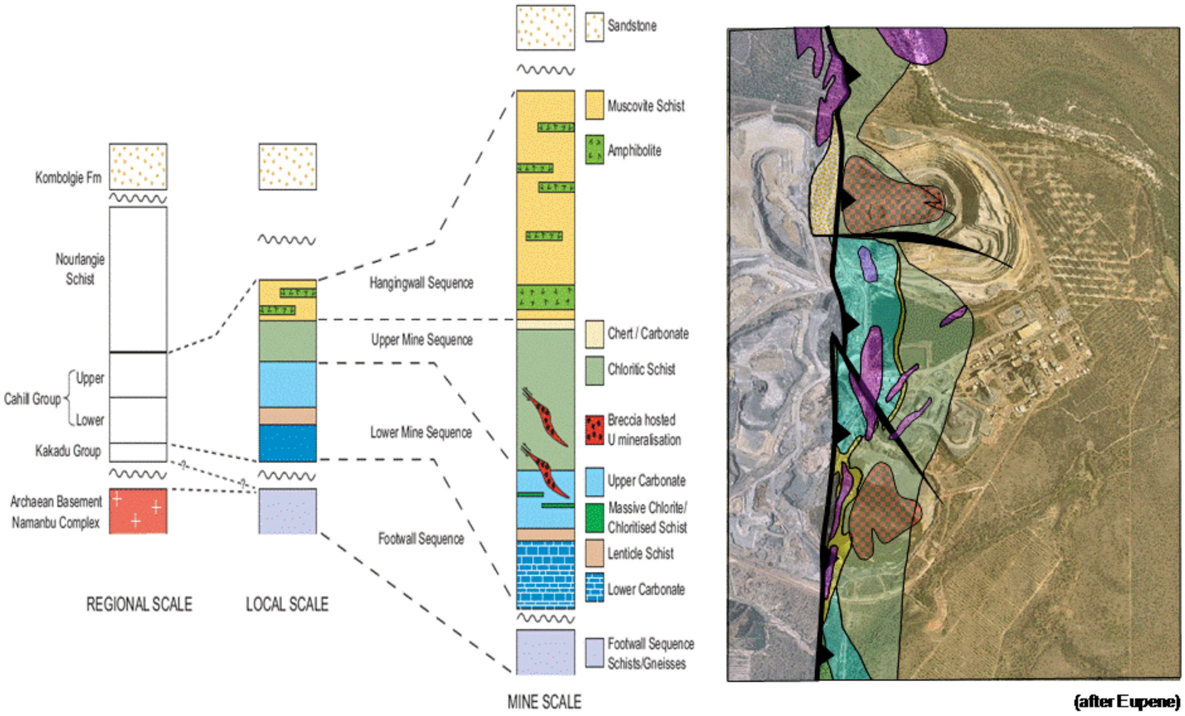


Figure 5-6: Stratigraphic sequence from regional to mine scale and corresponding geological map of the immediate area of the Ranger Mine orebodies

5.1.1.5 Geomorphology

The Magela floodplain, which lies 15 km downstream of the Ranger Mine, represents a catchment of 815 km^2 and joins with the floodplain of the East Alligator River.

The Magela floodplain is very flat with elevation changes of less than 0.7 m over more than 40 km. Although the inflow to the floodplain is well defined, waters continue to disperse across poorly or undefined channels until eventually discharging into the meandering channel of the East Alligator River. Average flow rates during a wet season, depending on channel definition, have been estimated at 0.02 – 0.05 m per second (Roos & Williams 1992). Wet season vegetative growth within the floodplain proper accelerates quickly with the onset of the wet season and has a significant effect upon flow rates. Roos & Williams (1992) demonstrated that the aquatic vegetation retained flood waters in the lead up to, and in the period immediately after, the highest wet season flow.

The pattern of sediments accumulated in the Magela floodplain has been examined using radionuclide analysis. Wasson (1992) found that 90 percent of the sediments transported by Magela Creek were deposited within the first 18 km of the floodplain. The rest of the floodplain sediments are sourced from smaller catchments that enter the floodplain further down the Magela Creek catchment. It was also found that Magela Creek has had no significant influence on sediment deposition below Jabiluka Billabong for the last 3,000 to 4,000 years.

5.1.2 LAN2 Understanding the landscape-scale processes and extreme events affecting landform stability

KKN title	Question
LAN2. Understanding the landscape-scale processes and extreme events affecting landform stability	LAN2A. *What major landscape-scale processes could impact the stability of the rehabilitated landform (e.g. fire, extreme events, and climate)?*

5.1.2.1 Extreme natural events and the stability of tailing repositories at Ranger Uranium Mine, Northern Territory (NT)

This study identified and explored the extreme natural events which might affect the stability and longevity of the three potential tailings repositories and violate the safe storage of mill tailings. The three tailings repository sites examined were the below-grade Pit 1 and Pit 3 and the above-grade Ranger Water Dam (RWD, formerly the Tailings Storage Facility[2]).

The potential extreme natural events considered within the study included probable maximum precipitation (PMP), probable maximum floods (PMF), wind, drought, fires, erosion, sea level change, meteorite impact, seismic events, tsunami, volcanic eruptions, and mass failure. At the time of the study (1996), records of natural hazard magnitude and frequency spanned only a few decades for the Northern Territory. There was little certainty about the probabilities of extreme events and their potential consequences in the next 1,000 years or so, with estimates of the magnitude of 1:1,000 year events a matter of opinion. The probabilities of larger events, 1:10,000 to 1:20,000 years, would occur in a 1,000 year period range from 4.9 to 9.5%. The study therefore considered that Maximum Credible Events will occur in the 1,000 years under assessment and recognised that the background level of both atmospheric and geophysical extreme events fluctuate with time.

Table 5-5 summarises the existing knowledge of the likelihood of a wide range of extreme events and their potential consequences at Pit 1, Pit 3, and the RWD. Table 5-6 summarises the significant hazards and consequences for each of the three tailings repository options.

No hazards fell into the two highest concern categories, and at the next highest level the hazards of concern were all in relation to the RWD. Pit 1 and Pit 3 had identical hazards that were determined to require further consideration of risk reduction strategies.

For most extreme events there is little to choose between the potential consequences possible at the three sites. At the RWD the potential consequences of hazards such as drought, fire, tree throw, were demined to be of higher concern than at Pit 1 and Pit 3 because of the hazards potential to exacerbate erosion. The key difference between the three areas, is that the RWD is subject to a wider variety of natural hazards at a higher level of concern than at Pit 1 and Pit 3.

[2] The Tailings Storage Dam and Tailings Dam are former names of the Ranger Water Dam

Table 5-5: Extreme event likelihood and consequence summary for tailings repositories

Potential hazard	Likelihood of occurrence in 1,000 years[3]	Potential severity of consequence[4]			Confidence in estimates of occurrence and consequences[5]
		Pit 1	Pit 3	Ranger Water Dam	
PMP or near PMP events	M	L	L	L – M	M
PMF or near PMF events	M	N	M	N	M
Tree throw	E	N	N	L	L
Wind erosion	M	N	N	L	L
Cyclonic winds	M – H	N	N	M	M

[3] The scale is used for likelihood of occurrence unless better estimates are available:

N	Negligible	(<1%)
L	Low	(10%)
M	Moderate	(50%)
H	High	(90%)
E	Extreme	(>99%)

[4] The potential severity of consequences are rated N, L, M, H or E:

N	Negligible	No evident threat to tailings repository
L	Low	No evident threat to security of tailing repository though minor damage might occur
M	Moderate	Possible minor damage to containment structure
H	High	Possible damage to structure; some risk to security of tailings
E	Extreme	Likely damage to containment structure threatening security of tailings

[5] Use N, L, M, H, E scale

Potential hazard	Likelihood of	Potential severity of consequence[4]			Confidence in
Tornado winds	L	L	L	M	L
Drought	H – E	N	N	L – M	M
Tsunami	L	N	L	N	N
Volcanic eruption	L – M	N	N	N	H
Mass failure	L – M	N	N	N	H – E
Fires	M -H	N	N	L	L
Erosion – severe soil and gully erosion	M	L – M	L – M	H – E	M
Sea level change >1 m	M	N	L	N	M
Storm surge	L	N	L	N	L
Meteorite impact	N – L	L	L	L – M	M
Earthquake – near field ground shaking	L – M	L	L	L – M	M
Liquefaction	L – M	H	H	H – E	L
Long-term settlement	H	L – M	L – M	M – H	M
Earthquake – far field ground shaking	L	N – L	N – L	N – L	M

Table 5-6: Summary of significant hazards and consequences

Level of concern	Pit 1	Pit 3	Ranger Water Dam
Level 1 (lowest)	Erosion Cyclonic winds Drought Tree throw	Erosion Cyclonic winds Drought Tree throw	Probable Maximum Precipitation Earthquake (near field) Fires
Level 2	Liquefaction Long term settlement	Liquefaction Long term settlement	Cyclonic winds Tree throw
Level 3	N/A	N/A	Liquefaction Long term settlement Erosion Drought
Level 4	N/A	N/A	N/A
Level 5 (highest)	N/A	N/A	N/A

5.1.2.2 Evaluation of features, events and processes and safety functions for the Ranger Uranium Mine

The Environmental Requirements (ERs) for Ranger Mine include maintaining the world heritage attributes of Kakadu National Park and the ecosystem health of the Ramsar wetlands, protecting the health of people living in the region, and the biological diversity and ecological processes of the Alligator Rivers Region. Many of these attributes may be directly or indirectly affected by the behaviour and performance of the placement of all mine tailings in Ranger’s Pit 1 and Pit 3 tailings repository system.

ERA have completed a number of studies and risk assessments over various years including a systems assessment undertaken by INTERA in 2012. Systems assessment evaluates the ability of an environmental system to meet regulatory performance objectives over very long periods of time, in this case 10,000 years. The ideas and approaches used in systems assessments consider the entire system and all potential influences on the ability of the system to protect human health and the environment.

Two systems assessment methodologies were applied to the tailings repository systems; features, events, and processes (FEPs) and safety functions. The FEPs methodology identified all conditions that may affect the ability of a disposal system to meet its performance objectives over long time periods, as well as identifying alternative scenarios for the future evolution of the system, or alternative conceptual models for the behaviour of the system under the scenarios. The safety function methodology focused on system elements which contribute to the ability of the system to meet performance objectives.

INTERA and ERA developed a set of basic assumptions and requirements to evaluate FEPs and safety functions for the site tailing repositories. For Ranger, this is the ability of the tailings disposal system to meet the ERs for tailings containment for at least 10,000 years.

The FEPs analysis was conducted in two steps. First, an initial screening of the FEPs using the available literature was undertaken to develop a draft set of scenarios for consideration and discussion by a broader audience, including Ranger staff and stakeholders. A FEPs workshop was held in December 2012. The second step identified and evaluated a fully comprehensive list of FEPs for the environmental assessment and the associated safety function analysis.

The FEPs list derived from the Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM) list, Appendix C of International Atomic Energy Agency (IAEA) (2004). The FEPs evaluation included review of available literature, conceptual and numerical modelling of surface water and groundwater systems, and geomorphic stability modelling of the final landform.

The FEPs evaluation for the Ranger mine included all items in the ISAM list, with each FEP considered and screened for relevance. The safety function analysis identified one potentially deleterious FEP associated with the depth of tailings burial, an engineered barrier system, and four potentially deleterious FEPs associated with groundwater flow in the saturated zone and/or water flow in Magela Creek, which are natural barrier systems. The identified potentially deleterious FEPs and alternative scenarios for the future evaluation of the Ranger mine fall into two categories: those related to climate or erosion/sedimentation related FEPs.

The former has the potential to alter the hydrological behaviour of the system. The latter has the potential to change the path length of groundwater flow to Magela Creek and the tailings burial depth. Climate change and erosion are linked, such that changes in climate may affect erosion and sedimentation of Magela Creek and the final landform. Therefore, climate change is indirectly linked to changes in landform only as it is linked to erosion. Further discussion on climate change and associated FEPs in provided in Section 5.6.

The safety strategy for Ranger tailings lies primarily in several features of the site and tailings characteristics. In relation to landform, the depth of gullies projected to form on the final landform as a result of erosion are less than the tailings burial depths indicating the tailings will remain buried and, therefore, not be exposed at ground surface.

5.1.2.3 Managing for extremes: potential impacts of large geophysical events on Ranger Uranium Mine, NT

The Ranger Mine is located in the seasonally wet tropics with a potential to be exposed to extreme geophysical events that may impact on landform stability such as large rain events, longer time frames for variation in wet or dry years, increased number of flood events or cyclone number and intensity.

High intensity storm events are a main contributor to soil erosion in the Alligator Rivers Region, with Erskine and Saynor (2000) approximating 69% of total soil erosion during individual storms occurs during multiyear measurements.

Extreme rainfall and intense storms can significantly impact landform stability of a rehabilitated mine. Intense storms and large floods caused by tropical cyclones may also exhibit high wind speeds. Tropical cyclones can cause tree throw, further increasing soil erosion rates across landforms.

Erskine *et al*. (2012) noted further research on catastrophic floods and tropical cyclones was required to better define the risk to the mine site. ERA have completed a number of studies and risk assessments over various years in relation to future climatic events, discussed in Chapter 5.6.

5.1.3 LAN3 Predicting erosion of the rehabilitated landform

KKN title	Question
LAN3. Predicting erosion of the rehabilitated landform	LAN 3A. *What is the optimal landform shape and surface (e.g. riplines, substrate characteristics) that will minimise erosion?*
	LAN3B. *Where, when and how much consolidation will occur on the landform*
	LAN 3C. *How can we optimise the landform evolution model to predict the erosion characteristics of the final landform (e.g. refining parameters, validation using bedload, suspended sediment and erosion measurements, quantification of uncertainty and modelling scenarios)?*
	LAN3D. *What are the erosion characteristics of the final landform under a range of modelling scenarios (e.g. location, extent, timeframe, groundwater expression and effectiveness of mitigations)?*
	LAN3E. *How much suspended sediment will be transported from the rehabilitated site (including land application areas) by surface water?*

5.1.3.1 Landform evolution modelling

A number of landform studies have been undertaken to address key closure issues and risks, including removal of all site infrastructure and backfilling of pits, containment of tailings and erosion of the final landform. These studies, including those completed by both ERA and the SSB on the trial landform (TLF), have informed the overall design and predicted performance of the current final landform design.

The final landform aims to simulate the hill slope environmental processes that determine the sustainability and diversity of ecosystems in analogous undisturbed environments. The land use values ascribed to the mine area by the Traditional Owners are also being considered in the design. These values relate to restoring safe access to the site to allow cultural uses that occurred before mining.

The design of the final landform has been determined using a digital terrain model of natural analogue areas with the aim of producing a landform with similar indices of erosion and runoff distribution to the natural landscape (Hollingsworth & Lowry 2005). The shape of the current final landform is largely determined by the requirement to maintain pre-mining drainage and catchment areas and to ensure stability in either the current climate/rainfall regime or the predicted regime that may result from climate change. The Ranger Water Dam (RWD, formerly the Tailings Storage Facility) walls and western edges of the southern and western stockpiles sit atop high ridgelines of the pre-mining landscape. These ridges will form prominent features of the final landform and combined with a reinstated ridgeline over Pit 1, restore catchment areas similar to pre-mining. Topography of the final landform is similar to the pre-mining landform with the maximum elevation after consolidation increasing from 38 m pre-mining to a final landform maximum of 40 m Australian height datum (AHD).

Initial landform development was based on landform design criteria (Hollingsworth & Lowry 2005, Hollingsworth & Meek 2003, Hollingsworth *et al.* 2003a, Hollingsworth *et al.* 2003b) and described in the ERA 2005-06 Closure Model, which was subsequently issued to stakeholders (McGovern 2006). This was final landform version 1 (FLV1) with multiple versions being developed over the years. The current version is final landform version 6.2 (FLV6.2). ERA is in the process of designing FLV 7 incorporating stakeholder comments, kicked off in February 2022. FLV 7 design involves the utilisation of civil design software and assessment using CAESAR-Lisflood.

A preliminary slope analysis performed on final landform version 6.2 (FLv6.2) shows very gentle slopes across the landform with maximum slopes, measured from the ridgelines to the edge of the disturbed area, ranging in grade from approximately 2 percent to 4 percent (Figure 5-7). A slope analysis was also completed as part of the erosion and sediment control design work showing slopes varying from about 1 in 30 (3 %) to 1 in 200 (0.5 %), with larger catchments tending to have lower slopes, although this is not always the case. This has not changed significantly in the working progress of FLV 7 design versions, which continues to meet the original design intent with concave slope concept included.

In addition to the slope analysis, each version of the landform has been subjected to landform evolution modelling to assess the geomorphic stability of the final RPA landform over timeframes ranging from decades to millennia and the performance of the landform against closure criteria. The landform evolution modelling to date has been undertaken by SSB (Lowry & Saynor 2015; Supervising Scientist 2016b; Supervising Scientist 2019a; Supervising Scientist, 2020b). The outcomes of the modelling have been used to update the final landform design, with each version getting closer to meeting the closure criteria.

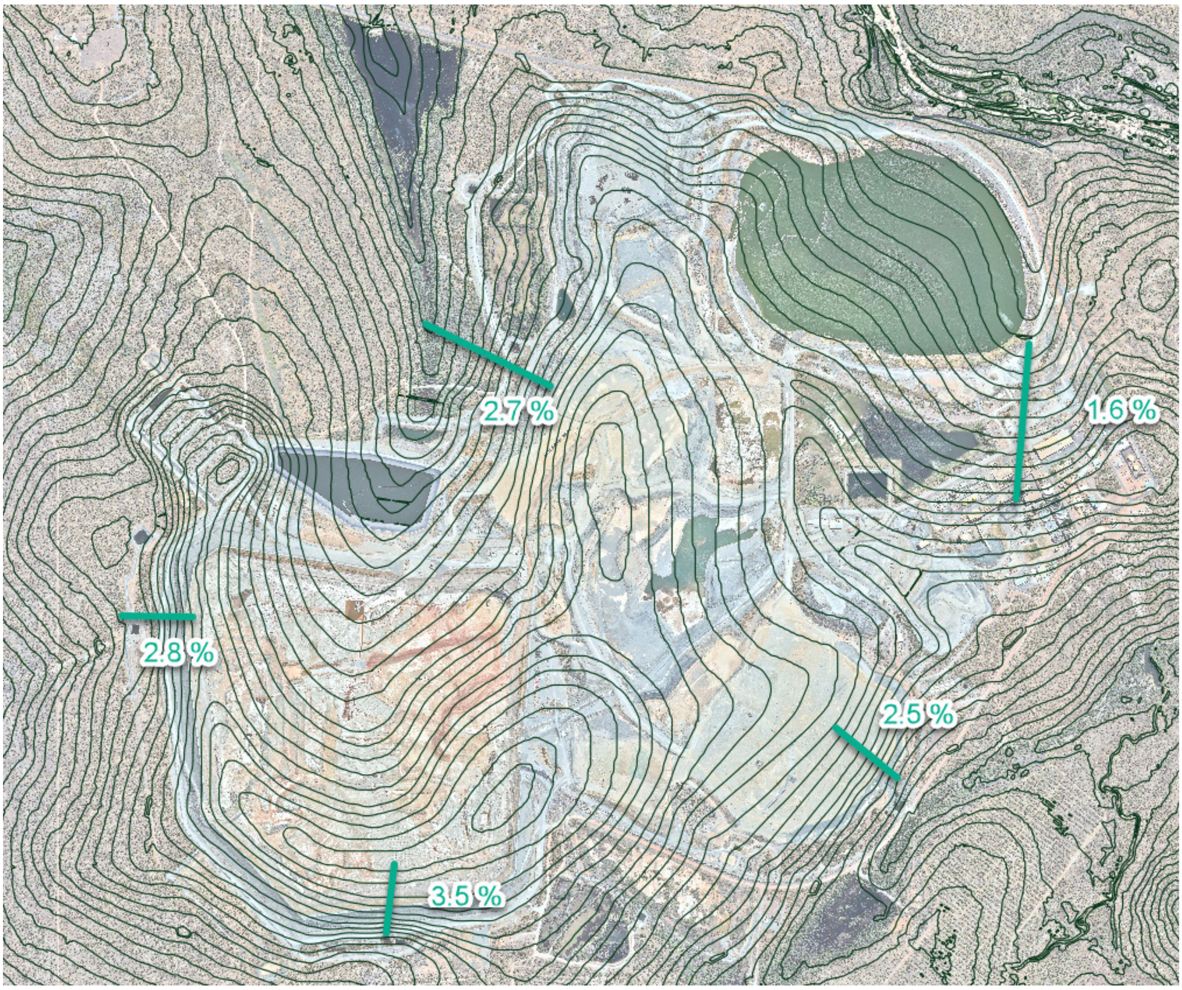


Figure 5-7: Preliminary slope analysis looking at the steepest slopes in FLV 6.2

The modelling applied a modified version of the CAESAR-Lisflood landform evaluation model (Coulthard *et al.* 2002, Coulthard *et al.* 2013). The CAESAR-Lisflood is an enhanced version of the CAESAR landform evaluation model. The key data inputs used by the CAESAR-Lisflood landform evaluation model were a digital elevation model (DEM), rainfall and surface particle size. The catchment areas used for assessing the Ranger Mine conceptual landform are shown in Figure 5-8.

A study on the calibration of parameters in CAESAR-Lisflood using the geomorphic monitoring data in Ranger Mine TLF and sensitivity analysis was completed by SSB (Lowry et al. 2020). Several parameters have been calibrated to provide a more accurate modelling prediction of erosion features on TLF. Information about the TLF parameters and monitoring that formed part of the calibration are discussed under KKN ESR7. It has been noted that further works are required to extrapolate the results to a larger spatial and temporal scales appropriately.

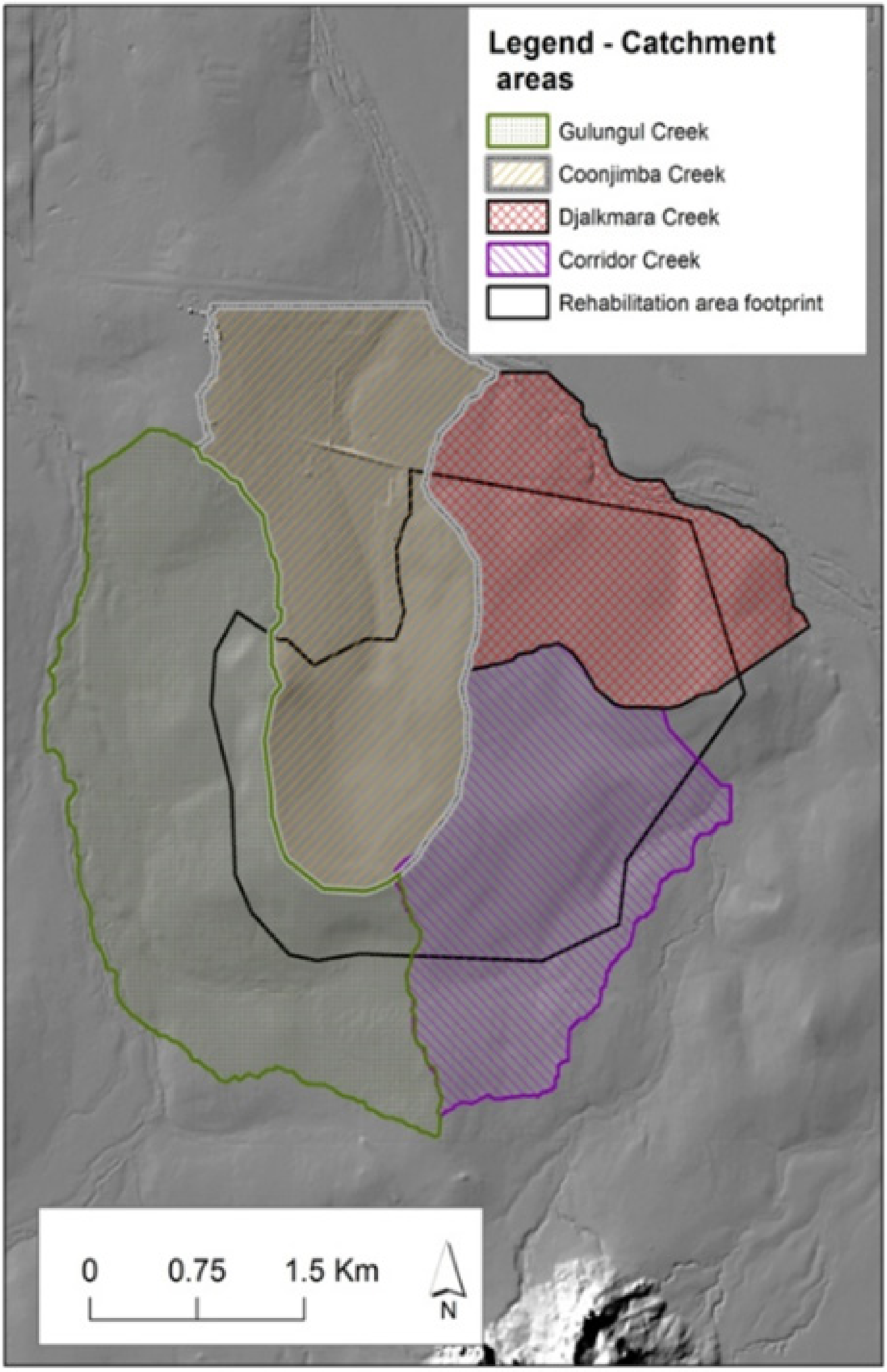


Figure 5-8: Catchment areas – Ranger Mine conceptual landform (Lowry & Saynor 2015)

The model has, to date, been conservative in nature, currently excluding any orthodox storm water and erosion control structures to reduce bedload yields and until recently no vegetation on the surface for the entire 10,000-year period. The SSB incorporated a grass cover layer in their assessment of the Corridor Creek Catchment (Supervising Scientist, 2020b).

The most recent assessment by SSB on FLv6.2 has been reported in a memorandum to ERA dated 21 February 2019, additional advice in Technical Advice #010 on 13 September 2019 and an overall assessment update in Technical Advice #22 on October 2020 (Supervising Scientist, 2020b). The predicated denudation rates and gullying depth for each catchment on are provided in Table 5-7 and the predicted erosion for simulated periods of up to 10,000 years in the Corridor Creek and Djalkmarra catchments are shown in Figure 5-9 to Figure 5-12.

The results show most of the deposition occurs in the first 100 years with erosion ongoing throughout the model. Denudation rates decrease over time and are found to approach the published background denudation rate for the region. A revised background denudation rate of 0.07 +/- 0.04 m per year for the landscape surrounding the Ranger mine has been recently published by Wasson *et al*. (2020).

The results also show the potential formation of gullies up to 9 m deep in Pit 1 and 7 m deep in Pit 3, which confirm that the locations and depths are unlikely to expose tailings based on approved final depth of tailing[6]. The identified locations have been used to inform the design of drainage channels and other erosion mitigations to minimise the potential impact on landform stability and support revegetation success (refer Section 9).

As noted above the modelling is a worst case assessment but provides a good indication of the stability of the current final landform and where additional engineering and design is required. The key things noted by the SSB as a result of the modelling were:

- Landform evolution assessment using CAESAR-Lisflood and SIBERIA have similar gully formation area across the landform, which includes Pit 1, Pit 3, and the former TSF while the gullies depth are unlikely to expose the tailings according to the approved tailing storage level in pits (Figure 5-9 to Figure 5-12).
- The final landform is unlikely to achieve the background denudation rate under extreme worst case scenario model setting over 10,000 years with the absence of vegetation surface cover while the denudation trajectory over does approach an equilibrium over time. However, Corridor Creek catchment under the dry rainfall scenario with the simulation of vegetation cover in CAESAR-Lisflood achieve the background denudation rate over 10,000 years (Table 5-7).

[6] The SSB has advised ERA that landform erosion modelling results are indicative only and should not be used to identify precise locations or depths of potential gully erosion. As such this information is used to guide the development of the final landform.

- Gulungul and Coonjimba catchments were assessed using CAESAR-Lisflood based on worst case scenario model configuration indicating the denudation rate will not approach the denudation background rate over a simulation period of 3,000 years.

Table 5-7: Predicted denudation rates and gullying depth for each catchment on FLv6.2.

Catchment	**Denudation rate (mm yr^{-1})**			**Gullying (maximum predicted depth, m)[1]**		
	CAESAR-Lisflood		SIBERIA	CAESAR-Lisflood		SIBERIA
	Dry rainfall scenario	Wet rainfall scenario		Dry rainfall scenario	Wet rainfall scenario	
3,000 years						
Djalkmara	0.19	0.27	–	4.5	5	–
Coonjimba	0.51	1.01	0.07	4	7	9.6
Gulungul	0.15	0.24	0.11	4	4.5	12.2
10,000 years						
Corridor	0.15 (*0.04*)	0.21 (*0.09*)	0.06	7	9	11.7
Djalkmara	0.21	0.24	0.11	6.5	7	10.4

*Bracketed numbers indicate denudation rate with grass cover present (Supervising Scientist, 2020)

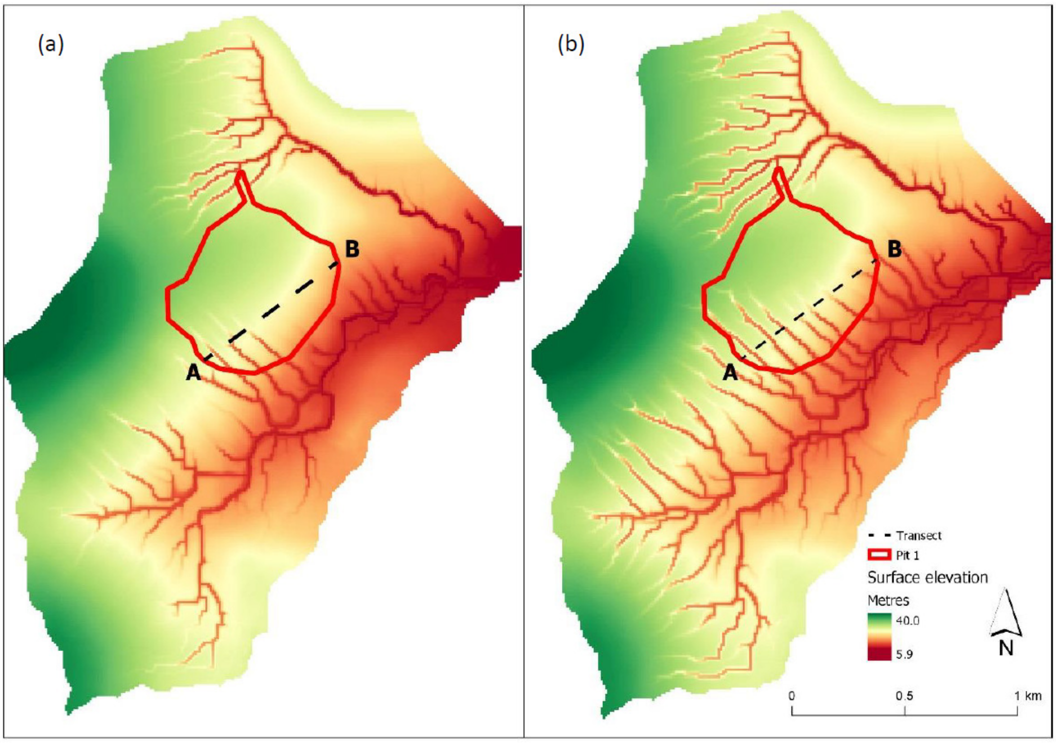


Figure 5-9: Surface of Corridor Creek catchment after a simulated period of 10,000 years under (a) dry and (b) wet rainfall scenarios.

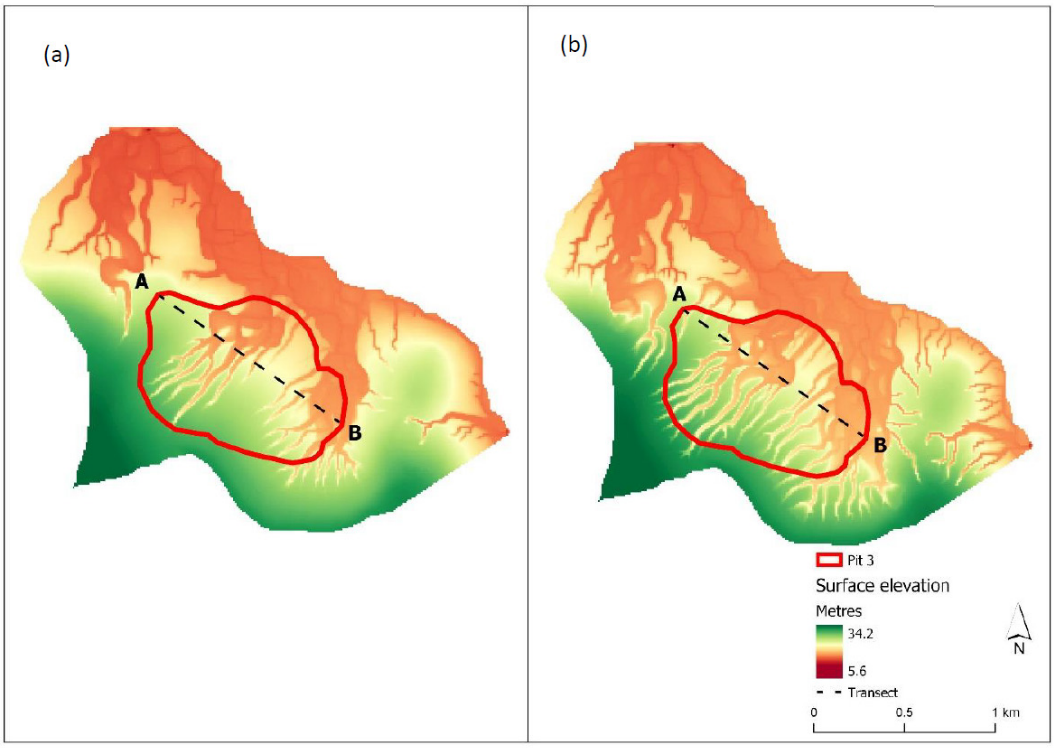


Figure 5-10: Predicted distribution of gullies in Djalkmarra catchment after 10,000 years under (a) dry and (b) wet rainfall scenarios.

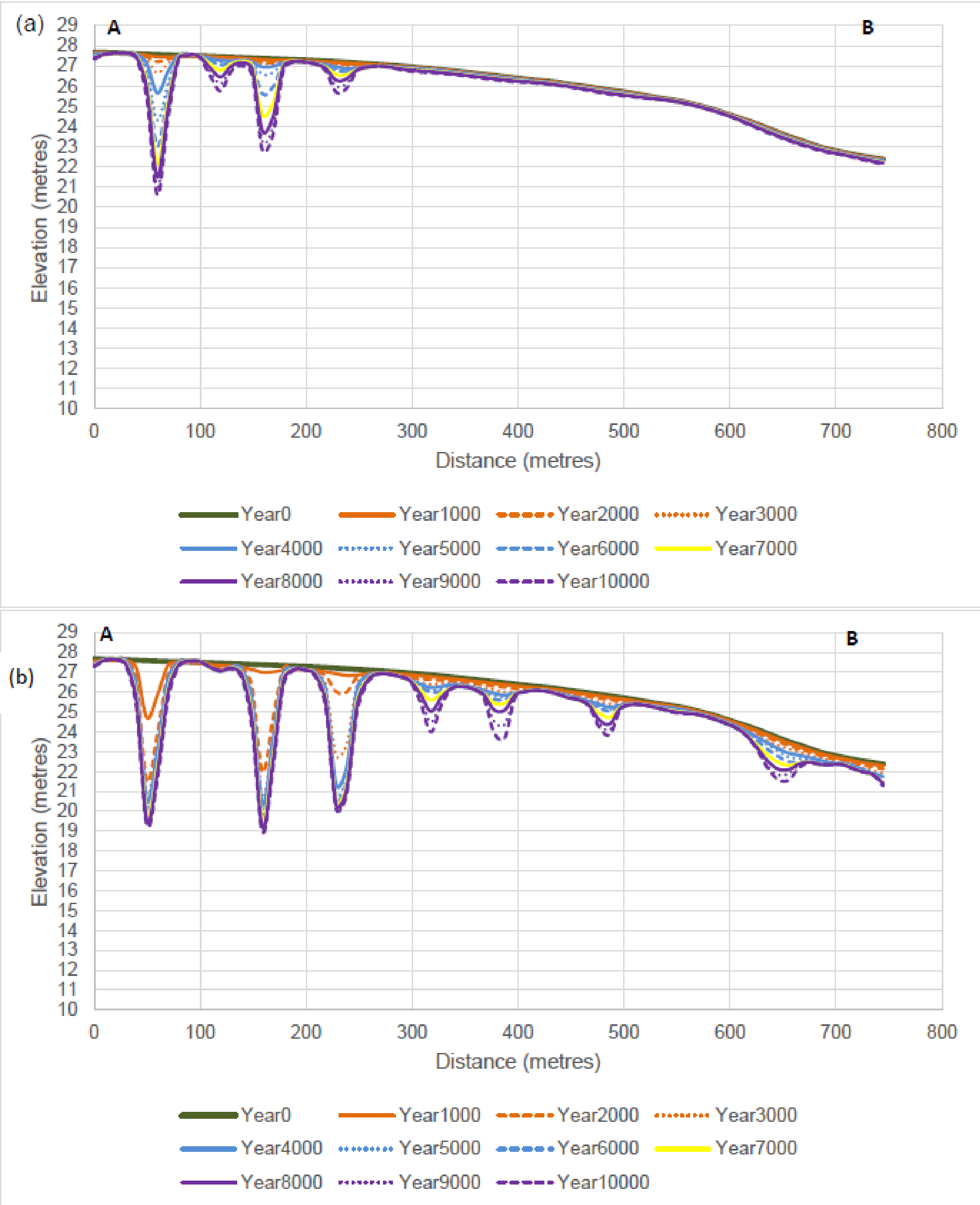


Figure 5-11: Cross sectional profile of transect A-B across Pit 1 under (a) dry and (b) wet rainfall scenarios.

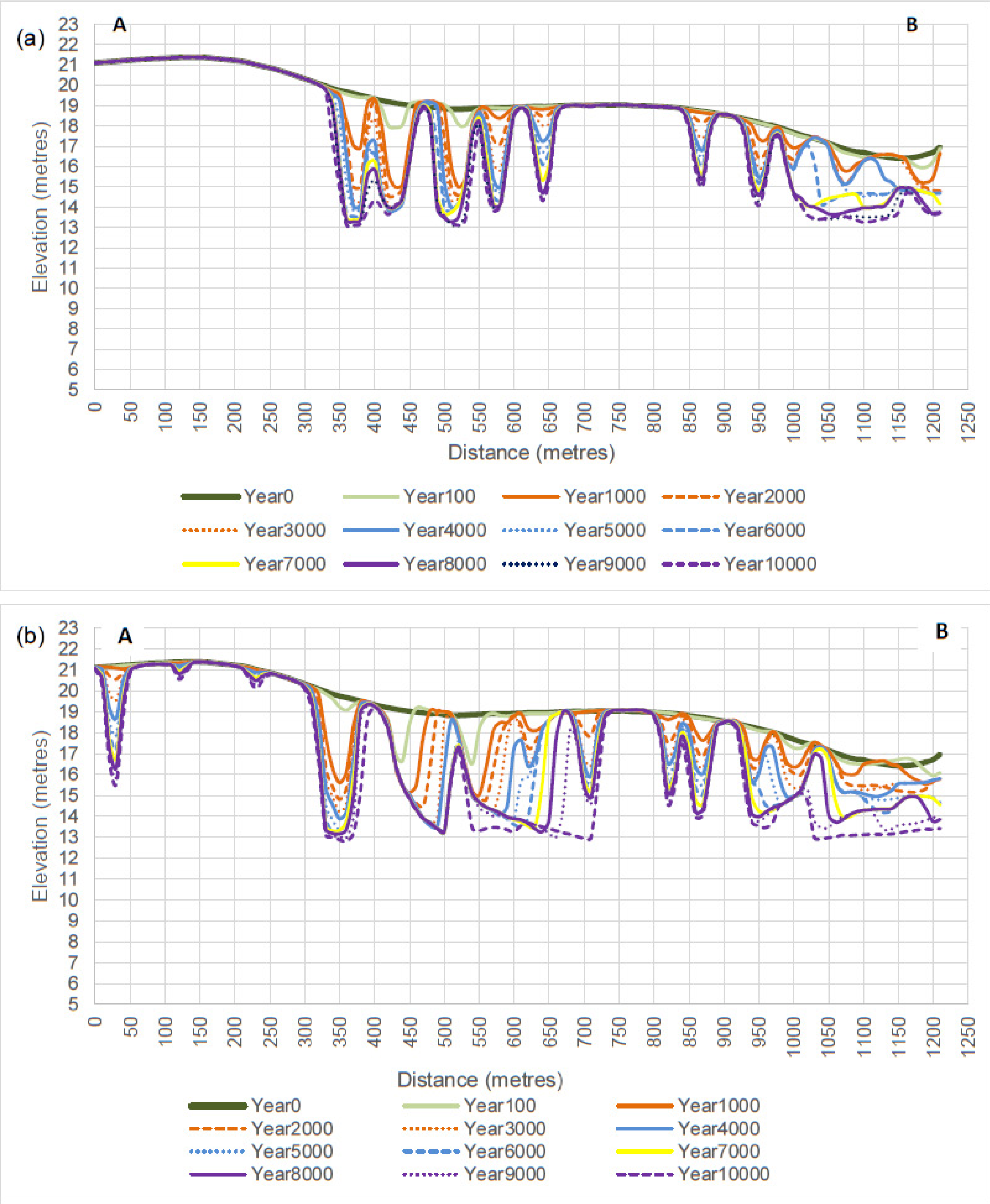


Figure 5-12: Cross sectional profile of transect A-B across Pit 3 under (a) dry and (b) wet rainfall scenarios.

ERA is expecting SSB to provide modelling results for Coonjimba and Gulungul catchments for periods up to 10,000 years utilising extreme wet-rainfall and extreme dry-rainfall scenarios data sets to complete the full suits assessment on FLV 6.2. SSB also noted that further assessments may be required for the FLv6.2 landform outside of the Corridor Creek catchment, thereby identifying locations on the final landform which may require additional mitigation such as surface armouring to eliminate any significant gullying. Results of these simulations will be presented in subsequent versions of the Mine Closure Plan (MCP), once completed.

Through late 2019 to early 2021, ERA engaged a hydrologist to build internal technical capacity to utilise CAESAR-Lisflood landform evolution modelling software. In addition to the SSB modelling, ERA has commenced studies into evaluating closure landforms and undertaking sensitivity testing of some key model parameters including climate sequences, rainfall losses, particle size distribution and vegetation cover. This project will enable faster evaluation of landforms, provide a better understanding of the modelling process and implications for erosion outcomes dependent upon both landform design and parameter choice. The other objective of building internal LEM capacity is to optimize modelling parameters to simulate a more realistic and yet conservative landform evolution processes. Initial parameter optimisation recommendation including optimised vegetation parameters to represent a surface roughness in a full vegetation cover scenario post rehabilitation, as well as hydrological parameters reflecting the local catchment behaviors in Ranger (ERA, 2021a).

Final Landform Design Optimisation

In February 2022, an ERA internal landform design group was formed which comprised of a bulk material movement modeller, a 12D civil software expert and a landform evolution modeller. The initial purpose of the landform design optimisaton is to incorporate the concave slope and first-order drainage recommendations from stakeholders into the design of a Final Landform version that achieves the background denudation rate (Wasson *et al*., 2020) in LEM 10,000-year worst-case scenarios. Future opportunistic engineering controls will be designed to ensure final landform stability performance is in the trajectory of achieving background denudation rate and the closure criterion.

Landform design is an iterative process. A workflow of literature review, concept design, design implementation and landform modelling assessment were developed in the landform design group. The landform assessment results then in turn informed the second iteration of landform design. Each landform version, once it is completed, is imported to CAESAR-Lisflood for modelling to assess its stability performance (i.e., denudation rate and vertical incision over the landform) in wet scenario using calibrated parameters from Trial Landform (Lowry et al., 2020) and vegetation cover parameters derived from an analogue site (Coulthard, 2019). This process, so far, demonstrates its reliability and robustness to generate results informing subsequent direction on landform optimisation from desktop study aspects. Where possible, the landform constructability is captured in the design to ensure it is practical to construct.

The landform optimisation project started from the Coonjimba catchment as a result of the closure sequence. A literature study was undertaken, including the historical landform studies in Ranger Mine and the ones capturing analogue sites, which demonstrated the benefits of concave design to landform stability (East et al., 1995; Hancock, 2004; Şensoy and Kara, 2014). The design criteria in Table 5-8 are adopted for the Final Landform design based on the statistical analysis on Georgetown analogue area (Hollingsworth, 2010). Channel geometry also has an impact on channel erosion: a low value of radius of channel curvature would accelerate the erosion rate due to a higher flow velocity (i.e., higher flow kinetic energy) directed towards the lateral channel cut (Janes *et al*., 2017). By contrast, the channel with higher radius of curvature in relief area can function as a buffer zone where flow velocity slows down and allow coarser sediment to drop out.

Table 5-8: Analogue landform terrain properties adopted as FLV 7 design criteria (Hollingsworth, 2010)

Variable	Units	Range
slope (%)	%	0 – 6.5
relief (m)	m	25
profile curvature	radius (m)	-5000 (concave) to 5000 (convex)
plan curvature	radius (m)	-100 (vale) to 100 (ridge)

In addition, appropriate software was utilised to analyse the slope curvatures aiming to extract the landform curvature design criteria in parallel to literature review, thus third polynomial equations were derived showing the relationship of landform cross section profile in main drainage lines form in surrounding analogue sites. Also, it was observed that the drainage line joins with the next higher order drainage line usually presented an almost perpendicular intersection. This leads to one of the reasons that location of drainage lines was introduced in FLV 7.00 (Figure 5-13a). The other factor determining the introduced channel locations are based on the slope analysis of Coonjimba Catchment in FLV 6.2 and the feasibility of introduced drainage lines to introduce concavity.

The key design features introduced and/or changed features of each subsequent version of FLV 7.00 (Figure 5-13) are summarised as follows with landform evolution modelling results provided as justification:

- FLV 7.00 used the introduced straight five drainage line locations and a sinuous main drainage before flowing out to undisturbed area as a design base. The concave profile curvature in Table 5-8 from Hollingsworth was adopted for drainage profile design.
- The third order polynomial equation was utilised to replace the -5000 concave profile curvature design criterion in FLV 7.01. The others design features stay the same as FLV 7.00
- The total sediment yield over 1000 years in FLV7.00 deceases by 4.01% compared to FLV 6.2, whereas FLV 7.01 produce about 24% more sediment compared to FLV 6.2. This led to the adoption of design criteria in Hollingsworth (2010) again in FLV 7.02. Two new elements were trialled in Channel 2 and Channel 3.1 compared to the drainage layout in FLV7.00, respectively wider and constant width in Channel 2 and a V-shape Channel 3.1 (Figure 5-13).
- The modelled erosion rate at the V-shape channel and the wider channel in FLV 7.03 were investigated. The wider (i.e., 60 m channel width) overall has a lower denudation

rate in the channel compared to the 30 m wide channel in FLV 7.00. The gradual increasing channel width exhibits a natural landform feature, therefore was adopted as the channel shape in FLV 7.03 while the modelling result favours a constant channel width.

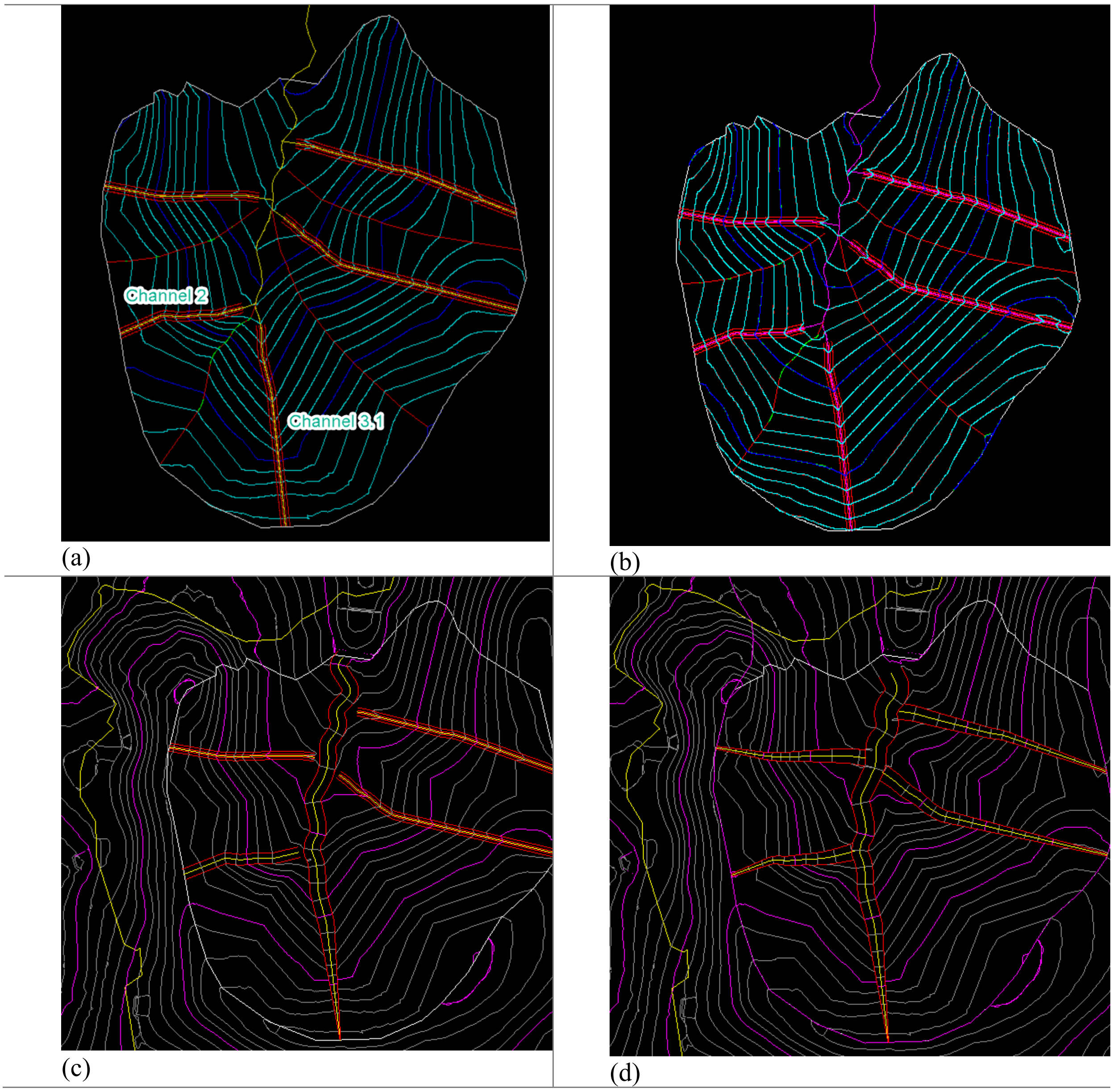


Figure 5-13: Drainages in each Final Landform 7 deisgn iteration versions, respectively FLV 7.00 (a), FLV 7.01 (b), FLV 7.02 (c) and FLV 7.03 (d) of Coonjimba working area (southern Coonjimba Catchment)

Table 5-9: CAESAR-Lisflood simulation results of FLV 7 iterations in Coonjimba catchment compared to FLvV6.2 base case

	verage denudation rate (mm/year) over 1000 years	tal sediment yield (m3)	ediment Yield reduction compared to FLV 6.2
FLV6.2	0.2979	1131991	n.a.
FLV7.00	0.2860	1086631	4.01%
FLV7.01	0.2865	1403033	-23.94%
FLV7.02	0.2897	1100985	2.74%
FLV7.03	0.2944	1118728	1.17%

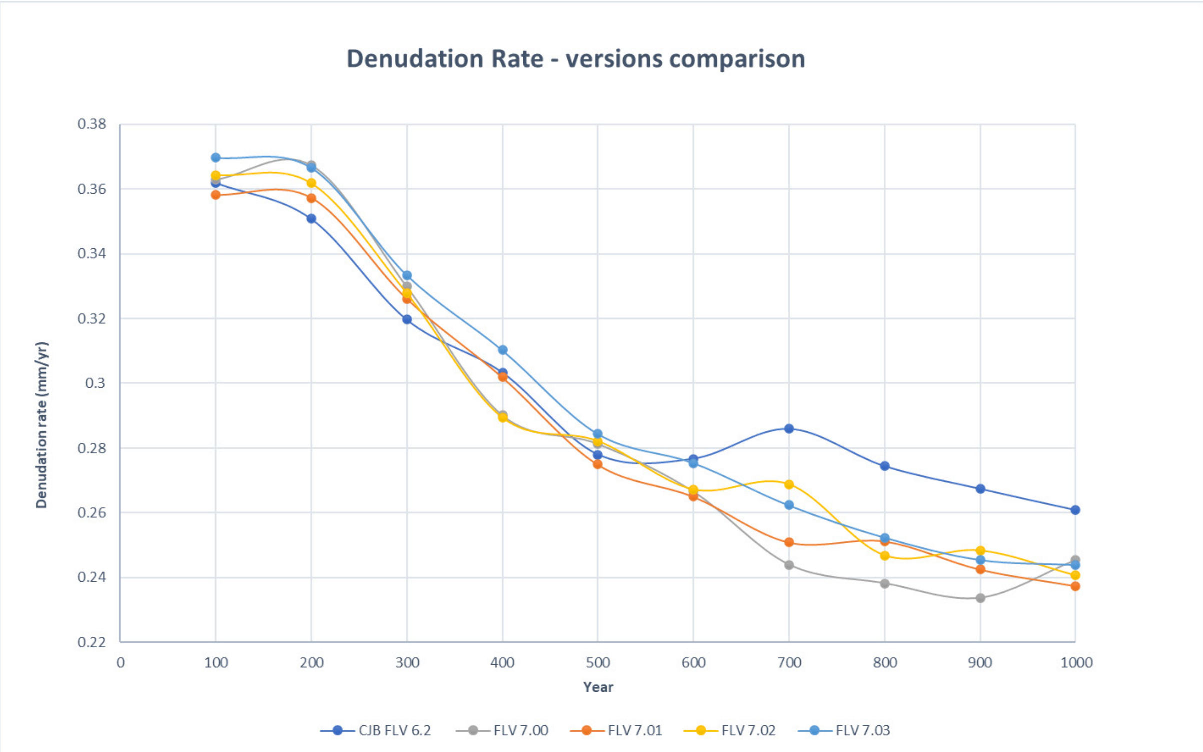


Figure 5-14: 1000-year average denudation rates of different landform versions in wet-scenario model running

Table 5-9 summarises the sediment yield of four Coonjimba catchment landform iterations over a 1000-year simulation period. It demonstrates, together with the denudation trajectories shown in Figure 5-14, FLV 7.00 has the best stability performance amongst the design versions solely according to the modelling results. Ongoing literature search and stakeholder recommendations suggest introducing low relief first-order drainages will create flow confluence, and in turn provide confidence on future infrastructure design requirements (e.g., location and design magnitude) to for a better long-term erosion control. FLV 7.04 in Coonjimba including multiple upper-stream order drainages with gradual increase widths and a wider central drainage channel is being developed during this mine closure plan update.

The landform design features tested effective in erosion reduction in the landform design iteration version of Coonjimba are kept and is being applied to the conceptual landform design in Djalkmarra catchment, and it will be applied to landform optimisation in Corridor Creek and Gulungul catchments.

Landform optimisation (FLV 7 design) including drainage channels design and other erosion mitigations is ongoing to minimise the potential impact on landform stability and revegetation success. The results of the simulations to date provide a guide for future enhancements both to the landform design and the landform evaluation model software. As a consequence, in parallel to the landform design optimisation in which LEM using calibrated parameters based on landform studies carried out in TLF, ERA will continue to work collaboratively with SSB in selecting and reaching agreement for optimised parameters for input into the landform evolution model (LEM) maximising the accuracy of the model predictions as the mine rehabilitation knowledge is further progressed. The rehabilitation knowledge includes the ecosystem re-establishment (e.g. canopy cover increase providing erosion protection) and evolution behaviour on the freshly constructed landform.

5.1.3.2 Infiltration, runoff, and erosion

Four erosion plots (approximately 30 m × 30 m) were constructed on the TLF during the 2009 dry season (Saynor *et al.*2009) (Figure 5-15). The TLF surface was ripped on the contour prior to construction of the erosion plots. The plots represent two types of potential final land cover layers; a waste rock only and waste rock – laterite mix with planting methods of both direct seeding and tube stock. The plots were physically isolated from runoff from the rest of the landform by raised borders.

Sensors installed in each plot included a tipping bucket rain gauge, primary shaft encoder with a secondary pressure transducer to measure stage height, a turbidity probe to measure suspended sediment concentration, electrical conductivity (EC) probes located at the inlet to the stilling basin and the entry to the flume to provide a measure of the concentration of dissolved salts in the runoff, an automatic pump sampler to collect event based water samples, a data logger with mobile phone telemetry connection and a rectangular broad-crested flume to accurately determine discharge from the plots (Saynor *et al.* 2014) (Figure 5-16).

Monitoring results including generation and transport of solutes, hydrology and bedload yields, have been reported (Saynor *et al.* 2009, Saynor *et al.* 2011, Saynor *et al.* 2012b, Saynor *et al.* 2014, Saynor *et al.* 2015). These studies also inform KKN ESR7.

Infiltration

In his PhD study into surface hydrological modelling for rehabilitated landforms, Shao (2015) developed a modified runoff model (RunCA) applying it to the TLF as a case study. Good agreement was achieved between the simulated and observed discharge volumes, runoff curves and flow distributions for the rainfall events monitored during four wet seasons from 2009 to 2013. The study utilised the existing SSB erosion plots on the TLF (e.g. Saynor *et al.*

2012b) undertaking additional field infiltration measurements (September 2013) to determine the hydraulic properties of the TLF and the infiltration parameters for the RunCA model.

The following is an excerpt from Shao (2015) and details the field methods used to obtain infiltration measurements on the TLF in September 2013:

> *Due to the large width of the rip lines, four measurements were conducted on the rip lines at randomly selected areas on the waste rock cover, using a ring infiltrometer with a large diameter of 1 m. Another four measurement were also conducted randomly on the non-ripped areas between the rip lines, using a smaller ring infiltrometer with a diameter of 0.4 m. The falling head method was employed in all these measurements. Each measurement lasted until a stable infiltration state was reached, and then the final steady infiltration rate* i_f *was calculated by averaging the last three measured infiltration rates. Core samples were also taken in the areas immediately adjacent to the infiltration measurements for the laboratory determination of various properties. Specifically, the total porosity TP was assumed to be equal to the saturated water content, which was reached by leaving the core samples in a tray filled with shallow water for 2-4 days, and field capacity* θ_{FC} *was achieved by leaving the saturated core samples on a suction plate with 33 kPa (0.33 bar) suction pressure for 7 days. Initial soil moisture* θ_0*, TP and* θ_{FC} *were then determined by weighing the core samples before and after oven-drying at 105°C for 24 hours in the laboratory.*

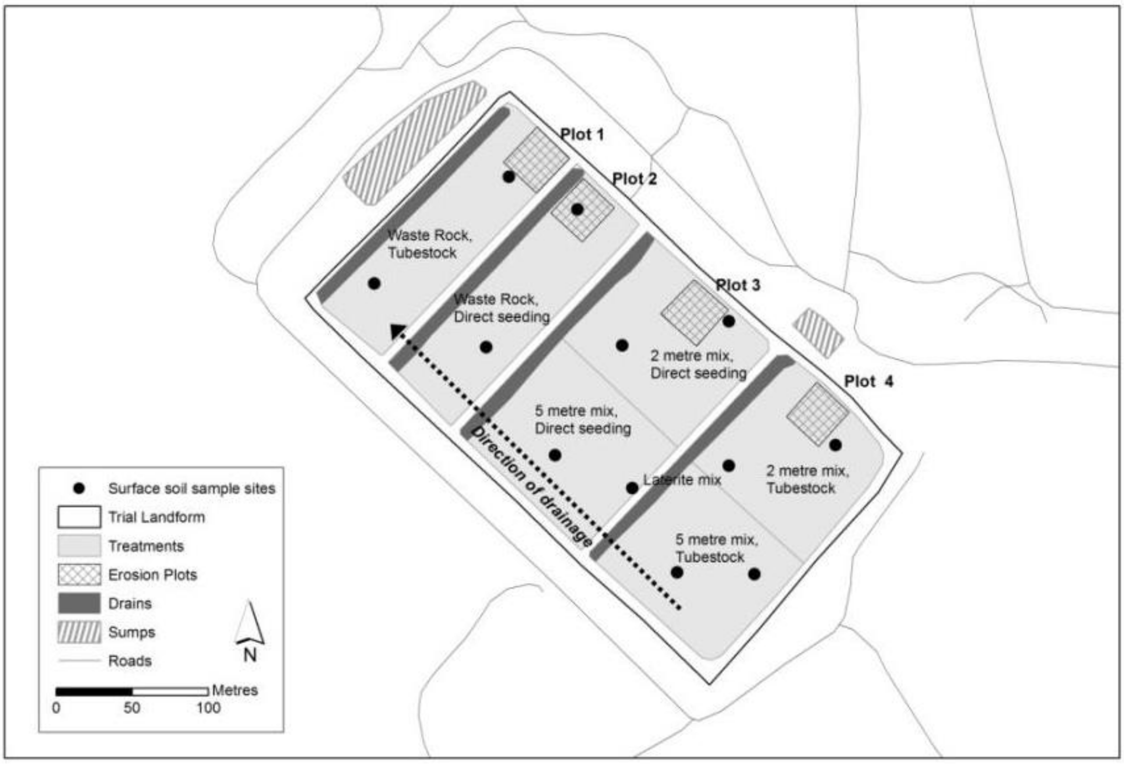


Figure 5-15: Layout of the erosion plots on the trial landform (Boyden et al., 2016, Saynor et al., 2016)

Figure 5-16: Runoff through the flume on the trial landform erosion plot 3 during a storm event (Saynor et al., 2014)

Discharge volumes, runoff curves and flow distributions for the rainfall events monitored during four wet seasons from 2009 to 2013 were used to determine the hydraulic properties of the TLF (Shao 2015) (Table 5-10 and Table 5-11). Shao's direct measurements from the TLF were used to calibrate the WAVES model (ESR7).

Table 5-10: Statistical values for the observed rainfall events in the four wet seasons (water years) from 2009 to 2013

Water year [a]	Annual rainfall (mm)	Annual runoff (mm)	Number of events	Event duration (min)		Runoff coefficient (%)	
				Range	Mean	Range	Mean
			Plot 1				
2009-10	1528.1	77.7	68	15-534	113.1±104.2	0.7-14.2	5.6±2.5
2010-11	2205.4	300.2	96	15-631	139.0±140.3	2.6-88.2	6.0±9.1
2011-12	1481.0	101.2	78	16-713	87.5±127.6	2.2-40.3	5.4±4.4
2012-13	1283.0	121.8	62	8-2135	88.1±275.8	1.2-29.9	4.6±4.3
			Plot 2				
2009-10	1531.5	132.0	68	26-543	156.2±114.3	1.1-22.3	8.0±4.0
2010-11	2293.6	328.5	96	31-760	177.5±148.5	3.7-78.2	8.7±7.9
2011-12	1531.4	166.3	78	26-1017	130.2±154.0	2.5-30.9	8.9±5.0
2012-13	1274.2	196.4	62	13-2154	127.8±270.8	2.2-57.9	11.7±9.7

[a] A water year is defined as the period from 1 September to 31 August of the following year

Table 5-11: Summary of field infiltration parameters for the TLF

Measurement No.	Infiltration parameters [a]						*RMSE* (mm h^{-1})	R^2
	i_f (mm h^{-1})	θ_{FC} (m^3 m^{-3})	θ_0 (m^3 m^{-3})	*TP* (m^3 m^{-3})	a [b] (mm)	D [b] (mm)		
			Rip lines					
1	25.20	0.09	0.07	0.30	0.60	180	7.37	0.84
2	24.00	0.12	0.09	0.26	0.50	90	5.09	0.84
3	18.00	0.11	0.07	0.30	1.30	100	6.79	0.82
4	30.00	0.09	0.08	0.26	2.50	120	7.76	0.95
Mean	24.30	0.10	0.08	0.28	1.23	122.50	6.75	0.86
SD	4.94	0.02	0.01	0.02	0.92	40.31	3.35	0.03
			Non-ripped areas					
5	7.50	0.08	0.06	0.23	0.75	100	9.38	0.83
6	19.20	0.08	0.07	0.23	1.50	150	6.23	0.96
7	12.00	0.06	0.06	0.21	1.50	50	5.00	0.96
8	14.00	0.11	0.07	0.25	1.00	80	7.73	0.85
Mean	13.18	0.08	0.07	0.23	1.19	95.00	7.08	0.90
SD	4.85	0.02	0.01	0.01	0.38	42.03	1.90	0.07

[a] i_f: final steady infiltration rate (mm h^{-1}); θ_0: initial soil moisture (m^3 m^{-3}); θ_{FC}: field capacity (m^3 m^{-3}); *TP*: soil porosity (m^3 m^{-3}); a: a constant (mm$^{-0.4}$ h^{-1}) in modified Holtan model; D: depth of control zone which affects the infiltration process (mm).

[b] unmeasurable parameters determined by curve-fitting with observed infiltration rates.

Runoff

Annual runoff from the TLF was greatest in the wettest year, and there is a close relationship between event rainfall and event runoff over the full range of rainfall for all monitored years.

There is an apparent exponential relationship between event rainfall and event runoff over the full range of rainfall for five years monitoring of plot 1 (Figure 5-17), however due to technical issues with large events this has not yet been tested statistically (Saynor *et al.* 2015). Saynor *et al.* (2015) hypothesised that event rainfall greater than 30 mm generates proportionally greater runoff as smaller events do not totally infill the rip lines with water. Event rainfall greater than 30 mm can totally infill the surface storage, generating runoff from the whole plot surface.

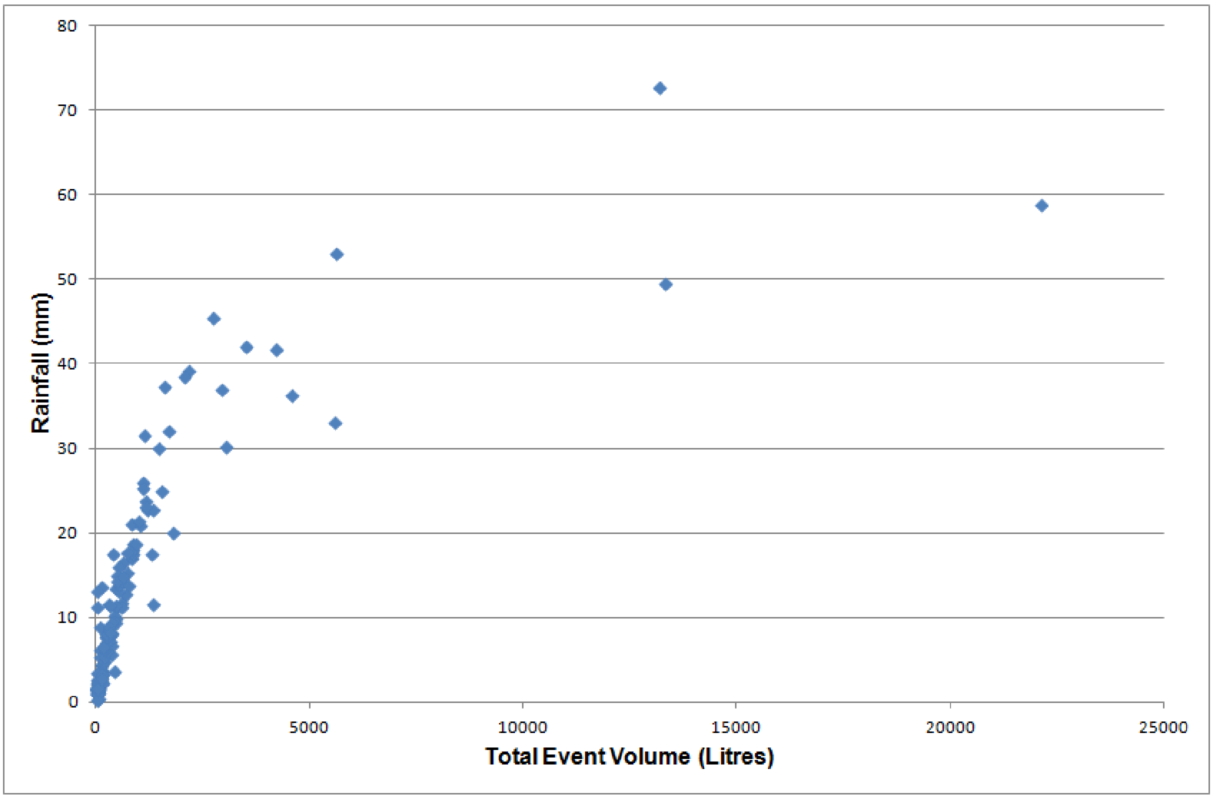


Figure 5-17: Relationship between total event rainfall and runoff for erosion plot 1 for 156 runoff events in the 2013–14 wet season (Saynor *et al.* 2015)

Erosion

Run-off and erosion rates measured on the TLF have been used to assess the long- term geomorphic stability of the TLF and have been applied by extension to the final landform (comparing measured export rates with those modelled from the landform evolution model).

Bedload samples were collected at weekly to monthly intervals during each wet season, depending on the magnitude of runoff events and staff availability. In general, sediment yields for major land disturbances, such as construction or landslides, are characterised by an initial pulse followed by a rapid decline (Duggan 1994 cited in Saynor *et al.* 2015). This is true for the TLF annual bedload yield, which is characterised by an exponential decline since construction (Figure 5-18). Saynor *et al.* (2015) also noted that since construction, eroded material has been washed into the rip lines, but there is still a large amount of potential sediment storage before the rip lines are diminished. Fine materials and fines earth accumulated in the rip lines and other depressions are important for the soil formation on the final waste rock landform and sustainability of the revegetation. The formation of soils is further discussed under KKN ESR7.

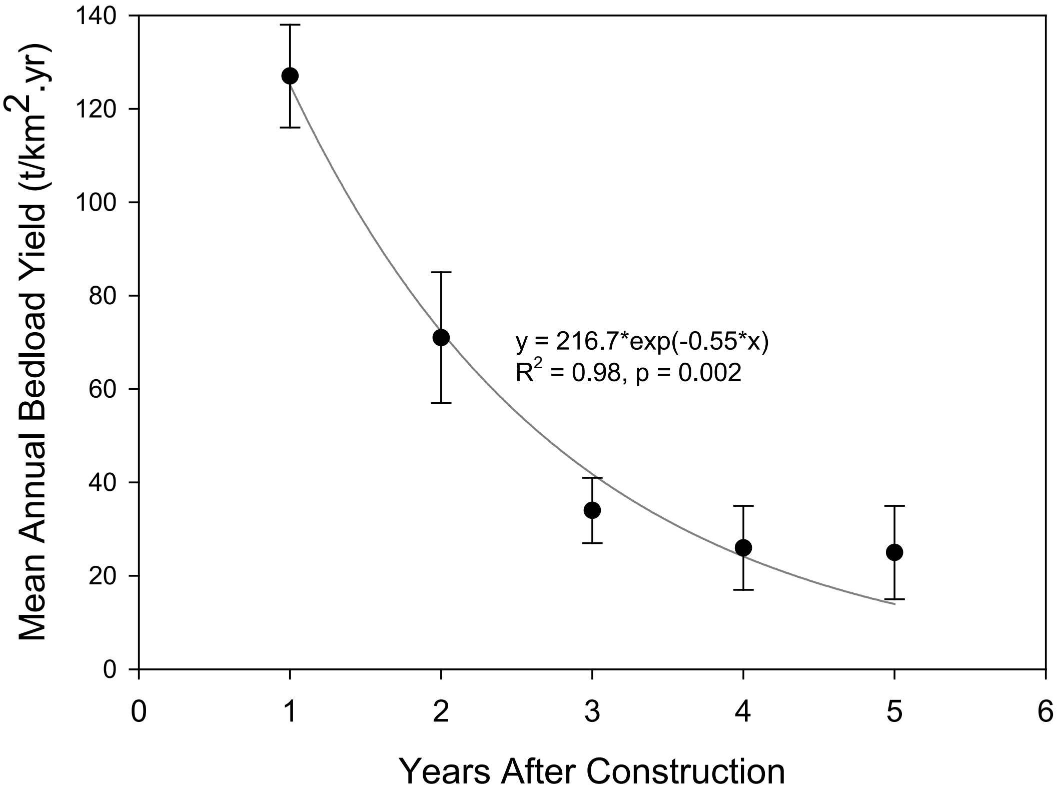


Figure 5-18: Exponential decrease in mean annual bedload yield with time since construction for the four plots on the trial landform. Data represent annual mean and standard error of estimate for all plots (Lowry & Saynor, 2015)

5.1.3.3 Landform material properties and Landform Evolution Modelling improvement

Studies on the particle size distribution of waste rock have been completed by both ERA and SSB. Table 5-12 shows the indicative particle size distribution for the 1s waste rock material taken from the TLF (Saynor & Houghton 2011). SSB has also undertaken particle size distribution analysis over ten years using sieve analysis in 2009 and the grid by numbers method in in 2012, 2014 and 2018 (Hancock et al., 2020).

Pit 1 top 6 m material (1s grade material) was undertaken as per commitments made in the Ranger Application to Progress Pit 1 Final Landform and associated *Pit 1 Progressive Rehabilitation Monitoring Framework*. The sampling plan was developed from this framework and aligns with the research objectives of project 1230-04 under KKN LAN3. Samples were taken on a 100 m designed grid following the completion of waste rock placement in Pit 1

(Figure 5-19), between October 2019 and September 2020. The sampling and analysis regime was executed by Douglas Partners and followed the Northern Territory Government Standard Test Method *NTTM 217.1* for oversized materials and *AS 1289.3.6.1* for determining the PSD by sieving analysis.

Table 5-12: Particle size distribution in percentage for the waste rock dump materials and Koolpinyah surface materials, adapted from Hancock et. al (2020)

Phi	Size (mm)	Waste Rock in Pit 1 (%)	Waste Rock in current LEM (%)	Koopinyah (%)
-7	128	18	8	0
-6	64	22	9	0
-4	16	11	33	0
-2	8	11	22	1
0	1	9	14	12
1	0.5	9	4	14
2.47	0.18	10	6	42
3.47	0.09	3	3	15
4	0.063	7	1	16

Figure 5-19: PSD sampling locations in Pit 1

A visual approximation of the results showing the fines (mass fraction < 2.36 mm in fraction size) in upper (U; 1.5 m) and lower layer (L; 1.5 m to 6 m) are shown in Figure 5-20 and Figure 5-21.

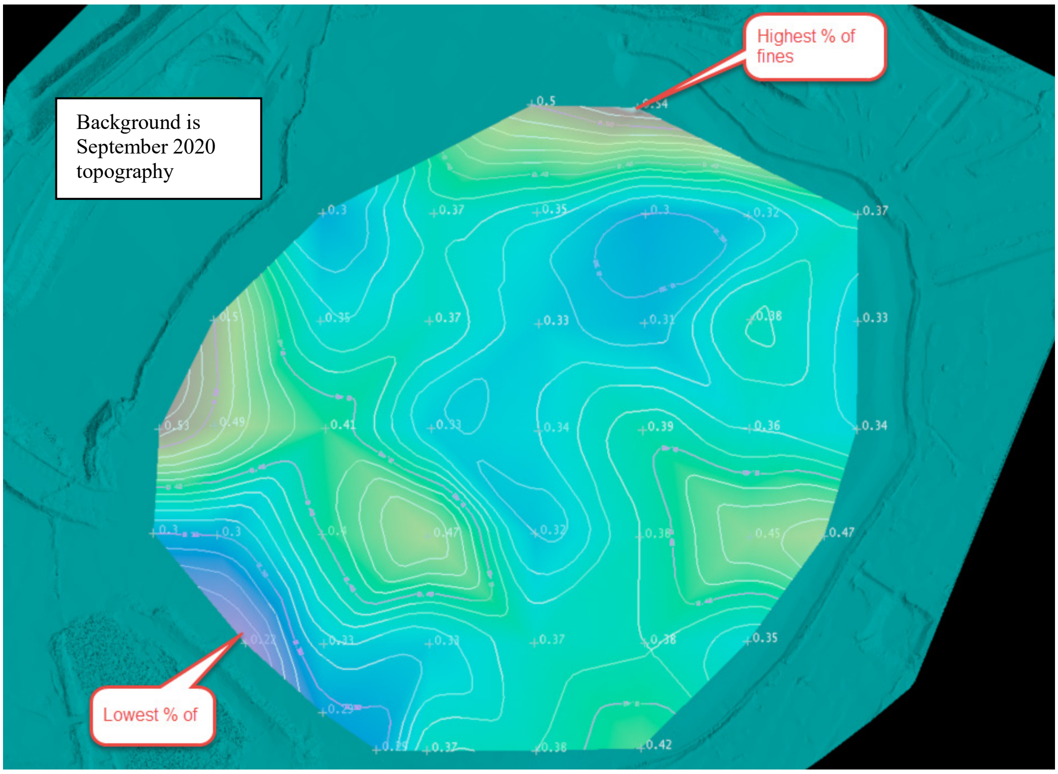


Figure 5-20: Upper layer with the mass fraction less than 2.36mm

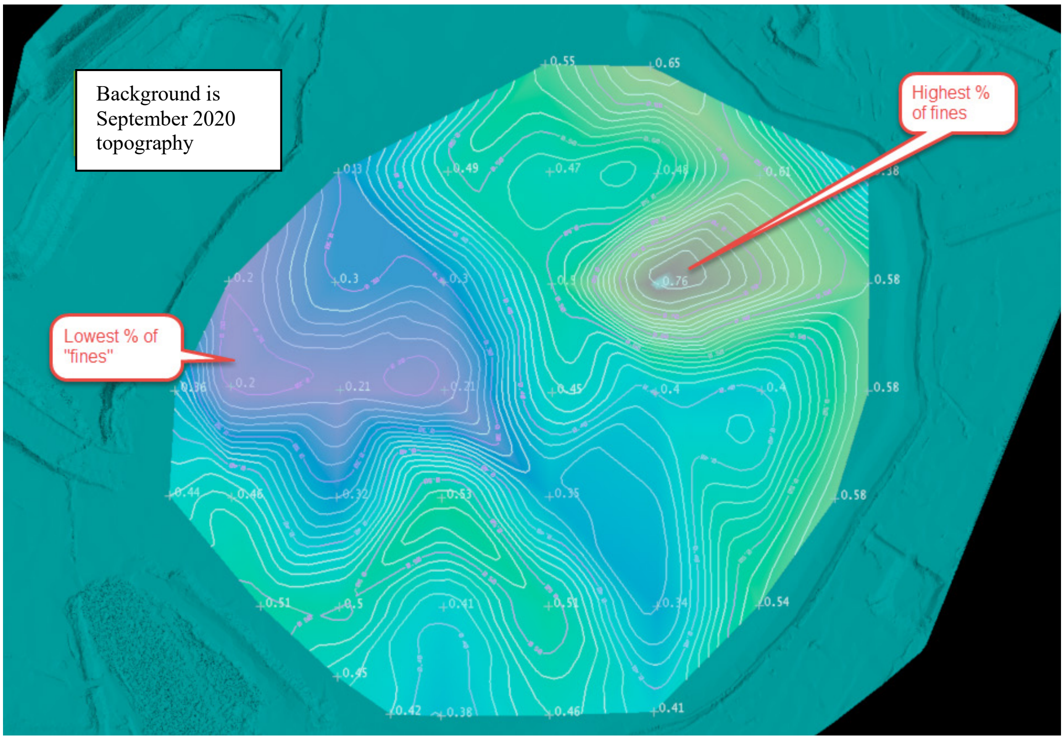


Figure 5-21: Lower layer with the mass fraction less than 2.36mm

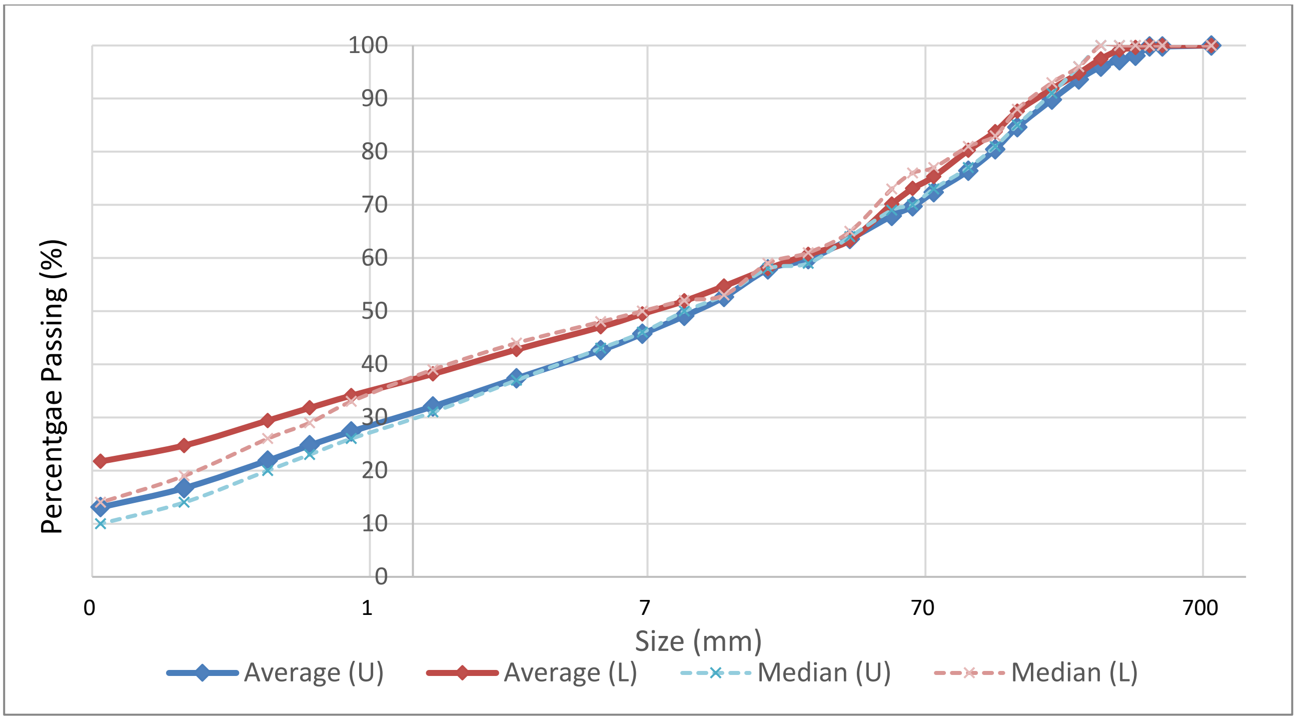


Figure 5-22: PSD result average and median for upper and lower layer

Figure 5-22 shows the average and median PSD results of the upper layer and lower layer materials sampled. There is an approximate ten percent difference between the average and median value of the fine fraction for the lower layer, indicating material characteristics of the lower layer potentially present a more heterogeneous form in the fine size fractions compared to that in the upper layer materials.

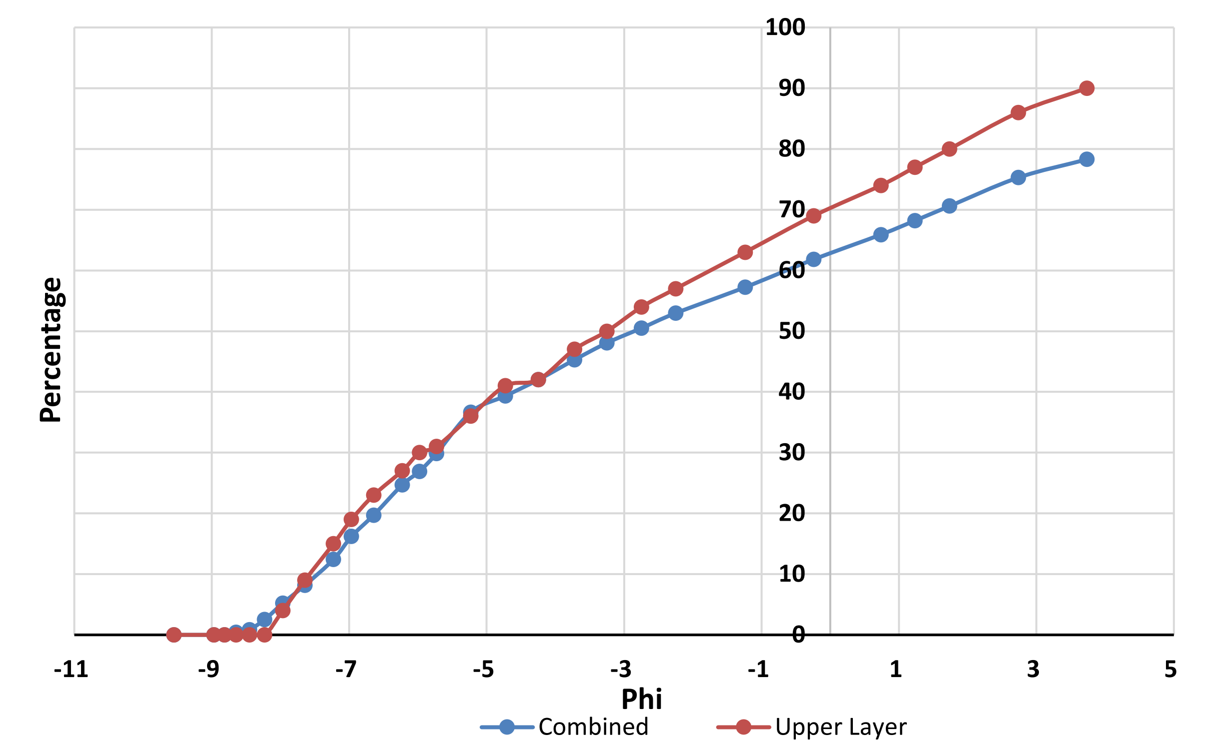


Figure 5-23: Upper layer PSD curve and combined PSD curve.

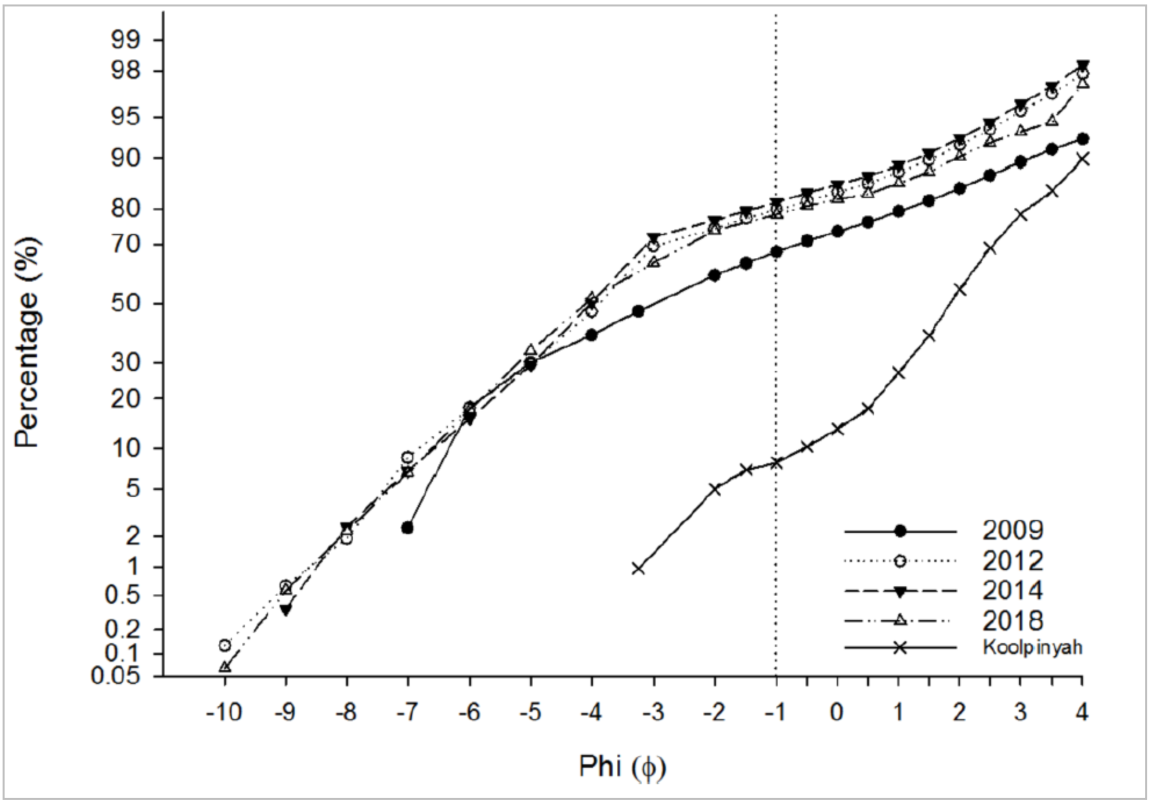


Figure 5-24: Particle size distribution from the Ranger trial landform in 2009, 2012,2014 and 2018 (Hancock et al., 2020).

Figure 5-23 indicates the Pit 1 upper layer material has a coarser distribution compared to the combined material (i.e., top 6-m material). This figure can also be used to compare the Pit 1 PSD results with that previously plotted for the Particle size distribution from the Ranger trial landform (TLF) in 2009, 2012, 2014 and 2018, and Koolpinyah sediment in Figure 5-24. The comparison suggests the Pit 1 materials are generally in line with the TLF surface material PSD results determined using sieve and hydrometer methods.

The PSD results can then further be used to update the waste rock PSD applied in CAESAR-Lisflood for landform evolution model. CAESAR-Lisflood only allows a maximum of nine PSD size fractions to be modelled. To enable use of the most recent dataset collected on Pit 1, a single PSD curve using the average of upper layer and lower layer materials for each size group was generated and plotted in Phi scale (Figure 5-25). This enabled a single PSD compatible dataset to be used in CAESAR-Lisflood. A realistic, conservative approach was undertaken for compressing the data into a single PSD dataset, suitable for landform evolution modelling.

The default setting currently used in CAESAR-Lisflood has a set of predetermined PSD intervals, ranging from -7 Phi to 4 Phi, or 128 mm to 0.063 mm. When calculating the single PSD dataset, the fraction size intervals remained the same, and were treated as the median of each interval (i.e. 128mm, 64mm etc). This allowed for the interval boundary values in the Phi scale to be extrapolated using Figure 5-25. In doing this, fraction sizes for a single PSD dataset could also be easily aligned to existing waste rock and Koolpinyah PSD datasets which are currently used in the LEM. Table 5-12 summaries the particle size group derived from Pit 1 PSD result (refer to the third column) compatible for CAESAR-Lisflood in comparison to the waste rock PSD datasets used prior to obtaining Pit 1 PSD data and the natural Koolpinyah PSD datasets surrounding the mine footprint areas.

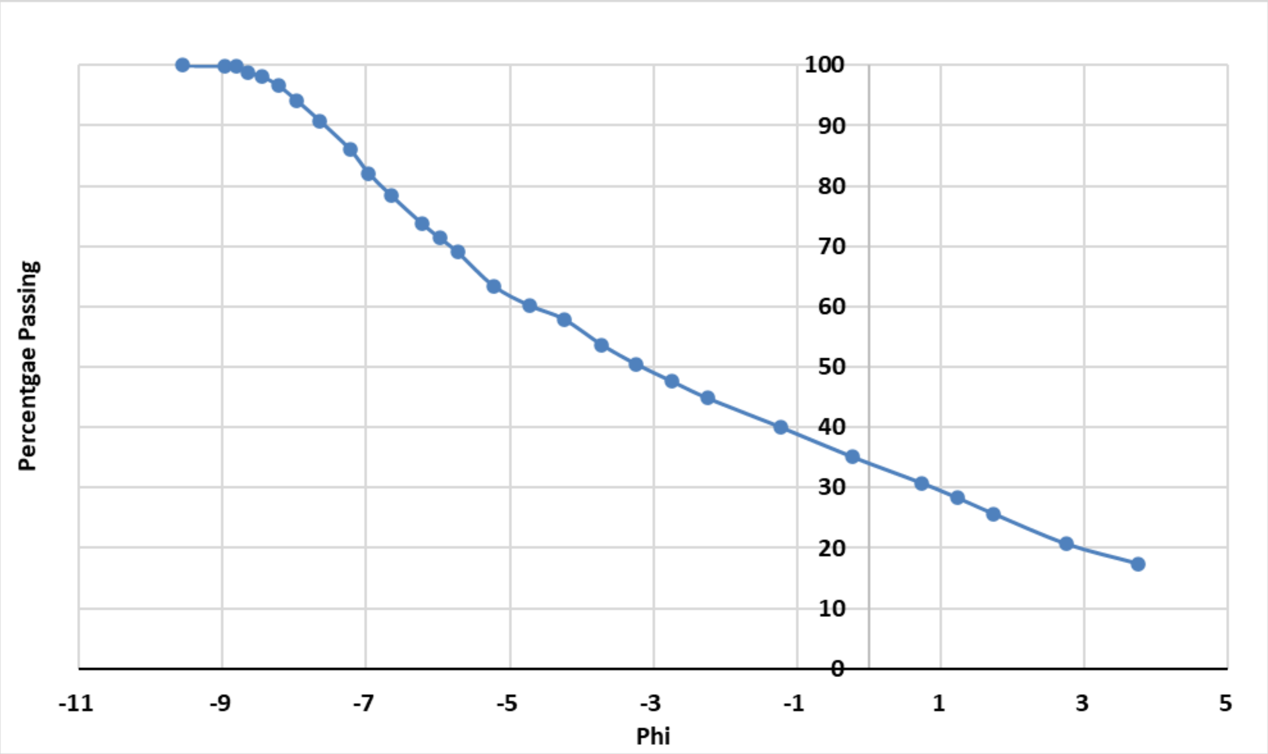


Figure 5-25: Pit 1 waste rock PSD curve in Phi scale

The progressive understanding of the material properties on newly constructed landforms forms part of the closure knowledge needs and will continue to evolve as new data becomes available.

5.1.3.4 Tailings consolidation model

KKN LAN3B asks question around consolidation, in particular the degree of subsidence within the rehabilitated landform (e.g. over Pits 1 and 3 associated with tailings consolidation) may influence erosional processes. Determining these rates will require some knowledge of predicted location and extent of consolidation over the pits.

As part of Pit 1 closure planning, ERA commissioned a series of Pit 1 tailings consolidation models (Australian Tailings Consultants, 2003, 2007, 2009, 2012, 2014, Fitton 2015, 2017). These models allow the prediction of final tailings elevation within Pit 1 and the forecast volume of process water to be expressed during consolidation. The model was then later adapted for use in Pit 3. This section describes the model. Subsequent sections detail the specific models of both Pit 1 and Pit 3.

The consolidation models have been supported (verified) by a number of tailings characterisation studies by geotechnical investigations and geophysical surveys. These studies are summarised later in this section.

The consolidation modelling software was established in the late 1980s and is based on a formulation developed by Somogyi (1980). The initial purpose of the program was to provide inputs into a sophisticated water balance developed by the author for the Golden Cross Gold Mine in New Zealand (Murphy & Williams 1990).

The program solves the various partial differential equations describing self-weight consolidation using an implicit finite difference method. The author extended the original Somogyi model to include:

- a technique to allow for variable basin geometry and/or changing solids deposition rate with time;
- underdrainage to atmospheric pressure; and
- the application of surcharges.

The program models tailings deposition at user defined time steps and quiescent consolidation with or without a surcharge.

The program was presented as a minor thesis (Murphy 1994) as part of a Master of Engineering Science at Monash University in 1994. The examiner was David Williams (now Professor) of the University of Queensland.

Method of addressing variable basin geometry

Variable geometry is addressed by considering the tailings impoundment as a series of five annular areas, as described in Appendix 5.2. As the tailings level rises, the effective discharge rate reduces as the area increases at each stage. At each stage, the mass of solids discharged into each annulus is modified to compensate for the greater consolidation settlement in deeper columns. The relative mass of solids deposited is greatest in the deepest column and reduces towards the edge of the TSF. This technique ensures that the model compensates for the greater settlement in deeper parts of the deposit. For example, in a deep pit, such as Pit 1 at the Ranger Mine, a dished surface does not exist until after deposition ceases. At this time, tailings no longer progressively fill the area above the deeper parts of the pit where consolidation is greatest, and a ‘dish’ subsequently develops.

The technique, developed in 1987, is effectively a pseudo 3-dimensional consolidation model and is believed to pre-date other such models. Figure 5-26 compares the actual Pit 3 at the Ranger Mine with the "as-modelled" pit. The "annular" boundaries are shown on the figure.

Typical density profiles for an earlier Pit 3 consolidation analysis are shown in Figure 5-27. The figure shows density profiles at the end of deposition. The impact of the effective discharge rate is seen as the degree of consolidation being greater for tailings of lesser depth at the end of deposition.

Underdrainage

Underdrainage is introduced into the model by allowing for seepage forces and negative excess pore pressure. The various pore pressures for an under-drained deposit are presented in Appendix 5.3.

It should be noted that at equilibrium, provided a water pond is maintained at the surface and the underdrain remains operational, there will be constant flow from the surface to the base. At this time consolidation is complete and the flow is constant seepage. This concept is illustrated in Lambe & Whitman (1997: page 258, Figure 17.11).

Outputs

Program outputs include:

- density, permeability, void ratio and effective stress profiles for each "column" at user defined times
- cumulative consolidation flows to the surface and base for each "column".

With respect to flows, the integrated flow out of the base of each "column", effectively determines the flow out of the base and sides of the pit.

Validation

The computer program was initially validated against a number of published examples (Townsend 1990). The Townsend paper presented the results of a number of scenarios whereby practitioners were invited to present solutions to the scenarios. All of the modelled scenarios resulted in excellent agreement.

The underdrain case was validated against a large-scale experiment carried out by Glenister & Cooling (1986). Again, the model showed excellent agreement and the author has been able to validate the model against many real applications including:

- Golden Cross Gold Mine New Zealand (Murphy 1997)
- Century Zinc Mine, Queensland (Murphy 2006)
- The Granites Gold Mine, Northern Territory (Murphy 2007)
- A coal mine in the Hunter Valley (Seddon & Pemberton 2015)

In these examples the model was able to predict:

- tailings elevation with time
- density profiles
- pore pressure profiles.

It should be noted that closure of Bullakitchie Pit (Murphy, 2007) at The Granites Gold Mine is featured as a case study in *Tailings Management: Leading Practice Sustainable Development Program for the Mining Industry* published by the Australian Government (2016). The original paper for this example was presented by the author at a conference in 2007.

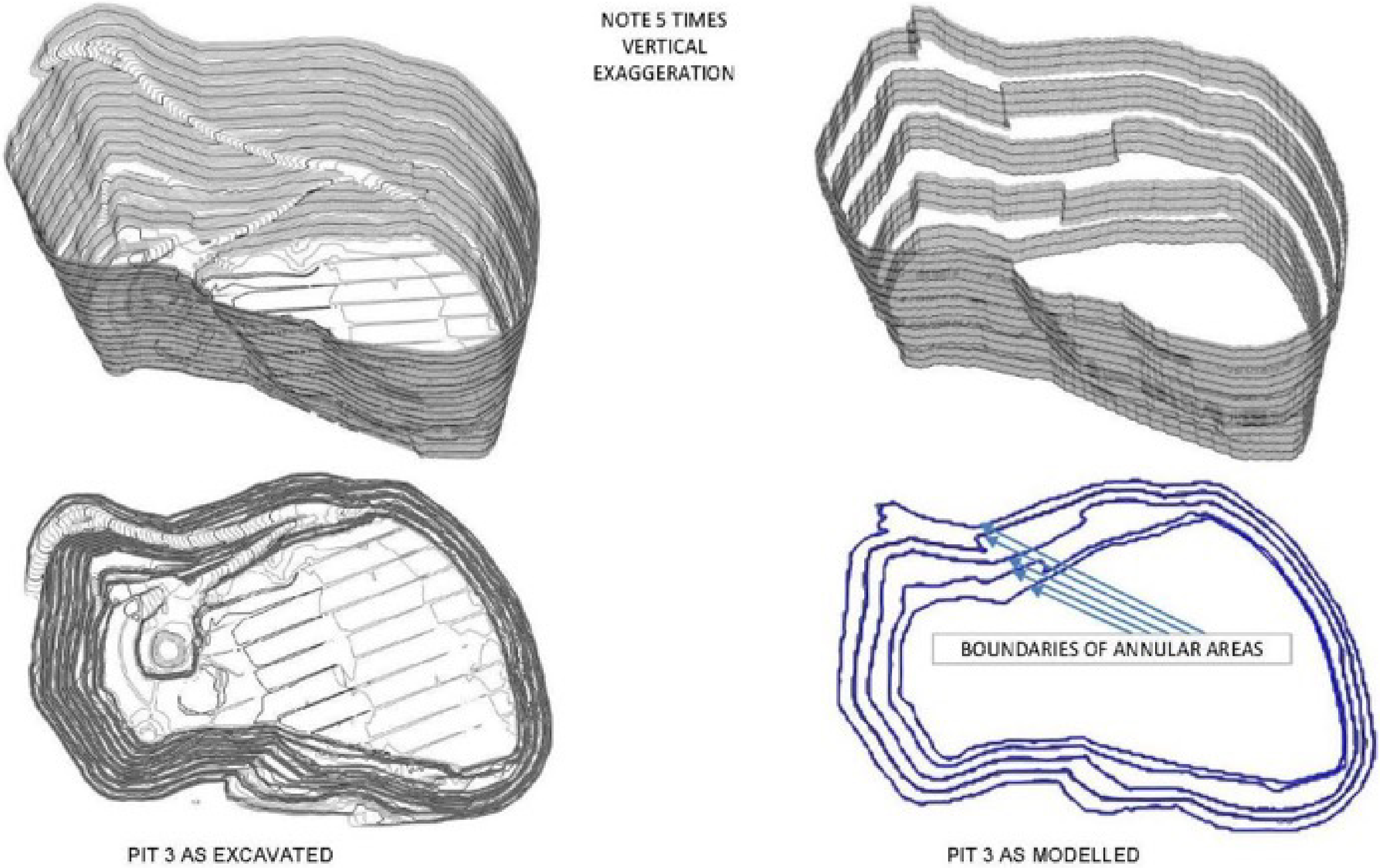


Figure 5-26: Pit 3 as excavated and as modelled

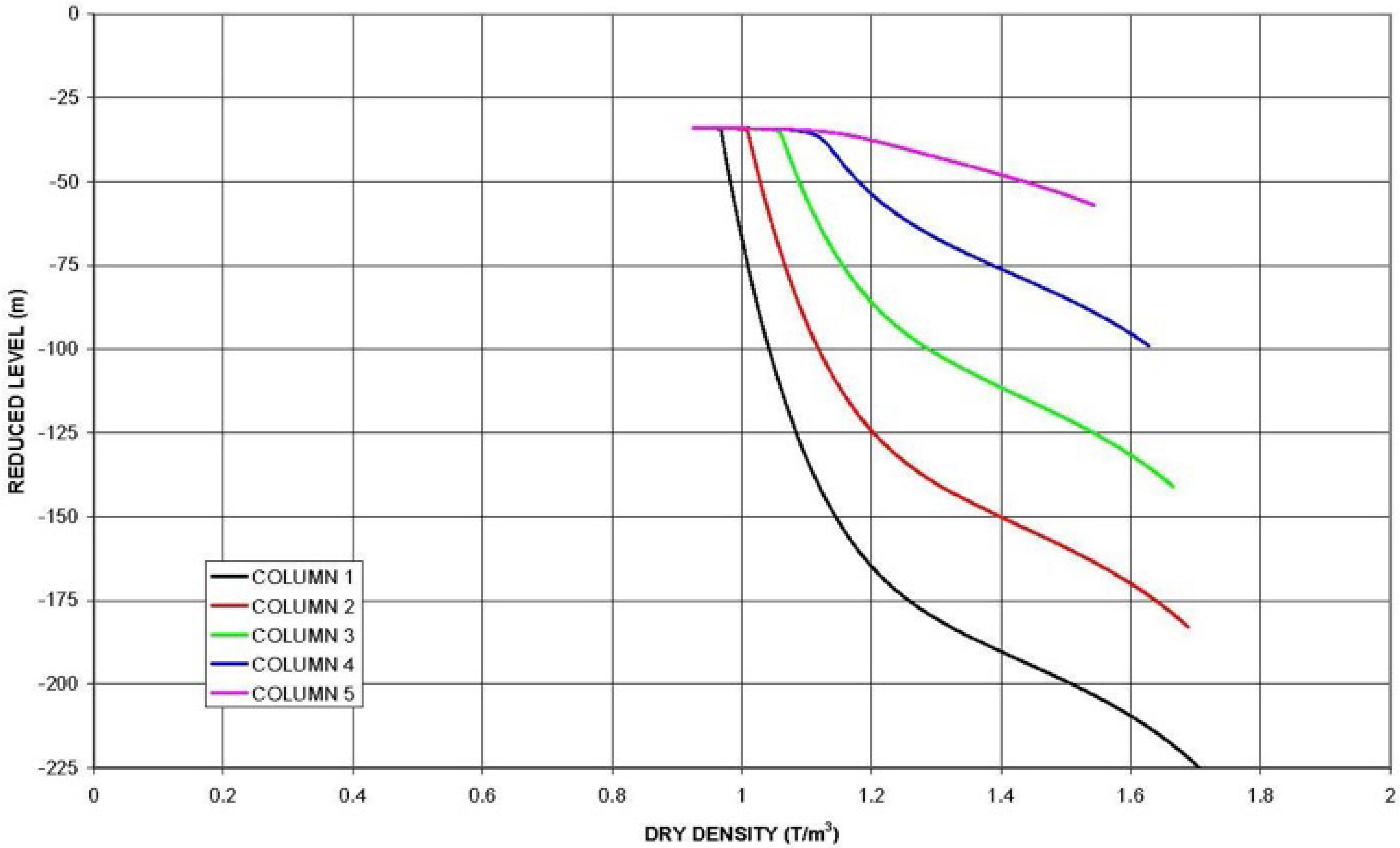


Figure 5-27: Pit 3 density profile - end of filling

5.1.3.5 Pit 1 tailings consolidation

Tailings consolidation modelling in Pit 1 has been ongoing since 2003. The Australian Tailings Consultants (2012) model predicted that the average final tailings level in Pit 1 would be 7.72 mRL with a minimum level of 0.5 mRL in the centre and approximately 12 mRL near the edges. This surface is presented as a contoured digital elevation model (DEM) in Figure 5-28.

In 2015 the Australian Tailings Consultants model was updated by Fitton Tailings Consultants (Fitton). The 2015 model assumed that the 2012 model was essentially correct but provided updates to some of the assumptions in the model (Fitton 2015a). The model also estimated the volume of expressed process water over time (Figure 5-29) and indicated that most process water (greater than 99 %) will be removed via the decant structures by January 2026.

Validation of the consolidation model is enabled by surveying 28 standpipes, attached to settlement monitoring plates, installed across the tailings surface prior to the placement of the initial capping. Validations were initially completed in 2017 and 2020, and then on a regular basis, following the completion of backfilling activities.

Consolidation in Pit 1 is determined by the standpipe survey measurements and presented in terms of average vertical settlement. Average vertical settlement is calculated through dividing the settlement volume by the tailings area (Fitton 2020). Figure 5-30 plots the corrected average vertical settlement from 2008 to April 2021 and compares it with the predicted settlement from the 2012 and 2015 consolidation models (Fitton 2020). This figure shows that measured settlement has generally followed the trajectory of the 2015 consolidation model, but the final settlement will be closer to the 2012 prediction than the 2015 prediction.

Changes in the rate of consolidation were driven largely by the timing of capping and backfill placement (Fitton 2020). This is shown in Figure 5-31, which compares cumulative backfill volume, with the progressive consolidation volume. Initially, tailings were consolidating under their own weight (quiescent consolidation) (Fitton 2020). This had largely plateaued by August 2013 when initial capping commenced (Fitton 2020). Initial capping was carried out until early January 2016 when about 2.8 m depth of fill, including 1 m depth of laterite, had been placed. At this time the rate of consolidation was tapering off. Placement of bulk fill commenced at a rapid rate on 10 May 2017 and the rate of consolidation increased. The rate of fill placement slowed between March 2018 and April 2019 and the rate of consolidation again plateaued. The rate of bulk fill placement increased again in May 2019 and the rate of consolidation increased again.

Following the completion of backfill activities in August 2020, Fitton made a prediction of the ultimate settlement value using methodology developed by Asaoka. The method uses the results from settlement monitoring to predict long term settlement and involves plotting, for a constant time interval, the previous settlement value against the current value (Fitton 2021a). The ultimate settlement is taken to be the point at which the plot intersects a 45- degree line passing through the origin (Fitton 2020). Figure 5-32 shows the settlement data plotted in accordance with the Asaoka method, predicting an ultimate settlement of approximately 4.52m.

Consolidation of tailings, in Pit 1, has proceeded in accordance with predictions (Fitton 2021b). Using the data from the settlement standpipes, and the surveyed tailings surface prior to backfilling, a DTM of the current tailings surface has been produced (Figure 5-33). The average tailings level, as of June 2021, was +7.75 mRL (Steven Murphy, personal communication, 12 January 2022). Based on the predicted ultimate settlement of 4.52 m the degree of consolidation at the time of the last survey is approximately 98 to 99% complete (Fitton 2021b & Steven Murphy, personal communication 5 July 2021).

With consolidation virtually complete, in July 2021 the standpipes were cut to just below the level of the landform, capped and buried. This process was completed to allow other rehabilitation activities to commence unimpeded. The location and height of the pipes was surveyed, so the monitoring system can be reinstated should the need arise.

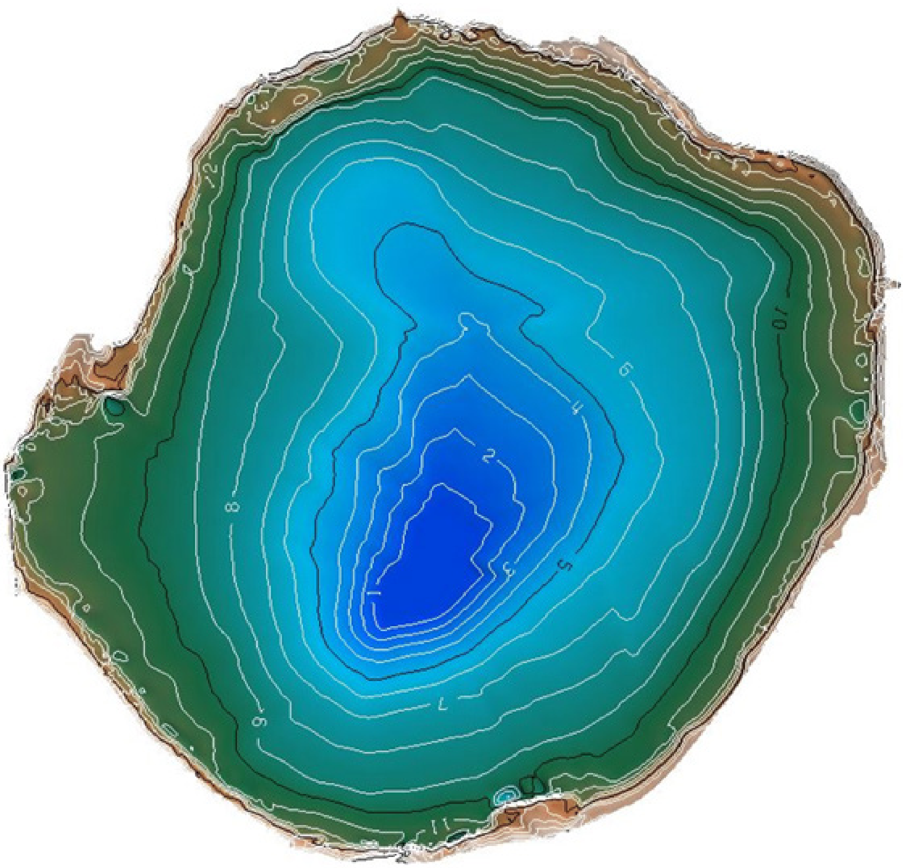


Figure 5-28: Predicted final tailings level (m) across Pit 1

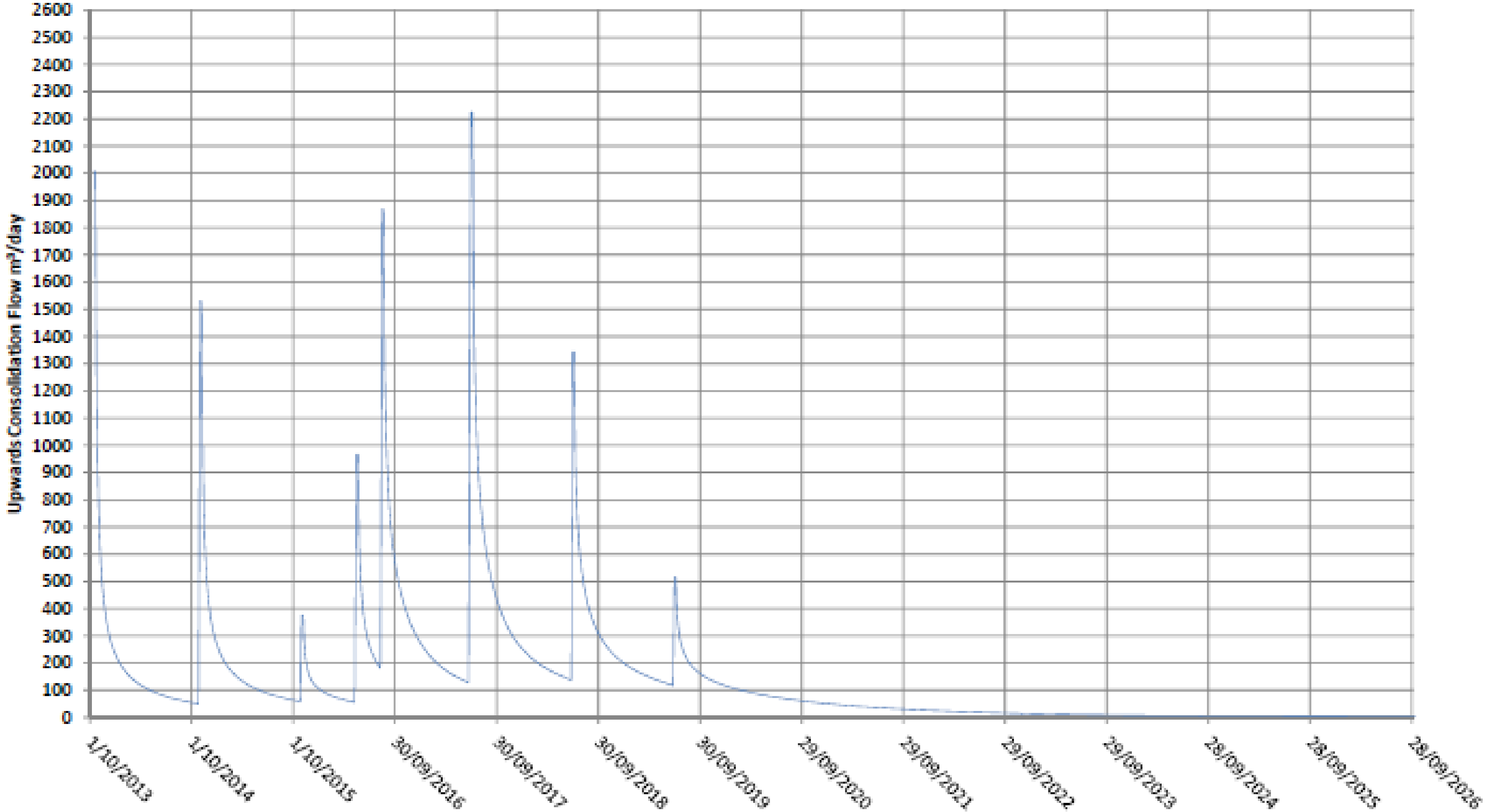


Figure 5-29: Predicted flow of process water from Pit 1 during consolidation (Fitton 2015, 2017; Figure 5)

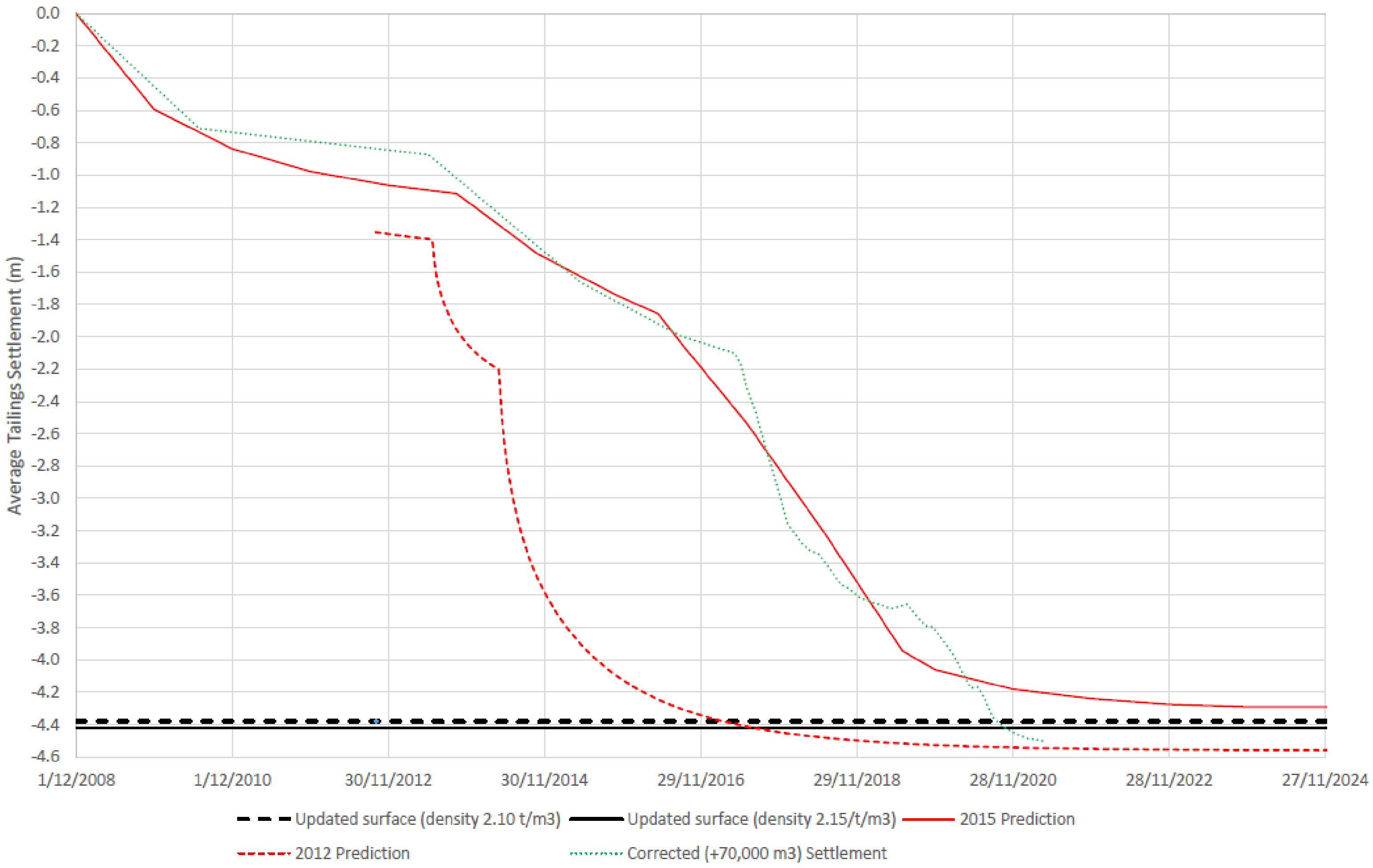


Figure 5-30: Predicted versus measured average tailings settlements in Pit 1

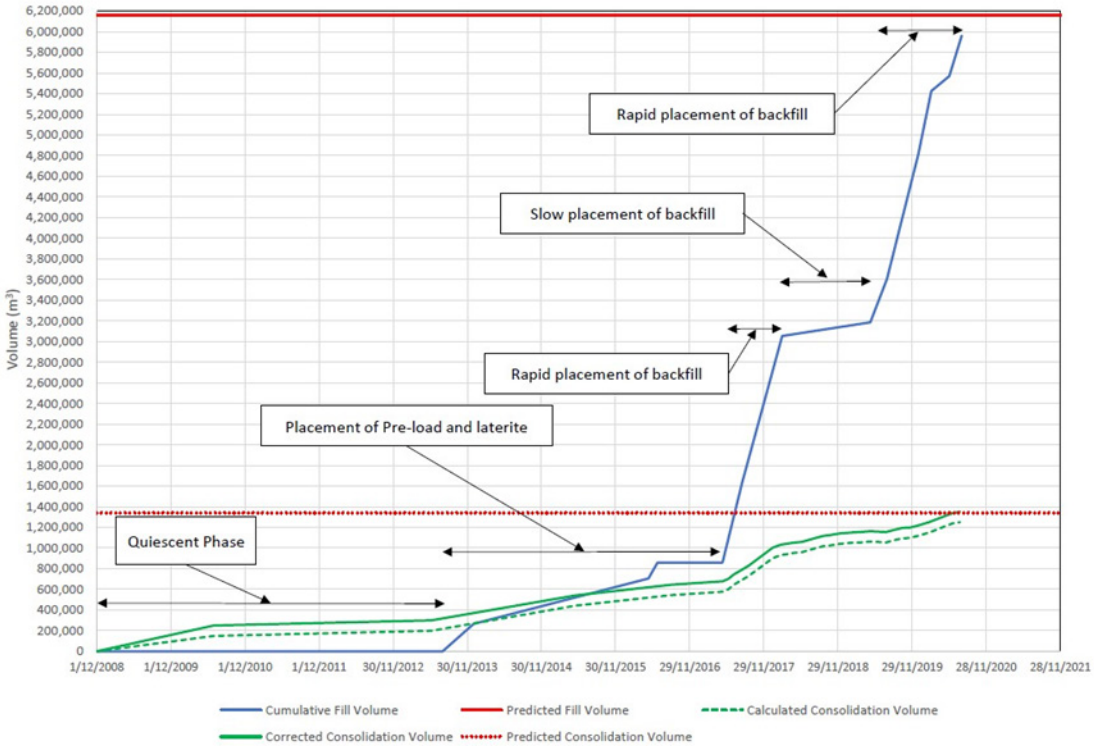


Figure 5-31: Cumulative backfill volume compared with the progressive consolidation volume (Fitton 2020)

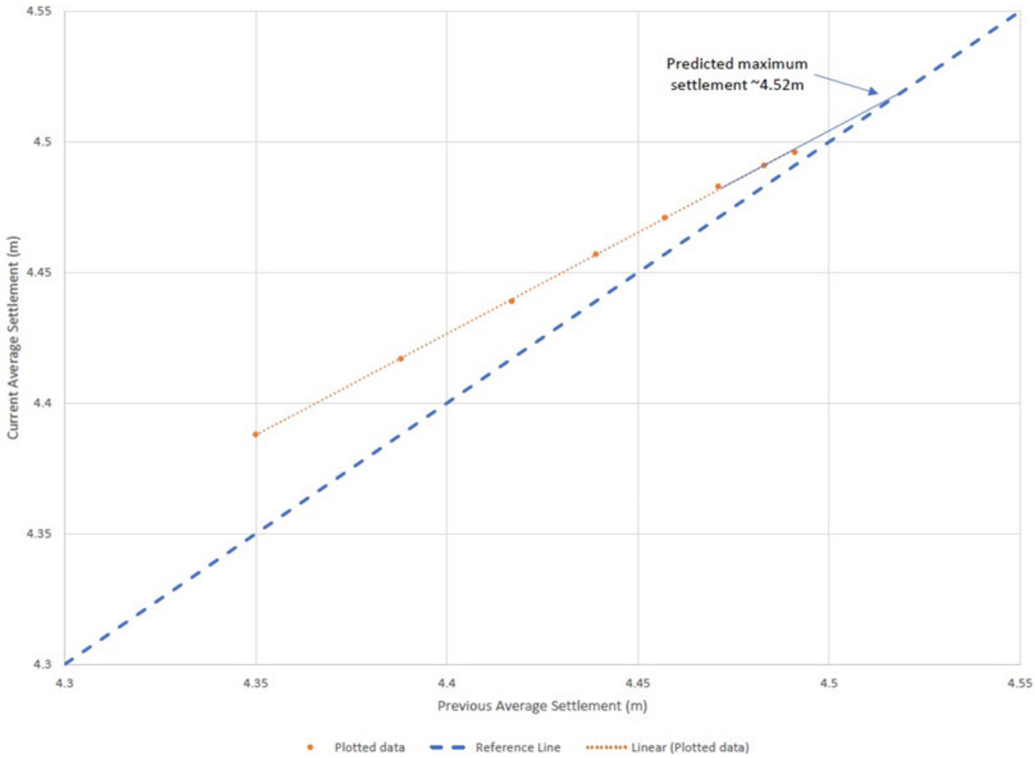


Figure 5-32: Settlement data plotted in accordance with the Asaoka method, predicting an ultimate settlement of approximately 4.52m (Fitton 2021a)

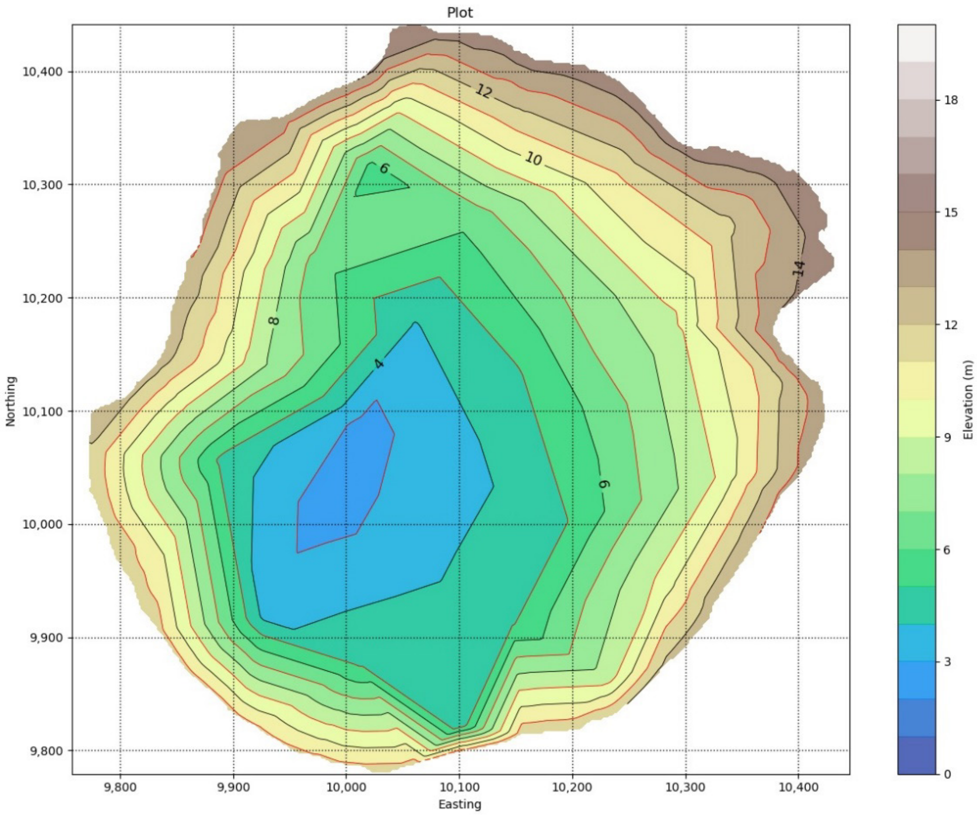


Figure 5-33: Calculated tailings surface as of May 2021 (Steven Murphy, personal communication, 1 June 2021)

5.1.3.6 Pit 3 tailings consolidation

ERA made a submission to the MTC in August 2014, describing the assessment of potential environments impacts from the interim final tailings level in Pit 3 (ERA 2014a). Included in this submission were the results of the predicted tailings consolidation; excerpts of which are provided below, along with the most recent updates of the tailings consolidation model.

Australian Tailings Consultants (2014) outlined the various field and laboratory studies they have conducted to confirm the tailings geotechnical properties and provide up-to-date parameters for the in-pit tailings consolidation modelling.

Testing indicated that the geotechnical properties of the Ranger Mine tailings have and will continue to vary with time, likely due to the inherent variability of the ore type and historical changes to the process. To account for this and provide a sensitivity analysis, three sets of consolidation parameters were considered in the modelling as follows:

- conservative (i.e. relatively slow consolidation) model - based on a Rowe Cell test of the reconstituted sample of pre-1996 TSF tailings and recent mill tailings
- best estimate model - based upon 'best fit' curves from Rowe Cell test results
- non-conservative (i.e. relatively fast consolidation) model - based on the consolidation process in Pit 1.

Consolidation modelling was conducted for all three parameters. Results demonstrated that consolidation could be achieved by 2026 for all cases. The consolidation model was updated to reflect the "as constructed" situation in early 2016 and was completed for the best estimate case only. The model was again updated in 2018, 2019 and 2020 to understand the impact of tailings segregation, tailings deposition, tonnes transferred and estimate the tailings surface over the deposition and post deposition phases. Results of the consolidation models are summarised in Table 5-13. It can be noted that, over time, the predicted end of deposition dry density has reduced from 1.42 t/m^3 to 1.30 t/m^3. This is due to a number of factors:

- The 2014 model was based on thickening the tailings after the first year; for all other cases the thickener was deleted from the closure plan;
- In the earlier homogenous model, the finer particles are trapped in the interstices of the coarser tailings leading to a lower overall volume;
- Segregation results in coarser tailings that are less compressible and finer tailings that are more compressible, but when fully consolidated, the combined overall dry density is lower;
- In the most recent case, due to a slower than expected dredging rate, the rate of deposition must accelerate with time to meet the closure date. The more rapid rate of deposition towards the end of deposition results in a lower final dry density; and
- In the most recent case, the mass of tailings is approximately 1.4 and 0.83 Mt more than the previous segregated models prepared in 2018 and 2019, respectively.

The latest (2020) model update considered two cases of wicking:

- Case 1 – The wicks fail after about six months due to kinking and clogging; and
- Case 2 – The wicks continue to operate though the closure period and beyond

The modelling indicates that consolidation will be practically complete by January 2027 and July 2025 for Cases 1 and 2 respectively. It should be noted that practical completion in this case means that 95 % consolidation has been achieved. It has since been identified in the water pathways risk assessment that a higher consolidation targe may need to be set (e.g. 97%), this is currently under evaluation and will be subject to stakeholder consultation and review during the Pit 3 backfill application and approval process. Figure 5-34 shows the flow of process water in Pit 3 estimated from the most recent model.

The Pit 3 consolidation model was used in the design of the Pit 3 tailings deposition plan implemented during operations phase and currently being used in the Pit 3 backfill and capping design. Additional details of these have been provided in Section 9.

The tailings consolidation model has also been used as input into the groundwater solute transport modelling undertaken by INTERA. A detailed assessment of the post-closure Mg loading to Magela Creek from Pit 3 tailings was undertaken to support the Pit 3 tailings deposition application, this study specifically considered the heterogeneous nature of the deposited tailings following consolidation.

Table 5-13: Summary of Consolidation model results

	Feb-14	May-16	Sep-18	Nov-19		Sep-20	
				Case 1	Case2	Case 1	Case 2
Average base level (RL m)	-100	-99.7	-99.7	-99.7	-99.7	-99.7	-99.7
Underfill/drain volume (m^3)	15,298,380	15,658,180	15,658,180	15,658,180	15,658,180	15,658,180	15,658,180
Tonnes	41,781,246	40,345,324	40,345,324	40,882,759	40,882,759	41,709,136	41,709,136
Deposition duration (yrs)	5.75	5.92	6	5.92	5.92	6	6
Thickening?	After year 1	No	No	No	No	No	No
Dry density - end of deposition (t/m^3)	1.42	1.39	1.35	1.38	1.31	1.30	1.30
Dry density - end of consolidation (t/m^3)	1.68	1.66	1.63	1.63	1.63	1.62	1.62
Average level -end of deposition (m)	-21.3	-21.53	-20	-19.8	-17.8	-16.2	-16.2
Average level - end of consolidation (m)	-31	-31.3	-30.3	-29.9	-29.9	-29.5	-29.5
Average cover depth (m)	48.64	48.94	50.93	50.3	50.3	50.2	50.2
Cover volume (m^3) **	25,292,800	25,448,800	26,534,530	26,204,815	26,204,815	26,523,188	26,523,188
Water expressed - during deposition (m^3)	14,707,410	21,938,520	16,860,080	?	?	13,647,631	13,647,631
Water expressed - post deposition (m^3) ***	4,370,360	4,721,000	5,163,690	4,454,068	6,126,766	6,395,879	6,395,879
Wick area (m^2)	238,235	416,216	145,000	?	?	145,000	145,000
Water expressed by wicks (m^3)	2,334,780	2,125,840	430,439	?	?	1,132,775	1,132,775
Consolidation complete	May-27	May-27	May-28	?	?	Dec-35	Dec-29
Consolidation practically complete****	Feb-25	Dec-24	Jun-25	?	?	Mar-27	Apr-25

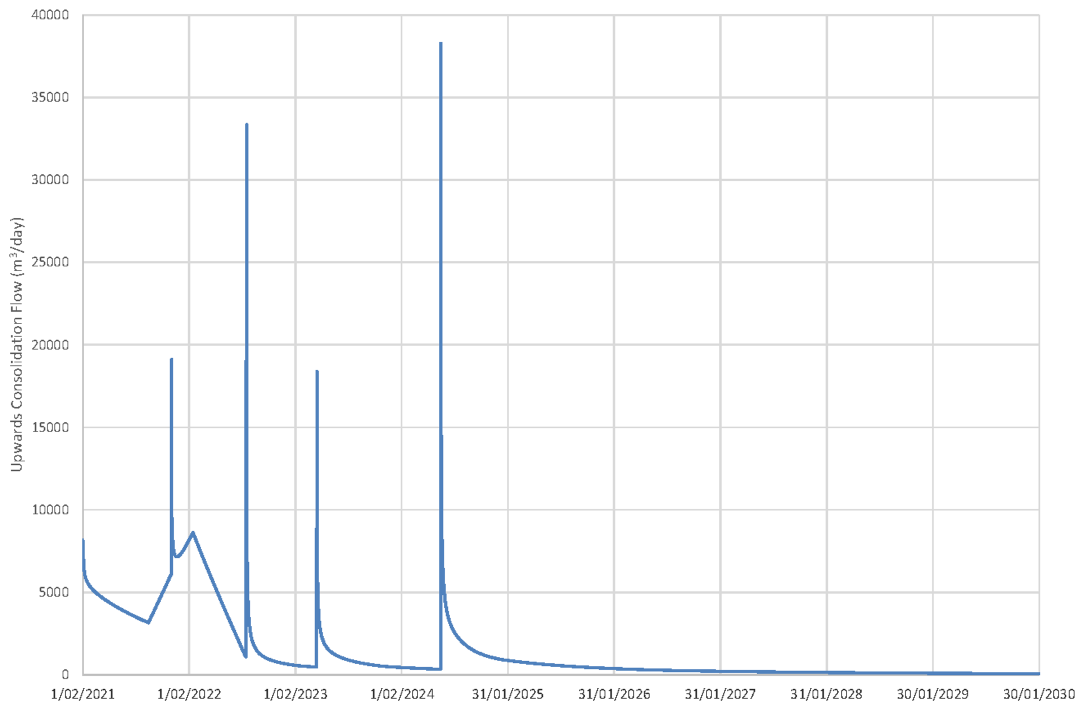
The number of decimal places presented in this table does not imply a level of accuracy. The numbers are presented to identify, sometimes, small differences in results.

**In previous reports volumes were based on an adopted pit edge. The volumes in this table for Feb 14 and May 16 are less than previously presented as they have been based on final tailings area in accordance with this report.

***Includes wick volume.

****Based on removal of 95% of mobile pore water.

? Not calculated for this analysis.



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ENERGY RESOURCES OF AUSTRALIA LTD

RANGER URANIUM MINE

Pit 3 Consolidation Update

Case 1 Post Deposition Upwards Consolidation Flow

Date: 1/09/2020 **Job No:** 1504.20 **FIGURE 32**

Figure 5-34: Typical predicted flow of process water from Pit 3 during consolidation

5.1.3.7 Tailings properties

Around 43 Mt of dry tailings from the mill and the TSF will be transferred to Pit 3 by November 2021. It was calculated that tailings would be deposited to a thickness of approximately 80 m and a volume of about 33.1 Mm^3. Section 9 provides details of tailings transfer activities.

Tailings transfer from the TSF is supported by a number of studies undertaken in order to validate the expected tailing volumes and also to provide key information to feed into the overall dredge program. Studies included:

- TSF geophysical surveys (Fugro 2012 and 2018)
- TSF magnetometer survey (Fugro 2012)
- Magnetic survey (Surrich 2019)
- TSF characterisation and cone penetration test (CPT) program (Shackleton 2013; in2Dredging 2020).

5.1.3.8 TSF Bathymetric surveys and geotechnical investigation

Prior to commencement of dredging and every quarter during the dredging operation a bathymetric survey was completed. The initial bathometric survey determined that there were 23.1 Mm^3 of tailings contained within the TSF. At the completion of bulk dredging in February 2021, 20.4 Mm^3 of tailings had been dredged to Pit 3. Typical survey results are presented in Figure 5-35.

Magnetometer surveys were conducted prior to and during dredging. These surveys provide magnetic intensity data from a towed magnetometer. The data from the 2019 magnetometer survey compared to that from 2012 is shown in Figure 5-36 The primary objective of the survey was to locate any potential buried iron objects which could impact proposed dredging operations.

As expected, 'magnetic' objects were identified close to the TSF embankments, whilst the central area was relatively free of anomalies. The magnetometer detected a very strong anomaly on the south-eastern side of the dam, believed to be the sunken remains of the old survey barge/pontoon. No other features of similar magnitude were found. Many anomalies, either localised or diffused, are likely to be caused by magnetic material in the tailings, accentuated by variations in the water depth that changes the range between source and detector. Small, localised anomalies, particularly around the TSF perimeter, probably represent iron debris.

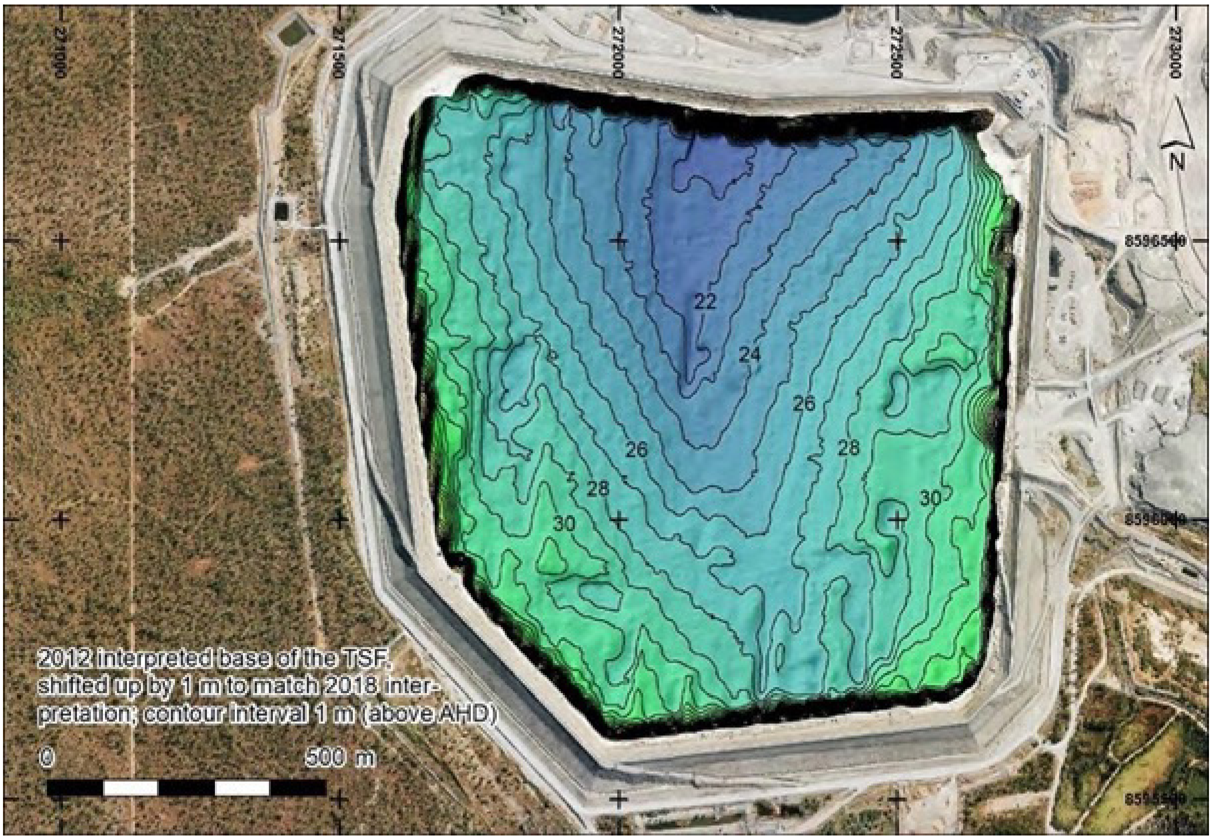


Figure 5-35: TSF topography (blue: low elevation; green: high elevation) (Fugro 2018)

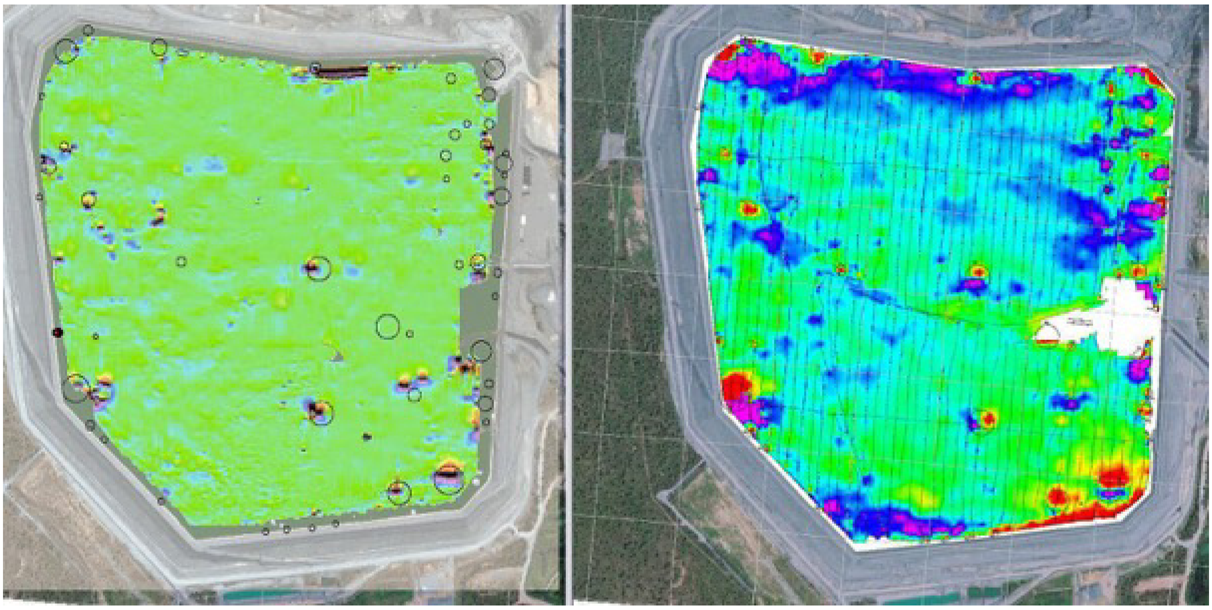


Figure 5-36: April 2019 Magnetic Anomaly Map (left frame) comparison with the 2012 Magnetic Anomaly Map (right frame)

Between 27 August and 25 November 2012, ATC Williams was assigned to undertake an investigation into the in situ condition of the tailings in the TSF (Shackleton 2013) to facilitate the selection of an appropriate dredge and pumping equipment, along with the design of a feasible work method. This work entailed cone penetrometer tests and tailings sampling (Figure 5-37).

The data analysis from the CPTs, laboratory results and onsite observations indicated two separate zones within the TSF:

- an outer zone comprising of sands and silty sands, overlying a sandy layer, followed by the foundation on the perimeter of the TSF in shallower water.
- an inner zone of under consolidated fines of very low strength, overlying a sandy layer, followed by the foundation, located within the deeper sections of the TSF (Shackleton 2013; p 11).

The outcome of the TSF geophysical and magnetometer surveys validated the expected tailings volumes and provided valuable knowledge on the segregation and characterisation of tailings in the TSF. These studies together with the CPTs assisted the overall design of the TSF dredge and subsequent dredging method. Additional geotechnical investigation was carried out in the TSF by in2Dredging (May 2020) to augment the previous investigation conducted by Australian Tailings Consultants (2012). It involved CPT, vane share test (VST), and tailings sampling. The study determined the undrained shear strength of the tailings and the approximate floor of the TSF to optimise the use of the two dredges, Brolga and Jabiru (In2Dredging 2020).

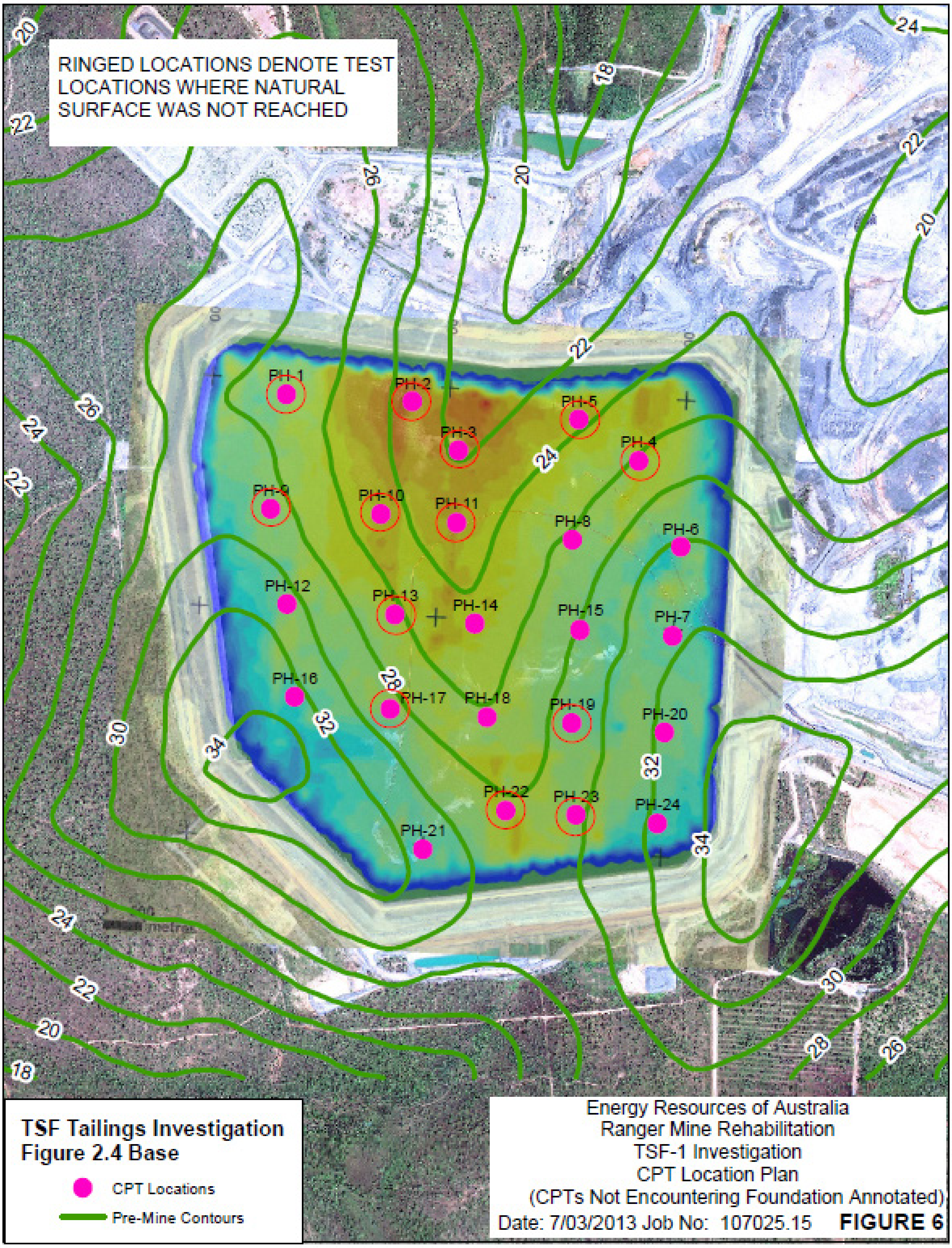


Figure 5-37: Cone penetration locations (Shackleton 2013)

5.1.3.9 Pit 3 geotechnical investigation

Geotechnical investigations were conducted in Pit 3 in 2018 (Fitton 2019), 2019 (Fitton 2020b) and 2020 (Fitton 2021) to verify the consolidation model. The 2020 investigation involved CPT, pore pressure dissipation test, tailings sampling, and VST at locations shown in Figure 5-38. A few test locations from 2018 and 2019 investigations were re-tested to understand how the fine tailings consolidation was occurring. Details of the 2020 CPT is summarised in Table 5-14.

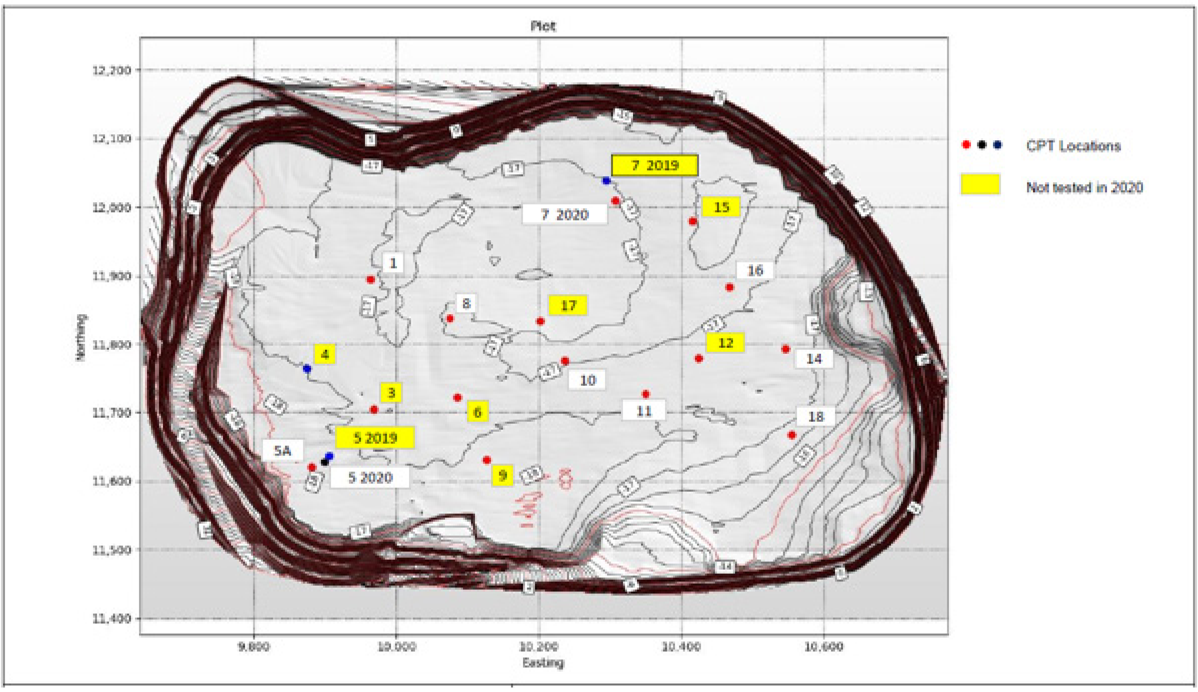


Figure 5-38: CPT Locations

Table 5-14: Details of 2019 CPT

Location	Date	Water RL (m)	Water Depth (m)	Top of Tailings (m)	CPT Depth (m)	Base RL (m)	RL Reached (m)	Operator	Location E	Location N
1	16/10/2020	-18.17	0.90	-19.07	79.86	-97.88	-98.03	David Chapman	273711	8597984
5	21/11/2020	-16.33	2.25	-18.58	59.86	-75.33	-76.19	David Chapman	273625	8597713
5A	14/02/2021	-9.93	7.80	-17.73	51.38	-63.06	-61.31	Russell Vincenzi	273606	8597707
7	14/12/2020	-14.71	3.75	-18.46	64.30	-97.49	-79.01	David Chapman	274065	8598055
8	21/10/2020	-18.09	1.28	-19.37	80.58	-100.03	-98.67	David Chapman	273823	8597904
10	28/11/2020	-15.75	2.30	-18.05	60.45	-99.51	-76.20	Russell Vincenzi	273975	8597828
11	5/12/2020	-15.08	2.90	-17.98	55.96	-99.01	-71.04	Russell Vincenzi	274077	8597773
14	8/12/2020	-14.92	2.98	-17.90	43.10	-98.23	-58.02	Mitch Ebrington	274274	8597817
16	16/11/2020	-16.88	1.00	-17.88	41.40	-98.20	-58.28	David Chapman	274208	8597919
18	12/12/2020	-14.81	1.90	-16.71	42.96	-98.25	-57.77	David Chapman	274281	8597695

It is noted that only 2 out of 10 probes reached the base of the pit – the target depth. This is due to the very challenging conditions within Pit 3. Typically, there is a considerable depth of very soft under consolidated tailings overlying consolidated tailings. The soft tailings provide no lateral support to the rods resulting in potential, and actual, buckling of the slender rods used to advance the CPT cone. Buckling can occur when consolidated tailings are encountered at depth. This can be overcome, to a certain extent, by driving casing when lateral deflection is observed to commence. Unfortunately, this did not always alleviate the issue as tailings within the casing caused binding of the rods and buckling still occurred.

The CPT data was analysed with software package (CPet-IT), provided by Geologismiki. The software can draw on the results of laboratory testing to enhance the estimation of soil behaviour type (SBT), which is different from soil classification usually based on index testing including particle size distribution and Atterberg Limits and is often referred to as textural based classification. The CPT software classifies a soil based on correlations of soil behaviour type, not textural classification. For example, a soil may classify as silt, but its SBT may be more like sand. The SBT of the tailings encountered are grouped into two:

- Group 1 (Probes 1, 5, 5A, and 8, on the west of the Pit): It consists predominantly of finer tailings over the full depth of the probes. The tailings are initially classified as fine-grained sensitive due to zero or near zero friction sleeve reading. At depth, the friction sleeve reading increases and the tailings behave as clay and silty clay.
- Group 2 (Probes 10, 11, 14, 16 and 18, on the east of the Pit): In this group, the finer tailings behave in a similar way to the fines in group 1 until coarser tailings are encountered. The tailings below the fines behave as sandy silt and silty sand with thin bands of clean sand.

Typical SBT profile for Group 1 and 2 are presented in Figure 5-39 and Figure 5-40, respectively. The SBTs are one piece of evidence that confirms the tailings deposition model adopted for the consolidation analysis.

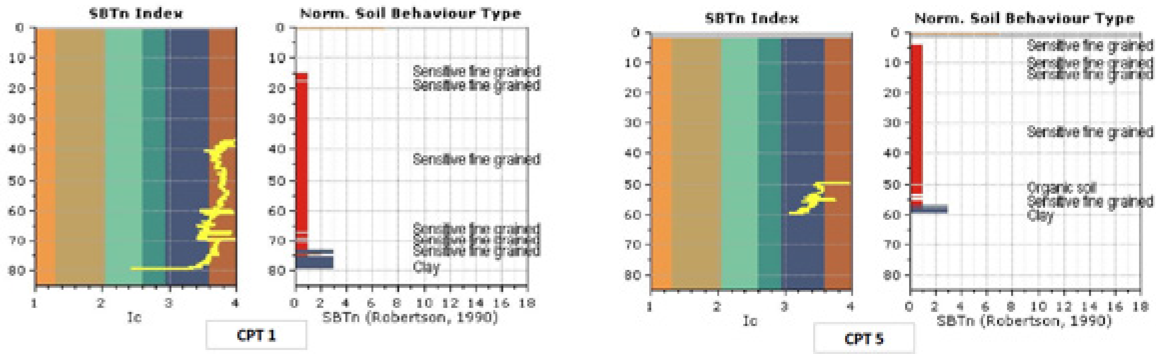


Figure 5-39: Group 1 SBT profile on the west of the Pit

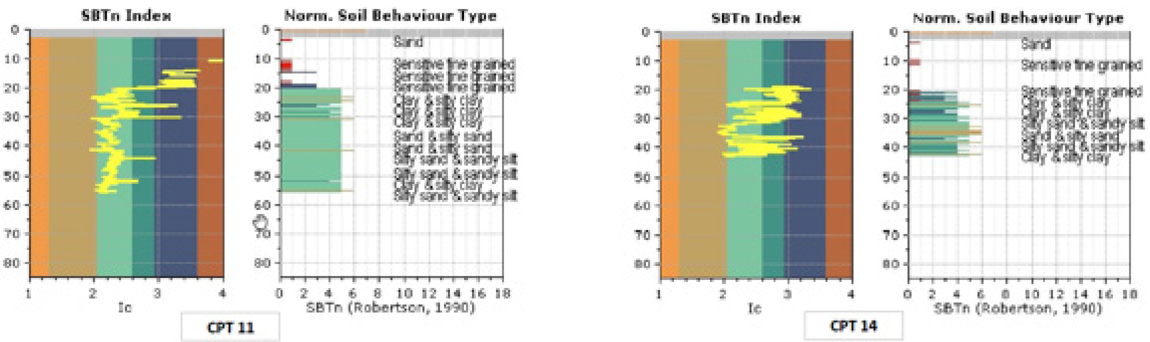


Figure 5-40: Group 1 SBT profile on the west of the Pit

The west, is greater than that obtained from the 2018 and 2019 (Figure 5-41), indicating that the in-situ density and undrained shear strength of the tailings have increased and thus pore pressure dissipation and hence consolidation of the tailings has occurred.

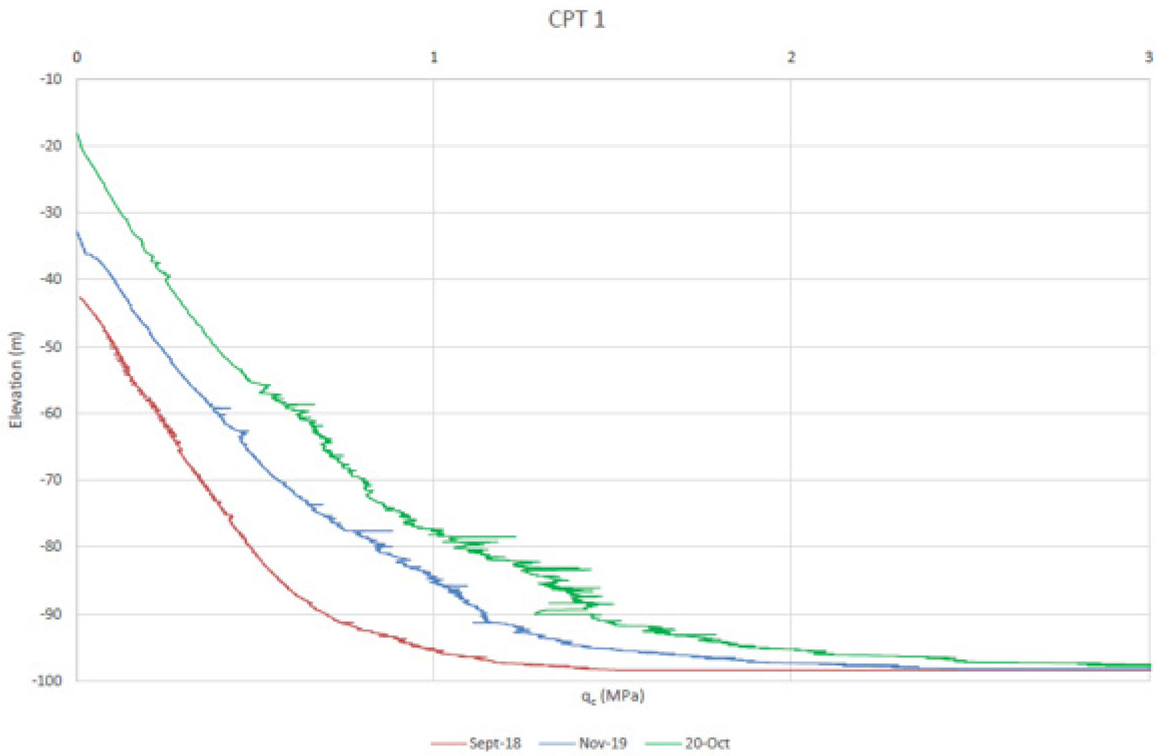


Figure 5-41: Typical 2018/2019/2020 cone resistance comparison

Some of the output from the consolidation model are the fine/coarse tailings boundary and excess pore pressure profile which are compared with the *in-situ* data in Figure 5-42 and Figure 5-43, respectively. It is noted that the measured excess pore pressure profile and fine/coarse tailings interface closely agree with those predicted by the consolidation model. An update of the consolidation model is occurring following the completion of trucked deposition of remnant tailings from the above ground TSF floor into the Pit.

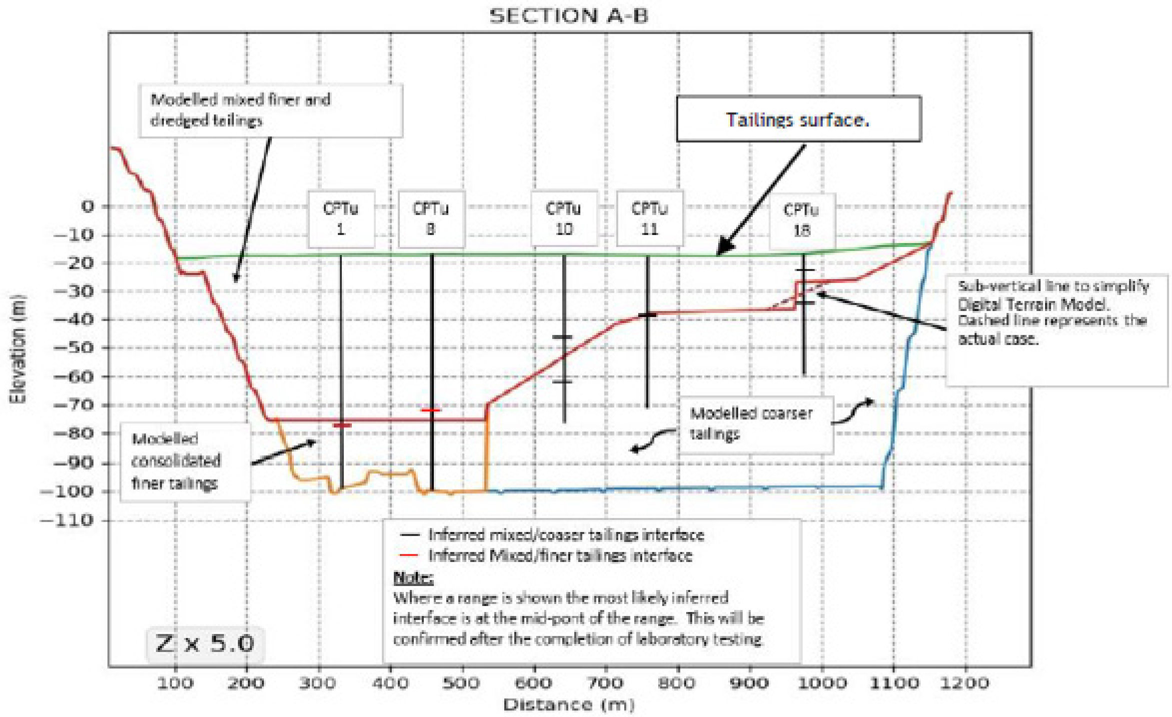


Figure 5-42: Predicted versus measured fine/coarse tailings interface

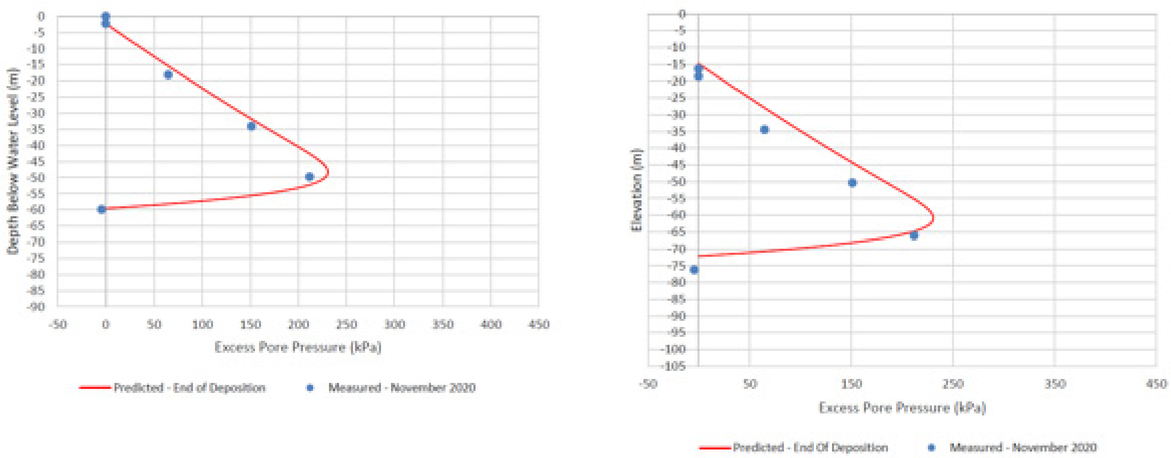


Figure 5-43: Measured versus predicted excess pore pressure profile

The 2022 CPT program was carried out from January to March, following completion of the remnant tailings transfer described in detail in Section 9, in December 2021. The aims of this program were to:

- Determine the impact that the deposition of remnant tailings had on the consolidation of tailings already in Pit 3; and
- Investigate the condition of the tailings in the vicinity of the proposed eastern platform to determine whether the area is suitable for construction (Fitton 2022).

This section describes the parts of the CPT program concerned with determining the impact of the remnant tailings placement on consolidation. The investigative works carried out in the vicinity of the proposed eastern platform are described in Chapter 9.3.2.2, as this program is more aligned with the implementation of Pit 3 closure activities.

CPTu probes 1, 5, 8, 10 and 11 were performed at the locations of previous investigations to compare results from the recent and earlier probes. These locations are provided in Figure 5-44.

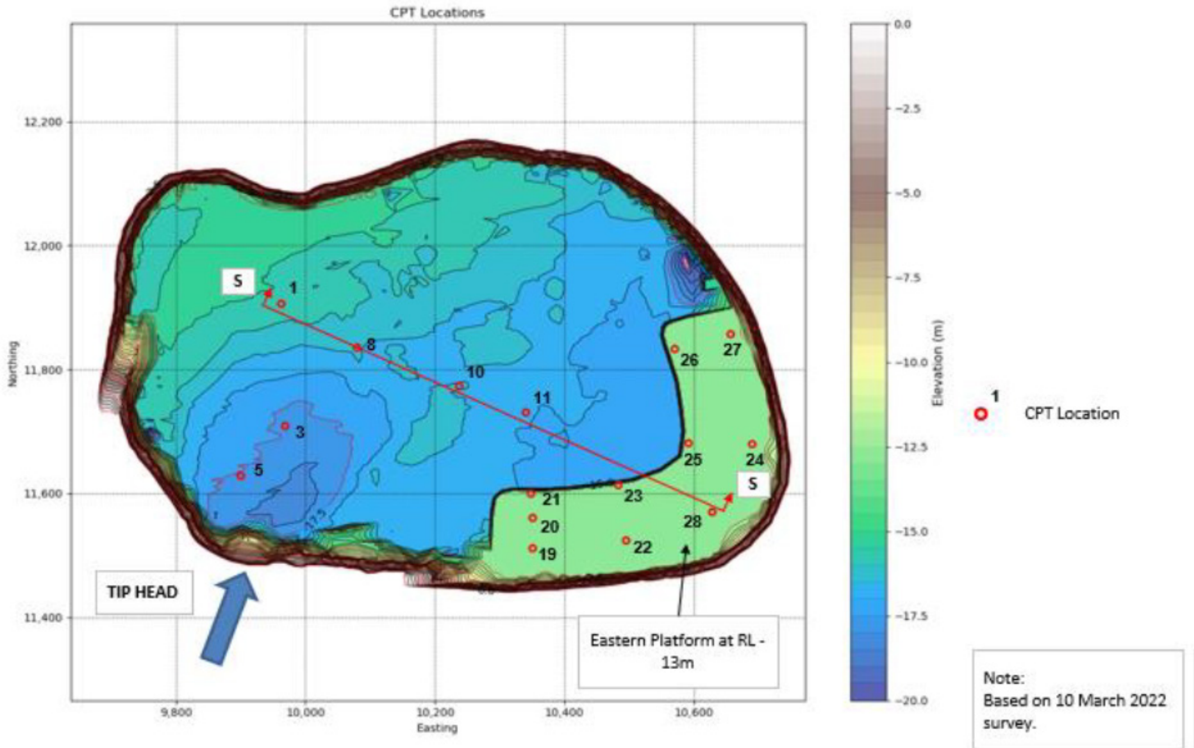


Figure 5-44: CPTu probe locations in relation to the Pit 3 tip head and proposed eastern platform

Cone resistance at common elevations, for all locations, has increased with time (Figure 5-45). This provides basic confirmation of ongoing consolidation (Fitton 2022). Locations 3 (Figure 5-46) and 5 (Figure 5-47) have been impacted by remnant tailings deposition. These locations show significantly higher cone resistance over very small depth intervals, likely a result of rocks entrained in the remnant tailings (Fitton 2022).

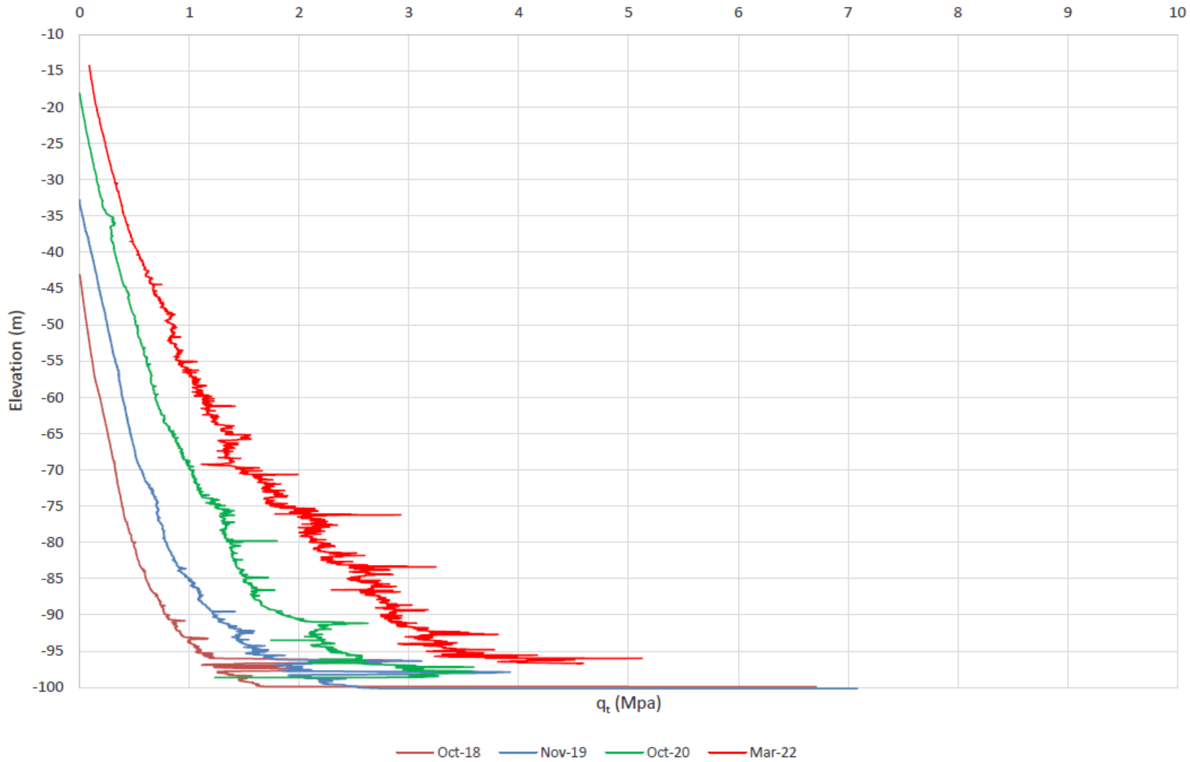


Figure 5-45: Comparison of corrected cone resistance at location 8

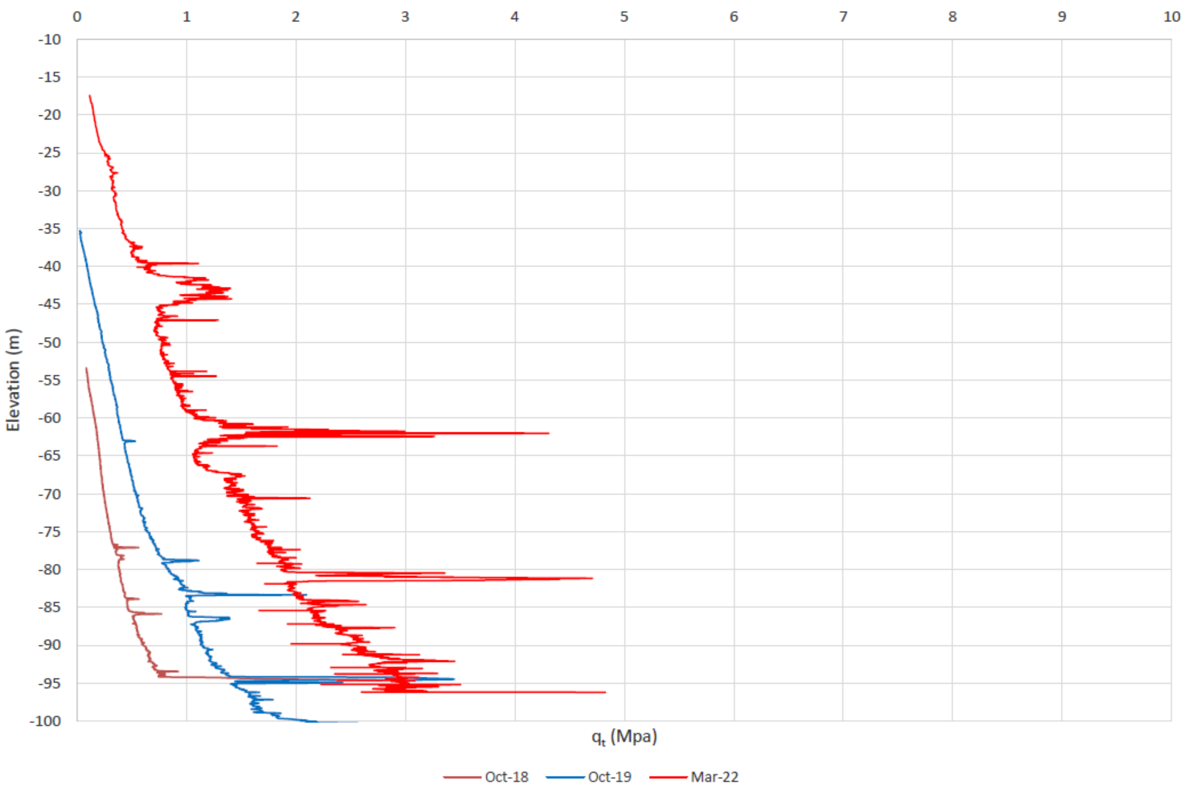


Figure 5-46: Comparison of corrected cone resistance at location 3

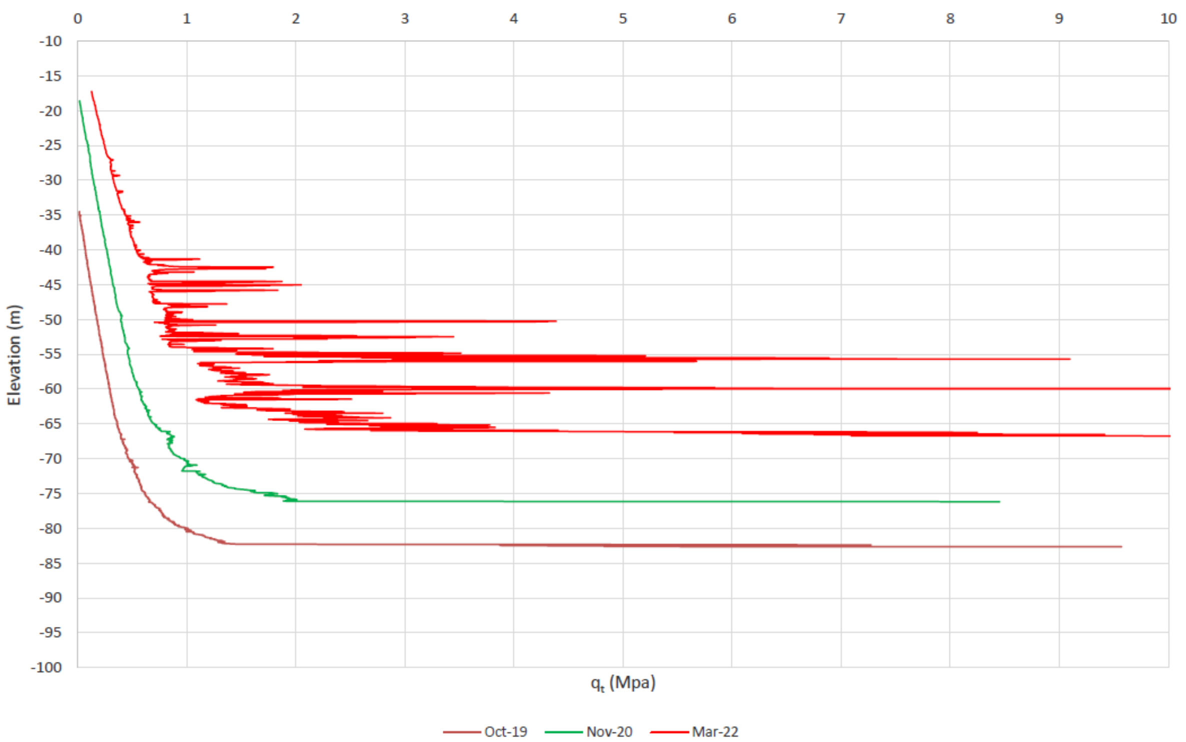


Figure 5-47: Comparison of corrected cone resistance at location 5

Excess pore pressures at locations 1, 8, 10 and 11 are largely unchanged (Figure 5-48). However, the excess pore pressures at location 5 (Figure 5-49) have increased considerably since late 2020 and the excess pore pressures at location 3 (Figure 5-50) are considerably higher than those predicted by consolidation modelling in 2020. Given that the 2020 predictions were generally accurate, it is likely that the excess pore pressures at location 3 are higher than would have been measured in 2020 (Fitton 2022).

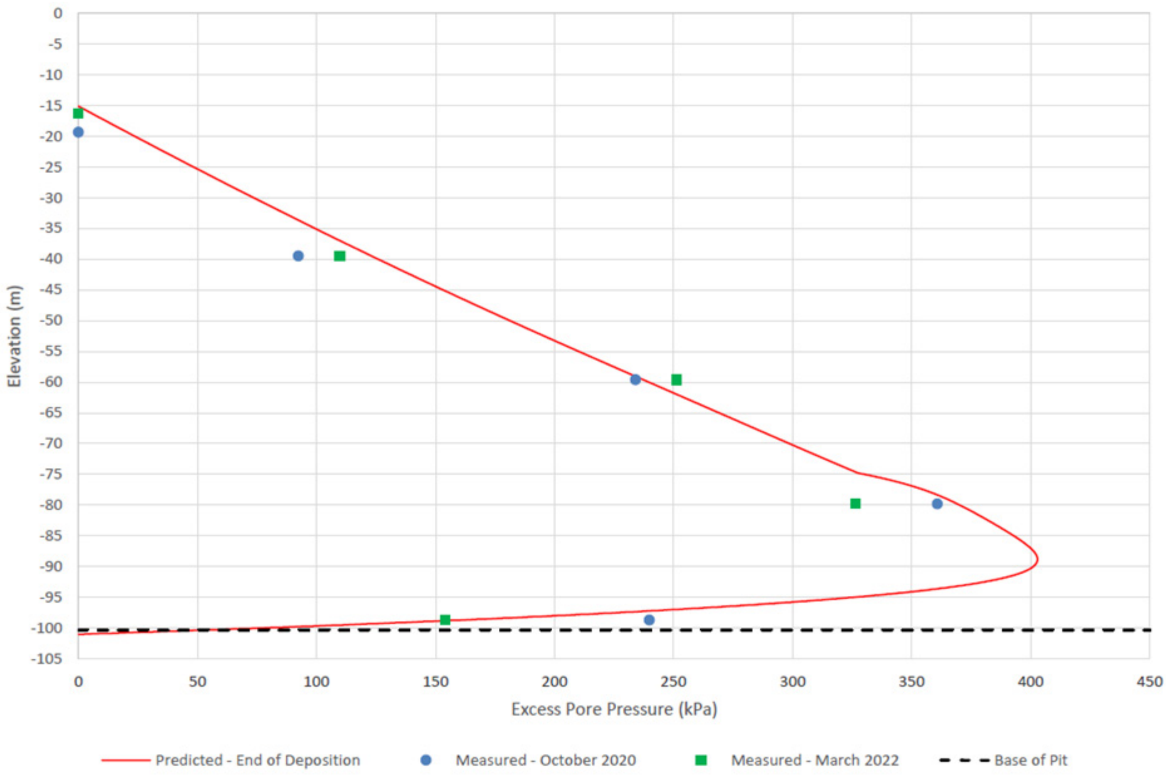


Figure 5-48: Comparison of excess pore pressures at location 8

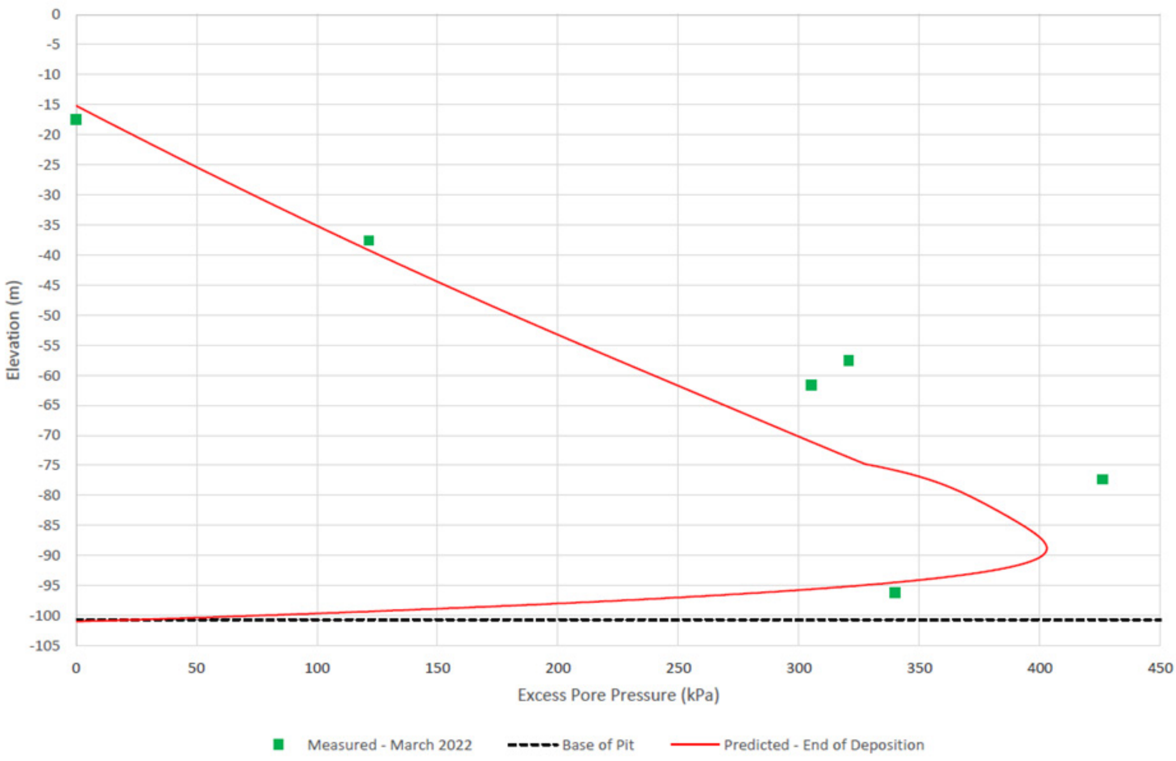


Figure 5-49: Comparison of excess pore pressures at location 3

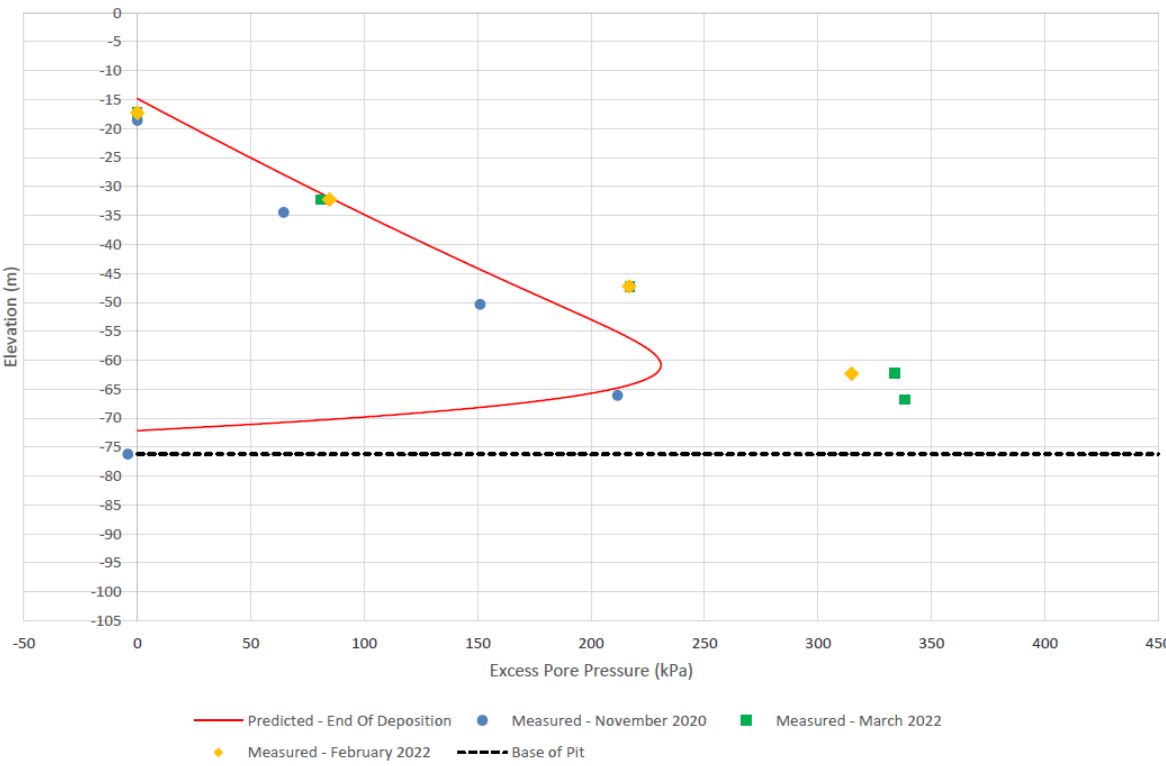


Figure 5-50: Comparison of excess pore pressures at location 5

The variable cone resistance response and increased excess pore pressures at locations 3 and 5 indicate that the impact of remnant tailings deposition is localised to the area in the vicinity of the tip head (Fitton 2022). The increase in excess pore pressure is due to the relatively rapid rate of tailings deposition (Fitton 2022).

This localised impact is supported by the results of the regular bathymetric surveys. These surveys indicate a general depression near the tip head and heave of the finer tailings radiating out from the tip head (Fitton 2022). The elevated coarser tailings in the south-east corner of the pit have been unaffected by TSF tailings deposition (Fitton 2022).

The Fitton (2022) report concluded that the placement of the residual TSF tailings in Pit 3 will have no impact on long term consolidation or closure of the pit.

5.1.3.10 Pit 3 geophysical surveys

Geophysical surveys were conducted in Pit 3 during 2018, 2019 and recently in 2021 by Fugro Australia Marine Pty Ltd (Fugro). The surveys determined the tailings distribution, including fine/coarse tailings interface, and their quantity within the pit as well as the quantity of water. The 2020 campaign comprised a bathymetric and seismic surveys. The bathymetric survey included Single Beam Echosounder (SBES) and the seismic survey included single channel seismic reflection (Boomer), sub-bottom profiling methods (Chirp) and parametric profiling. The volumes of tailings and water in the pit, established from the 2020 campaign are summarised in Table 5-15 and their surfaces are presented in Figure 5-51.

The volume of water, total tailings and total pit fill, estimated during the investigation, is 7.15 Mm^3, 31.66 Mm^3 and 38.77 Mm^3, respectively. The volume of water has increased from 0.55 Mm^3 to 7.17 Mm^3, and tailings from 24.19 Mm^3 to 31.66 Mm^3 since the last survey in 2019. It should be noted that the results from the geophysical surveys are used to augment the geotechnical investigation (CPT) data, especially the fine/coarse tailings interface and volume or mass ratio, to verify the consolidation model.

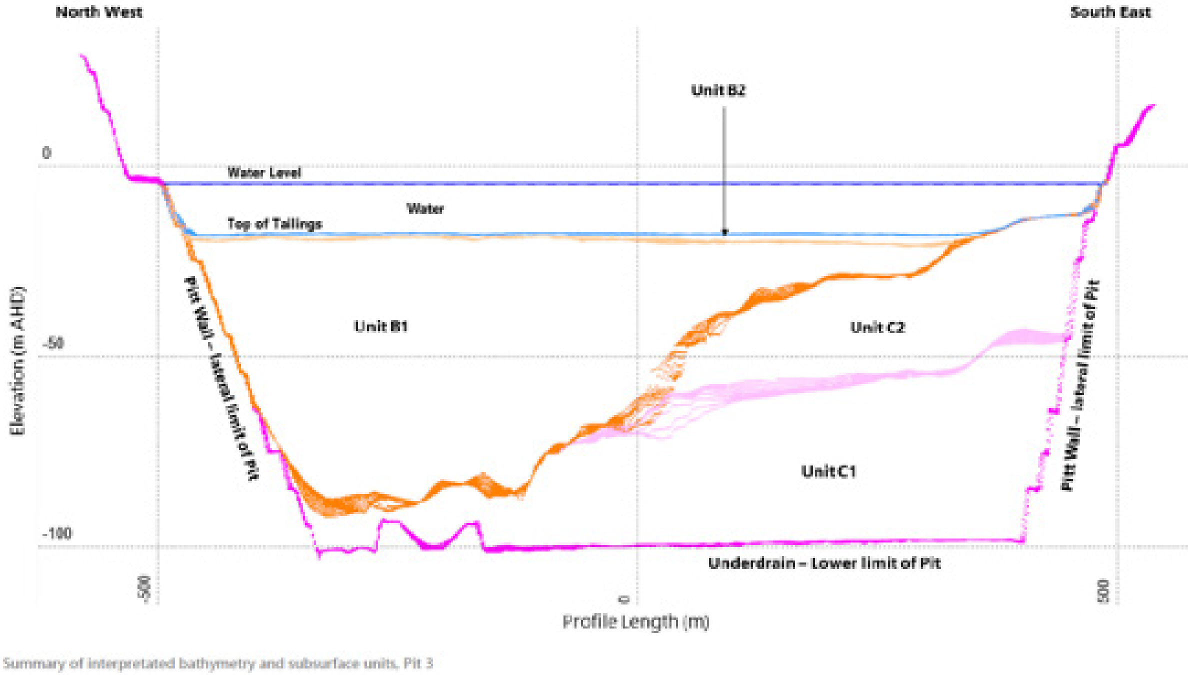


Figure 5-51: Cross section of tailings and water within the Pit

Table 5-15: Summary of Geophysical survey

No.	Volume	Est. Quantity [Mm^3]	Comment[A]
1	Total Pit Fill	38.77	The total pit fill volume estimated between the upper boundary provided by the water level (dark blue) and the lower boundary provided at the base of unit C1 by the Pit Shell and Underdrain (pink)
2	Water	7.15	The volume estimated between the upper boundary provided by the water level (dark blue) (-4.616 m AHD) and the lower boundary provided by the bathymetry level, interpreted to be the Top of the Tailings (light blue). The bathymetry levels have been interpolated to intersect the Pit Shell where the bathymetric coverage was limited at the perimeter of the site.
3	Unit B	13.64	The volume provided by sum of Unit B1 and Unit B2. The volume estimated between the upper boundary provided by the surface of the Top of Tailings (blue) and the lower bounds of Unit B1, provided by the interface with B1 (reflectors R2.0, R1.3, R1.2 and R1.1) and the Top of Tailings (orange).
4	Unit B1	12.94	A sub-unit of Unit B. The volume estimated between the upper boundary provided by the reflector surface *R3.0* (light orange) and the lower boundary provided by the lower bounds of Unit B1, provided by interface with B1 (reflectors R2.0, R1.3, R1.2 and R1.1) and the Top of Tailings (orange).
5	Unit B2	0.70	A sub-unit of Unit B. The volume estimated between the upper boundary provided by the reflector surface Top of Tailings (blue) and the lower boundary provided by the reflector *R3.0* (light orange).
6	Unit C	18.00	The volume provided by summing Unit C1 and Unit C2. The volume estimated between the upper boundary, provided at the interface with B1 (reflectors R2.0, R1.3, R1.2 and R1.1) and the Top of Tailings (orange), and the lower boundary provided by the *Pit Shell and Underdrain* (pink).
7	Unit C1	11.94	A sub-unit of Unit C. The volume estimated between the upper boundary, provided at the reflector *R1.0* (light pink) and the lower boundary provided by the *Pit Shell and Underdrain* (pink)
8	Unit C2	6.05	A sub-unit of Unit C. The volume estimated between the upper boundary, provided at the interface with B1 (reflectors R2.0, R1.3, R1.2 and R1.1) and the Top of Tailings (orange) and the lower boundary provided by the reflector R1.0 (light pink).
9	Total Tailings	31.66	The sum of the Unit volumes. Further, the volume is estimated between the upper boundary provided by the Top of Tailings (blue) and the lower boundary provided by *Pit Shell and Underdrain* (pink).
10	Delta Total Pit Fill	14.03	The difference between the total pit fill between December 2019 and May 2021. The total pit fill volume in December 2019 survey was 24.74 Mm^3 Note: • the difference in water volumes between December 2019 and May 2021 surveys is 6.60 Mm^3 • the difference in Total Tailings volumes is 7.43 Mm^3

[A] The reflectors are referenced from the drawings provided in Appendix H. The reflectors are summarised for interfaces of contiguous interpreted units and are referenced to the colours provided in Figure 2.6

5.2 Water and sediment theme

This section discusses the knowledge base of the aquatic ecosystems and a variety of historical and current water and sediment KKN related studies.

5.2.1 Aquatic Ecosystems background

BMT WBM (2010) describe the ecological character of the Kakadu NP Ramsar site, which now includes the entire national park. According to BMT WBM (2010) the site contains five major landscape types, including two found on, adjacent to, or immediately downstream of the RPA, i.e. Lowlands containing open woodlands and creeks, and Floodplains containing freshwater wetlands, creeks and billabongs. The terrestrial flora and fauna of Kakadu NP described in the Ecosystem rehabilitation KKNs discuss important water birds and semi-aquatic species.

On the RPA there are no listed or endangered macroinvertebrate or fish species, aquatic fauna species, rare or restricted distribution, environments of special significance including significant breeding sites, seasonal habitats or wetlands areas. Chapter 5.4 Ecosystem Restoration Rehabilitation Theme (ESR) KKNs disucsses several migratory bird species of international importance andthe vulnerable Merten's water monitor which have been recorded on the RPA.

5.2.1.1 Vegetation types

The lowland riparian and rainforest vegetation type represents denser vegetation of the lowlands, typically associated with streams, creeks and billabongs discussed in Chapter 5.4. This habitat type represented throughout the Kakadu NP Ramsar site covers approximately 1% of the RPA. Multiple reports of floodplain vegetation of the Magela Floodplain identify different numbers of classes suggesting high variability over time.

Rainfall volume and patterns affect inundation periods, water level, and soil moisture which combined with fire events impact species distribution seasonally and inter-annually (Whiteside and Bartolo 2014). Combining remote sensing and literature review, Whiteside and Bartolo (2014) identified twelve classes of vegetation on the Magela floodplain in May 2010 shown in Table 5-16. Time-series mapping by the SSB will build on this dataset and classification providing further information on vegetation dynamics on the floodplain.

Table 5-16: Twelve classes of Magela floodplain vegetation (Whiteside and Bartolo,2014)

Class name	Composition and occurrence	Area of cover on the floodplains in May 2010
Melaleuca woodland	Typically contains *M. cajaputi* and *M. viridiflora* in the northern regions and at the edges of the floodplain, and *M. leucadendra* in the backswamps that are inundated for most of the year. Open forest communities are typically inundated for 5–8 months of the year. This land cover was mostly located in the southern	10–50 % woody cover; covering 5039 ha
Melaleuca open forest		open forest communities have 50–70 % cover;

Class name	Composition and occurrence	Area of cover on the floodplains in May 2010
	reaches of the floodplain and around the perimeter.	covering 821.8 ha
Oryza grassland	Dominated by the annual grass, *Oryza meridionalis* towards the end of the Wet season. In the Dry season there is mostly bare ground or dead *Oryza*.	4040 ha
Hymenachne grassland	Dominated by *Hymenachne acutigluma* throughout the year. Other species that may occur include *Oryza meridionalis*, *Nymphaea spp.*, and *Pseudoraphis spinescens.*	3639 ha
Para grass	The weed grass, *Urochloa mutica* (Para grass), is an introduced invasive species. It forms dense monocultures and can outcompete native vegetation in communities of *Hymenachne*, *Oryza* and *Eleocharis*. The community cover on the floodplain was mostly in the central plains region.	2181 ha
Eleocharis	Dominated by the sedge, *Eleocharis dulcis* with larger areas mostly occupying the northern areas of the floodplain.	1054 ha
Leersia grassland	Floating mats of *Leersia hexandra.* Larger mats can be found on the western border of Red Lily Swamp.	967 ha
Pseudoraphis	Dominated by the perennial grass, *Pseudoraphis spinescens*. Particularly in the southern half of the floodplain.	943 ha
Pseudoraphis/ *Hymenachne* grassland	Co-dominated by *Pseudoraphis spinescens* and *Hymenachne acutigluma*.	375 ha
Mangrove	Mangrove community is located mostly bordering the Magela Creek as it enters the East Alligator River. (Species not described).	249 ha
Nelumbo herbland	This community is dominated by the water lilies, *Nelumbo nucifera* or to a lesser extent *Nymphoides* spp. These communities occur in permanent and semi-permanent wet areas. Other species that may be present include *Leersia hexandra*, *Hymenachne acutigluma*, *Nymphaea* spp. The largest community is found on the eastern extents of Red Lily Swamp (the open body of water in the western part of the floodplain).	243.3 ha
Salvinia	Dominated by the floating fern, *Salvinia molesta*. This declared Class-B weed can completely cover small areas of open water that are protected from wind. On larger stretches of open water, the fern can be found on the leeward edge.	107.5 ha

BMT (2019) describe the patterns, components, key species and primary productivity of the aquatic ecosystems, of the RPA and surrounds as presented the following sections.

5.2.1.2 Aquatic ecosystem patterns

The aquatic ecosystems of the RPA and surrounds are highly dynamic, with seasonal rainfall patterns being a major driver of temporal variability. While fine scale temporal patterns such as timing, duration, frequency and magnitude of rainfall events may vary from year to year, seasonal patterns in the physio-chemical and biological character of waters broadly follow predicable flood-drought cycles.

The wet season is characterised by large increases in aquatic habitat extent, and lateral and longitudinal connectivity, as floodwaters fill lotic and lentic waterbodies and inundate floodplains (Ward *et al.* 2016; Bunn *et al.* 2015). This leads to an explosion of aquatic ecosystem productivity. Most aquatic species have peak reproduction, recruitment and biomass during the wet season (e.g. Bishop *et al.* 2001; Douglas *et al.* 2005, Wharfe *et al.* 2011). Flows are also key drivers of physical (geomorphological) and biological processes that control the structure of aquatic habitats.

Surface water flows cease during the dry season, and aquatic ecosystems are comprised of isolated billabongs on the floodplain and in channels, and sub-surface groundwater-dependent ecosystems (GDE) in channels. In wetter years, substantial floodplain areas of the Magela Creek catchment may remain inundated well into the dry season (Bunn *et al.* 2015).

Shallow billabongs experience a decline in water levels and water quality, leading to local population crashes, or in the case of semi-aquatic species such as crocodiles, dispersal elsewhere. The dry season retraction in habitat and food resource availability reduces overall aquatic ecosystem biomass, and top-down biological interactions such as predation or competition become increasing important ecosystem controls. Water quality deterioration can lead to significant ecosystem stress, especially in shallow waterbodies (Wharfe *et al.* 2011). Shallow lowland billabongs do not represent important refugia due to their shallow nature and associated dry-season habitat and water-quality deterioration (Humphrey *et al.* 2016). Furthermore, wet seasons of low rainfall, when combined with an extended dry season may result in many shallow lowland billabongs completely drying out (Humphrey *et al.* 2016). Similarly, creek channels and seasonally inundated floodplain environments that completely dry out during the dry season do not provide refugia functions.

Deep permanent billabongs such as Mudjinberri Billabong generally have good water quality year-round. They represent important dry season refugia, providing a source for subsequent population replenishment during the wet season.

5.2.1.3 Aquatic ecosystem components

Biodiversity values, and associated cultural values, are comprised of a variety of ecological components at different hierarchical levels (i.e. species, assemblages, habitats/vegetation types, ecosystems). BMT WBM (2010) describe a number of critical and supporting ecosystem components of the Kakadu NP Ramsar site. That study and the Garde (2015) report describing culturally important species was reviewed to identify key species and groups which are indicators of Ramsar listed and cultural values (BMT 2019).

The key species and groups and their presence in relation to the RPA are described in Table 5-17.

Table 5-17: List of key species indicators of Ramsar and cultural values in relation to the RPA (BMT, 2019)

Category	**Species, Conservation Listing and or cultural value**	**Presence on the RPA or downstream aquatic environment**	**Species Group**
Threatened species	Yellow chat (Alligator Rivers) - *Epthianura crocea tunneyi* (EPBC Endangered)	Possible – occurs in palustrine wetlands and saltmarsh	Water birds
	Pig-nosed turtle - *Carettochelys insculpta* (IUCN Vulnerable)	Not present – not recorded in catchment	Reptiles
Locally endemic species	Kakaducarididae shrimps (*Leptopalaemon* and *Kakaducaris*) (Bruce 1993, Page *et al.* 2008). Endemic genus of isopod (*Eophreatoicus*) (Wilson *et al.* 2009). Seven of the nine *Leptophlebiidae* species (prong-gilled mayflies) in Kakadu are endemic to the Timor Sea Drainage Division (Finlayson *et al.* 2006).	Not present. Restricted to stone country	Macro-invertebrates
Species with large proportion of geographic range in Kakadu	See locally endemic species	Not present. Restricted to stone country	
	Exquisite rainbowfish *Melanotaenia exquisite*	Not present.	Fish
	Magela hardyhead *Craterocephalus marianae* Sharp-nosed grunter *Syncomistes butleri* Midgley's grunter *Pingalla midgleyi*	Present. Stone country and lowland areas	Fish
	Woodworker Frog *Limnodynastes lignarius*	Not present – restricted to stone country	Frogs
Species identified as having important populations in Kakadu based on Ramsar	Significant breeding aggregations of magpie geese *Anseranas semipalmata* and comb-crested Jacana *Irediparra gallinacea*	Present – billabongs and floodplain	Water Birds
	Resident water birds with >1% population criterion in Kakadu: Wandering whistling-duck *Dendrocygna arcuate,* Plumed whistling-duck *Dendrocygna eytoni,* Radjah shelduck *Tadorna radjah,* Pacific black duck *Anas superciliosa,* Grey teal *Anas gracilis,* Brolga *Grus rubicunda,* Black-necked stork	Present – billabongs and floodplain	Water Birds

Category	Species, Conservation Listing and or cultural value	Presence on the RPA or downstream aquatic environment	Species Group
	Ephippiorhynchus asiaticus		
	Migratory shorebird species with >1% of the East Asian – Australasian Flyway population size in Kakadu (Bamford *et al.* 2008): Marsh sandpiper *Tringa stagnatilis*, Little curlew *Numenius minutus*, Common sandpiper *Actitis hypoleucos*, Australian pratincole *Stiltia Isabella*, Sharp-tailed sandpiper *Calidris acuminata*	Present – billabongs and floodplain (mostly coastal)	Water Birds
Species of notable cultural significance and values	*Acacia holosericea*[7]*, Pandanus spp.*, *Melaleuca spp., Barringtonia acutangula* – resource	Present – billabongs and floodplain	Riparian and Floodplain Trees
	Water lily *Nymphaea* spp. fruit and seeds – food Aquatic macrophyte tubers – *Amorphophallus paeoniifolius, Aponogeton elongatus, Dioscorea bulbifera, Dioscorea transversa, Eleocharis dulcis, Eleocharis spp., Nelumbo nucifera, Nymphaea macrosperma, Nymphaea pubescens, Nymphaea violacea, Triglochin procerum* - food	Some species present – billabongs and floodplain	Macrophytes
	Mussels and freshwater prawns – food	Present – billabongs and floodplain	Aquatic Invertebrates
	Barramundi *Lates calcarifer*, Salmon catfish *Sciades leptaspis,* Black bream *Hephaestus fuliginosus*, Saratoga *Scleropages jardinii* – food	Present – billabongs and floodplain	Fish
	File snake *Acrochordus arafurae*, Water python *Liasis fuscus*, Crocodiles *Crocodylus porosus* and *C. johnstoni* eggs, Monitors *Varanus* spp., Turtles - *Chelodina oblonga* and *Elseya dentata* – food. See also *Carettochelys insculpta* above	Present – billabongs and floodplain	Reptiles
	Magpie goose *Anseranas semipalmata* – food (meat/eggs)	Present – billabongs and floodplain	Water Birds

The movement patterns and reproductive/recolonisation processes of several of the key species' groups listed in Table 5-17 are summarised in the following chapters by BMT (2019).

[7] Although this species is common on site due to use in early revegetation trials at the site, it is considered a native invasive in Magela Creek Catchment.

5.2.1.4 Aquatic invertebrates

Marchant (1982) describes patterns in the richness and abundance of aquatic macroinvertebrates in billabongs of the Magela Creek catchment. In shallow billabongs, the on-set of the wet season saw rapid increase in richness and abundance of invertebrates. The rapid resurgence of fauna early in the wet season suggests very fast growth and/or reproductive/recruitment rates. Both richness and abundance peaked in the late wet/early dry, which was two (richness) to five (abundance) times greater than recorded during the end of the dry season.

There were seasonal differences in composition in shallow billabongs, with high densities of Ephemeroptera, Trichoptera, Mollusca, Hemiptera and Chironomidae during the wet season, and Coleoptera (especially Dytiscidae), Tanypodinae chironomids, Ceratopogonidae, some Hemiptera and Gastropoda, and Macrobrachium prawn numerically dominant in the dry season. Many fewer common taxa occurred in variable abundance throughout the year. Marchant (1982) speculated that these changes were related to seasonal changes in aquatic macrophyte abundance, an important habitat for many aquatic invertebrates.

By contrast, deep channel billabongs did not show such strong seasonal variability, and maximal richness and abundance values were similar to that in shallow billabongs. Despite differences in habitat structure and wetting-drying cycles, fauna composition was largely similar between shallow and deep billabongs.

Marchant (1982) suggested that short life cycles (measured in weeks to months rather than 10s of months) and very fast rates of larval growth likely prevail in most invertebrate groups in the Magela catchment billabongs. These are necessary adaptations for organisms living in ephemeral environments subject to seasonal wetting and drying cycles (Williams 1987).

The seasonal patterns described by Marchant (1982) are summarised in Table 5-18.

Table 5-18: Seasonal patterns in aquatic macroinvertebrates in Magela catchment billabongs (BMT 2019 after Marchant 1982)

Taxa	Pattern
Gastropoda	Peak abundance of the common species in wet season Hibernate during dry season Planktonic larvae
Ostracoda and Conchostraca	Peak early to mid-wet
Atyidae and Palaemonidae	Atyidae - Dry season peak abundance and breeding (shallow), common year-round in deep billabongs Palaemonidae – dry season peak, absent early wet, breeds in estuary
Ephemeroptera	Peak in late wet/early dry in shallow. Emergence and reproduction continuous for many species
Odonata	Peak abundance in late wet/early dry for most species, but some species only found in early wet and late dry. Breeding peak in wet season for most species

Taxa	Pattern
	only found in early wet and late dry.
Hemiptera	Peak abundance in late wet/early dry for most species, but some uncommon species
Neuroptera	Wet season only, in association with sponges
Diptera	Emergence and breeding of Chironomids appeared to occur continuously while large numbers of larvae were present. Tanypodinae more abundant in dry season Ceratodontidae were more abundant in dry season, disappearing in early wet season
Lepidoptera	Most species only present in wet season, and in low numbers
Trichoptera	Peak abundance typically in early dry, but many species recorded throughout the year
Coleoptera	Adult Dytiscidae peak at the end of dry season, larvae mostly in wet season Except for the Hydrophilidae in the shallow billabongs, breeding of all families appeared to occur during the wet season

5.2.1.5 Fish

Bishop *et al.* (2001) examined the autecology of fish species in the Magela Creek system. Most fish species in the catchment undertake broad-scale movements for reproductive and feeding purposes. Many fish species disperse into lowlands and floodplains during the wet season for feeding and breeding purposes, resulting in high fish productivity during this period.

As water levels decline, fish move from seasonally inundated floodplain and sandy channel environments into dry-season refuges including permanent billabongs, or, for euryhaline[8] species such as barramundi to estuarine river channel environments. Sandy creek channels represent important fauna movement corridors during the recessional stage (i.e. late wet/early dry transition). Smaller fish move upstream along the slow-flowing edges of creeks, which was suggested to be due to lower water velocities on the edges of the creek, or as an evolutionary mechanism to avoid larger predators residing in deeper sections of creek channels (Bishop and Walden 1990).

From a reproductive ecology perspective, most species breed around the on-set of the wet, coincident with flooding and associated increase in habitat availability, nutrients and algae production, and food availability (Bishop *et al.* 2001). A small number of spawners can breed at any time of the year, but most of these species typically have a wet season peak.

Within the Magela Creek catchment the most important spawning habitat for most species were the lowland backflow billabongs, and several species breed exclusively in this habitat type (Bishop *et al.* 2001). The escarpment area and sandy creek bed

[8] Species able to tolerate a wide range of salinity.

habitats were also commonly used spawning sites for numerous species, with only a small number breeding exclusively in these habitat types (including *Neoarius erebi*, *Leiopotherapon unicolor*, *Neosilurus hyrtlii* and *Porochilus rendahli*). A small number of species are catadromous (migrate to sea to breed). Notwithstanding this, most catadromous species are large-bodied species that can be a dominant component of the fauna biomass, as many are important from a fisheries and cultural heritage perspectives – for example, barramundi, tarpon and eels.

5.2.1.6 Bird/Reptiles/Amphibians

Most bird species in the catchment undertake broad-scale movements for feeding and breeding purposes. During the dry season, water birds are very abundant and diverse (Morton *et al.* 1991). Water birds prefer habitat with varying water depths, however towards the end of the dry season with receding water levels, water birds congregate in high abundances wherever water remains. These areas include the upper floodplain, the western part of the plain and channels through the Melaleuca swamps in the central plain). As flooding of the floodplain increases during the wet season, water birds fly away to other areas and become less abundant (Morton *et al.* 1991).

Migratory birds migrate to the catchment prior to and just after the wettest months (January–March). The most common migratory water bird species include the little curlew (*Numenius minutus*), oriental plover (*Charadrius veredus*), large sand plover (*C. leschenaultii*) and the Mongolian plover (*C. mongolus*) (Morton *et al.* 1991).

There are few water bird species that breed in significant numbers within the Magela Creek system, however, the Comb-crested Jacana (*Irediparra gallinacea*) breeds in abundance (Press *et al.* 1995). The main breeding period of the Comb-crested Jacana is during the late wet season, between the beginning of March to April.

Most reptiles are abundant during the wet season, while in the dry season they are concentrated to remnant waterbodies, such as billabongs (Gardner *et al.* 2002). Some species, such as freshwater turtles, bury themselves in mud as the water dries up during the end of the dry season.

Most frog species breed at the onset of the wet season before the floodplain is completely inundated (Tyler and Crook, 1987). During the dry season, most frog species are totally inactive, with some species burrowing underground, while others are restricted to billabongs.

5.2.1.7 Trophic processes and ecosystem productivity

Based on data in Adame *et al.* (2017), macrophytes represented the dominant primary producers in the freshwater reaches of the Kakadu wetlands (1870 - 2892 mg C/m^2/day) during the wet season, followed by terrestrial inputs (e.g. 970 mg C/m^2/day for Melaleuca litterfall; Finlayson *et al.* 1993), phytoplankton (122-334 mg C/m^2/day) and periphyton attached to macrophytes (13-219 mg C/m^2/day). This agrees with estimates of the relative contribution of primary producer groups in other tropical floodplains (Adame *et al.* 2017). The deeper floodplain backswamp areas had the highest periphyton and macroalgae productivity; these areas also hold water the longest, remaining productive into the dry season (Bunn *et al.* 2015).

Adame *et al.* (2017) found that while primary production in Kakadu wetlands was high compared to many other ecosystems, the wetlands were heterotrophic. This reflects the high inputs of organic matter to the system, such as dead macrophytes, fish carcases and other organic matter during the dry season (Adame *et al.* 2017). The decomposition of organic matter during the following flooding season can results in anoxia in places (Adame *et al.* 2017).

While macrophytes are highly productive, isotope analysis indicates that algae (periphyton and phytoplankton) can be the dominant internal source of carbon to aquatic fauna in the wet-dry tropics (Douglas *et al.* 2005). Douglas *et al*. (2005) suggested that much of the biomass of macrophytes may enter a detrital pool with a microbial 'dead-end' for aquatic ecosystems. Macrophytes do represent important habitats for the periphyton assemblages that sustain aquatic ecosystems (Bunn *et al*. 2015; Adame *et al*. 2017), and are important to the diets of some semi-aquatic and terrestrial fauna (Douglas *et al*. 2005), especially water birds (e.g. magpie goose; Frith and Davies 1966).

Isotope analysis by Bunn *et al*. (2015) in the ARR found that while insects, crustaceans and small fish can be sustained by 'internal' producers from the within the waterhole, external food sources from outside the home waterhole are critical to larger animals such as saratoga, barramundi and crocodiles. External sources can include marine fish and invertebrates (e.g. crabs, prawns, molluscs), small floodplain-associated freshwater fishes, and, in the case of the crocodiles, land mammals such as wallabies and pigs. Bunn *et al*. (2015) concluded that "the greater importance of external sources with increasing body size is a common feature of Kakadu food webs".

Figure 5-52 depicts a food web for aquatic ecosystems in the Magela Creek catchment[9]. Diet data of fishes from Magela Creek, and tropical rivers in northern Australia more broadly, show little evidence of dietary specialization. For example, Bishop and Forbes (1991) found that fish assemblages in Magela Creek were largely omnivorous (20-50%, depending on habitat). Because many fish and many other aquatic vertebrates feed on a broad range of items, food webs are short, diffuse, and highly inter-connected (Douglas *et al*. 2005).

Douglas *et al*. (2005) notes that a key characteristic of aquatic foodwebs in the Australian wet-dry tropics is that a 'few large bodied consumers control the flows of energy and matter into and through the animal community. Strong top-down control by such macroconsumers is emerging as a characteristic feature of tropical streams and rivers with fish and shrimp capable of exerting a disproportionately large influence on benthic sediments, detritus, nutrient demand and algae and invertebrate communities'. Predation by birds and fish is a key top-down control on aquatic productivity at low water levels. High mortality rates can occur in refuge areas due to reduced resources and high rates of predation. During the wet season, bottom-up processes are thought to be more important.

[9] Notes: there are differences between seasons. In dry seasons the system is more closed. Wet seasons the system is open and connected. Most organisms are omnivorous feeding on a range of different items. This is important and makes them less susceptible to small changes to food species

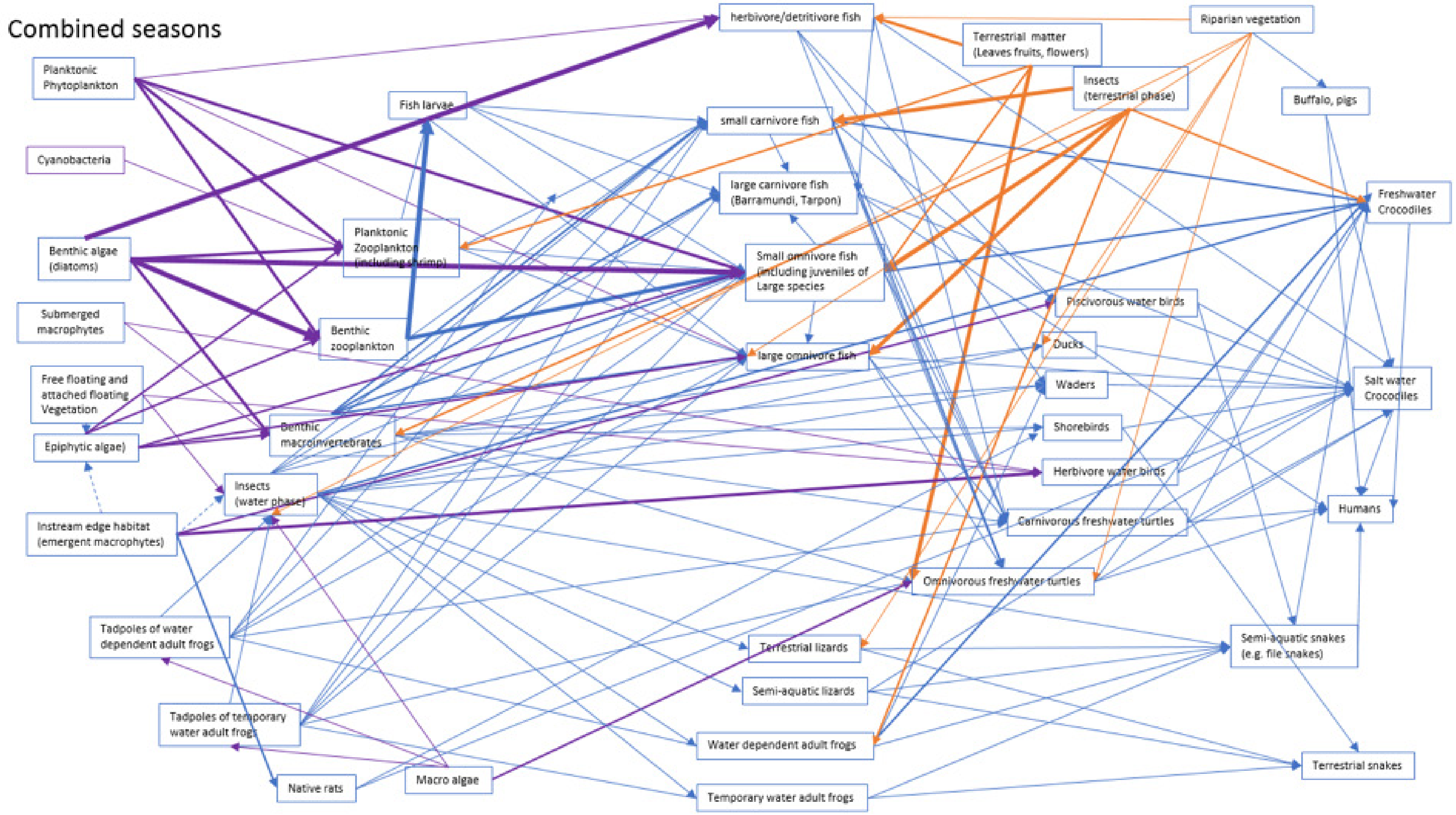


Figure 5-52: Food web for aquatic ecosystems in the Magela Creek catchment (from BMT 2019)

5.2.2 Water pathway risk assessments (release pathways onsite)

As part of the environmental studies required for closure of Ranger Mine, an assessment of the risks associated with contaminants across the site transported via water pathways was conducted.

The Water Pathways Risk Assessment project was conducted by ERA and BMT Ltd to develop a risk assessment tool to identify the risks posed from the different contaminants and sources on the mine site, or predicted to come from the site. While these risks are primarily predicted to arise during the monitoring and maintenance period of the closure processes, the risks also apply to the activities undertaken during the closure phase. The risk management classification is useful to identify which contaminants need to be managed and where further information is required for the next level of assessment. These findings represent Phase 1 of the aquatic pathways risk assessment, which will be used to further inform the assessment of potential impacts from closure activities for contaminants and water bodies on the RPA and the development and implementation of management plans. The following summarises the work undertaken in the Phase 1 processes and how this links into other assessment and management processes.

5.2.2.1 Phase 1 of the water pathways risk assessment

The initial phase of the risk assessment was the development of a conceptual understanding of the system which included determining sources, pathways, receptors and processes and aligning these with values relating to the broader environment in the surrounding landscape. The values reflect the Commonwealth ERs and the broader concerns of stakeholders about the long-term impact of the mine and relate to what they hope to see achieved following the mine rehabilitation process.

The conceptual underpinning was derived from a range of previous conceptual models for various solute pathways that were refined during the ecological risk assessment for mine closure (Pollino *et al.* 2013; Bartolo *et al.* 2013). While those models were developed to identify assessment end points and knowledge gaps, the focus of the integrated conceptual model for this assessment was the influence of the contaminant sources on values. Figure 5-53 below shows the integrated conceptual impact pathways model for this assessment along with the assessment methods used and what aspects were included or excluded from the phase 1 assessment.

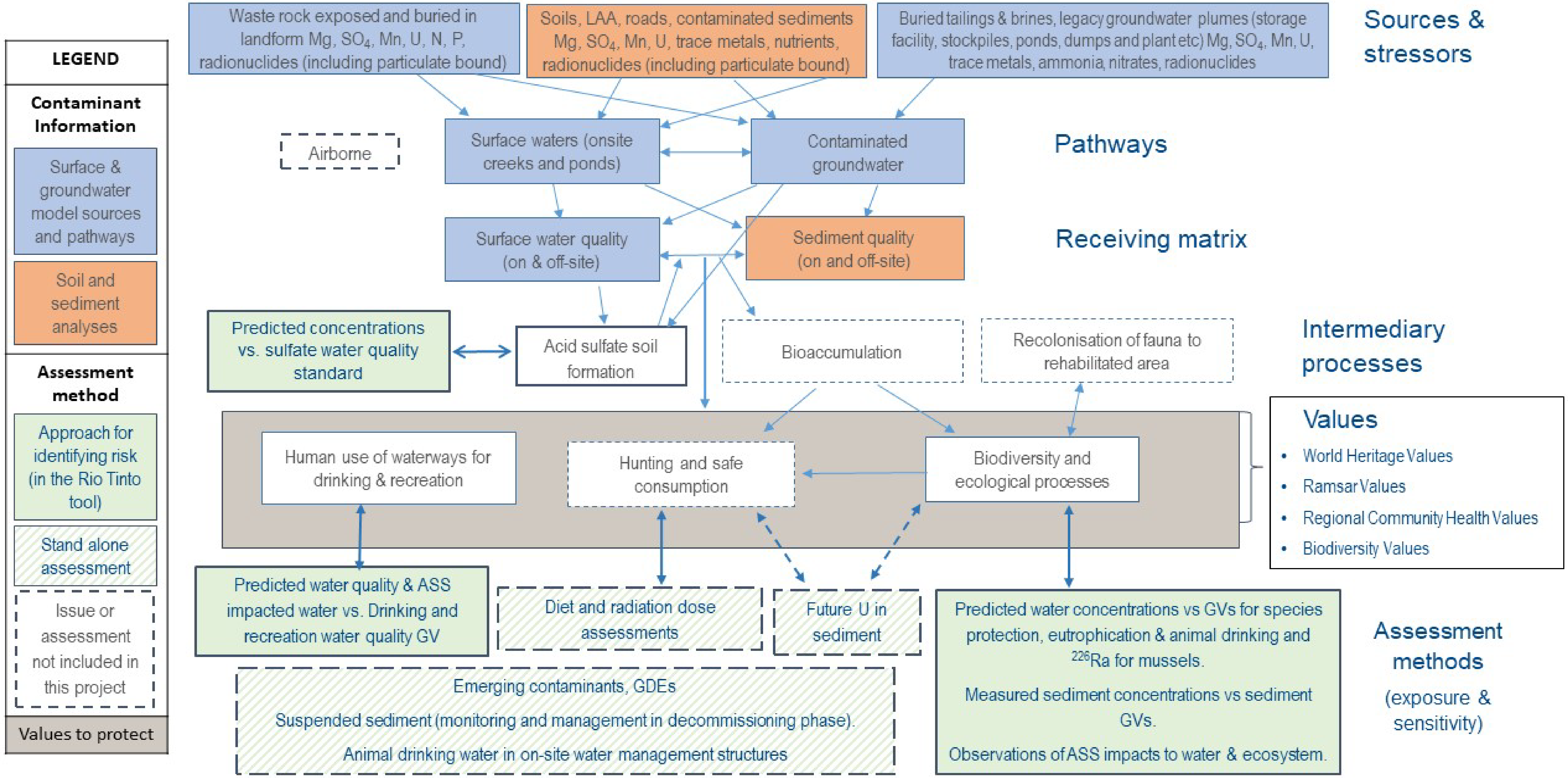


Figure 5-53: Aquatic source pathway receptor model and risk assessment approach

A workshop was held in March 2020 to:

- Compare water and sediment quality (measured and predicted) to endpoints identified in conceptual models developed in previous stakeholder risk assessments to reflect the community values and Commonwealth ERs for protection of people and the biodiversity of the region.
- Test and revise descriptors and/or the proposed assessment approach
- Classify and rank risks to receptors offsite and in the four sub-catchments on-site where adequate information was available
- Identify any additional information available/required to support the assessment.

Representatives from ERA, BMT and SSB were present with the NLC attending in a an observing role). The risk scoring was completed by ERA and BMT following the workshop with consultation with SSB on descriptors and evidence interpretation.

The assessment using the ERA risk assessment tools modified to:

- tailor risk questions and descriptors of likelihood and consequences to align with the conceptual model of aquatic risks and available evidence and guideline values,
- adopt improved assessment approaches recommended in national guidance documents on acid drainage prevention or acid sulfate soils (ASS) assessments,
- enable results to be displayed by contaminant sources, receptors and values, and
- include a numeric score for each risk to assist in prioritising management actions.

Predicted future water quality from RSWM and data from sediment sampling and poor water quality events caused by exposure of ASS was compared to guideline values for the protection of (i) people using the water for drinking and cultural/recreational purposes, (ii) aquatic and benthic species protection, and (iii) animals drinking the water. Information from monitoring and studies of exposed ASS in a billabong on site were used to assess the risks to human use of the water and biodiversity.

The evidence base for the risk assessment, what pathways and risks the evidence relates to and how it was used is summarised in Table 5-19. The phase 1 report describes the evidence base, how it was used in the assessment process, the confidence in the evidence base and the implications of that to the outcomes.

Table 5-19: Summary of information sources and how used in the risk assessment

From conceptual model and threat questions				Exposure		Sensitivity
Threat	**Source**	**Pathways**	**Receptors**	**Exposure evidence**	**Likelihood assessment logic**	**Human health or biodiversity consequence assessment process**
Poor water qaulity impacts on cultural land use (human health) and ecosystems	All solute transport model source terms (metals, ions, nutrients from tailings, brine, waste-rock, groundwater plumes, etc.).	Ground and surface water. Groundwater - surface water interactions.	Aquatic ecosystems (surface water) Humans (drinking & recreation) Wildlife (drinking) Sediment (U accumulation)	Surface water model water predictions Water Solutions (2021)	Probable; P50 loads from groundwater model used in surface water model.	On and offiste descriptor matrix of SWM exceedence probabilites vs Water quality GVs for species protection, drinking water, recreational water, wildlife/livestock drinking water.
Elevated nutrients cause eutrophication	Nutrients from all solute transport model source terms	As above	Aquatic ecosystems (surface water)		Probable; P50 loads from groundwater model used in surface water model.	Site specific thresholds based on nutrient concentrations corresponding to trophic bands for January to May. Thresholds compared to median SWM prediction for creek sites and 75th and 90th percentile SWM predictions for billaong site (to be reviewed once predictions for Jan-May period only available for billabongs)
Elevated sulfate in water creates future ASS and impacts ecoystem	Sulfate from all solute transport model source terms	As above, plus water and sediment interactions.	Aquatic ecosystems via future ASS formation in aquatic sediments		SWM exceedence probability vs Site-specific sulfate water quality threshold for ASS protection	Consequences for current ASS applied to future ASS.
Elevated uranium in water accumulates in sediments and impacts biota	*Uranium from all solute transport model source terms*	*As above, plus water and sediment interactions.*	*Sediment biota via future U accumulation*		*Probable; P50 loads from groundwater model used in surface water model.*	*U in water concentration equivalent substitued into sediment consequence descriptors. Not included at this stage. Problem with applying algorithm for U partitioning being addressed.*

From conceptual model and threat questions				Exposure		Sensitivity
Threat	**Source**	**Pathways**	**Receptors**	**Exposure evidence**	**Likelihood assessment logic**	**Human health or biodiversity consequence assessment process**
Metal contaminants in sediments impact biota	Contaminated sediment	Insitu exposure	Sediment biota	Sediment sampling results (ERA datasets and ERA 2021a)	Probability (%) of sediments exceeding default or site specific GV (based on timeseries plots of metals in sediments).	Matrix of thresholds; natural distribution, national default sediment GVs, site-specific U GV vs mean value for waterbody.
Poor water qaulity from ASS impacts on cultural land use (human health) and ecosystems	Acid sulfate soils	Flux of contaminants from sediments to water column	Aquatic ecosystems (surface water) Humans (drinking & recreation) Wildlife (drinking)	Sediment sampling results and Coonjimba Billabong data & studies (ERA datasets and ERA 2021b, ERA LIMS water quality data, SSB 2020)	Frequency of events likely to cause consequence. Likelihood of acidity hazard factored into assessing consequences of sediment contamination to biota	Data from past ASS at Coonjimba Billabong effecting water quality and biodiversity. Extraploation to other sites considering processes relative to CB. *Consequence at End of RPA (no sediment ASS data) captured in ASS summary table.*
Sediment bound contaminants in LAAs cause poor water quality that impacts cultural land use (human health) and ecosystems	Contaminants bound to LAA soils	Surface water transport (particulate/dissolved) (ground-water path included in SWMI)	Aquatic ecosystems (surface water) Humans (drinking & recreation) Wildlife (drinking)	Soil sampling results & potential for transport to waterbodies (ERM 2020)	Conceptual model and risk of transport at each LAA reported in ERM 2020.	

This phase I assessment identified 57 threats; 51 of those had enough information to evaluate the risks (Table 5-20, Figure 5-54 and Figure 5-55). Of the 51 risks, 29 were Class 1 (low) risks, seven were Class 2 (moderate) risks, five were Class 3 (high) risks, and ten were Class 4 (critical) risks. This assessment of threats is based on the information and assumptions based on modelling available at the time of the Phase 1 processes and does not include additional threats which may arise in relation to matters excluded from the Phase 1 processes.

The initial assessment of the 10,000 year risks found 19 that were Class 1 (low risks) and two that were Class 4 (critical risks).

Table 5-20: Results of risk assessment

Risk Class	**Class I**	**Class II**	**Class III**	**Class IV**
Risk	**Low**	**Moderate**	**High**	**Critical**
Overall	29	7	3	10
10,000 Years	19			2

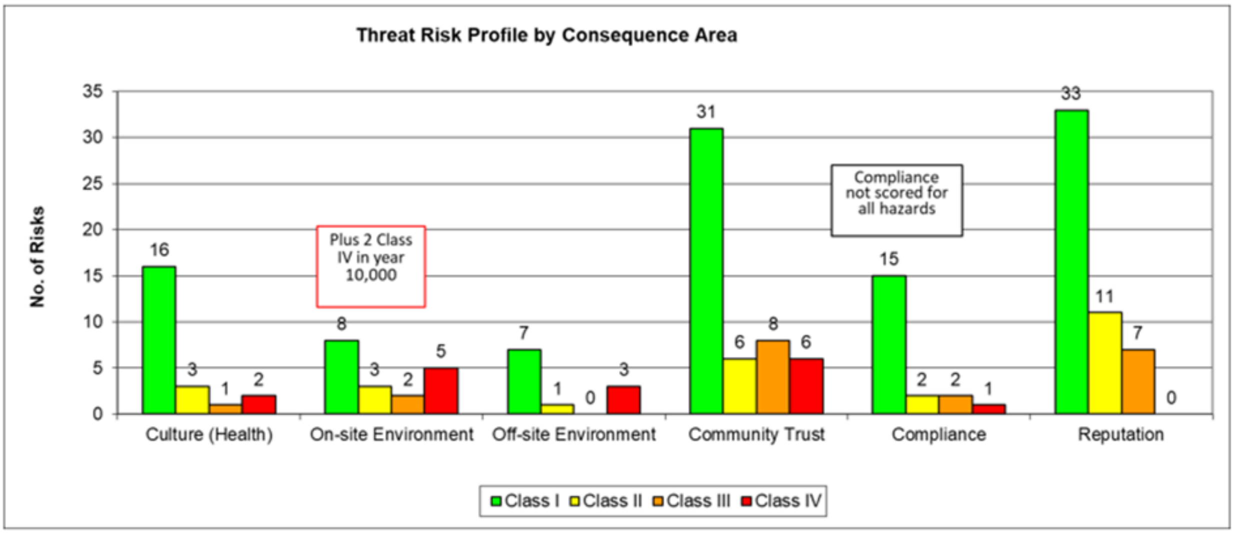


Figure 5-54: Risks by consequence category

A breakdown of risks by contaminant source (Figure 5-55) shows that of the class 3 and 4 risks (the classes that require active management), one is from exposure of ASS in the Coonjimba catchment, and the others are associated with the predicted future water quality from a several sources:

- five relate to different COPC within the Pit 3 tailings flux;
- three relate to different COPC within the TSF plume or waste rock vadose zone in Coonjimba catchment;
- two relate to different COPC within the Pit 1 tailings flux; and

- two are associated with the modelling scenario for 10,000 years from a combination of contaminant sources.

The risks are based on modelling of predicted future water quality using conservative assumptions regarding quantities and behaviour of contaminants. Many of the COPC are reactive and are expected to attenuate during transport, thus the models over predict the concentrations that may occur and therefore the risk is also overestimated at this stage.

The use of conservative assumptions in the risk assessment enables the identification of which COPC, at which sites, present higher risks. Subject to the consideration of additional threats outside the scope of the risk assessment, the Phase 1 findings enable further assessment and management measures to be focussed on those activities and COPCs of greater risk with lower focus being required for those COPCs considered unlikely to present a material risk.

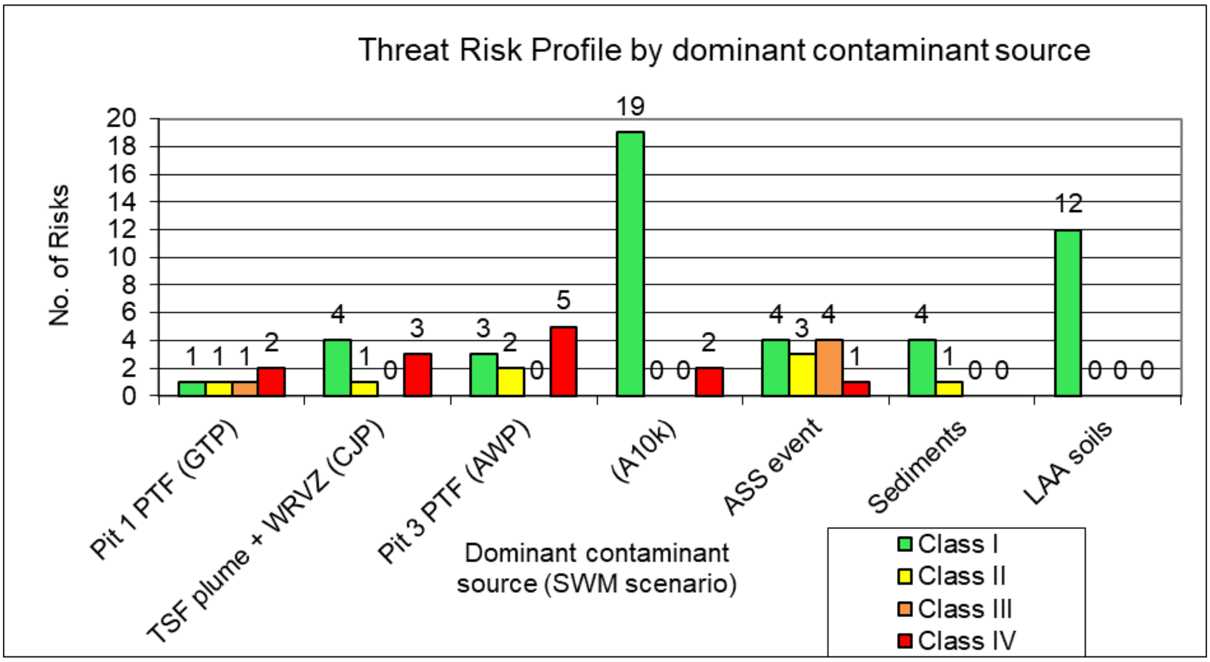


Figure 5-55: Threat risk by dominant contaminant source. The first four sources (from the right side) are contamination sources predicted by the surface water model (SWM) to enter the surface water after closure. The last three sources are associated with current contaminated soils and sediments.

Table 5-21 summarises the 10 Class IV risks identified in the Phase 1 Assessment. It is noted that the Class IV risk ratings are based on the conservative assumptions used in modelling and are considered preliminary assessments only. In particular, the assessment assumes a 350ML PTF volume in Pit 3, which is significantly higher than is proposed. Further refined assessment of these threats will be included in future assessments and combined with additional management controls to be identified and/or considered, these risk rankings are likely to reduce.

Table 5-21: Ten highest ranked threats identified in the risk assessment

Rank	Threat ID	Detail
1	TJ07-17	Water quality: Eutrophication consequences very high GTCk ammonia (> GV at 10,000 years)
2	TJ07-23	Water quality: Very high species protection consequence score at Gulungul Billabong from slight exceedances of Mn and Cu AWP scenario only
3	TJ07-02	Water quality: Eutrophication consequences from ammonia: End of RPA Very high
4	TJ07-01	Water quality: Offsite 99% species protection GV exceeded at End of RPA site for Mg, Mn, Cu, U.
5	TJ07-08	Water quality: Coonjimba Billabong species protection consequences V.High - Mg, Mn, Cu, Zn, U, Pb, Ni; Mg high consequences extend to 10,000 years
6	TJ07-16	Water quality: GTCk Very high species protection consequences for Mg, Mn, TAN, Zn and GTB for Mn. Mn consequences at GTCk extend to 10,000 years.
7	TJ07-01	Water quality: Offsite drinking water slight Mn exceedances at End of RPA
8	TJ02-03	Water quality: Coonjimba Billabong drinking water Mn and U exceedances at CB.
9	TJ07-10	Water quality: Coonjimba Billabong sulfate > ASS GV
10	TJ07-15	ASS exposure: Ecosystem consequences at Coonjimba Billabong

Based on the Phase 1 assessment, the following actions have been assigned for all class 3 and 4 risks (several have commenced):

- Improving confidence in the evidence and assessments that underpin the risk assessment (such as reviewing and fine-tuning sources and reactive transport modelling, assessing the sensitivity of the model to certain drivers to help identify where management plans are required) and communication of the conservative nature of the models used in the assessment.
- Development of targeted management plans and/or further studies to address on-site contamination sources and ASS, naturally occurring and possible development of PASS.
- Understanding the implications of climate change on certain drivers.

- Consultation with Traditional Owners to better understand cultural water use and to integrate this understanding of appropriate assessment criteria relevant to these uses, including any temporal constraints on use.

In considering risks for a 10,000-year time horizon it is noted that there are large uncertainties with all input variables to models and in the outputs of models and results should be considered indicative at best. However, identifying such long-term risks can be used as further evidence of contaminants that are likely to remain as issues of concern for long time periods and must be managed.

ERA are also considering comments raised by SSB on the report provided on the Phase 1 risk assessment and this will be discussed with an aim to resole to phase 1 assessment in late 2022. The SSB comments will also be considered in the application of the Phase 1 Risk Assessment in the Pit 3 Backfill Application assessment.

The second phase(s) of the risk assessment will be undertaken as part of the detailed assessment of closure activities and will consider new information and address initial stakeholder feedback on this tool. The risks relating to other closure activities (Final landform, TSF deconstruction) will be further assessed based on refined modelling and design inputs as part of their respective regulatory applications.

5.2.3 WS1 Characterising contaminant sources on the RPA

KKN title	Question
WS1. Characterising contaminant sources on the RPA	WS1A *What contaminants (including nutrients) are present on the rehabilitated site (e.g. contaminated soils, sediments and groundwater; tailings and waste rock)?*
	WS1B *What factors are likely to be present that influence the mobilisation of contaminants from their source(s)?*

5.2.3.1 Background contaminants on the RPA

Background COPCs require characterisation to identify the natural range of concentrations in different HLUs across the site. HLUs for Ranger are discussed further in the conceptual site model (KKN WS2) Characterisation of the background COPCs enable a better understanding of the site source terms which inform solute transport modelling described in further in KKN WS2.

Previous background concentrations of COPCs in groundwater were presented by Esslemont (2015) and were updated in 2017 (Esslemont 2017). These background concentrations were based on a limited COPC list and only included data up to 2013. Substantial updates to the Ranger conceptual model, major expansion of the Ranger bore network and an improved analytical database, enabled ERA to re-assess the background COPCs.

Environmental Resource Management (ERM) was engaged by ERA to undertake the re-assessment of the site background COPCs. At the time, no prescriptive approach was suggested, and as such a combination of a population partitioning approach followed by a weight of evidence evaluation was undertaken. Extraction of a background dataset from a larger site investigation dataset has support from various guidance documents (US Navy 2004; ITRC 2013; USEPA 2014). The dataset used extended from July 1980 through August 2019.

A key requirement of the study was the development of a consistent and transparent decision framework which is outlined in Figure 5-56, in Figure 5-57 and Figure 5-58.

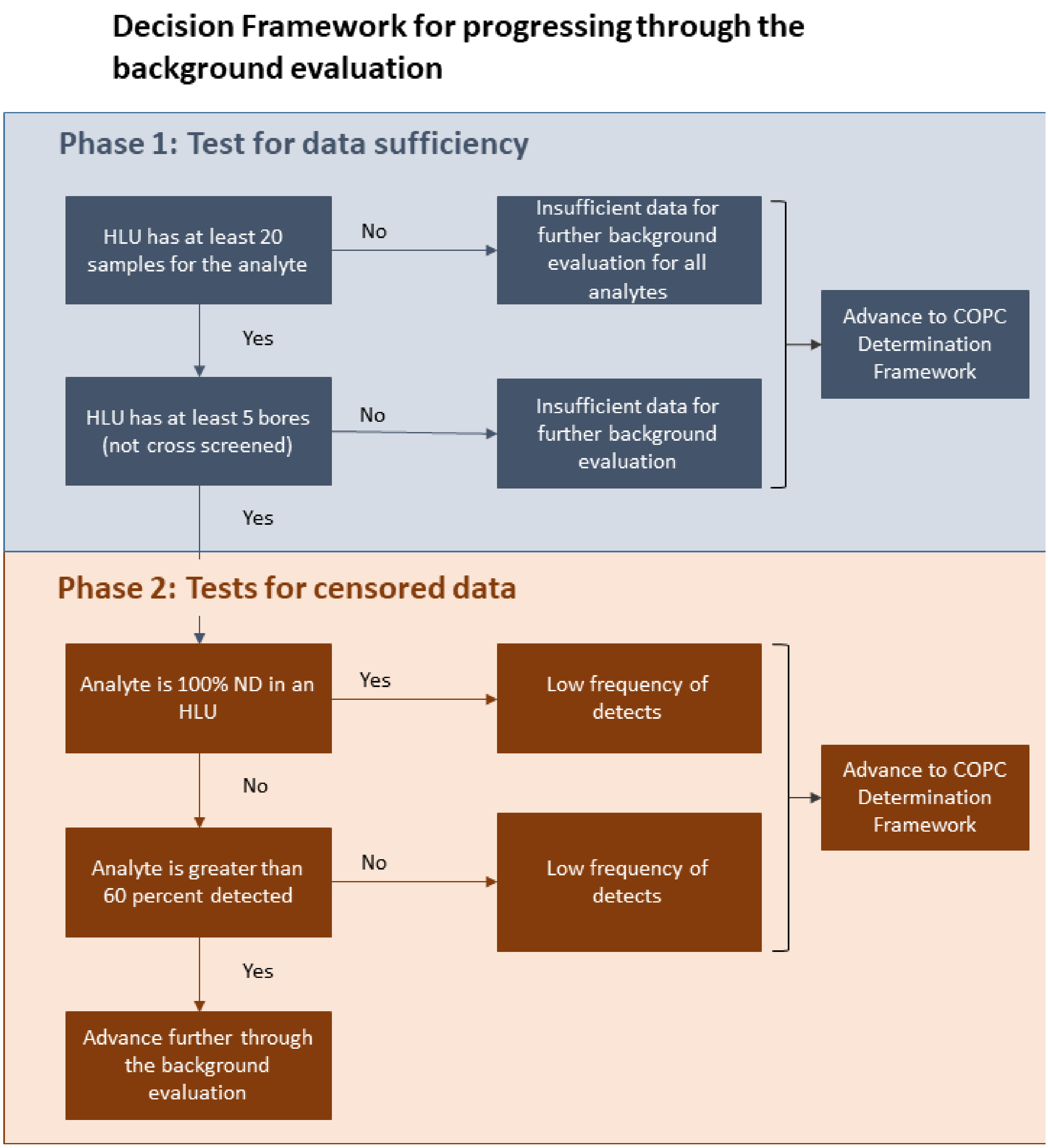
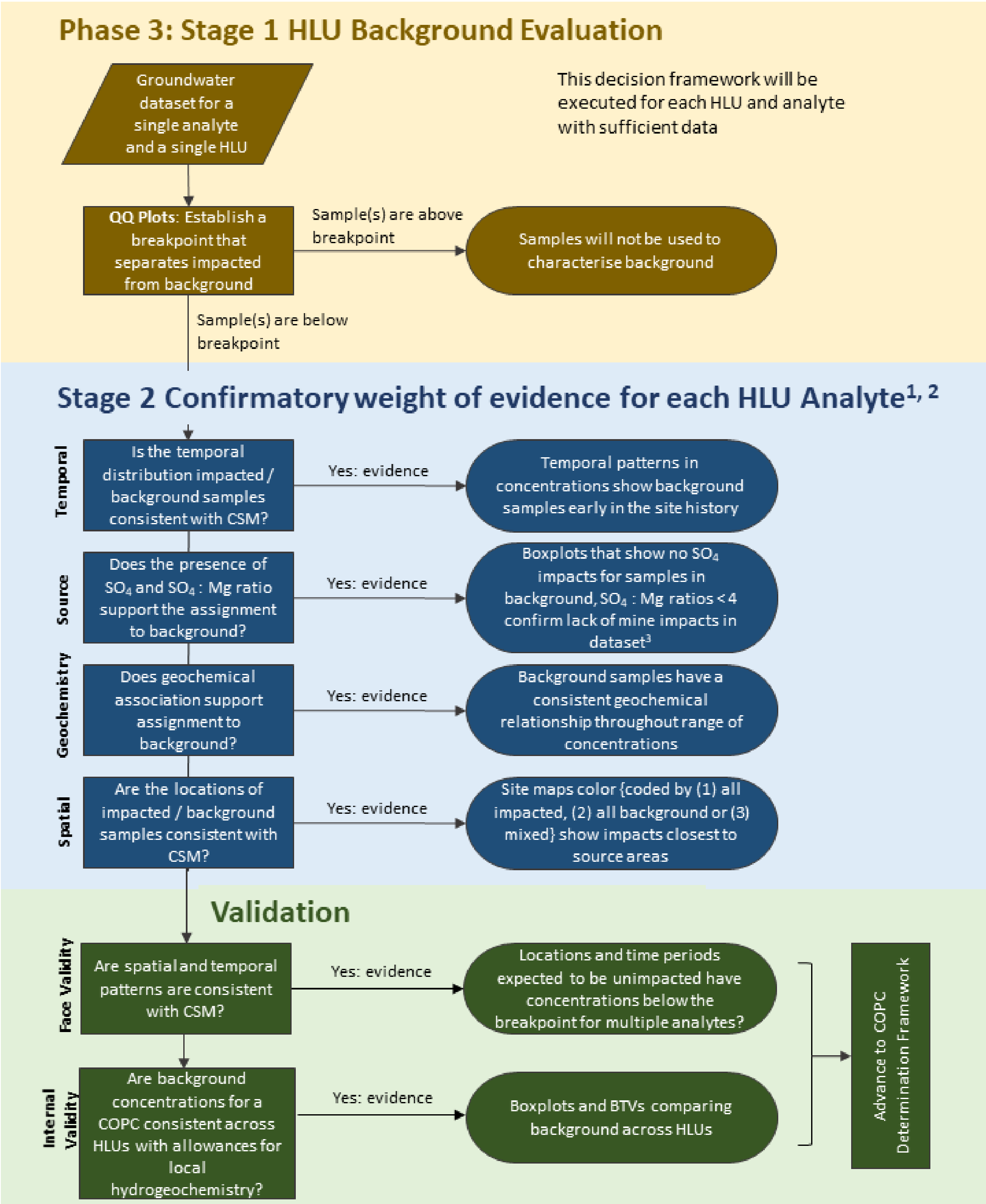


Figure 5-56: Decision framework for determining data sufficiency, ERM (2020c)



Notes:
[1]Some iteration back to the QQ plot may be needed based on findings from confirmatory evaluation
[2]To aid with interpretation, data points in the visuals will be coded as impacted / background for subsequent evaluations
[3]$SO_4 : Mg$ ratios ≥ 4 may be used as another sulfate-related line of evidence

Figure 5-57: Decision framework for extracting and establishing background using weight of evidence, ERM (2020c)

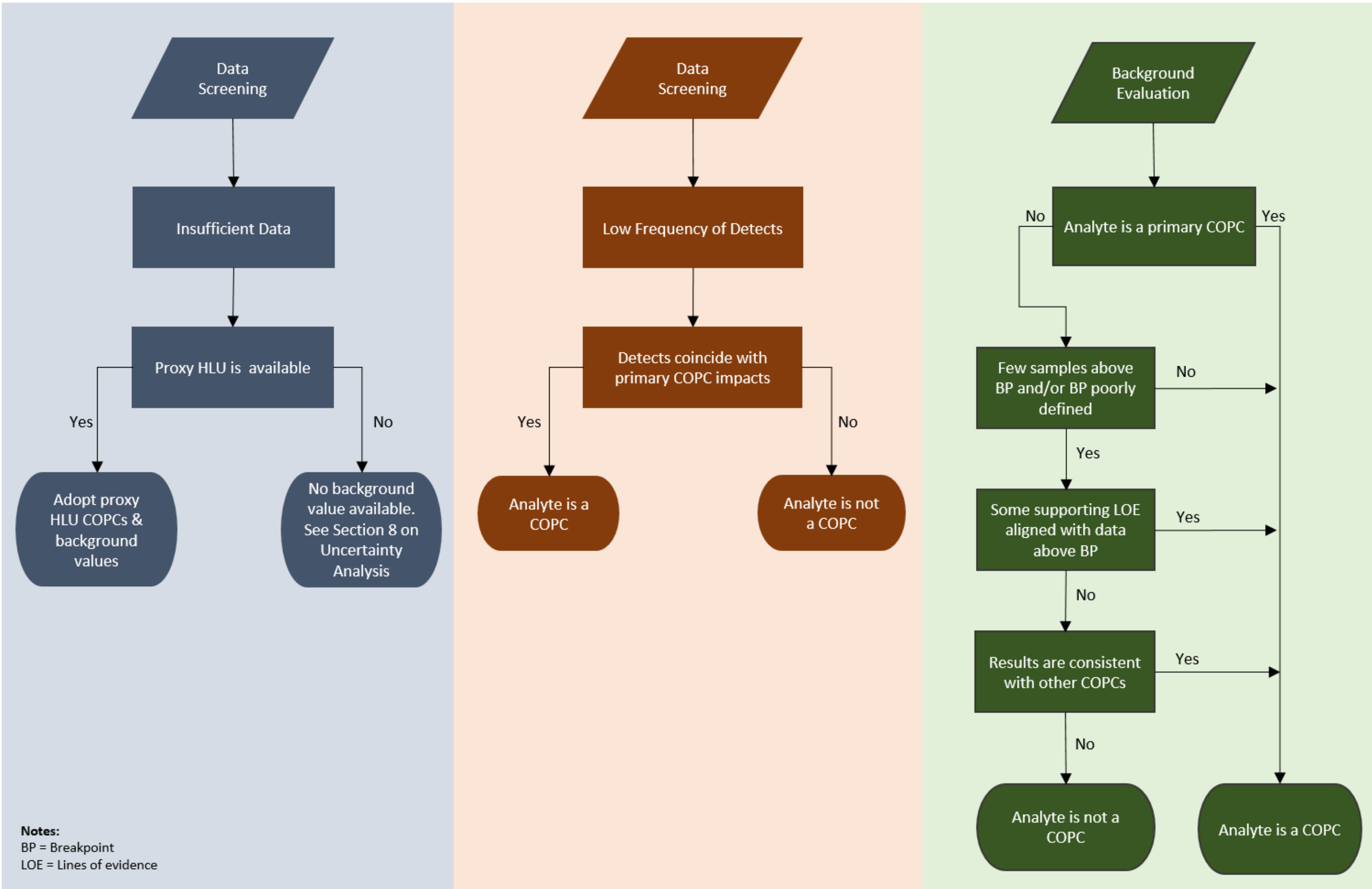


Figure 5-58: Framework for developing background for datasets with insufficient data, ERM (2020c)

Following the development of the site-specific background COPC datasets, background threshold values (BTV) were determined. Where there was sufficient data, 95/95 Upper Tolerance Limits (UTL) were set for each HLU and analyte combination, shown in Table 5-22. Where there was insufficient data either proxy HLU's were utilised where there was supporting rationale, or in the case where all samples for the HLU analyte combination were below laboratory limit of reporting, the limit of reporting was used as a surrogate BTV.

This background evaluation process has refined the COPC list for the site, established background datasets for HLUs and analytes, and calculated BTVs for analytes and COPCs on an HLU-by-HLU basis. The BTVs were established using an objective decision framework that supported a defined process that was generalisable and repeatable across analytes and HLUs. This resulted in a transparent and defensible process and the uncertainty evaluation did not identify material inconsistencies in the data or the approach that would need to be considered when using the resulting BTVs to inform site closure decisions. The results were supported by multiple forms of validation that help to create a high level of confidence in the conclusions.

In support of the final report (ERM, 2020c), nine interactive html dashboards were developed allowing for full interrogation of the dataset and statistical analysis undertaken to develop the BTVs. The study effectively refined the COPC list and identified the background dataset, established site-specific background datasets where minimum data criteria were met, and established BTVs for COPCs in groundwater at the Ranger Mine.

The COPC BTVs have been used to inform the site source terms by providing a concentration threshold to identify where groundwater quality has been influenced by mining activities and where the water quality is representative of no mining impacts. This is vital for delineating the extent of impact and quantifying the solute source terms. The site source terms are discussed further in the next section.

5.2.3.2 Characterising mine derived contaminant sources on the RPA

Conceptual models and COPC concentrations for groundwater source terms are a required input for numerical groundwater modelling of post-closure solute loads from groundwater to surface water receptors for assessment of environmental impacts from Ranger mine closure and rehabilitation. The solute source term conceptual model details the contaminants present, and the concentration or mass of the contaminants present for all the major contaminated locations on the RPA as required by WS1A. The solute source term also includes reference to any geochemical processes that result in mobilisation of COPCs from the waste rock landform. Previous models developed solute source term conceptual models for the major contaminant sources on the RPA for the INTERA (2014) and INTERA (2016) post closure solute transport modelling. This modelling considered vadose zone waste rock leachate and tailings-derived materials as sources, focused primarily on a single solute (magnesium [Mg]) transport, and provided a single deterministic result. These conceptual models required update to expand the list of possible sources, expand the list of COPCs that were assessed and were appropriately characterised for inclusion in the uncertainty analysis component of the post closure solute transport modelling.

Table 5-22: Calculated BTVs for HLUs and Analytes in the Background Evaluation where data sufficiency requirements were met, ERM (2020c)

Analyte	Unit	Shallow Bedrock Cahill	Deep Weathered Cahill	Shallow Weathered Cahill	Shallow Bedrock Nanambu	Deep Weathered Nanambu	Shallow Weathered Nanambu	MBL Zone (UMS subunit)
Aluminium	ug/L			27.6	14.4[a]	24.9	19.3	
Ammonia	mg/L				0.88	0.312	0.43	
Arsenic	ug/L				0.25	8	4.5	
Boron	ug/L				30	55	25	
Copper	ug/L			3.8		4	6.15	
Lead	ug/L			0.9			2.05	
Magnesium	mg/L	21.7	57.9	11.1	39.8	26.7	52.3	40.5
Manganese[b]	ug/L	190	87.5	483	1420	401	890	18
Nickel	ug/L				2.3	4.9	11.5	
Nitrates	mg/L		0.554	3.17				0.554
Radium	mBq/L	130	50	27.3[c]	130[c]	90	30	37.3[c]
Sulfate	mg/L	1.5	4.3	1.88	2.5	7.6	1.6	1.6
Uranium	ug/L	7.74	21.9	3.03	5.76	5.7	3.37	1.92
Vanadium	ug/L					3		
Zinc	ug/L			13	3	16.5	11.5	

[a] This BTV was calculated using Lognormal 95/95 UTL (Upper tolerance limit with 95% confidence and 95% coverage)

[b] Evaluating data against the manganese BTV requires the use of two criteria: concentrations must be below the manganese and sulfate BTV to be considered unimpacted

[c] Although Radium is a primary COPC, the background evaluation did not indicate this was the case for the Shallow Weathered Cahill, Shallow Bedrock Nanambu and MBL Zone.

Notes:

Greyed out BTVs are for analytes that are not COPCs in that HLU.

UTLs were calculated using a Nonparametric Binomial 95/95 UTL.

Depending on the sample size, 95% confidence was not always achieved, but the achieved confidence was never less than 74%.

No BTVs were calculated for Pit 1 as this HLU was entirely impacted.

Statistical methodology follows United States Environmental Protection Agency (USEPA) Guidance (USEPA 2015)

The solute source term conceptual model update in itself does not directly address any specific ERs, however it does form a critical part in a number of groundwater and surface water studies that do, including the post closure solute transport with uncertainty analysis and the Ranger surface water modelling.

The solute source term update consisted of a data-driven approach to determine COPC concentrations and uncertainties for inclusion in the post closure solute transport modelling with uncertainty analysis. A log-normal probability distribution described by moments (concentration mean and standard deviation) was assumed for the source terms. The moments were defined using source-specific data when available and solute relationships based on surrogate data in the absence of source-specific data. Site specific data consisted of groundwater quality data, contaminated sites investigations, site specific investigations, operational water quality data, tailings sample data and water treatment modelling predictions.

Mining activities have resulted in groundwater source terms associated with active mine operations and site closure activities will result in post-closure groundwater sources. The operational period groundwater source terms that were identified and characterised are:

- The groundwater solute plume developed from seepage of tailings pore fluid from the TSF.
- The groundwater solute plume associated with the ore processing and other operations conducted in the plant processing area (PPA).
- The groundwater solute plume developed from rainfall infiltrating through the historical stockpiles (Stockpile Plume).
- The groundwater solute plume developed through seepage from retention pond 2 (RP2).
- The groundwater solute plumes at land application areas (LAAs) developed from application of RP2 pond water.

The post-closure groundwater source terms are:

- Tailings located in Pit 1.
- Tailings located in Pit 3.
- Pit tailings flux (PTF) remaining in Pit 1 after cessation of decant operations (Pit 1 PTF).
- PTF remaining in Pit 3 after cessation of decant operations (Pit 3 PTF).
- Leachate from the waste rock vadose zone in the final landform, including shallow waste rock backfill in the pits (VZ WR leachate).

- Residual mass in waste rock located below the water table in the final landform, including the shallow waste rock in the pits, saturated zone waste rock (SZ WR).
- High density sludge (HDS) (three source terms)
  - Deposited in Pit 3 (HDS in Pit).
  - Consolidated sludge in an HDS out-of-pit disposal cell (HDS OOP cell consolidated sludge).
  - Fluid expressed during consolidation of the HDS out-of-pit disposal cell (HDS OOP cell expressed fluid).
- Brine located in the Pit 3 underfill.

The post-closure source terms include those that will be initially present at site closure but will not be long-term sources and those that will continue to release solutes to the groundwater for a long time after site closure. The initial source terms are the pit tailings flux in Pits 1 and 3, TSF plume, residual mass in the saturated waste rock, the expressed fluid from the HDS out-of-pit disposal cell, and brine. The long-term sources are tailings, leachate from the waste rock vadose zone, HDS deposited into Pit 3, and the consolidated sludge in the HDS out-of-pit disposal cell.

A number of targeted studies have also been completed to improve the substantial data set used in the source term update study. In November 2019 through to January 2020, a targeted drilling campaign was undertaken to address data gaps identified within the 2018 Feasibility Study (ERA, 2021c). Some locations were subsequently converted into groundwater wells to facilitate future closure monitoring. Data obtained through this campaign informed the operational period groundwater source terms (TSF, PPA, and the Stockpile Plume).

Updating the source term conceptual models considered 20 solutes as potential COPCs: aluminium (Al), calcium (Ca), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), nickel (Ni), nitrate (NO3-N), lead (Pb), total phosphorus (P total), polonium-210 (210Po), radium-226 (226Ra), selenium (Se), sulfate (SO4), total ammoniacal nitrogen (TAN), uranium (U), vanadium (V), and zinc (Zn). A screening process utilised groundwater background threshold concentration values (BTVs) described in the previous section (ERM 2020c), to identify the solutes considered to be COPCs for each source term.

A summary of the solutes identified as COPCs for the Ranger source terms are shown in Table 5-23.

Table 5-23: Summary of solutes identified as COPCs for the Ranger solute source terms

Solute	Source Terms													
					TSF Plume									
	Pit 1 tailings & PTF	Pit 3 tailings & PTF	VZ WR leachate	SZ WR	Inside Footprint	Outside Footprint	Stockpile Plumes	PPA Plume	RP2 Plume	LAAs	HDS in Pit	HDS OOP cell consolidated sludge	HDS OOP cell expressed fluid	Brine
Al	x	x			x	x		x			x			x
Ca	x	x	x	x	x	x	x	x	x		x	x	x	x
Cd	x	x			x	x			x			x		x
Cr	x	x			x	x		x	x		x			x
Cu	x	x			x	x		x			x			x
Fe	x	x	x	x	x	x	x	x	x		x			x
Mg	x	x	x	x	x	x	x	x	x		x	x	x	x
Mn	x	x		x	x	x	x	x	x		x			x
Ni	x	x		x	x	x		x	x		x			x
NO3-N	x	x			x	x		x						x
P-total	x	x	x	x	x	x			x		x			x
Pb	x	x			x	x		x						x
Po210	x	x	x	x	x	x	x	x	x		x	x	x	x
Ra226	x	x		x	x	x	x	x	x		x	x	x	x
Se	x	x			x	x		x	x		x			x
SO4	x	x	x	x	x	x	x	x	x	x	x	x	x	x
TAN	x	x		x	x	x		x					x	x
U	x	x		x	x	x	x	x	x		x			x
V	x	x			x	x		x	x					x
Zn	x	x			x	x		x			x			x

x – solute identified as a COPC
green highlighted cell – concentration developed based on source-specific data
yellow highlighted cell – concentration estimated, typically from a ratio in a surrogate source
unhighlighted cell – solute not a COPC
OOP – out-of-pit

Follow up review of the study by SSB identified that shallow groundwater, below and downstream of RP1, could also be considered as an initial condition post closure source but were not included in the source term study. ERA undertook a desktop assessment to review available data and assess the potential environmental risk, (ERA 2021a; ERA 2021b). These assessments concluded that while the shallow groundwater source was not included in the updated solute source term model, the potential source size and resultant comparable impact identified that if the source was included, it would not influence the results of the post closure solute transport modelling with uncertainty analysis. The assessment also identified that if the initial-condition, elevated solute concentrations in shallow groundwater are associated with mining activities, then the source would be associated with historical waste rock stockpiling which is included as a post closure source.

The solute source terms were used as input to the post closure solute transport groundwater modelling with uncertainty analysis discussed in WS2.

5.2.3.3 Literature review on contaminant mobility

Factors influencing contaminant mobility in the sources and several pathways are covered by multiple KKNs. Literature reviews inform each of the projects in these KKNs. The activity titled *Literature review on contaminant mobility* relates to summarising how this information has been used in modelling and identifying information that could be used to support future modelling or understand contaminant behaviour for assessing risks.

Details relevant to each KKN are described below. Several of these have been closed during the MCP reporting period leaving the focus of this activity being the surface and groundwater pathways.

KKN	Compartment	Why factors controlling mobility need to be understood	Status
WS1B	Sources	Contributes to whole-of-site contaminant transport modelling to predict post-closure water quality. Inform the rehabilitation and risk management of the site.	ERA undertook a literature review of contaminant mobility in the sources and the groundwater and surface water pathways in 2020. SSB reviewed this work and suggested reviewing the need for additional information once final scenarios for predicting post-closure surface water quality are completed. The water pathways risk assessment showed which predicted post-closure COPC concentrations are not acceptable. Actions to review the reactive nature of those COPC have been raised and will provide the scope for completing the review of contaminant mobility.
WS2B	Groundwater pathway	Is conservative modelling or reactive modelling required? What factors are important?	
WS3C	Surface water pathway		
WS3G	Surface water –sediment interactions	To determine if closure criteria will protect both environmental compartments	U & S identified as sediment CoPEC (contaminant of potential environmental concern). McMaster *et al.* (2020)

KKN	Compartment	Why factors controlling mobility need to be understood	Status
			developed and algorithm for predicting concentrations of U in sediment based on water quality and showed that the SSB U rehabilitation standard for water protects biota in both the sediment and water matrices. The SO_4 rehabilitation standard derived by SSB to protect ASS forming is based on the water quality associated with the formation of ASS at Coonjimba Billabong and RP1. ARRTC closed this KKN in November 2020.
WS3E	Groundwater – surface water interactions	Potential to limit or increase their concentrations from groundwater to surface water. Which could affect surface water quality predictions.	Based largely on INTERA (2021a) ARRTC closed this KKN in May 2021 noting that the focus was now moving to adaptive management and monitoring.
WS5B	Bioavailability and toxicity of sediments contaminants	Bioavailability mentioned in KKN title not in question. Question is about the Influence of toxicity modifying factors to enable (U) guideline value to be adjusted if sediments different from Gulungul Billabong.	Sediment was one of the sources reviewed in the draft contaminant mobility report reviewed by SSB. Relevant reports were provided to SSB who completed work on this project (McMaster *et al.* (2020). ARRTC closed this KKN in November 2020.
RAD9B	Concentration factors for bushfood	Quantify transfer from the environment (e.g. soil and water) to food items.	This is a SSB KKN.

5.2.4 WS2 Predicting transport of contaminants in groundwater

KKN title	Question
WS2. Predicting transport of contaminants in groundwater	WS2A *What is the nature and extent of groundwater movement, now and over the long-term?*
	WS2B *What factors are likely to be present that influence contaminant (including nutrients) transport in the groundwater pathway?*
	WS2C *What are predicted contaminant (including nutrients) concentrations in groundwater over time?*

5.2.4.1 Groundwater movement and modelling

The tropical, monsoon climate of the NT creates seasonal changes that drive groundwater flow into and out of the Ranger Mine area. Groundwater occurrence and flow through the RPA consists of a shallow groundwater flow system, within the relatively permeable alluvium and weathered rock, and a deeper bedrock groundwater flow system with relatively low permeability, in which groundwater is encountered within faulted, sheared, cracked and brecciated rocks. Groundwater also occurs in intermediate layers of weathered bedrock between the shallow and deeper groundwater flow systems.

The alluvial and weathered rock aquifers are more connected to each other than to the deeper, fractured rock aquifer, and show similar seasonal variations in groundwater levels and quality (INTERA 2016). Groundwater within the fractured rock aquifer is weakly connected to near-surface processes, particularly rainfall-recharge, and there is limited mixing of groundwater between the shallow and deep aquifer units.

Groundwater generally flows northward across the minesite towards Magela Creek (Salama & Foley 1997, Weaver et al. 2010). Figure 5-59 shows the annual groundwater level behaviour illustrating fluctuations that follow a similar, distinctive wet season – dry season oscillation akin to, but in a more subdued form than the typical surface water flow hydrograph, typically peaking following wet season recharge and declining during the dry season recession (INTERA 2019a).

In general, groundwater heads appear to increase several metres during the first one to two months of the wet season and then decrease several metres within the first two to three months of the dry season. Along Magela Creek, water exchange between the subsurface and flowing creek depends on groundwater and surface water dynamics (INTERA 2016). When surface water flow ceases in Magela Creek and Corridor Creek, subsurface groundwater flow continues through the deeper alluvial sediments of the creek beds throughout the dry season (Ahmad et al. 1982).

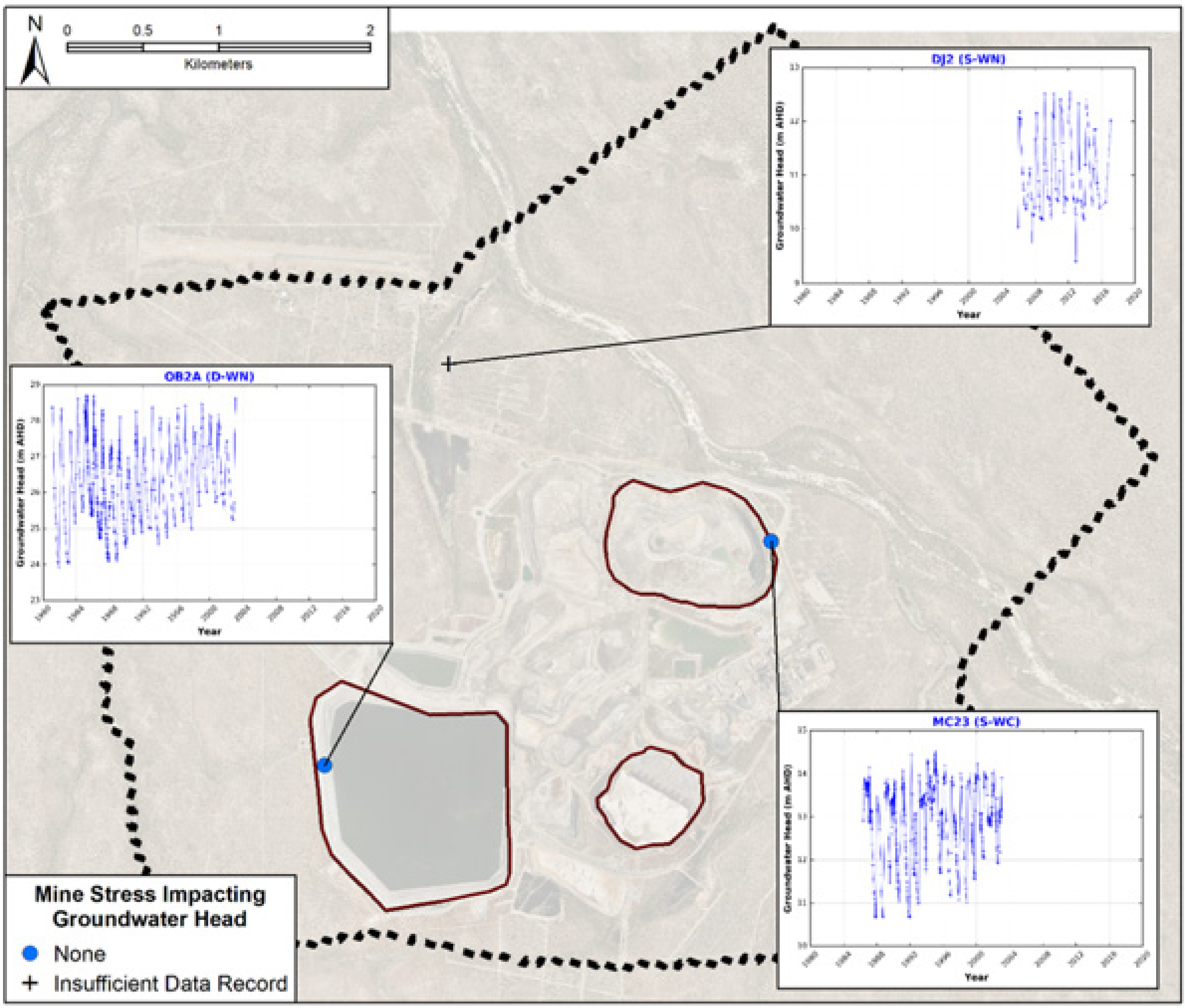


Figure 5-59: Hydrograph showing examples of seasonal groundwater head fluctuations (INTERA 2019a)

5.2.4.2 Ranger Conceptual Model

The calibrated flow model is intended to provide the foundation for simulating groundwater flow and transport from all mine sources to potential receptors under post-closure conditions. The Ranger Conceptual Model (RCM) report describes the data, methods, and results for the site wide hydrogeological conceptual model update; construction, calibration, and sensitivity analysis of the site wide groundwater flow model; and completion of a preliminary groundwater flow model for post-closure conditions. The executive summary from the 2019 Ranger Conceptual Model report is provided below.

The conceptual model for the new site wide domain was iteratively updated through compilation and examination of all available climate, surface water, groundwater, geologic, and bore data to provide the highest level of detail and confidence in accordance with the modelling objectives and available resources. The updated conceptual model describes the most important hydrogeologic elements governing groundwater flow and transport at the

Ranger Mine. The work produced data sets from nearly 2,000 exploratory bores, many hundreds of monitoring and other bores, many dozens of pump and slug tests, all major geologic contacts, more than 80,000 individual groundwater head measurements collected at more than 450 monitoring bores across the sitewide domain, and information about rainfall, evapotranspiration (ET), and creek stages spanning 37 years from 1980 to 2017.

The Ranger Conceptual Model domain was expanded to encompass all available information both upstream and downstream of the Ranger minesite. The conceptual model domain is larger than that for the calibrated groundwater flow model in order to use data outside of the model domain to constrain the HLU extents at the model boundaries and to define HLUs for an area large enough to fall within an appropriate extent for post-closure groundwater flow and transport modelling. The model domains are presented in Figure 5-60.

The RPA contains three distinct regional HLU zones: alluvial, weathered and bedrock. These HLU zones are discretised into specific HLUs, which describe the geological, groundwater flow and transport characteristics of that unit.

A HLU can consist of a single geologic unit, part of a geologic unit, cross geologic units and mining related units in the subsurface that will be in contact with groundwater. HLUs can be aquifers or aquitards depending on their permeability. All material in which groundwater flows is assigned to an HLU, and the HLUs are the building blocks for the material components of the groundwater flow model.

The HLUs were originally conceptualised as part of the development of the Ranger conceptual model in 2016 by INTERA (INTERA, 2016). The HLU's were reviewed and updated as part of the Ranger Conceptual Model update (INTERA 2019a). Further review and update of the HLUs were undertaken as part of the solute transport modelling with uncertainty analysis (INTERA 2021b) to support Key Knowledge Need (KKN) WS2. A breakdown of the Ranger Mine HLUs is shown in Table 5-244.

Table 5-24: Ranger Conceptual Model HLUs, INTERA (2021b)

Shallow HLUs	**Deeps HLUs**
Magela Creek sediments (MCS)	Shallow bedrock Cahill (S-BC)
Other creek sediments (OCS)	Shallow bedrock Nanambu (S-BN)
Higher-K zone of deep weathered Nanambu in the north of TSF	Higher-K zone of shallow bedrock Nanambu in the north of TSF (D-WN-H)
Shallow weathered Cahill (S-WC)	MBL zone (MBL)
Deep weathered Cahill (D-WC)	Depressurised UMS (D-UMS)
Zone C weathered carbonate (ZCWC)	Zone C shallow bedrock (ZCWC)
Pit 1 permeable zone (Pit1-P)	Hanging wall sequence (HWS)
Depressurised UMS confining unit (D-UMS-C)	Upper mine sequence (UMS)
Shallow weathered Nanambu (S-WN)	Lower mine sequence (LMS)
Higher-K zone of shallow weathered Nanambu in the west of TSF (S-WN-HW)	Lower-k deeps water-producing zone (DWPZ-L)

Shallow HLUs	Deeps HLUs
Higher-K zone of shallow weathered Nanambu in the north of TSF (S-WN-HN)	Higher-k deeps water-producing zone (DWPZ-H)
Deep weathered Nanambu (D-WN)	Nanambu Complex (Nam)
Djalkmara sands (DS)	

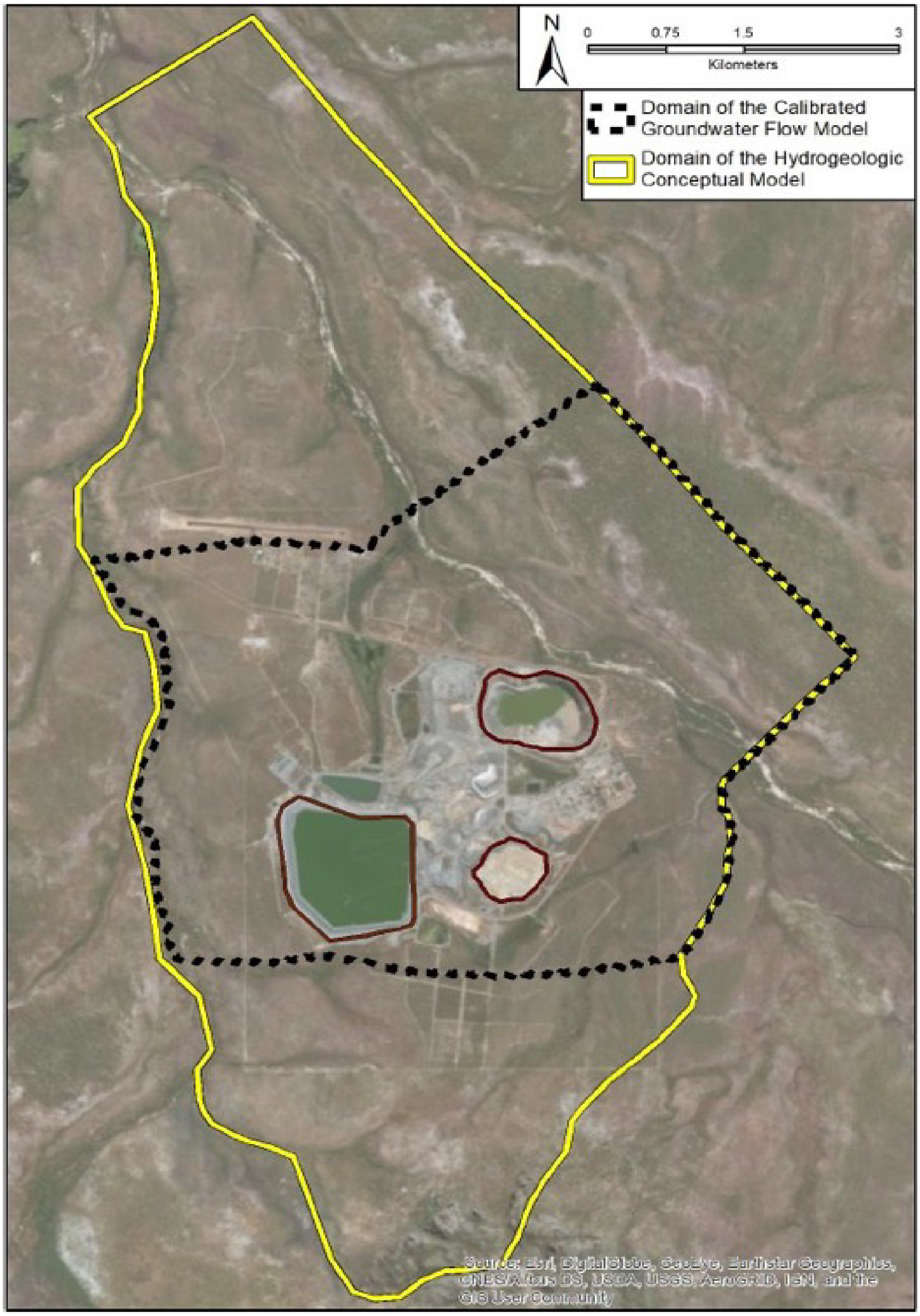


Figure 5-60: Spatial domain of the hydrogeological Ranger Mine conceptual model relative to the domain of the calibrated groundwater flow model.

Updates to the conceptual model focused on extending and improving the HLUs and hydrogeologic framework as well as determining site-specific estimates of recharge and ET. The extensive data sets from bores, geologic mapping, and hydraulic testing were used to modify existing HLUs and add new HLUs. Estimates of recharge and ET were calculated using observed seasonal changes in groundwater heads at shallow bores distributed across the Ranger mine site.

The calibration of the groundwater flow model incorporates the major stresses applied to the Ranger Mine groundwater flow system at Pit 1, Pit 3, and the TSF over the 40 years of operation. Mining of Pit 1 and associated pumping of a dewatering bore, and mining of Pit 3, caused very large head decreases in the adjacent HLUs over many years. Partial backfilling locally raised the heads in the pits in relatively short times. For more than 37 years, process water storage in the TSF applied a head increase on the footprint of the TSF. These mining activities stressed large volumes of the shallow and deep Ranger Mine groundwater flow systems to a far greater degree and spatial extent than any long-term pump tests.

To accommodate all the changes in pit materials and stresses over time, the calibrated flow model is sub-divided into five sequential models: a pre-mining, steady-state model, and four transient models covering the time periods 1980 to 1996, 1997 to 2005, 2006 to 2012, and 2013 to 2017. To enable reasonable calibration model run times, annual stress periods representing water years were used for 33 of the 37 water years simulated. For four water years, monthly stress periods were used to calibrate the model to observed seasonal fluctuations in groundwater heads. Recharge, ET and surface water stages are also included as stresses.

The numerical groundwater flow model was constructed using the MODFLOW-NWT code to encompass the Ranger Mine, all surface water receptors downgradient of the mine, all important areas driving groundwater flow to the receptors from the mine area, and all HLUs from shallow to deep. The calibrated model covers about 29 km2 and vertically spans nearly 800 m, making it the largest Ranger Mine groundwater flow model to date. Discretised into 30 m by 30 m grid cells in the horizontal plane and 19 layers, the model grid contains roughly 612,940 active cells. The model simulation period encompasses a pre-mining, steady-state period and the 37-year mining period, which is far longer than in any previous Ranger Mine calibrated flow model.

The transient groundwater flow model, INTERA (2019a), was calibrated by compiling calibration head targets and iteratively using manual and automated methods to adjust model parameters, compare simulated and observed head targets, and calculate calibration statistics. From examination of the available groundwater head data from more than 450 bores, about 100 head targets were estimated for the pre-mining, steady-state calibrated flow model and more than 8,500 head targets were developed for the transient calibrated flow model. A manual or trial-and-error process was used to define, modify, and refine the spatial extents of model zones representing key HLUs. Calibration of zone hydraulic properties for all appropriate HLUs was conducted by coupling parameter estimation tool (PEST) software with MODFLOW-NWT. Calibration statistics, hydrographs, and other standard metrics were used to quantify whether the change in zone properties improved the match between observed and simulated heads.

Results from the flow model calibration undertaken in 2019 revealed that the model adequately simulates groundwater flow with small average error relative to measurement errors and captures temporal groundwater head variations. Further transient model calibration was undertaken as part of the preparation task of the groundwater modelling of the uncertainty analysis study, INTERA (2021b). This calibration was undertaken as an additional 1469 calibration targets were available due to the time passed since the previous model calibration which ensured all available data was used to support the uncertainty analysis. The calibration statistics are provided in Table 5-25 for all HLUs with the exception of HLUs with less than 25 calibration targets due to insufficient data to provide meaningful statistics.

Simulated monthly heads at many bores adequately represent observed seasonal head changes in both timing and magnitude and simulated annual average heads at most bores adequately represent year-to-year changes. Scatter plot of simulated versus observed heads depict random scatter about the 1:1 line for both the entire model and most individual HLUs, indicating negligible bias, as shown in Figure 5-61. Overall, the calibration metrics indicate that both the pre-mining, steady-state and transient models are well calibrated to the observed data. Water balance errors are negligible for the pre-mining, steady-state and transient calibrated flow models and the water balances show good agreement with conceptualisation.

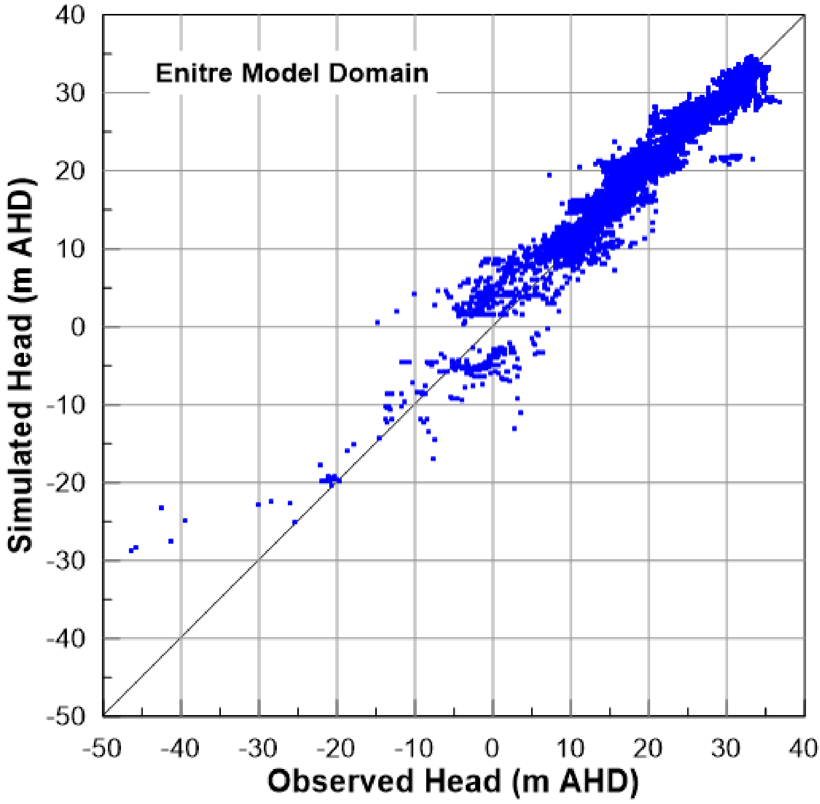


Figure 5-61: Scatter plot of simulated versus observed groundwater heads for all calibration targets in the entire calibrated model domain for the updated transient model, INTERA (2021b)

Table 5-25: Calibration statistics for the updated transient groundwater flow model, INTERA (2021b)

HLU	Count	Mean Error (m)	Mean Absolute Error (m)	Root Mean Square Error (m)	Absolute Minimum Residual (m)	Absolute Maximum Residual (m)	Measured Range (m)	RMSE/ Range (%)	MAE/ Range (%)
Model Domain	10,118	-0.48	1.55	2.2	0	19.08	83.07	3	2
Shallow HLUs									
All	6,432	-0.49	1.26	1.76	0	14.26	44.99	4	3
Djalkmara sands	98	-0.04	1.14	1.65	0.02	6.3	9.73	17	12
shallow weathered Cahill	193	-0.25	0.91	1.24	0.01	3.92	10.35	12	9
deep weathered Cahill	1,012	-0.77	1.56	2.14	0	14.26	33.82	6	5
Zone C weathered carbonate	156	-0.38	1.73	2.38	0.01	5.86	21.77	11	8
Pit 1 permeable zone	378	-1.8	1.96	2.37	0.02	6.37	7.94	30	25
shallow weathered Nanambu	1,766	-0.07	0.82	1.08	0	4.65	28.97	4	3
higher-K zone of shallow weathered Nanambu in the west of TSF	88	-0.9	1.04	1.69	0.04	12.16	19.23	9	5
higher-K zone of shallow weathered Nanambu in the north of TSF	162	-0.45	1.27	1.58	0	9.35	10.92	14	12
deep weathered Nanambu	2,459	-0.57	1.37	1.87	0	7.33	25.85	7	5
higher-K zone of deep weathered Nanambu in the north of TSF	120	0.68	1.09	1.39	0.01	3.66	7.23	19	15
Deep HLUs									
All	3,686	-0.46	2.05	2.8	0	19.08	83.07	3	2
shallow bedrock Cahill	450	-2.66	2.85	3.48	0.02	9.55	24.56	14	12
shallow bedrock Nanambu	1,425	0.66	1.66	2.33	0	11.76	22.82	10	7
higher-K zone of shallow bedrock Nanambu in the north of TSF	334	-2.04	2.2	2.57	0.03	7.76	8.85	29	25
MBL zone	1,161	-0.88	1.81	2.41	0	8.42	23.25	10	8
depressurised UMS	262	1.37	3.59	4.77	0.02	19.08	61.65	8	6
Zone C shallow bedrock	43	-1.47	2.37	4.32	0.07	15.15	30.31	14	8

Model validation, through comparison of simulated and observed inflows to the Ranger 3 Deeps (R3D) decline over roughly 5 years, reinforces the high level of confidence in the conceptual and calibrated flow models. The calibrated groundwater flow model was updated to include the stress on the groundwater system from the excavation of the R3D decline and was used to simulate inflows into the R3D decline for comparison to observed data from start of excavation in 2013 through August 2017 (end of transient model calibration period). This implementation of the model provided a check on the calibrated hydraulic properties for both shallow and deep HLUs intersected by the decline. Inflow to the decline modelled using the calibrated hydraulic properties yielded a good match to the observed inflows. This simulation of inflows to the R3D decline serves as validation for the calibrated flow model and shows that the model calibration process incorporated both groundwater head and flux data.

A thorough sensitivity analysis was performed on the INTERA (2019a) calibrated model to determine how model predictions varied with changes to model parameter values and boundary conditions. A sensitivity analysis is a widely accepted means of formally describing the change in model outputs (predictions) caused by changes in specific model inputs or groups of inputs (parameters). The sensitivity analysis on the Ranger Mine calibrated flow model first systematically increased and decreased individual model input parameters for hydraulic properties and boundary conditions from their calibrated values whilst all other input parameters remained constant, ran the model and recorded changes in model predictions for the pre-mining, steady-state model and the transient model. The sensitivity analysis also looked at how model predictions were affected by changing the properties of the Ranger Fault used to define the model southern boundary and by changes to the amount of recharge applied to the waste rock stockpiles.

The analysis revealed that the calibrated flow model is sensitive to a sizeable number of model parameters, demonstrating that the site-specific data used to build and calibrate the flow model do constrain the values of the model parameters. The real-world constraints on the parameters effectively decrease the uncertainty in the parameter values, which in turn means there is increased confidence gained through the calibration process. In particular, the sensitivity analysis shows that the calibrated groundwater flow model for the Ranger Mine is sensitive to many of the parameters previously identified to be important for evaluation of post-closure solute loading to receptors. Removing the Ranger Fault as a low-permeability barrier to groundwater flow did not affect the calibration statistics. A large increase in the amount of recharge applied to the waste rock stockpiles also did not affect the calibration statistics.

The hydraulic stresses driving groundwater flow during the post-closure period are essentially the same as those in the pre-mining period. For the purpose of this task, and consistent with previous modelling, the stresses driving groundwater flow during the 10,000-year assessment period were represented as steady driving forces based on long-term averages. The steady flow stresses were calculated using the same 37-year historical record that was used to develop the pre-mining, steady-state stresses for the INTERA (2019a) calibrated flow model.

Simulated shallow and deep groundwater heads demonstrate that the post-closure groundwater flow model is a topographically driven flow system. Heads are highest where the topography of the final landform waste rock is highest, and groundwater flows from the higher elevation recharge areas to the lower elevation discharge points in the creeks. Vertical groundwater head gradients are also consistent with topographically-drive flow, with downward gradients in topographically higher areas and upward gradients in topographically lower areas.

Development of the post-closure groundwater flow model consisted of modifying the calibrated groundwater flow model to represent backfill, landform conditions, and the time scale of post-closure hydrogeologic conditions. The HLU assignments for the post-closure flow model mostly follow those from the calibrated model except where additional backfill materials were included in the pits and where waste rock will be placed to create the final landform.

The Ranger Mine site wide modelling process and conceptual and numerical flow models were examined to determine compliance with the relevant guiding principles from the Australia groundwater modelling guidelines. The examination demonstrated that the Ranger Mine site wide modelling process complies with the guiding principles from the Australian Groundwater Modelling Guidelines. Agreement of the calibrated Ranger Mine groundwater flow model with the applicable guiding principles demonstrates that the planning, conceptualisation, design and construction, calibration and sensitivity analysis, and reporting of the Ranger Mine conceptual and numerical calibrated flow models were completed appropriately and provide the model with a very high level of confidence. The Ranger Mine groundwater calibrated model will meet all indicators for the Level 3 confidence level (highest confidence level).

The Ranger conceptual model has undergone multiple independent reviews and was found to be a significant improvement over past models with the only major outstanding concerns at the time relating to the lack of a formal uncertainty analysis which has since been completed and discussed in the next section. The Ranger conceptual model was found to meet appropriate industry standards and is fit for purpose.

5.2.4.3 Post-closure groundwater solute transport modelling with uncertainty analysis

A calibration-constrained, predictive groundwater model with uncertainty analysis, based on an updated Ranger flow calibration model (INTERA 2019a), has been developed to provide COPC loads at selected probability values for input to a predictive surface water model (SWM), to address KKN WS2 and inform WS3. INTERA were engaged by ERA to complete the modelling study following the development and update of the RCM, INTERA (2016) and INTERA (2019a), and update of the Ranger Solute Source Terms, INTERA (2020a) described in previous sections. The predictive Ranger groundwater model with uncertainty analysis (Ranger GW UA) study was completed in 2021, INTERA (2021b). The Ranger GW UA provides probabilistic simulations of solute loads to the creeks for 20 COPCs: magnesium, uranium, manganese, radium-226, total phosphate, nitrate as nitrogen, total ammonia as nitrogen, polonium-210, iron, copper, lead, cadmium, zinc, chromium, vanadium, calcium, nickel, selenium, aluminium, and sulfate.

The Ranger GW UA comprised three sets of tasks: preparation, implementation, and results compilation. The development of conceptual models for COPC sources for the Ranger GW UA is described in a separate report, INTERA (2020a), to support KKN WS1. All tasks were carried out with review and input from the SSB and IGS, during a series of eight presentations in conference calls that began at project kick-off in December 2019 and ended in October 2020.

The preparation tasks focused on:

- Identifying and compiling relevant information to define prior parameter probability density functions for all randomly varied model parameters,
- Updating and re-calibrating the Ranger sitewide groundwater flow model, and
- Constructing and testing the predictive flow and transport model.

The implementation tasks focused on:

- Create prior probability density functions, which include expert and site-specific knowledge, for all model parameters after identifying and compiling site-specific data and relevant information from the scientific literature.
- Generate random samples (stochastic realisations) from prior parameter probability density functions and then use a null space projection operation to condition these realisations so that they reproduce historic site-specific observations. These projected realisations are, by definition, posterior parameter realisations since they were drawn from the prior parameter probability density functions and honour the site-specific observations used for model calibration.
- Generate stochastic realisations from the prior parameter probability density functions for parameters that are only present in the predictive model. By definition, these parameters cannot be conditioned on historic observations. The random predictive model parameter values were appended to the posterior parameter realisations to create 983 realisations of parameter sets needed to run the predictive model.
- Run the resulting realisations in the predictive model to produce 983 equiprobable predictions of Mg loading with parameters that honour the large set of historic observations.

The results Compilation tasks focused on:

- Compile predicted Mg loads within the Ranger mine area's four ground water sheds to compute probability values for peak loads.
- Run selected predictive model realisations over 10,000 years.
- Run selected realisations in the variable density predictive model for the brine source.

- Calculate total Mg loads at 10,000 years from all sources.
- Compile peak loads and loads at 10,000 years for all other COPCs.
- Prepare input tables of COPC loads for surface water modelling through the updated groundwater surface water interaction to support KKN WS3.

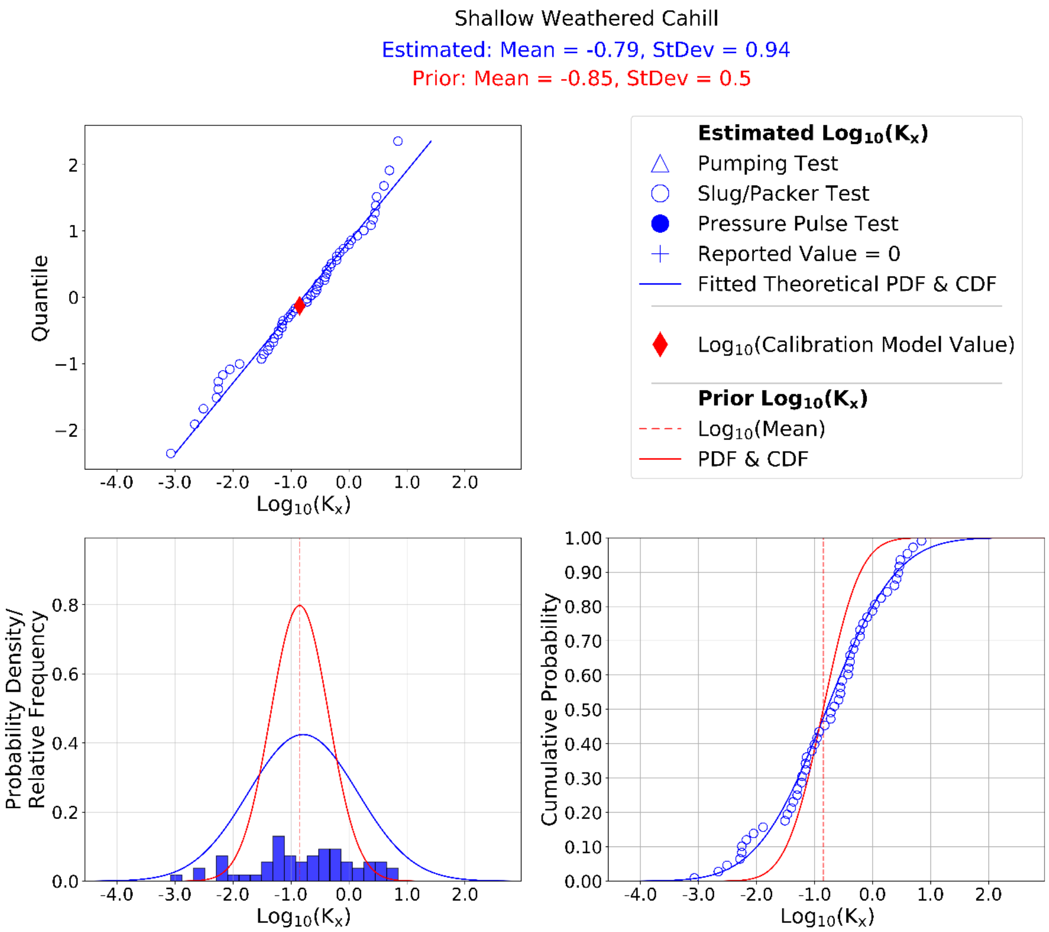
The Ranger GW UA was a comprehensive modelling study that determines groundwater loads of 20 COPCs, and their posterior predictive uncertainty, to Magela Creek and its three tributaries from all Ranger mine sources at a sitewide scale over a 10,000-year post-closure assessment period to address KKN WS2. The COPC loads are intended to inform a predictive surface model to predict COPC concentrations in receptor creeks to address KKN WS3.

The implementation tasks involved compiling all site-specific data and scientific literature information about hydraulic conductivity (K) and specific storage measurements, recharge rate estimates, and source term COPC data. This information was used to both update the calibration of the Ranger Conceptual model, described in the previous section, and used in defining prior parameter probability density functions required to support the uncertainty analysis process. Following update and re-calibration of the Ranger conceptual flow model, the predictive flow and transport model was developed and tested to simulate COPC loading from the Ranger mine sources, described previously to address KKN WS1, to surface water receptors over the 10,000 year post-closure assessment period. Groundwater flow was simulated as steady-state flow specified to represent average long-term conditions for groundwater recharge, evapotranspiration, and creek stage after he groundwater flow system has re-equilibrated with climatic stresses. These initial simulations, undertaken with the calibrated flow model were considered the base-case simulations.

A separate predictive model was constructed and tested to simulate, under variable-density conditions, the loading from the dense, viscous brine stored in the Pit 3 underfill to Magela Creek.

Following development and testing of the post closure flow models, the next set of tasks commenced to implement the uncertainty analysis. The implementation tasks started with the development of the prior probability density functions for the 135 model parameters found in both the calibration and predictive models. These model parameters include the normal hydraulic parameters as well for groundwater recharge, groundwater evapotranspiration, and anisotropy ratios. An example of a prior probability density function describing the horizontal conductivity of the shallow weathered Cahill HLU is provided in Figure 5-62.

The prior parameter probability density functions means and standard deviations were used as inputs to the PEST RANDPAR utility (Watermark Numerical Computing, 2019) to generate 1,000 prior parameter realisations, each of which contains a randomly sampled value for each of the 135 parameters. The 1,000 realisations were then subjected to the null-space projection operation for conditioning, and, where necessary, an additional PEST re-calibration optimisation iteration, to produce posterior parameter realisations that honoured the calibration data to the extent possible. Out of the 1,000 realisations, 17 produced unacceptably high posterior phi (calibration) values and were rejected, yielding 983 posterior parameter realisations, all of which had negligible water balance errors.



Prior		
Quantile	K_x (m/d)	$Log_{10}(K_x)$
0.05	2.1E-02	-1.67
0.5	1.4E-01	-0.85
0.95	9.4E-01	-0.03

Figure 5-62: Prior Kx probability density function for the shallow weathered Cahill HLU

Prior probability density functions were defined for the 70 model parameters found only in the predictive flow and transport model by examining available site-specific and literature data. This information was used to choose the mean and standard deviations for each prior probability distribution function (PDF). Predictive parameter priors were defined for the hydraulic (K and anisotropy) and transport (i.e. effective porosity) properties of HLUs found only in the predictive model (three types of Pit 3 consolidated tailings, Pit 1 consolidated tailings, and waste rock), groundwater (GW) recharge and GW ET on the landform waste rock, and COPC concentrations for the sources. Each major source was represented as a separate species in the predictive simulations to enable tracking of loads from each source to each of the four groundwater sheds.

Constructing parameter realisations for the predictive flow and transport model required two steps. First, random samples from each of the predictive parameter prior PDFs were generated with PEST's RANDPAR routine. The resulting predictive parameter realisations, each containing randomly sampled values of the 70 predictive model parameters, were combined with the posterior parameter realisations from the calibration model to create 983 realisations with the parameters needed to run the predictive model. These 983 realisations were then run in the predictive MDOFLOW-NWT (Niswonger et al. 2011) flow model and the MT3D-USGS (Bedekar et al. 2016) solute transport model.

Results from the modelling simulations were compiled for 3 physical settings, all groundwater sheds total loading, Coonjimba groundwater shed loading and Corridor creek groundwater shed loading, and for two time periods, the period during which peak loads are predicted to occur and at. 10,000 years. Peak Mg loads for each setting were calculated from the 983 equiprobable predictions by combining loads from the output files for all Mg species and determining the peak load and year of peak load for each realisation.

Examination of the total loading values for all 983 realisations over the 300-year initial simulation time revealed that all peaks occurred within the first 100 years post closure.

Probability values were computed for these peak Mg loads by compiling cumulative density functions from the 983 predictive realisations. Loads at seven probability values, called P-values, were selected to prepare loads for use in the predictive surface water model: 0.05, 0.10, 0.20, 0.50, 0.80, 0.90, and 0.95 (i.e. P05, P10, P20, P50, P80, P90, and P95). A chart showing the cumulative distribution function for Mg loads is presented in Figure 5-63.

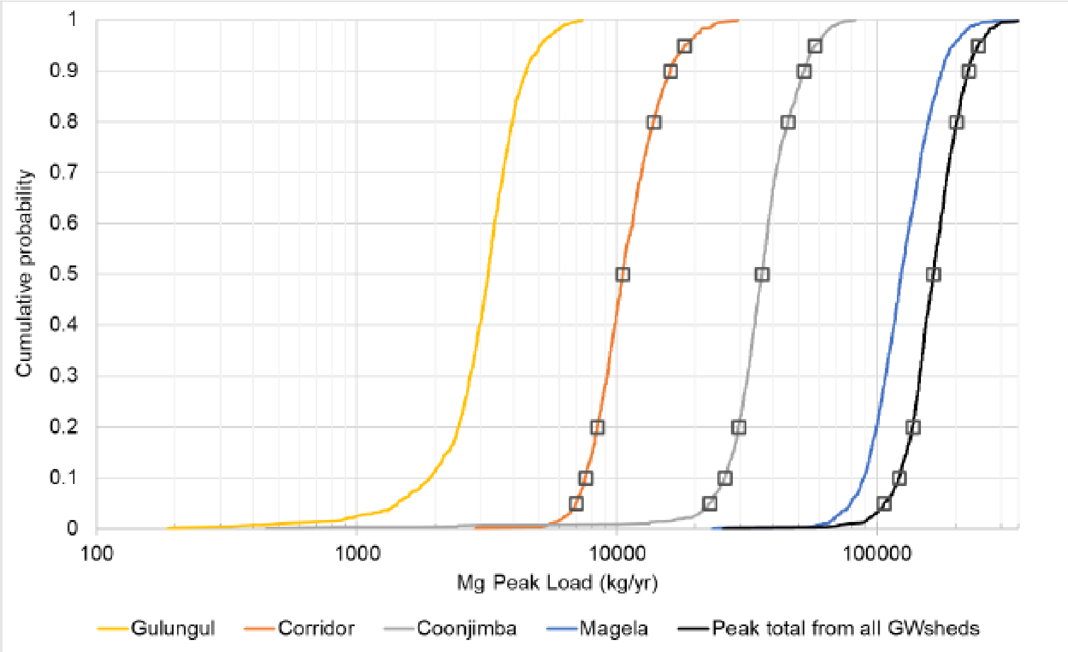


Figure 5-63: Cumulative distribution functions for peak Mg loads from the 983 predictive model runs.

Peak loads for other COPCs were calculated using a combination of scaling of Mg loads for some sources and simulations of COPC loads from plume sources. Other COPC results for the seven P-values were scaled using ratios of COPC to Mg concentrations for all but the plume sources. Loads from COPCs in the plume sources were determined from model simulations and added to the scaled loads to compute peak COPC loads.

Total loads for other COPCs at 10,000 years at the seven P-values were calculated using concentration ratios to scale Mg loads at 10,000 years from all active sources: brine, vadose zone waste rock leachate, tailings, and HDS (both in-pit disposal and consolidated sludge in the HDS out-of-pit disposal cell). SO_4 loads from vadose zone waste rock leachate were corrected to account for the exhaustion of pyrite over time.

The final compilation step was to prepare COPC loading input files for the predictive SWM. Loads at each GW shed for each setting and time period were compiled for each of the seven P-values into files for use in predicting surface water (SW) concentrations. Four of the compiled P50 simulation results were carried forward into the surface water modelling, the peak all groundwater sheds loading, the peak Coonjimba groundwater shed loading, the peak Corridor Creek groundwater shed load, and the all water sheds 10,000 year loading. Additionally, to support sensitivity analysis in the surface water modelling the P10 and P90 all groundwater sheds peak loading simulations were simulated in the surface water model. Surface water modelling is discussed later in this section to address KKN WS3.

In summary the Ranger GW UA provides robust predictions of post-closure COPC loads to creek receptors because it defined and incorporated parameter uncertainty from over 200 model parameters into its predictions of groundwater flow and transport to quantitatively estimate the predictive uncertainty.

Peak loads and total loads to creek receptors at 10,000 years for all COPCs were estimated with probability values that define the predictive uncertainty in the Ranger GW UA. These load values are derived from 983 equiprobable realisations that combine calibration-constrained posterior parameters with random samples of predictive model parameters. This means that the 983 predictions of interest were made with 983 equally well calibrated sets of parameters, many of which had values that ranged randomly across multiple orders of magnitude. The predictive parameter realisations together effectively sampled the uncertainty in model parameters and boundary conditions across a wide range of probability values, and so provide a robust estimate of predictive uncertainty that imparts increased confidence in the Ranger post closure solute transport modelling with uncertainty analysis COPC loadings results.

The uncertainty analysis also included climate variability to assess influence of climate change to the extent possible by treating groundwater recharge rates as random parameters to account for uncertainty, both with and without conditioning by historical data.

The Ranger GW UA process and numerical models were examined to determine compliance with the relevant guiding principles from the Australia groundwater modelling guidelines and uncertainty analysis (UA) guidelines. The examination demonstrated that the Ranger GW UA process fully complies with the guiding principles for planning, conceptualisation, design and construction, calibration and sensitivity analysis, prediction, uncertainty, and reporting, and provides the Ranger GW UA modelling with the highest level of confidence. Perhaps more importantly, the combination of best scientific practice for a calibration-constrained Ranger GW UA, regular review and discussion with key stakeholders, technical guidance from one of the leading scientists for GW UA, Dr John Doherty, and access to the enormous amount of data collected at Ranger provide the highest level of confidence.

5.2.5 WS3 Predicting transport of contaminants between groundwater and surface water

KKN title	Question
WS3. Predicting transport of contaminants in surface water	WS3A. *What is the nature and extent of surface water movement, now and over the long-term?*
	WS3B. *What concentrations of contaminants from the rehabilitated site will aquatic (surface and ground-water dependent) ecosystems be exposed to?*
	WS3C. *What factors are likely to be present that influence contaminant (including nutrients) transport in the surface water pathway?*
	WS3D *Where and when does groundwater discharge to surface water?*
	WS3E *What factors are likely to be present that influence contaminant transport (including nutrients) between groundwater and surface water?*

5.2.5.1 Groundwater / Surface water interaction

Understanding and quantifying groundwater to surface water interaction forms a key component for the linking the groundwater solute transport model to the surface water model. The groundwater to surface water interactions relate to the timing, and location of groundwater flow and in turn potential for solute transport from groundwater into the receiving environments. Understanding this relationship and accurately representing it in the modelling is vital to accurately predicting the possible contamination concentrations in the receiving environment.

INTERA were engaged by ERA to develop an updated groundwater to surface water interaction conceptual model to support integration of solute load predictions from the groundwater solute transport modelling into the surface water model update, INTERA (2021a). The conceptual model of groundwater/surface water interaction was updated based on an approach considering hydraulic gradients and surface water EC data. A hydraulic gradient assessment was conducted to calculate hydraulic gradient magnitudes and directions using site-specific groundwater head data at bores along Magela Creek and Magela Creek stage data from a surface water station near the Ranger mine.

An assessment of the EC data for both Magela and Gulungul creeks was also conducted. The updated conceptual model remains consistent with the conceptualisation presented in 2018 but is improved by the new data-driven understanding that:

- The hydraulic gradient and rate of groundwater discharge to Magela Creek surface water during high creek flow are not constant but vary in time.
- Groundwater loading decreases at a rate commensurate with the decrease in creek discharge after flood events, as indicated by the EC and historical Mg concentration data in Magela and Gulungul creeks.

The data used to define the timing of the start and end of groundwater discharge to Magela Creek surface water and the time-varying rates of that discharge not only improved the conceptual model of groundwater/surface water interaction, it also increased confidence in the integration of solute loading results from the groundwater modelling as surface water model inputs. Historical EC and point-in-time groundwater head data confirmed that the updated conceptual model is appropriate historically and for all locations along the portion of Magela Creek located next to the mine.

The conceptual model was updated using continuous (2018 to 2020) and historical (late-1980s to 2020) groundwater head data at six bores, historical (late-1980s to 2020) groundwater head data at an additional three bores, continuous historical and recent creek stage data (late-1980s to 2020), and continuous EC data in Magela Creek, Georgetown Billabong, and Gulungul Creek (2017 to 2020). The data indicate that hydraulic gradients are consistently towards the creek at upslope bores whereas hydraulic gradients vary in direction between the creek and closer bores. Gradient directions and magnitudes calculated from point-in-time (dipped) groundwater head data are consistent with those calculated using recent continuous (logger) groundwater head data.

The gradient dynamics observed between Magela Creek surface water, the groundwater in bores and the surface water chemistry follow the general sequence identified in the previous conceptual model for groundwater/surface water interaction. The updated sequence comprises the follow stages:

- No groundwater discharge to surface water early in the creek flow period because groundwater heads are lower than creek stage and EC data show no indication of groundwater loading.
- Groundwater discharges to surface water at various rates during the middle of the creek flow period (with occasional, relatively brief interruptions during high creek flows).
- Groundwater discharges to surface water at a typically decreasing rate starting from the early part of the flow recession period.
- Groundwater loading to surface water decline after flood events at a rate commensurate with the decline in creek discharge.
- No groundwater discharge to surface water during late recessional flow because groundwater heads are lower than creek stage and surface water EC does not change with time.

An updated hydrograph visualising the creek flow vs groundwater loading for the 2018-2019 Magela Creek flow period is shown in Figure 5-64.

Evaluation of the similarities and differences in the hydrology and EC of Magela and Gulungul creeks was undertaken and indicated that groundwater/surface water interaction is similar for the two creeks. A pair of hydrographs is shown in Figure 5-65 demonstrating the similarities in EC and creek flow between the Magela Creek and Gulungul Creek. Therefore, the updated conceptual model is considered to be appropriate for both Magela and Gulungul creeks.

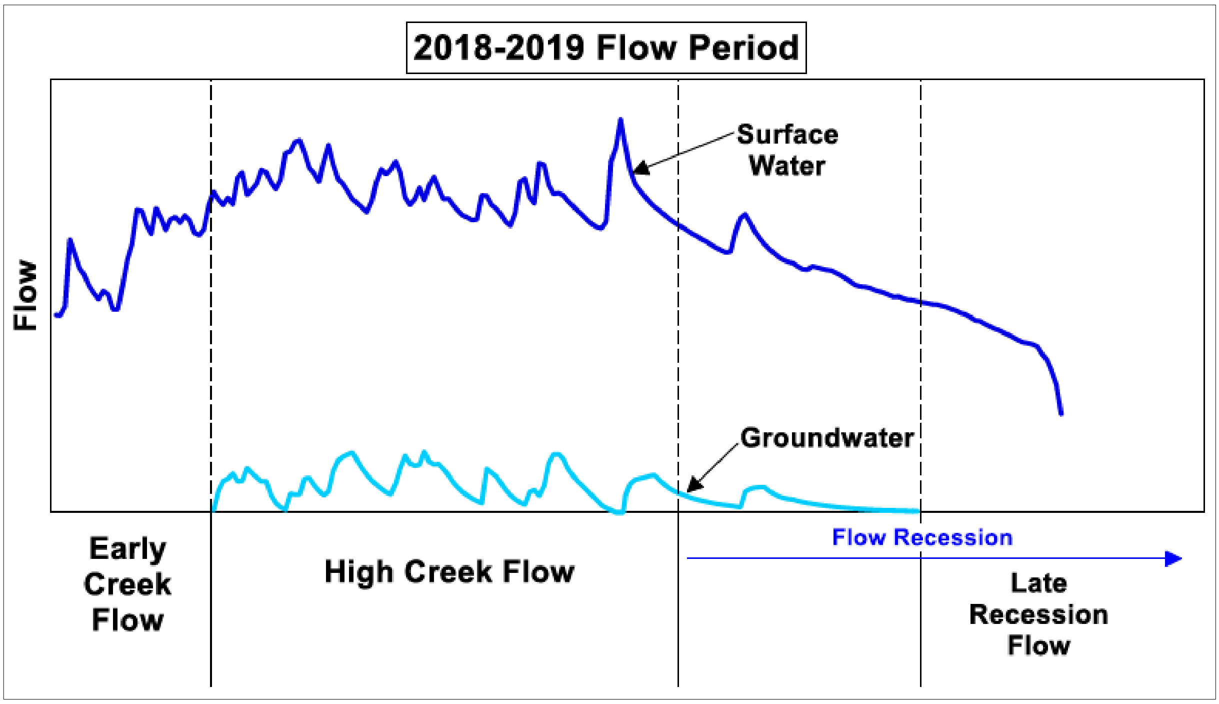


Figure 5-64: Updated conceptual model of groundwater surface water interaction

The amount of data used to develop the updated conceptual model is sufficient to provide confidence in the updated conceptualisation. Continuous groundwater head data are only available for the two recent wet seasons, but many historical point-in-time measurements corroborate the gradient findings from the recent data. In addition, the many years of continuous EC data provide historical confidence in the updated conceptual model. Monitoring of bores used in the groundwater to surface water investigation has continued and additional monitoring bores are in plan to be drilled alongside Gulungul creek to provide further confidence in the updated conceptualisation.

INTERA presented early findings of the study to the relevant ARRTC members at an out of session water and sediment focused workshop in October 2020 and the study report was provided to stakeholders for review and feedback in December 2020. Feedback on the study report was received from SSB in January and an updated report was provided to stakeholders in February. The study was endorsed by ARRTC in 2021.

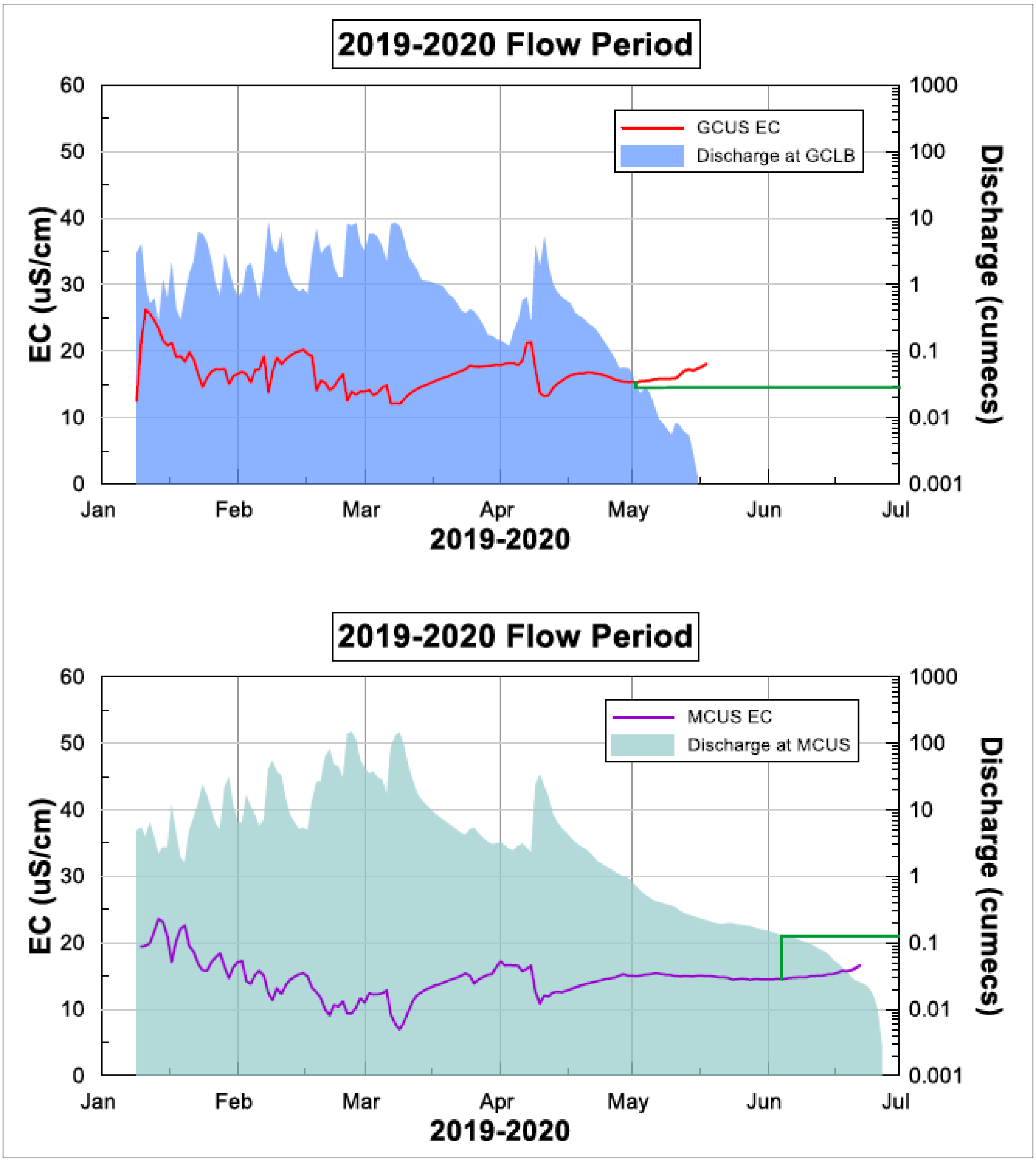


Figure 5-65: Similarity between EC increase at end of flow period and creek discharge at GCUS and MCUS for the 2019-2020 flow period.

5.2.5.2 Hydrology

Surface water management is a key focus of rehabilitation and closure, as it is one of the main pathways for COPCs to enter the environment. Understanding and modelling transport of contaminants in surface waters adjacent and down-stream of the mine site is required to address KKN WS3.

The Ranger Mine is located within the 1,600 km^2 of the Magela catchment and adjacent to Magela Creek (Figure 5-66). Two tributaries of Magela Creek are also located in close proximity to the mine: Gulungul Creek to the west and Corridor Creek to the south. Magela Creek is a seasonally flowing tributary of the East Alligator River, with a catchment originating from headwaters on the Arnhem Land Plateau.

The seasonal pulse of the wet season monsoon controls regional hydrology (Wasson 1992) with flows beginning in an average year in mid-December, after the onset of the monsoonal wet season which usually occurs in November. During the wet season, creeks become sheets of water that extend beyond the low banks. This water is reduced to a series of isolated backflow billabongs and swampy depressions in the dry season winter months. Poor drainage makes access to surrounding areas difficult, and roads and tracks are frequently cut off by flood waters for extended periods in the wet season. The sand aquifers in the channel of Magela Creek, in the middle catchment fill, with shallow groundwater and begin flowing as interflow within the creek channel, before surface flow commences in the creek. Average annual runoff for the Magela Creek system has been estimated at 420 GL (Moliere 2005, Salama & Foley 1997, Vardavas 1988).

Magela Creek and its tributaries flow north from the extensive sandstone Arnhem Plateau. In more specific terms, Magela Creek comprises four sections:

- escarpment channels that flow through deep narrow gorges, which make up around one third of the Magela catchment. These systems are fed by groundwater seeping into the fractured rock of the escarpment and can flow practically all year round. Escarpment rainforest vegetation species (dominated by Allosyncarpia ternate (a Kakadu hardwood tree species)) are found in the gullies due to year-round water supply.
- sand bed anabranching channels (Jansen & Nanson 2004) with sandy levees. Magela Creek flows through sandy soils that may be more than five metres deep along the creek channels. This is the section in which the Ranger Mine is located.
- a series of billabongs and connecting channels at Mudginberri (termed the Mudginberri Corridor)
- a 200 km2, seasonally inundated black-clay floodplain, at two to five metres above sea level, with permanent billabongs, and a single channel that discharges into the East Alligator River approximately 40 km to the north of the RPA and, ultimately, Van Diemen Gulf

Gulungul Creek, on the western boundary of the RPA, drains runoff from the catchment to the west and south of the TSF and from relatively undisturbed bushland to the west of RP1. The main stream of the Gulungul Creek has a length of around 12.5 km. The Gulungul sub-catchment has an area of approximately 98.4 km^2.

Figure 5-66: Regional extent of Magela catchment

Moliere (2005) reviewed historical stream flow data for Gulungul Creek to provide confidence in the flow and flood frequency estimations. Despite data gaps, an annual runoff of 25.5 GL at G8210012, immediately west of Ranger Mine, as shown on Figure 5-67 was determined, with a general flow period for Gulungul Creek of approximately six months between December and May. Observations from Ranger Mine operations have noted that the general flow period can, however, extend through to June or July in above average wet seasons. Stream flows are highly variable throughout the wet season and reach peak discharge during the months of February to March (Salama & Foley 1997).

Antecedent rainfall in the Gulungul sub-catchment that is required prior to overland flow in Gulungul Creek is similar to that for Magela Creek at approximately 295 mm (Moliere 2005).

Corridor Creek drains the southern side of the Ranger Mine. The natural catchment has been modified in the vicinity of the mine, with mine drainage water being redirected to water treatment areas. There is also a series of natural and artificial water bodies within the creek line that modulate the effects of storms and rainfall events. Corridor Creek runs into Georgetown Creek at Georgetown Billabong. The main water bodies in Corridor Creek include the pre-mining Georgetown Billabong and the constructed Corridor Creek wetland filter (CCWLF), the Georgetown Creek Brockman Road (GCBR) bund, Georgetown Creek Mine Bund Leveline (GCMBL) and Sleepy Cod Dam.

Prior to mining, the local hydrology included four separate sub-catchments, namely Gulungul to the west and southwest, Coonjimba in the centre west, Djalkmarra in the centre east and Corridor Creek in the east and south (Figure 5-68). Within the sub-catchments, backflow billabongs sit on the margins of Magela Creek creating complex localised hydrological relationships.

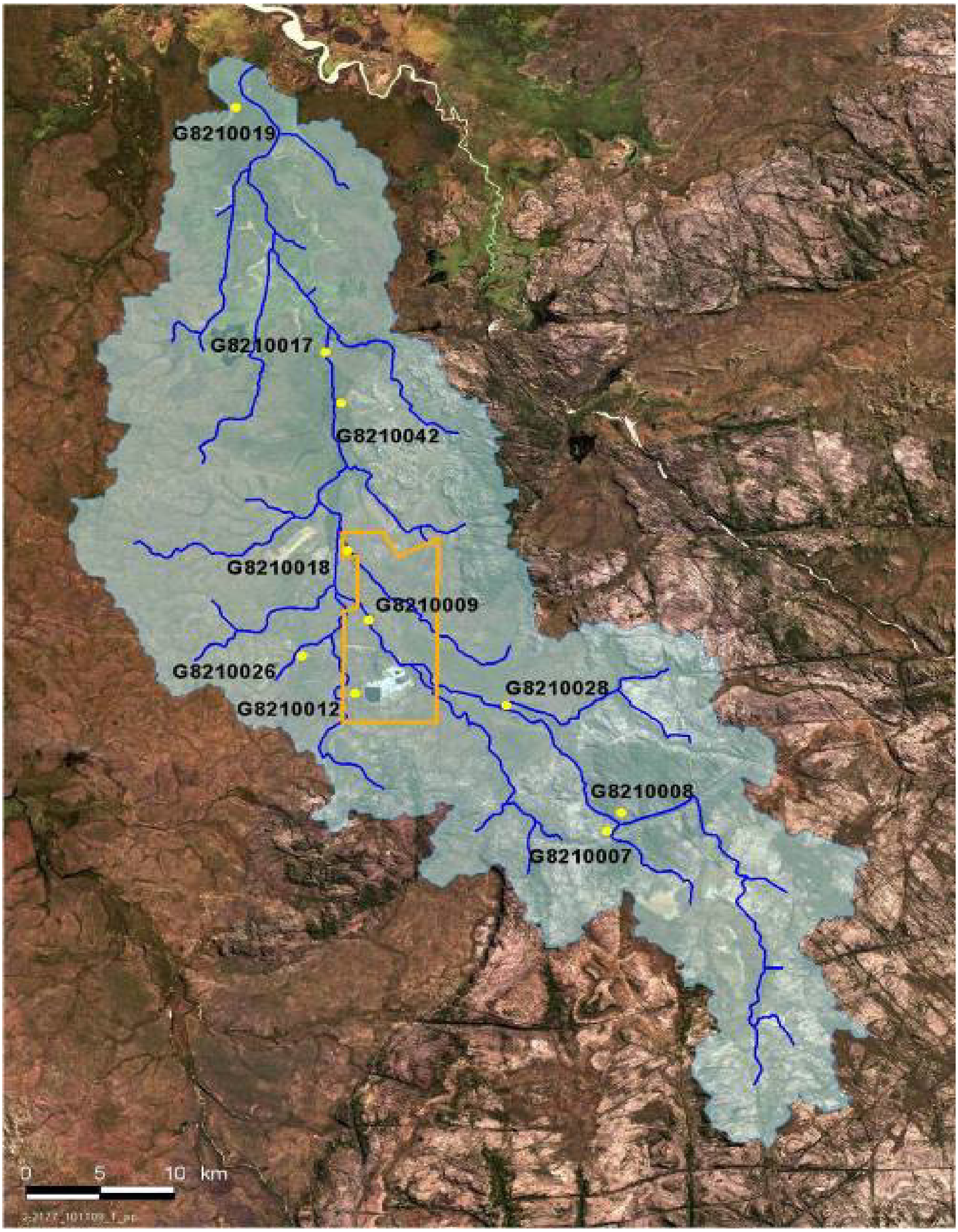


Figure 5-67: Magela catchment showing government agency gauging stations

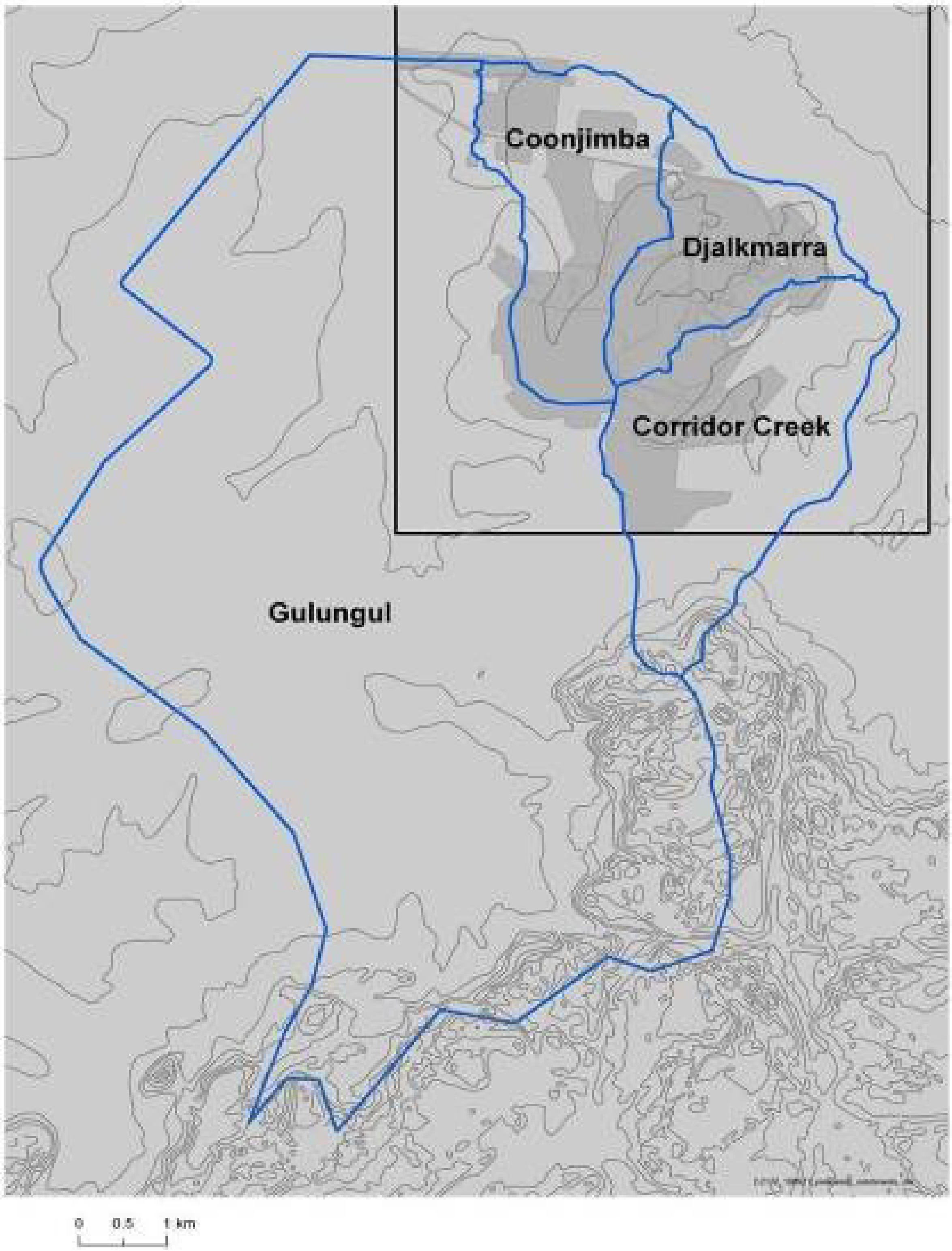


Figure 5-68: Pre-mining catchments in relation to the Ranger Mine

5.2.5.3 Surface Water Modelling

The site vegetation will mature over the decades and merge into the surrounding natural environment following the creation of the post-mine final landform. However, the solute sources related to the operation and closure of the mine site will lead to the gradual release of a range of COPCs into the environment.

To assist the planning and supporting the approval required for rehabilitation activities, Water Solutions were engaged in 2017 by ERA to develop an independent surface water model which predicts the concentrations of COPCs in receiving surface waters. The objective of the model is to providing estimates of the concentrations of nominated COPCs over a period of 10,000 years following the rehabilitation of the mine.

The model was configured, calibrated, updated and validated over the years, incorporating newly available field data and stakeholder's feedback. The final Ranger Surface Water Model (RSWM) is a composite model consisted of:

- Hydrology components:
  - Fifteen sub-catchments (Figure 5-69 and Figure 5-70) subjecting to 131 years of SILO database daily rainfall estimates and normalised evaporation
  - Creeks and billabongs projected to geometry characteristics as model nodes
  - Reach transmission losses and channel losses
  - Channel routing using WBNM
- Solute loads for 21 COPCs:
  - Calibrated natural catchment loads
  - Operational loads
  - Site solute loads derived from groundwater-surface water interaction studies.

The hydrological behaviour of the preliminary configured model was validated by undergoing flow calibration, to achieve a reasonable fit to recorded stream flow from gauging stations and billabong levels during wet season. Conceptual elements, i.e. channel loss, was configured into the model for realistic representation of the natural flow conditions under the wet-dry tropics. Billabong geometries had been reviewed and updated with new surveys and observations as a key step to calibrate the billabongs to match the behaviour during the recession flow.

The model was further calibrated for water quality under natural (no-mine) scenario to define the runoff quality from the natural landscape without the mine influence. Different conceptual model composition was applied to replicate the natural behaviour for each COPC, including Flat Concentration, First Flow, First Event, Exhaustion, Flat Load, and Flow vs Concentration correlation. It should be noted that due to the nature of available data, some of the calibrations were poor and a numerical goodness of fit was not possible for the modelled

COPCs and locations. Table 5-26 and Table 5-27 presents the final calibrated parameters for natural catchment COPC loads.

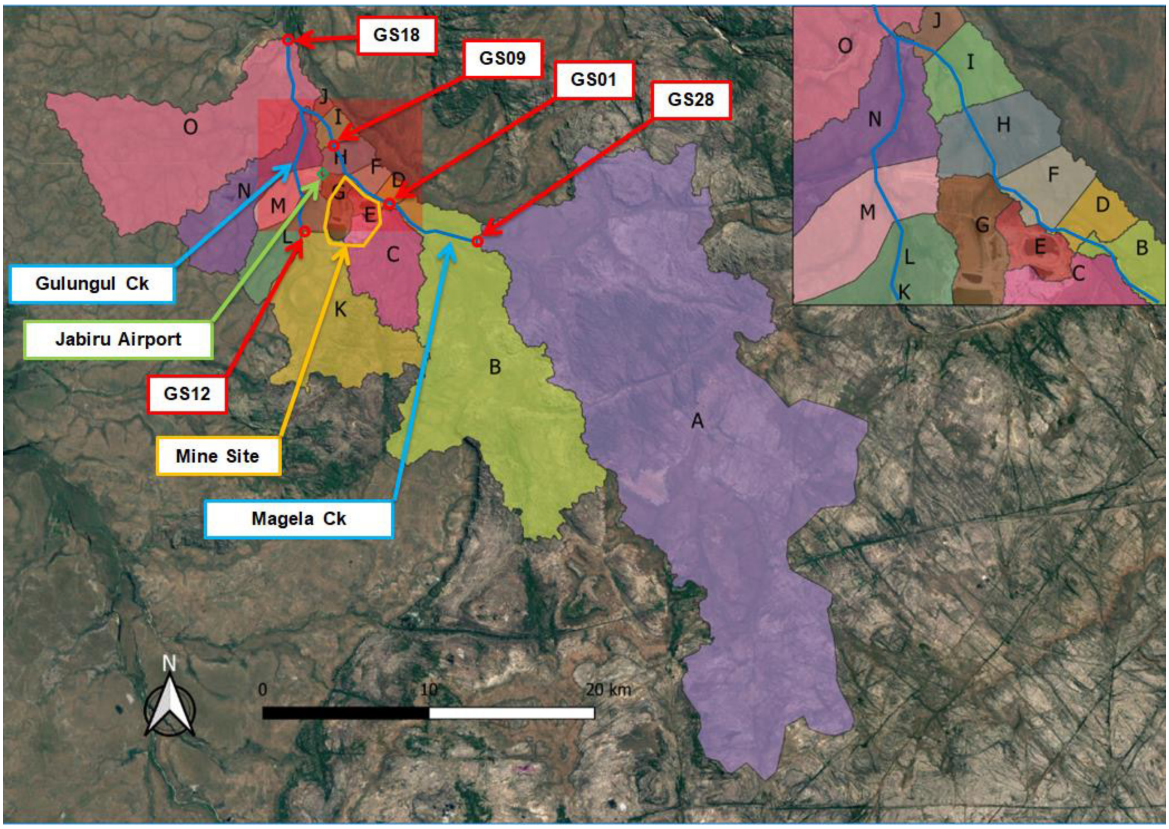


Figure 5-69: Surface water model catchment configuration and site features

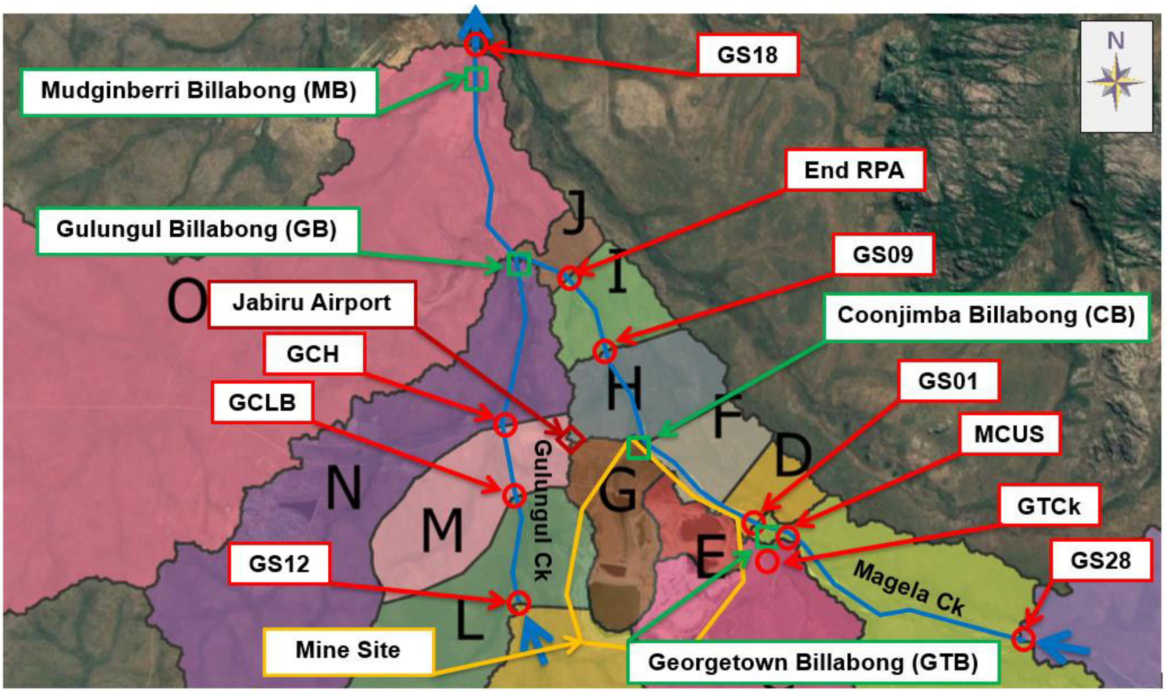


Figure 5-70: Surface water model sub catchments, billabongs, site features and key reporting nodes

Table 5-26: Natural catchment runoff water quality relationship parameters

COPC Description		Relationships Used and Parameters
Name	Symbol	
Magnesium	Mg	• Flat Concentration: 0.2 mg/L • Flat Load: 7.3 g/d/ha
Calcium	Ca	• Flat Concentration: 0.15 mg/L • Flat Load: 5.0 g/d/ha
Nitrate	NO3-N	• Flat Concentration: 3E-3 mg/L • First Flow: 0.197 mg/L
Manganese	Mn	• Flat Concentration: 4.5E-3 mg/L • Exhaustion: 0.01 mg/L, end day 167 (mid Feb)[7]
Uranium	U	• Exhaustion: 4E-5 mg/L, end day 365 (end Aug)
Ammoniacal Nitrogen	NH3-N	• Flat Concentration: 5E-3 mg/L • First Flow: 1E-3 mg/L
Orthophosphate	PO4-P	• Flat Concentration: 2.5E-3 mg/L • First Flow: 12.5E-3 mg/L
Copper	Cu	• Flat Concentration: 2E-4 mg/L
Lead	Pb	• Flat Concentration: 2.5E-5 mg/L
Cadmium	Cd	• Flat Concentration: 2.5E-5 mg/L
Iron	Fe	• Flat Concentration: 0.1 mg/L • First Flow: 0.18 mg/L
Zinc	Zn	• Flat Concentration: 4E-4 mg/L
Chromium	Cr	• Flat Concentration: 3E-4 mg/L
Vanadium	V	• Flat Concentration: 3.5E-4 mg/L • First Flow: 1E-4 mg/L
Nickel	Ni	• Flat Concentration: 1E-3 mg/L
Radium	Ra	• Flat Concentration: 60E-12 mg/L • First Event: 120E-12 mg/L
Polonium	Po	• Flat Concentration: 0.031E-12 mg/L • First Event: 0.037E-12 mg/L
Aluminium	Al	• Flat Concentration: 0.02 mg/L • Exhaustion: 0.07 mg/L, end day 242 (end Apr)
Selenium	Se	• Flat Concentration: 1E-4 mg/L • First Flow: 3E-5 mg/L
Sulfate	SO4	• Flat Concentration: 0.05 mg/L • Exhaustion: 0.85 mg/L, end date 197 (mid Mar)
Total Suspended Solids	TSS	• Exhaustion: 1.5 mg/L, end day 365 (end Aug) • Flow v Concentration, see Table 5.3.

Table 5-27: Flow vs Concentration correlation for TSS

Flow (ML/d)	TSS Concentration (mg/L)
0	0
1.0E+02	0
1.0E+03	1
1.0E+04	5
1.0E+05	35
1.0E+06	50
1.0E+07	50

Operational and closure influence quantified as site loadings were then introduced into the validated model to simulate solute concentrations in the areas of interest. Site loads during closure are configured according to the different scenarios of interest derived from the groundwater solute transport model. Four closure scenarios were modelled in the RSWM, the three peak load cases and the 10,000 year all combined watershed case using the 50% probability values (P50) for base simulations. The four arch-scenarios are modelled as:

- AWP (All watersheds peak scenario) – the peak loading case for locations downstream of the Gulungul Creek junction with Magela Creek, and also (as Gulungul Creek loads are relatively small) for sites between Coonjimba Creek Junction and Gulungul Creek Junction.
- GTP (Peak Scenario for the Corridor Creek) – the peak loading case for the Georgetown Billabong output location
- CJP (Peak Scenario for the Coonjimba and Gulungul Creek) – the peak loading case for tributary inflows to Coonjimba Billabong
- A10k (All watersheds, 10,000 year scenario) – indication of the impacts of the rehabilitated site on creek water quality at the 10,000 year time horizon

An additional Mg:Ca sub-scenario has been simulated to assist the understanding of the actual toxicity of Magnesium in relation to Calcium.

RSWM reports time-series of simulated concentration of COPCs under 131 years of climate record for each reporting node. A sample of plotted simulated results at End EPA node under all arch-scenario for Magnesium is shown in Figure 5-71. More site-specific scenarios will be configured into the RSWM to provided key reference for COPC risk as closure activity progresses.

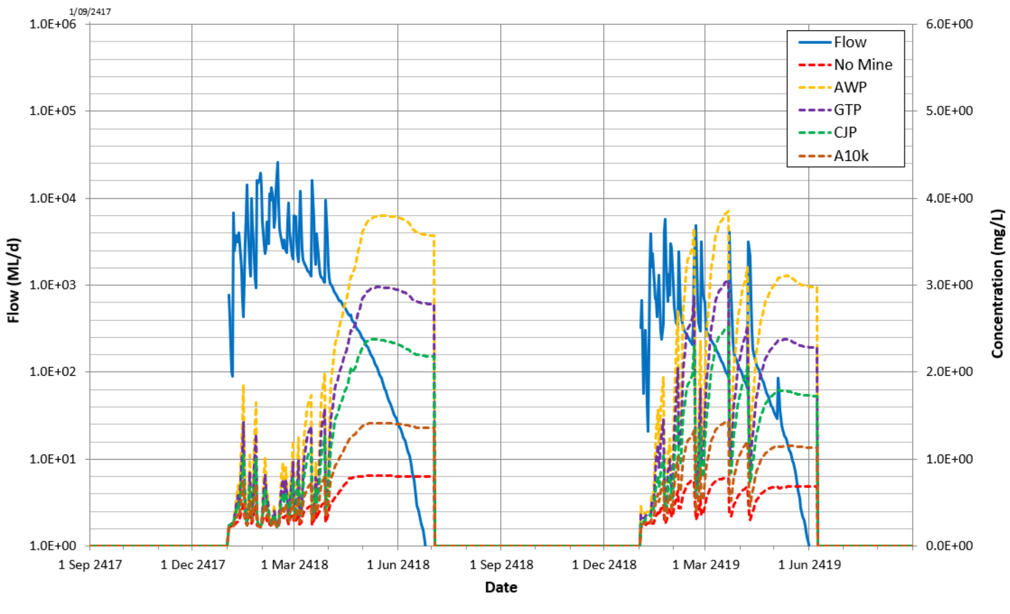


Figure 5-71: Sample of simulated model results

Additional uncertainty analysis was done on key model parameters or model mechanism (rainfall, annual groundwater site loads magnitude, daily load disaggregation method, concentration buffers) to assess the sensitivity of the model. The following sensitivity assessment has been made:

- Rainfall changes will result in more significant change of runoff particularly at downstream sites as expected, e.g. a 10% reduction of rainfall leads to 23-29% decrease in mean annul flow and a 7-19% increase of mean daily COPC concentration while a 10% increase of rainfall leads to 23-32% flow increase and a 5-13% concentration decrease. Note that more cautious needs to be taken for rainfall-related climate change assessment.

- P10 and P90 annual load was applied to compared with the P50 annual load from base case. A similar percentage change of concentration vs. annual load has shown as expected. It demonstrated that by applying various range of annual load from groundwater model output will result in a -31% to +39% difference in COPC concentrations.

- The change of End Flow for daily load disaggregation method varied to 8ML/d AND 16ML/day resulted in very limited 1% change of mean daily concentration at downstream sites.

- The removal of concentration buffering (as a conceptual component simulating stream bed sand) in the first flush storage node impacted the COPC concentration behaviour significantly throughout a wet season particularly at the further downstream sites. More studies had been recommended to assess the effect of sand bed buffering.

ARRTC has endorsed the RSWM at the May 2022 meeting. Future studies for surface water risk based on the methodology developed has been proposed. No additional KKN-related research is planned to be undertaken for the further development of the current tool. ERA will now use the tool to assess scenarios for closure planning (including climate change) and to inform future regulatory applications.

5.2.6 WS5 Determining the impact of contaminated sediments on aquatic biodiversity and ecosystem health

KKN title	Question
WS5. Determining the impact of contaminated sediments on aquatic biodiversity and ecosystem health	WS5A *Will contaminants in sediments result in biological impacts, including the effects of acid sulfate sediments?*

5.2.6.1 Background

Aquatic sediments at Ranger Mine and the Magela catchment have been studied since the late 1970s. This includes research projects as well as a routine monitoring to understand metal concentrations and bio-geochemical pathways, spatial distribution (vertically and within and between catchments), changes over time, and potential bioavailability.

1970 – 2001

A number of studies of sediment quality from billabongs along the Magela Floodplain were carried out in the late 1970's and early 1980's. The earlier work was done by Pancontinental in 1978 and 1979 as baseline studies, but did not include uranium data (Pancontinental, 1981).

Johnston and Milnes (2007) list a number of reports from the 1980s that assessed the fate of chemical species with respect to deposition as sediment and quantities stored in floodplain sediments and described the physico-chemical properties of sediments in billabongs. They describe the geochemical behaviour of sediments and their interactions with water and the use of sediment monitoring as a method for early detection of potential ecological effects.

Jones et al. (2001) collected sediment samples from the Magela Creek Floodplain billabongs in November and December 1997, at the end of the dry season as part of the Jabiluka baseline data collection.

Monitoring of sediments in selected billabongs on and adjoining the RPA formed part of the regulatory framework governing the authority to operate between 1981 and 2002. In 2002, the Supervising Authorities accepted a recommendation (Milnes et al. 2002) to cease the prescriptive statutory routine monitoring which they said was not a good basis for assessment of environmental protection. Instead, performance-based monitoring using a project based approach was to be undertaken.

Iles and Klessa (2010) provides a characterisation of sediments in billabongs on and off the Ranger site, based on a review of literature and a comprehensive summary of all the sediment data from Ranger wetlands and billabongs, collected by ERA from 1981 to 2002. Uranium was confirmed as the contaminant of concern. The uranium concentrations in Coonjimba, Gulungul and Mudginberri Billabongs were similar throughout this period, with an increase in concentration in Coonjimba Billabong from 1999.

2003 – 2015

Performance-based monitoring of the sediments in RP1, Georgetown Billabong (GTB) and the RP1 and CCWLF constructed wetland filters was undertaken by ERA in 2003 – 2006 to assess the current status of those sediments, in terms of spatial and temporal distribution of contaminants.

The results are reported in Iles et al. 2010 who describe the metal concentrations and relationships in surface and core sediments for different digestion methods and compares the measured concentrations in both to earlier data and to sediment quality guidelines. Based on total and bioavailable U concentrations in the surface sediments the ecological risk associated with the sediments at the onsite water bodies was ranked (from highest to lowest) as RP1 wetland filter > CCWLF > RP1 > GTB ≈ Coonjimba.

The Supervising Scientist conducted a sediment sampling and analysis program from billabongs in the Alligator Rivers Region in 2007, 2011 and 2013. The three data sets had comparable sampling and analysis methods and were designed to assess the different sampling, sediment fractions, and extraction methods. Results are reported in Parry 2016.

In 2013 an Independent Surface Water Working Group (ISWWG) was established by ERA and the Gundjeihmi Aboriginal Corporation (GAC) to review surface water management and monitoring at Ranger. Hart and Taylor (2013a) reported that the Traditional Owners were concerned that sediments were no longer routinely monitored and recommended that a sediment monitoring program be reintroduced to:

> *"…reliably evaluate possible adverse environmental impacts during the operational phase of the mine, while providing benchmark data to detect possible impacts after closure."*

2015 – 2020

To address the ISWWG recommendations, Parry (2016) reviewed past sediment studies, data and monitoring guidelines to:

- Identify, collate and document the available information.
- Design a sediment monitoring program that could identify mine related changes in sediment.
- Assess if any such changes had occurred.
- Provide a pre-closure baseline dataset.

Parry (2016) reported:

The historic dataset includes results from a variety of methods but are still useful with statistical analyses demonstrating comparable results. Analysis of the data sets showed the overall metal concentrations generally follow the order: nitric/perchloric (63 μm) > reverse aqua regia (63 μm) greater than 1 Molar HCl (63 μm) > nitric/perchloric (whole) > reverse aqua regia (whole) > 1 Molar HCl (whole).

Whilst the data sets from these variable sources could not readily be normalised, a consistent data set was identified from the ERA monitoring program and analysed using principal coordinate analysis. The principal coordinate analysis showed that for the majority of years Georgetown, Coonjimba, Gulungul and Djalkmarra billabongs (excluding radium-226) had similar compositions, with Mudginberri Billabong separated by higher concentrations of zinc and manganese, non-Ranger Mine sources. The results from this analysis demonstrated that with suitable data bases this type of statistical analysis can be used to determine any patterns of change spatially and/or temporally.

Jones et al (2001) 1997 sediment U data represents one of the best background sediment data sets, albeit based on the <63 μm fraction. It also demonstrated no change in metal concentrations in the floodplain billabongs since 1977-78.

The Supervising Scientist billabong sediment sampling in 2007, 2011 and 2013 provides a robust data set, especially for control water bodies in the Magela Creek and Nourlangie Creek catchments. The data clearly shows the distinction between on-site (within the Ranger

Project Area) water bodies and unimpacted off-site (outside the Ranger Project Area) water bodies. The 2013 Control Billabongs' data had lower concentrations than in the historic Mudginberri Billabong dataset.

Assessment of all available sediment data from 1982 to 2013 (ERA and Supervising Scientist) showed the following order of billabongs in terms of uranium concentrations: Mudginberri = Gulungul < Coonjimba ≈ Georgetown.

Sinclair (2015) showed that uranium, thorium and metal concentrations in the majority of the Ranger surface samples and sediment cores were low and comparable with concentrations at other creeks within the Alligator Rivers Region.

Lead isotope ratios showed sediments from Georgetown Billabong and the Gulungul Creek tributary in close proximity to the TSF, and to a much smaller degree the younger sections of the MCDS (Magela Creek downstream) core contain some mine derived material. This demonstrated the usefulness of the isotope method for determining the source of erosion products being transported albeit at low concentrations (equivalent to only about 1.1 mg/kg of lead at MCDS).

The Supervising Scientists biological monitoring program provides an indirect assessment of any potential sediment impacts.

Determination of uranium and radium levels in mussels from Mudginberri Billabong has shown consistently low levels with lack of any increase in concentration of U and analysis of isotope ratios in mussel tissues through time (2000 to present) indicating absence of any mining influence on the water and sediment in Mudginberri Billabong[10].

The biological monitoring results from 1988 to present across multiple sites in the Magela catchment have shown that biological communities (fish and macroinvertebrates) have not been adversely impacted as would be expected if sediments were adversely impacted.

Parry (2016) concluded that sediment concentrations in billabongs off the RPA had not increased due to mining and recommended a routine sampling and analyses program based on leading practice.

The recommendations, agreed to by a stakeholder working group, were trialled in 2015 and implemented and refined in 2016. The billabongs sampled in 2016 were Wirnmuyr, and Buba (control sites), Gulungul (exposed site), and Coonjimba and Georgetown (potentially mine affected). Corndorl (a control site) and Mudginberri Billabongs were not able to be sampled due to early rains. However, as noted above the SSB mussel monitoring program indicates the absence of any mining influence on the water and sediment in Mudginberri Billabong.

Esslemont and Iles (2017) compared the metal concentrations at these billabongs with historic data and used stable lead isotope ratios, principal component analysis, and associations with iron and aluminium to interpret the results. The updated dataset was also used to derive background concentrations for metals in sediment based the 80th, 95th and

[10] Concentrations of other metals in mussels from Mudginberri Billabong were also reported to be low and between 5 – 100 times lower than national food standards in the SSB Annual Report for 2014.

99.7th percentiles of data from un-impacted sites (control and un-impacted exposed sites, and data from potentially impacted sites prior to any identifiable change shown by time series data for each site). This follows the approach to derive background concentrations in Magela and Gulungul Creek waters (Turner et al. 2016). Regional background sediment concentrations based on this information are shown in Table 5-28.

Table 5-28: Regional background values and datasets

Element (mg/kg dry wt. <0.63mm)	**Percentiles**				**Data sets**
	50	**80**	**95**	**99.7**	
Copper	29	37	43	55	Metal concentration data from non mine-affected sediments were evenly represented from the billabongs, and percentiles developed from the pooled data.
Lead	21	30	40	68	
Zinc	18	27	41	73	
Manganese	84	119	174	247	
Uranium	6	9	20	25	

Based on 12 samples from Buba (2007-16), Wirnmuyurr (2007-16), Corndorl (2007-13), Coonjimba (pre 1999), Georgetown (pre 1999), Gulungul (pre 1999), and Mudginberri (pre 1999; Cu, Pb, U only)

Esslemont and Iles (2017) compared the 2016 and previous sediment-bound metal concentrations against the derived background dataset, national sediment quality guideline values or the site specific uranium guideline value derived by the SSB.

In general, sediment concentration in 2016 were generally below the sediment quality guideline values, or historical concentrations, in billabongs where sediment guidelines were lacking except for Buba Billabong.

Concentrations of metals had not increased in sediments in the offsite billabongs in the Magela catchment with concentrations within natural variation (at the low end of the range). Comparisons with historical data show that sediment concentrations of manganese were the lowest, and uranium close to the lowest, recorded for all sites except Buba Billabong.

All uranium concentrations were well below the site-specific guideline value of 94 µg/kg developed by the SSB, with the highest values for 2016 at Georgetown Billabong being less than one fifth of this and Buba Billabong being less than a tenth of this value.

Copper, lead and zinc concentrations in billabong sediments were below the national sediment quality guideline values, and with the exception of one zinc result in Buba Billabong were low relative to historical concentrations. Historical concentrations were consistently below the sediment quality guideline high values (SQG-H), and usually below the sediment quality guideline values (SQGV). As such the results show these are not metals of concern.

Elevated uranium, zinc and manganese concentrations at Buba Billabong, a control billabong not in the Magela Catchment, were not related to mining operation. However, understanding the reasons behind these elevations can help to determine if elevations that may occur at a mine exposed site in future are mining related. The associations of these metals with iron and aluminium were reviewed along with principal component and stable lead isotope analysis. These analyses showed these elevated concentrations are a result of natural accumulation of uranium with iron and aluminium oxides in alluvium, and a possible localised weathering anomaly (hydromorphic anomaly) of manganese and zinc.

Coonjimba Billabong data from the late dry season in 2015 showed some high uranium concentrations compared with historic data, in contrast with 2016 data that showed low concentrations compared with historic data. The 2015 conditions allowed aquatic sediments to be sampled from the dry central channel of the billabong which is usually submerged. In 2016 sediments were collected from the wetted edge of the billabong when the billabong still contained a substantial volume of water, and consequently samples were collected from a relatively high position up the bank and more similar to historic sampling locations. Therefore during 2015, there was a larger dataset and more spatial variation represented from across the billabong than in 2016, and the 2015 dataset identified replicate samples with concentrations above the control range as well as replicate samples with concentrations below the control range.

The 2015 dataset from Coonjimba identified that leachable (1M HCl) sediment-bound uranium concentrations within 460 meters of the RP1 release point were higher than background concentrations derived by Parry (2016), and total uranium concentrations in the billabong channel were in excess of ambient associations with bog-iron and aluminium oxides. Lead isotope ratios from 2016 and 2015 showed that uraniferous (206/207Pb) and thoriferous (208/207Pb) signatures of the sub-clay (<63 µm) sediment fraction were consistent with sediment from a uranium mineralised source. However, the thoriferous (208/207Pb) signature of the sub-sand (<2mm) sediment fraction in 2016 indicated that sand from a non-mineralised source had also contributed to the samples. As such the 2015 Coonjimba Billabong samples contained sediment from a mineralised source mixed with sediment from a non-mineralised source.

In summary the spatial variation of the sediment samples within Coonjimba Billabong are consistent with potential sources of sediment from the minesite, which had mixed with sediment from non-mineralised sources. This is expected to be observed during mine operation in a billabong located within a kilometre of the RP1 release point.

2020 onward

In collaboration with the Supervising Scientist Branch and subject matter experts, a review of historical data, best practice analytical methods and knowledge gaps culminated in the development of a memo (Iles 2020) and Sampling, Analysis and Quality Plan (SAQP) (ERA 2020) that detailed the rationale for further targeted assessments for ASS, metal(loid)s and radionuclides.

ASS exist extensively within the Magela Plain and the general lowland surrounds of the Ranger Uranium Mine (Willet 2008). As part of closure planning, consideration of environmental risks posed by naturally occurring and potentially mine-influenced ASS has led to the development of a preliminary site-wide conceptual model for ASS and risk assessment framework (ERM 2020a). The conceptual model was developed using the structure shown in Figure 5-72, with section references as in ERM 2020a. There are three key constituents that contribute to the potential formation of ASS: the potential water-logged conditions, elevated sulfate concentration (≥10 mg/L), and sufficient organic matter to establish the chemically reducing environment. Although considerable historical studies of ASS exists, a number of key knowledge gaps remained in relation to the characterisation of ASS conditions as they relate to closure.

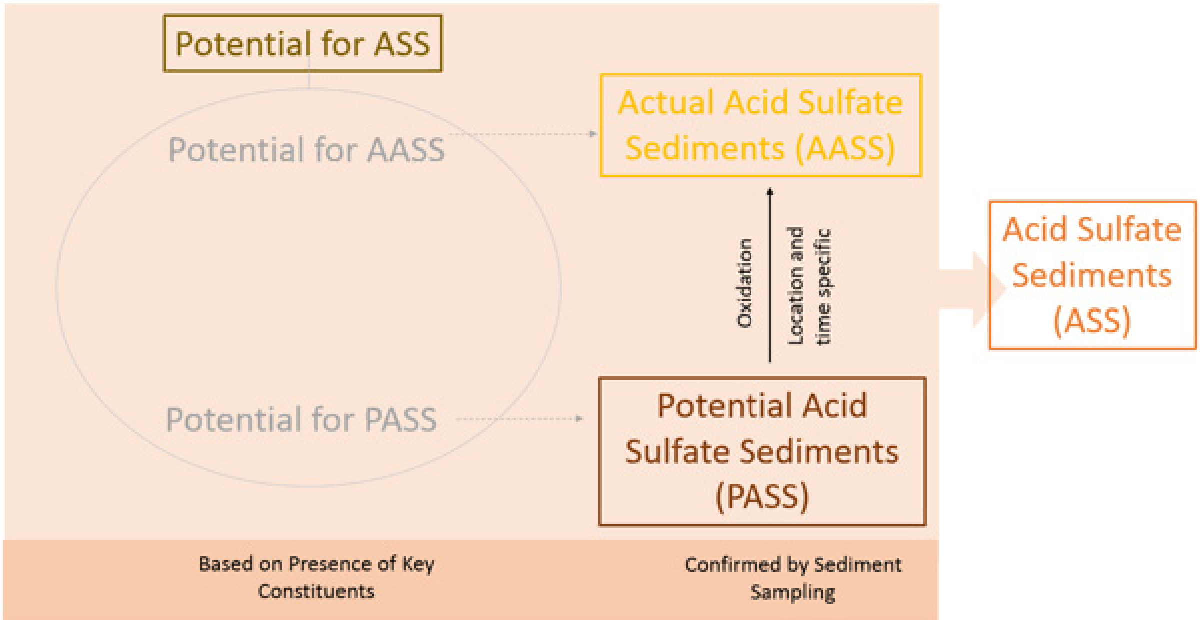


Figure 5-72: ASS terminologies (Source: ERM 2020a)

A total of sixty-three sediment samples were collected and analysed from nine sites within and downstream of the RPA; Indium Billabong, GCMBL, Sleepy Cod, Djalkmarra Release Point (DJKRP), Gulungul Billabong, Georgetown Creek Tributary 2 (GCT2), RP1, Mudginberri Billabong and GTB. Sampling was conducted over two campaigns; the first in the dry season (9-13 November 2020) and the second in the wet season (2-5 February 2021).

Samples were selectively analysed for ASS, metal(loid)s and radionuclides. The sample design and analytical methods were informed by specialist and stakeholder input and review and agreed to by the SSB. ARRTC was provided with the SAQP (ERA 2020) in November 2020.

ASS was confirmed in at least one or more samples at all sites assessed for ASS, totalling fifty positive samples. Monosulfidic Black Ooze (MBO) was identified in four of eleven samples within RP1 and one sample within GTB.

Metal and radionuclide concentrations were investigated at all sites except GCT2, with a total of 48 samples collected. This analysis builds on the previous investigations into metals in sediments that was conducted by Esslemont and Iles (2017) and others prior.

Due to laboratory error, all samples collected were initially analysed for metals on the < 63 µm sediment fraction using a weak aqua regia (WAR) digest, rather than the nitric/perchloric digest as was proposed in the SAQP (ERA, 2020) and was used to develop the regional background values (Esslemont & Iles, 2017). This error was identified at the end of the program, however where remaining sample was available, samples were re-analysed using the nitric/perchloric digest on the < 63 µm fraction to enable a comparison to historical trends and the RBVs.

The results and interpretation of this target investigation program is currently under stakeholder review and will be detailed in future iterations of the MCP.

Based on the results of the conceptual model and field assessments, a risk assessment of domains across the minesite is completed in the form of a water pathways risk assessment to understand the future ASS occurrences/persistence in the billabongs (Section 5.2.2) This will also inform the requirement of location-specific conceptual site models which will in turn inform the closure management plan. If the risk assessment indicates sulfate in water needs to be reduced or ASS sediments treated, trial mitigations and remediation options will be investigated.

5.2.7 WS6 Determining the impact of nutrients in surface water on biodiversity and ecosystem health

KKN title	Question
WS6. Determining the impact of nutrients in surface water on biodiversity and ecosystem health	WS6B *Can Annual Additional Load Limits (AALL) be used to inform ammonia closure criteria?*
	WS6C *Will the total load of nutrients (N and P) to surface waters cause eutrophication?*

There are three major sources of trace metals and nutrients to the Magela Creek system: natural (rainwater and pristine catchment), the Ranger uranium mining operation, and the Jabiru township (Hart *et al* 1986b).

The sources of nutrients at Ranger to the water management system are from; waste rock, ammonia and phosphate (in lime) added to the mill process circuit, residual nitrates from blast residue in waste rock, and fertiliser application. These sources result in the following different water quality profiles for nutrients:

- ammonia is high in process water but not pond or release water
- nitrate levels are negligible, moderate and lo in process, pond and release waters respectively
- phosphate is low in all waters

Currently ERA must comply with Annual Additional Load Limits (AALL) for the discharge of NO_3-N (4.4 t/a) and PO_4-P (2.8 t/a) to Magela Creek and with NH_3-N concentration limits in Magela Creek. The load limits were set in the 1980s (Brown *et al*. 1985). No load limit was set for ammonia; only a concentration limit was set as it was considered to pose a toxicological, rather than an eutrophication risk.

The risk from nutrients has been low during the operational phase as waters are segregated and treated before directing to the release water circuit. Following closure the nutrient profile and the potential to reach the surface waters on and downstream of the mine are different to that during the operational phase.

- In relation to nitrogen forms, *ammonia* will be present in high concentrations in tailings and concentrated brine contained in the mine pit voids. Ammonia may be mobilised under certain conditions and leach from the buried tailings and brine, entering surrounding surface water through groundwater egress. Waste rock is known to be a major source for *nitrate* due to N in blast residues on the waste rock. Although this is expected to wash out in a short time, it may also reach receiving waters through direct wet season runoff or through groundwater egress associated with rainfall infiltration of the waste rock landform cover and leaching.
- Waste rock is also known to be a source for *phosphate-P*. It may also reach receiving waters at mine closure through the same mechanisms as for nitrate above.

Concentrations of ammonia, nitrate and phosphate entering the surface water environment after closure are being predicted through solute transport modelling. The risk of eutrophication after closure needs to be assessed by comparing predicted post closure concentrations of nutrients to relevant thresholds. Default guideline values for northern Australia (ANZG 2018) are not appropriate as they are lower than the concentrations that occur locally. Load limits for nitrate and phosphate were developed for the Ranger mine in the mid 1980s but not for ammonia.

KKN WS6B focussed on reviewing the current load limits for nutrients and WS6C focusses on identifying concentrations of nutrients that cause eutrophication in the Magela system.

KKN WS6b asks two questions regarding nutrients:

- Are the current AALLs for nutrients still relevant?
- Can ammonia loads be considered in the same context?

A literature review by ERA found that between 1984 and 1986, the Supervising Scientist, through the Alligator Rivers Region Research Institute, developed water quality standards for release of water from Ranger mine to protect the broad downstream receiving environment (i.e. Mudginberri corridor and Magela floodplains) and people who sourced food from these environments (Brown *et al.* 1985). AALL and allowable concentrations were derived for a number of stressors including AALL and concentration limits for nitrate and phosphate, and concentration limits only for ammonia.

The standards are reported in Brown *et al.* (1985) together with a brief summary of the derivation process. More detail on the derivation and basis of the standards is available in Office of the Supervising Scientist (2002). The basis for the nitrogen-N and phosphorus-P AALL was listed in these reports as “ecological” (Table 5-29). The discussion of risks reveals the aim of the AALLs was to prevent eutrophication. For ammonia, a concentration limit was set to protect against toxicity, but it was not considered a stressor for eutrophication and so no AALL was set.

Table 5-29: Nutrient limits (concentrations or loads) from Brown et al. (1985)

Constituent	**unit**	**Magela Creek mean (or limit)**	**Basis**
Concentrations			
Molecular NH3 (as -N)	mg/L	(0.02)	Toxicological
Nitrate/nitrite (as -N)	mg/L	10	Drinking water
Phosphate (as -P04)	mg/L	0.01	Statistical
Additional Load			
Phosphate (as -P)	t/a	2.8	Ecological
Nitrate (as -N)	t/a	4.4	Ecological

Neither Brown *et al*. (1985) nor Office of the Supervising Scientist (2002) provide further detail on how the N and P AALL were derived except to refer to it being the subject of another study. Personal communications with Dr. Arthur Johnston (former Supervising Scientist) and Professor Barry Hart (former consultant to the Supervising Scientist) indicated the basis was the natural loads measured in Magela Creek in the mid-1980s (published values in Hart *et al.* (1986a, 1987a)).

A review of the literature shows the AALL are approximately the same as the natural loads in Magela Creek passing the Ranger minesite in the 1982-83 wet season, as reported in Hart *et al.* (1986a, 1987a) (Table 5-30). Allowing the same amount to be added to the creeks is effectively doubling the natural loads.

The "ecological" basis identified for loads (Brown *et al.* 1985) appears to be a misnomer with the limit based on change to natural loads rather than biological-effects information. Prevention of biological effects is the preferred approach to deriving water quality criteria for ecosystem protection (ANZG 2018). Even as reference-based limits, the data used to calculate AALLs were based on just one wet season which is not a robust statistical basis for guideline derivations (ANZG 2018).

In addition, the loads in Magela Creek passing the minesite and reporting to the downstream environment are not relevant to protecting Gulungul Billabong which the stakeholder water and sediment working group identified as the highest post-closure risk receptor.

Table 5-30: AALL for nitrate and phosphate compared to loads added to the Magela Creek in rainwater and transported to the flood plain by Magela Creek; load and (error)

Parameter	Rain water	Creek water	AALL	Relationship between 1982/83 loads and AALL
NO3–N (t/a)	60a 36 (51)b	5.1 a 5.1 (3.9) b	4.4 Nitrate as N	AALL is similar to natural load, effectively allowing a doubling of natural loads to the creek system.
Total-P (t/a)	30a 14 (32)b	0.91a 1.0 (1.2)b	2.8 Phosphate	0.91 t P = 2.8 t of PO4. Doubling of natural load allowed.

a – Hart *et al.* 1986a
b – Hart *et al.* 1987a

In summary:

- The current AALLs for nitrate and phosphate are based on a limited reference dataset and have limited relevance as a guideline for preventing eutrophication, particularly in Gulungul Billabong.
- An ammonia AALL should not be derived using the same approach used for the existing nitrate and phosphate limits.
- Biological effects information, which is more relevant to understanding eutrophication risks, is addressed in a separate KKN (WS6c).
- Stakeholders and the ARRTC agreed that the current AALL are not suitable for closure criteria, and that KKN WS6b can be closed because biological effects-based approaches for deriving water quality criteria have superseded the AALL philosophy and methods, and work is underway under KKN WS 6C to derive nutrient thresholds based on local biological effects.

KKN WS6C addresses a key step in assessing eutrophication risks by determining thresholds of nutrient concentrations that define different trophic states (or levels of enrichment) of primary producers in Ranger receiving waterbodies. SSB, with input from ERA, is undertaking a study to determine threshold concentrations, the approaches have the following focus:

- Consideration of all potential ecosystem receptors, i.e. sand creek channels, backflow billabongs (e.g. Gulungul) and channel billabongs (e.g. Mudginberri).
- Inclusion of all potential primary producers (ecological receptors), i.e. phytoplankton, attached algae and larger aquatic plants (or ‘macrophytes’), and the contribution of nutrients in sediments as sources of internal loading.

- Application of a site-specific, biological-effects based, approach – consistent with ANZG (2018) – to derive nutrient thresholds associated with change in trophic status of the different primary producer groups
- Identification of suitable nutrients and associated biological response data to derive biological-effects thresholds.

This study is in an advanced stage. Progress reports have been provided to ARRTC and a report detailing the findings is in preparation. The report will undergo peer review and is expected to be provided to ARRTC ahead of the November 2021 meeting. In lieu of finalised and agreed threshold values, interim values were provided to ERA to use in the water pathways risk assessment project.

5.3 Radiation theme

5.3.1 Background

5.3.1.1 Terrestrial baseline radiation

The pre-mining radiological conditions for the Ranger Mine have been investigated and reported by the Supervising Scientist (Bollhöfer *et al*. 2014). The study was based on pre-mining aerial surveys, with extensive ground measurements to provide calibration of the final external gamma radiation dose rates. Ground measurements taken for soil radon concentrations and radon exhalation rates were then correlated to the airborne gamma results to obtain averages for the area. The summary of results from this study is provided in Table 5-31.

Table 5-31: Pre-mining radiological baseline determined by the Supervising Scientist (Bollhöfer et al., 2014)

Location	Average gamma dose rate ($\mu Gy\ h^{-1}$) *	Average radium concentration ($Bq\ kg^{-1}$) *	Average radon exhalation ($Bq\ m^{-2}\ s^{-1}$) *
Pit 1	0.87 ± 0.18	1,880 ± 430	2.7 ± 0.8
Pit 3	0.44 ± 0.09	880 ± 200	1.3 ± 0.4
Djalkmarra land application area	0.20 ± 0.03	310 ± 70	0.46 ± 0.14
Corridor Creek land application area	0.14 ± 0.02	170 ± 40	0.25 ± 0.08
TSF	0.11 ± 0.01	110 ± 30	0.16 ± 0.05
Magela land application area	0.12 ± 0.01	110 ± 30	0.17 ± 0.05
RP1	0.11 ± 0.01	90 ± 20	0.14 ± 0.04
RP1 land application area	0.11 ± 0.01	90 ± 20	0.13 ± 0.04
Jabiru East land	0.10 ± 0.01	90 ± 20	0.13 ± 0.04

Location	Average gamma dose rate ($\mu Gy\ h^{-1}$) *	Average radium concentration ($Bq\ kg^{-1}$) *	Average radon exhalation ($Bq\ m^{-2}\ s^{-1}$) *
application area			
Jabiru	0.11 ± 0.01	90 ± 20	0.14 ± 0.04
Ranger Project Area	0.11 ± 0.01	110 ± 20	0.15 ± 0.05
* ± 95% confidence			

The results show that the average external gamma dose rate in areas removed from uranium mineralisation ranges between 0.10 and 0.20 microgray per hour, with the overall average for the RPA being 0.11 microgray per hour. Dose rates above the orebodies were, as expected, much higher, reaching an average of 0.87 microgray per hour above Pit 1.

Similar patterns to the gamma dose rates were observed for both average soil radium concentrations and average radon exhalation. Average radium concentrations over the orebodies (880 – 1,800 Becquerels (Bq)/kg) were much higher than for the surrounding area (110 Bq/kg), as were the average radon flux densities over the orebodies (1.3 -2.7 Bq/kg per square metre per second) relative to the surrounding area (0.15 Bq per square metre per second).

5.3.1.2 Aquatic baseline radiation

The RPA contains three distinct regional HLU zones which are described in KKN WS2. The derivation of the background threshold values for uranium and radium is discussed in KKN WS1. The results for uranium and radium groundwater background threshold values (discussed in KKN WS1) are presented in Table 5-32.

Table 5-32: Calculated BTVs for HLUs and Analytes in the Background Evaluation where data sufficiency requirements were met, ERM (2020)

Analyte	Unit	Shallow Bedrock Cahill	Deep Weathered Cahill	Shallow Weathered Cahill	Shallow Bedrock Nanambu	Deep Weathered Nanambu	Shallow Weathered Nanambu	MBL Zone (UMS subunit)
Radium	mBq/L	130	50	27.3[a]	130[a]	90	30	37.3[a]
Uranium	ug/L	7.74	21.9	3.03	5.76	5.7	3.37	1.92

[a] Although Radium is a primary COPC, the background evaluation did not indicate this was the case for the Shallow Weathered Cahill, Shallow Bedrock Nanambu and MBL Zone.

Notes:

Greyed out BTVs are for analytes that are not COPCs in that HLU.

Radionuclide concentrations in Magela Creek, upstream of the Ranger Mine, are routinely monitored throughout the wet season by both ERA and the SSB. Water quality at this location is considered to be unaffected by mining and therefore representative of baseline conditions. The statistical results of Magela Creek upstream monitoring conducted by ERA for the 2010 to 2014 wet seasons are presented in Table 5-33.

Table 5-33: Magela Creek upstream radionuclide concentrations (2010 – 2014 average)

Magela Creek upstream	Total radium-226 (mBq/L)	Total uranium (mBq/L)
Average	2.1	0.70
Minimum	1.2	0.16
Maximum	4.0	2.6
Standard deviation	0.9	0.48

5.3.1.3 Bushfood baseline radiation

Radiation work to date has focused on radiation exposure of people living a traditional lifestyle in the area, and downstream of the RPA, along with radiation exposure of plants and animals inside and downstream of the RPA. This work has included extensive monitoring to determine pre-mining, area-wide radiological conditions, as a first step to assessing post-mining changes and the success of rehabilitation from a radiological perspective (e.g. Bollhöfer et al. 2014, Bollhöfer et al. 2011, Esparon et al. 2009)

Aboriginal people living a traditional lifestyle in Kakadu NP consume bush foods that contain natural background concentrations of radionuclides. A summary of the available data on the uptake of radionuclides into aquatic and terrestrial foodstuffs was completed by ERISS and published in its annual research summary (Ryan et al. 2009).

A model diet for local Aboriginal people was obtained from the following sources:

- a questionnaire developed by ERISS and distributed to local Aboriginal people in 2006
- information provided by a local supplier of meats to Aboriginal outstations, and
- data gained from ERISS Kakadu bush food project over the last 11 years.

ERISS collated all available data on radionuclide activity concentrations in bush foods (from natural sources) and used this to determine a baseline radiation dose to Aboriginal people living in the region from ingestion of foodstuffs of 0.84 mSv/year. This radiation dose is irrespective of the mining activity and reflects the natural state for Aboriginal people living in Kakadu NP.

ERISS has compiled this data, along with more recently collected information, into a database (Doering 2013). The database can be used to determine bush food concentration ratios, from which the ingestion dose from various parameter inputs and a variety of situations can be calculated (Ryan et al. 2011). The database contains more than 1,500 individual records of radionuclide activity concentrations in various plants, animal tissues and environmental media. All information in the database has associated geospatial information to allow for spatial analysis. ERISS has also developed a bush foods geospatial information system called the "bushtucker database" (Walden 2011). This contains 30 years of data on radionuclide concentrations in traditional bush foods and is available to the public.

A summary of radionuclide concentrations published by ERISS for key flora and fauna of the Alligator Rivers Region is provided in Table 5-34 (Bollhöfer et al. 2011, Martin & Ryan 2004, Ryan et al. 2009, Ryan et al. 2005). Since completion of the baseline data assessment ERISS have since published updated radionuclide activity concentrations (Doering and Bollhöfer, 2016b, Doering et al., 2017). This data will be used in any further radiation dose assessments.

Table 5-34: Radionuclide concentrations in local bush foods

Bush food	Radionuclide activity concentrations (mBq g^{-1} fresh weight)[1]		
	Uranium	Radium	Lead
Wallaby flesh[2]	0.025	1.9	0.7
Magpie goose[3]	0.004	0.03	0.05
Mussels[1, 4]	2.7 – 7.6	450 – 2,500	360 – 800
Turtle flesh[2]	0.007	0.16	0.098
Fish[2]	0.005 – 0.085	0.22 – 3.5	0.043 – 0.20
File snake[2]	0.021	0.031	0.037
Cheeky yams[3]	0.06	0.26	0.042
Various fruits[5]	0.020 - 0.028	0.26 – 71	0.042 – 11
Water lily[2]	0.96	5.1	4.3

Notes:

[1] Mussels from Mudginberri Billabong, data provided are dry weights; [2] Source (Ryan *et al*. 2009);

[3] Source (Martin & Ryan 2004); [4] Source (Bollhöfer *et al*. 2011); [5] Source (Ryan *et al*. 2005)

5.3.2 RAD1A, RAD2A, RAD6E, RAD7A, RAD7B, RAD8A, RAD9A, RAD9C, RAD9D

KKN title	Question
RAD1. Radionuclides in the rehabilitated site	RAD1A. *What are the activity concentrations of uranium and actinium series radionuclides in the rehabilitated site, including waste rock, tailings and land application areas?*
RAD2. Radionuclides in aquatic ecosystems	RAD2A. *What are the above-background activity concentrations of uranium and actinium series radionuclides in surface water and sediment?*
RAD6. Radiation dose to wildlife	RAD6E. *What is the sensitivity of model parameters on the assessed radiation doses to wildlife?*
RAD7. Radiation dose to the public	RAD7A. *What is the above-background radiation dose to the public from all exposure pathways traceable to the rehabilitated site?*
	RAD7B. *What is the sensitivity of model parameters on the assessed doses to the public?*
RAD8. Impacts of contaminants on wildlife	RAD8A. *Will contaminant concentrations in surface water (including creeks, billabongs and seeps) pose a risk of chronic or acute impacts to terrestrial wildlife?*
RAD9. Impacts of contaminants on human health	RAD9A *What are the contaminants of potential concern to human health from the rehabilitated site?*
	RAD9C. *What are the concentrations of contaminants in drinking water sources?*

KKN title	Question
	RAD9D. *What is the dietary exposure of, and toxicity risk to, a member of the public associated with all contaminant sources, and is this within relevant Australian and/or international guidelines?*

The Ranger radiological impact assessment, required to assess the radiological impact to members of public and terrestrial and aquatic wildlife is in progress with information on the methodology followed in the section below. This impact assessment will address all the above mentioned KKNs under the reposnsibility of ERA.

5.3.2.1 Atmospheric dispersion modelling

All concentrations considered were above naturally occurring background levels. These incremental post closure levels were determined via source modelling as outlined below.

Atmospheric dispersion modelling of radon and particulate matter for post-closure conditions was completed in 2018 (SLR 2018a). This modelling included:

- meteorological modelling using the weather research and forecast model, and CALMET models to compile a three-dimensional meteorological dataset for the study domain
- emission estimation of radon from waste rock covered areas and the LAAs, based on radon flux rate information provided by ERA, with estimation of particulate emissions performed using published emission factors for wind erosion (DSEWPC 2012)
- dispersion modelling of the downwind dispersion of estimated emissions of particulate matter and radon using the CALPUFF dispersion model

For this study the meteorological data inputs have been compiled using the Weather Research and Forecast (WRF) and CALMET meteorological models. The meteorological dataset used in the modelling (based on the calendar year 2016) was validated by comparing key variables with the available measured data recorded at the nearest meteorological station, located at Jabiru Airport.

Radon and particulate emissions from the LAAs and waste rock area were modelled as ground level area sources based on the following emission rates:

- the radon emission rate provided by ERA for use in the modelling study was 0.5 Bq/m^2/s for both the Ranger Mine footprint (waste rock areas) and the LAAs
- the total suspended particulates (TSP) emissions from the waste rock area and LAAs were modelled based on an uncontrolled emission rate of 0.4 kg/ha/hour and the following control factors to account for the reduction in dust emissions that may be expected from increasing ground cover (trees, grasses, leaf litter etc) in the years following closure of the Ranger Mine:
    - scenario 1 – immediately post-closure

- scenario 2 – 100 years post-closure.

In addition to control factors accounting for vegetation growth, the modelling also investigated the sensitivity of the modelling results to the effects of rainfall, which will act to suppress dust emissions. This was done by assuming that no emissions occurred on days with greater than 5 mm rain, based on data recorded at Jabiru Airport during 2016 (i.e. during the same meteorological year used in the modelling).

A concentration of 630 Bq/kg for radionuclides in the U-238 decay chain, contained within deposited dust was used in the terrestrial assessment. This concentration was not expected to change significantly over time.

5.3.2.2 Radiological Impact Assessment

ERA has engaged JRHC Enterprises Pty Ltd to complete an impact assessment of the radiation related impacts to the public and non-human biota following the closure of the ERA Ranger Uranium Mine.

The following radiation exposure pathways were considered to determine the radiological impacts of the closure of the Ranger Mine on human and non-human biota:

- incremental radon concentrations
- gamma radiation levels
- radionuclide concentrations in dust
- environmental radionuclide concentrations

The method for assessing potential impacts varies depending on the exposure pathways. Table 5-355 provides an overview of the human exposure assessment methods for the different exposure pathways.

Table 5-35 Exposure estimation methods *(JRHC in draft)*

Exposure Pathway	**Assessment Method**
Gamma radiation	From first principles and based on changes in the substrate natural radionuclide concentrations.
Inhalation of radionuclides in dust	From air quality modelling results (section 5.3.2.1) based on predicted dust emission rates post closure.
Inhalation of radon decay products (also known as RnDP)	From air quality modelling results (section 5.3.2.1) based on predicted radon emission rates post closure.
Ingestion of radionuclides	Based on deposition of radionuclides into the environment from air quality modelling and estimates of water solute transfer.

The predicted concentrations of radionuclides above natural background levels will be considered for Mudginberri, Coonjimba, Georgetown and Gulungul billabongs for the peak surface water concentration timeframes. Future occupancy intentions and the bushfood diet discussed in Section 8 and Paulka (2016) plays an integral role in the calculation of the predicted radiation doses post closure.

For non-human biota, the ERICA assessment software tool (http://www.erica-tool.com/) is utilised. The impact to specific terrestrial and aquatic species is based on changes in radionuclide concentrations of the media within which the species resides. The impacts to biota will be assessed using these incremental concentration changes and the ERICA assessment software tool (http://www.erica-tool.com/).

Post-closure guidance values have been developed to provide radiological protection to terrestrial and freshwater aquatic species (Doering & Bollhöfer 2016, Doering *et al*. 2019). The guidance values will be compared to the predicted changes in media concentrations for above background concentrations of Ra-226. An update to the surface water modelling is underway (WS3) and the new predicted changes will be updated in the radiological impact assessment.

Progress on the radiological impact assessment is currently halted due to the update to the surface water modelling currently underway (WS3) as the concentrations inform the assessment.

5.4 Ecosystem rehabilitation theme

5.4.1 ESR1. Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the minesite, including Kakadu National Park

KKN title	Question
ESR1. Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the minesite, including Kakadu National Park.	ESR1A. *What are the compositional and structural characteristics of the terrestrial vegetation (including seasonally inundated savanna) in natural ecosystems adjacent to the mine site, how do they vary spatially and temporally, and what are the factors that contribute to this variation?*

5.4.1.1 Background

Bioregions for the Australian continent have been created as part of a national classification of ecosystems. There are currently 89 bioregions and 419 sub-regions in Australia. Each region is based on similarities in climate, geology, landform, native vegetation and species information. Most of the RPA lies within the northeast section of the 28,520 km2 Pine Creek Bioregion. Features of the Pine Creek Bioregion include:

- a landscape broadly consisting of hilly to rugged ridges with undulating plains;
- vegetation communities that include eucalypt woodland, with patches of monsoon forest;

- major land uses that include conservation, pastoralism, intensive rural freehold blocks, horticulture, mining and indigenous freehold; and
- major population centres at Batchelor, Adelaide River, Pine Creek and Jabiru.

The Pine Creek Bioregion, in the Top End of the NT, comprises hilly ridges with undulating plains within the foothills of the Arnhem Land Massif (ERA 2014b, DNREA 2005). Typical vegetation types consist broadly of tall eucalypt woodlands, dominated by Darwin woollybutt (*Eucalyptus miniata*) and Darwin stringybark (*E. tetrodonta*) with patches of monsoon forests, riparian vegetation and tussock grasslands (DNREA 2005). The bioregion supports a high diversity of flora and fauna, with 279 bird species, 100 reptile species and approximately 2,300 plant taxa recorded in 2005. During the wet season (November to March) approximately 90 % of annual rainfall occurs in this tropical monsoonal bioregion (DEE 2005).

The RPA is surrounded by, but separate from, Kakadu NP, where approximately 1,600 terrestrial and aquatic flora species have been recorded, including 15 species considered rare or threatened (Director of National Parks 2016). No terrestrial or aquatic flora species of conservation significance listed under the *Territory Parks and Wildlife Conservation Act 1978* (NT) (*TPWC Act*) or the *EPBC Act* have been recorded in the RPA.

There are distinct vegetation communities that occur across the RPA. Schodde *et al*. (1987) described four vegetation types, dominated by eucalypt open forest and/or woodland (Figure 5-73 and Figure 5-74). Similarly, Firth (2012) described the main vegetation / habitats on the RPA as comprising of woodland and open forest, mostly co-dominated by *E. tetrodonta* and/or *E miniata*. The RPA is surrounded for the most part by vast unbroken and undeveloped tracts of the same eucalypt woodlands and open forest savannas that cover at least 180,000 km^2 in the NT alone (Woinarski *et al*. 2005). The topography of the RPA is relatively simple and as with vegetation, mirrors that of the region as a whole. The different vegetation types are described below and the area and proportion of each vegetation type on the RPA and in Kakadu NP are given in Table 5-36.

Habitat 1: Myrtle-Pandanus Savanna/Paperbark Forest/Coastal Deciduous Rainforest

Paperbark forests line freshwater creek systems and the edges of billabongs and are dominated by *Melaleuca* spp. The canopy can be 15 to 20 m in height and can vary greatly from open to almost closed. The shrub layer varies from sparse to dense and comprises *Acacia* spp., *Ficus* spp. on marginal areas and the ubiquitous freshwater mangrove *Barringtonia acutangula*. *Pandanus aquaticus* and *B. acutangula* line streams and channels. In zones edging woodland (which is often the case in the RPA), the trees are wider spaced and often form an ecotone with myrtle-pandanus savanna. In this ecotone area eucalypts, bloodwoods and other savanna trees co-dominate with the paperbarks. Coastal deciduous rainforest habitat is not present in the RPA according to the description of Schodde *et al*. (1987).

Habitat 2: Myrtle-Pandanus Savanna

Consists of grassland with small open pockets of woodland, mixed shrubland and rainforest trees, interspersed with strips of Pandanus (*Pandanus spiralis*) along the edges of floodplains and with paperbarks (*Melaleuca* spp.) along creeks and streams. Tall trees from genera such as *Corymbia* and *Eucalyptus* are sparingly present. A very patchy shrub layer of *Melaleuca viridiflora*, *M. nervosa* and *P. spiralis* occur. Common grasses include annuals from genera such as *Digitaria*, *Ectrosia*, *Panicum*, *Schizachyrium* and *Sorghum* and perennial grasses including those from genera such as *Eriachne* and *Themeda*. Sedges (Cyperaceae) are also a common component of the ground cover.

Habitat 3: Open Forest

Tall (12 to 20 m) open forest dominated by *E. miniata* and *E. tetrodonta* and with other species of eucalypts present in the canopy. The only frequent non-eucalypt that occurs in the canopy is Ironwood *Erythrophleum chlorostachys*. The shrub layer consists of *Acacia* spp., *Calytrix exstipulata*, *Gardenia* spp., *Livistona humilis*, *Petalostigma quadriloculare*, *Planchonia careya*, *Terminalia* spp. and *Xanthostemon paradoxus*. Ground cover is usually sparse, inconspicuous and comprises mostly annual grasses of *Sorghum* spp. and other herbaceous plants.

Habitat 4: Woodland

This habitat typically lacks a distinct canopy and is more stunted (usually less than 12 m) than open forest, being dominated by bloodwoods (*Corymbia* spp.), but also contains eucalypts such as *E. miniata*, *E. tetrodonta* and *E. tectifica*. However, it is quite variable in structure and can be tall on slopes to the point where it grades into open forest. The shrub layer is the same as in open forest but much sparser. The palm *L. humilis* is common and pockets of *P. spiralis* may also be present. The ground cover is much denser than in open forest, containing mainly annual grasses, e.g. *Sorghum* spp. In stunted woodlands perennial grasses *Heteropogon triticeus* and *Sehima* sp. dominate.

Table 5-36: Area and proportion of vegetation communities on the RPA and Kakadu NP

Community (Schodde *et al.* 1987)	**RPA[1] (ha)**	**RPA[1] (%)**	**Kakadu NP (ha)**	**Kakadu NP (%)**	**RPA community as a percentage of equivalent habitat in Kakadu NP (by area)**
Myrtle-pandanus savanna/ paperbark/coastal rainforest	434	6	39,487	4	1.1
Myrtle-pandanus savanna	1,863	26	170,802	16	1.1
Open forest	3,018	42	336,269	32	0.9
Woodland	1,870	26	508,000	48	0.4

Note 1 – undisturbed (non-mine) sections only

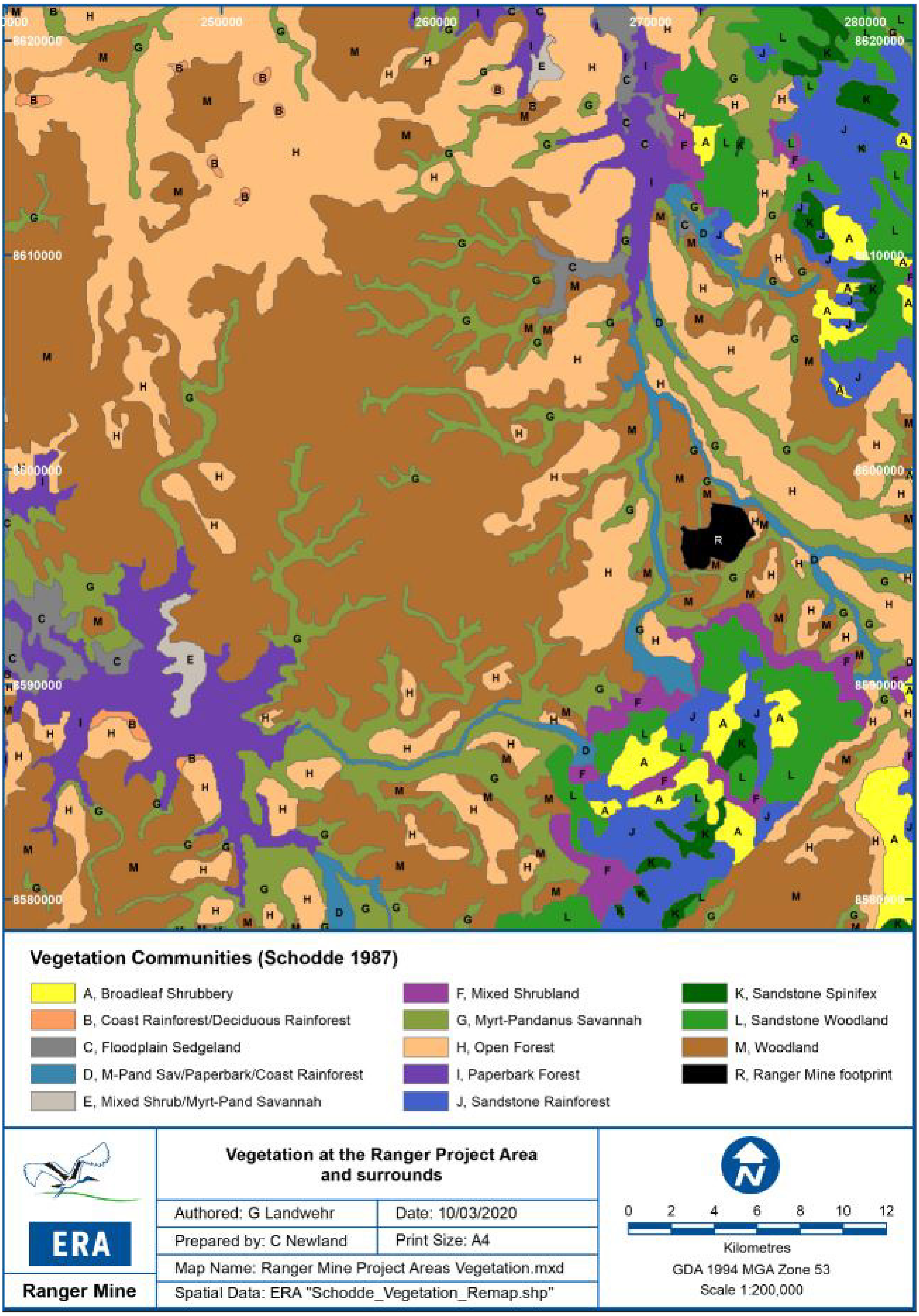


Figure 5-73: Vegetation of the RPA and surrounding Kakadu NP (Schodde *et al*. 1987)

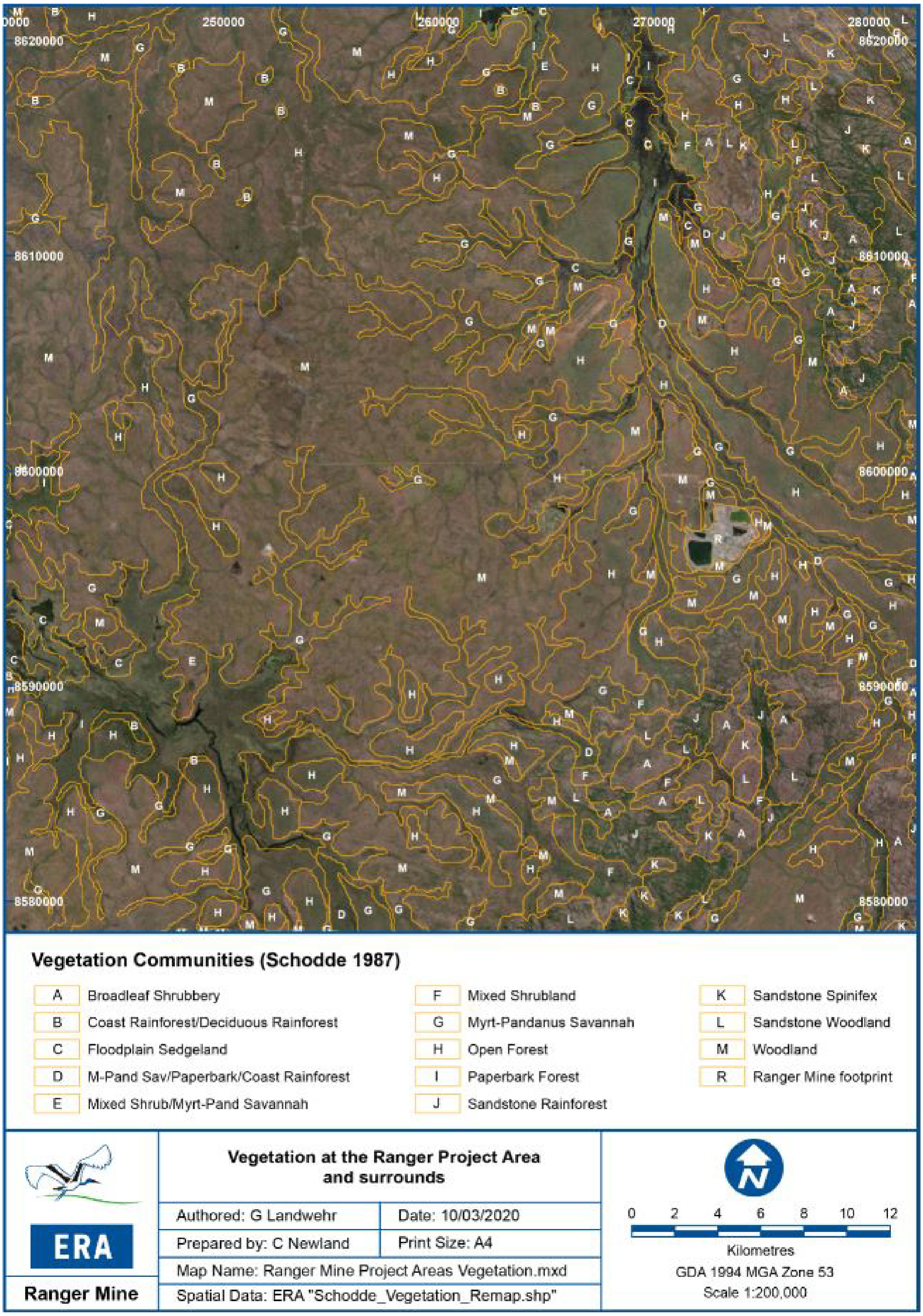


Figure 5-74: Vegetation types over aerial of the RPA and surrounding Kakadu NP

Figure 5-75: Vegetation habitat map (Schodde et al 1987) of the RPA

At the broad scale, the distribution of the more dominant native forest and woodland communities near Ranger in the wet-dry tropics of northern Australia is controlled predominantly by three factors:

- The underlying geomorphology (which influences site hydrological features and soil fertility);
- The seasonality and predictability (inter-annual variability) of climate; and
- The frequency and intensity of fire.

These factors govern the structural complexity (e.g. height, biomass, number of strata, size class distributions, root depth and distribution patterns), species compositions and the functioning of the vegetation (e.g. water use, nutritional uptake, regeneration strategies, and phenology). These are the environmental factors that have moulded (and constrained) the native vegetation, and its responses to disturbances. Within areas with similar climate and fire regime, geomorphology plays the major role in determining vegetation communities. This is reflected in distinctive catenary sequences of forest and woodland vegetation that are found throughout the lowland parts of Kakadu NP (Bowman *et al*. 1988) and is the basis of ‘land system’ and other mapping that has been undertaken in the region (Story *et al*. 1969). However, the way in which individual plant communities have been delineated and classified in these surveys has depended on factors such as the scale of the mapping (1:20,000 to 1:1,000,000) and the particular purpose for which the survey was conducted (e.g. broadscale vegetation description, fire risk management, fauna habitat mapping or mine environmental impact statement).

5.4.1.2 Ecosystem rehabilitation and influence of post-mining conditions

As prescribed in the ERs (Section 8), ERA must establish an environment using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu NP. This will be no mean feat considering the extreme level of disturbance from mining and the dramatically different characteristics of the final landform waste rock substrate compared to natural soils (see KKN ESR7).

Although ERA has demonstrated that the final landform material can support development of a native woodland ecosystem on the Trial Landform (TLF) and other trials (see KKN ESR3), there will likely be a degree of difference in these revegetated ecosystems to those that were there previously. In 2020, ERA produced a technical brief of potential physical and chemical constraints that may influence vegetation suitability (as evidenced by their ability to establish and develop into a sustainable ecosystem), particularly on the waste rock final landform. This brief was reviewed with key stakeholders (May 2020 Ecosystem Restoration Working Group, comprising ERA, SSB, NLC and select ARRTC representatives) and it was agreed that most constraints warranted further consideration as ERA continues to refine the agreed reference ecosystems and related criteria. These potential constraints are summarised below (and discussed in detail in Section ESR7), including:

- material type and relationships to plant water availability, rooting depth and so on;

- surface hydrology and subsurface hydrogeology, including seasonal variations;
- substrate chemical status, including nutrients and contaminants of potential concern; and
- slopes and aspect.

Material type

The key aspects of waste rock impacting vegetation establishment relate to plant water availability (PAW) and rooting depth. The studies relating to PAW are discussed under ESR7.

Waste rock PAW depends on the proportion of fines (<2mm) in the material as well as the total depth available for plant root establishment. For example, Section 1A of the TLF was constructed of material with an average of 33% fines and has been able to successfully establish a range of native overstorey and midstorey species (discussed in Section ESR3 and ESR5). Monitoring of the TLF and WAVES modelling has indicated that a minimum of 15% fines is sufficient to sustain a native woodland ecosystem (Lu et al. 2019). It is understood that material with higher fines will have a greater PAW, act more like a natural 'soil' and be able to support the local, natural woodland ecosystems with fewer adjustments.

Particle size distribution (PSD) analysis of waste rock in stockpiles indicates that the waste rock ranges between 10% - 60% fines. Mine planning and bulk earthworks processes have been developed to ensure that the material to be placed in the surface growth layers (e.g. up to 6 m depth) of the final landform is not below 15% fines and, wherever possible has more fines to optimise PAW.

Except for the backfilled pits and the upper reaches of the final landform, 62% of the final landform has less than 6 m of waste rock overlying natural soils (Table 5-37and Figure 5-76). This means that plants in these areas, particularly larger plants with greater rooting depths, may be able to access any PAW in these soil and possibly have improved plant-water relations in the late dry season when seasonal stresses are greatest. Plants on the other 38% of the final landform will have at least 6m of waste rock rooting depth available which has been modelled as sufficient to sustain a native woodland ecosystem dependent on the fines proportion (eg. minimum 15% fines) (Lu *et al*. 2019).

Surface hydrology and subsurface hydrogeology

The main impact of surface hydrology is in the distribution of basins and drainage features across the integrated final landform (Figure 5-77). A range of suitable vegetation will be required to colonise and stabilise these features, from the drier upper reaches down towards where drainage lines develop into riparian creeks.

Due to differences in hydraulic conductivity of the waste rock of the final landform and the underlying natural soils, modelling indicates that areas around the final landform perimeter may experience extended periods of saturated soils. Although relatively small in areal extent, this scenario would largely preclude the establishment of vegetation of the common regional woodlands which are used to a prolonged dry season each year. Similarly, the nature of the subsurface hydrogeology in the area of the TSF will likely be an influence on what vegetation can establish.

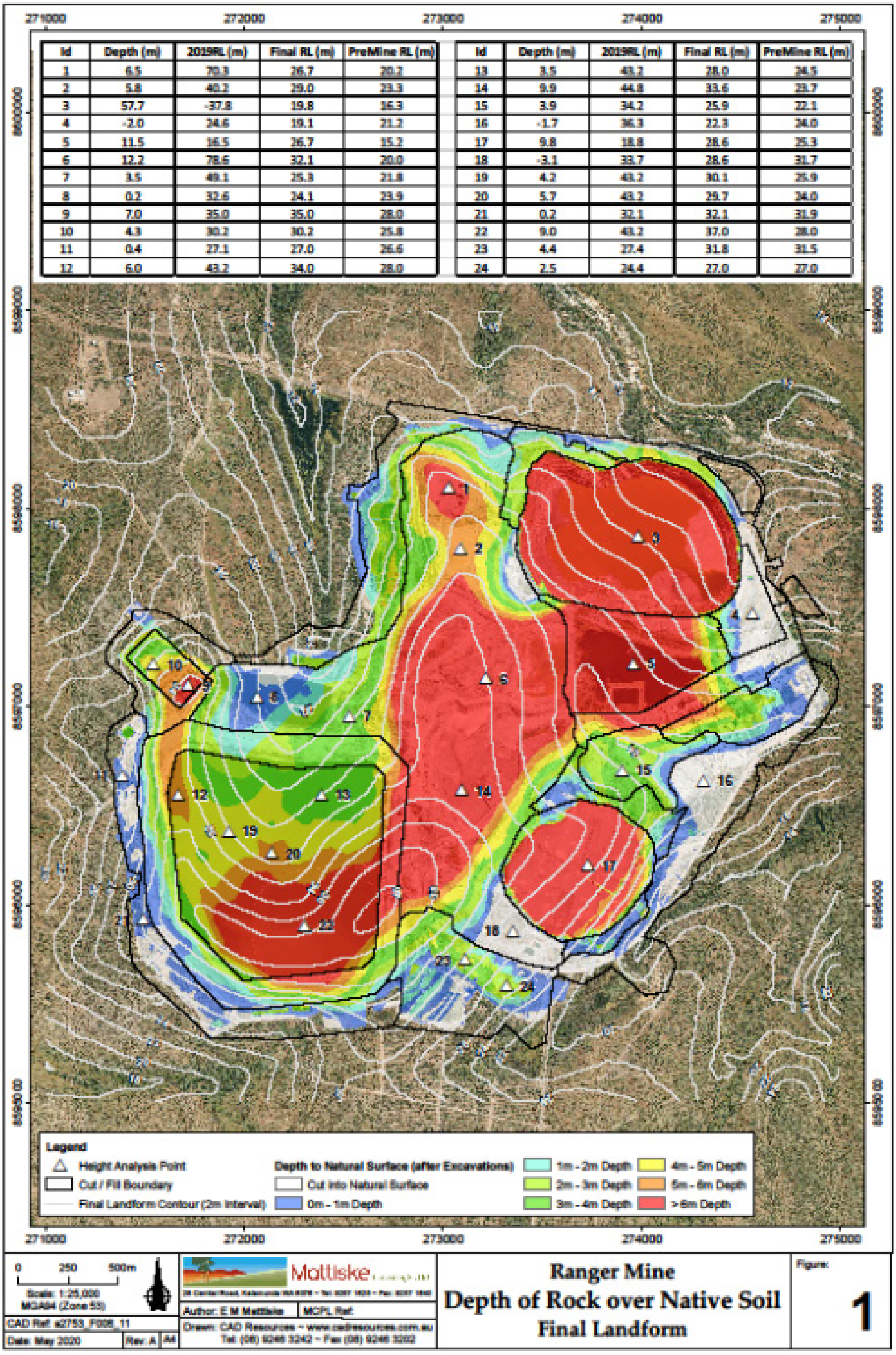
Table 5-37: Approximate depth of waste rock over natural soils (based on 2020 BMM plan)

Depth	Area (ha)
Cut into Natural Surface	65
0 m – 1 m	73
1 m – 2 m	52
2 m – 3 m	59
3 m – 4 m	86
4 m – 5 m	72
5 m – 6 m	57
> 6 m	283
Total	747

Substrate chemical status, including nutrients and contaminants of potential concern

As discussed in the 2018 *Cumulative ecological risk assessment for the rehabilitation and closure of Ranger uranium mine* (Bayliss 2018), chemicals in substrates can play a critical role in revegetation success, including: a limiting nutrient; a toxicant above a threshold effects level; a modifier or facilitator of other chemical processes/interactions; or a combination. Overall, the waste rock material at Ranger Mine differs from natural soils by having higher pH, EC, CEC, Mg, total P and SO4 concentrations, and having lower levels of organic carbon and nitrogen. The ecological risk assessment found that risks to terrestrial revegetation from mine-derived chemicals is assumed zero (Bayliss 2018).

As part of the technical constraints review, it was identified that areas of potential acid sulfate soils (PASS) may be present, particularly in areas requiring future 'riparian' revegetation. Studies into this are ongoing and a specific revegetation strategy, including suitable reference ecosystems, shall be developed if necessary.



Id	Depth (m)	2019RL (m)	Final RL (m)	PreMine RL (m)
1	6.5	70.3	26.7	20.2
2	5.8	40.2	29.0	23.3
3	57.7	-37.8	19.8	16.3
4	-2.0	24.6	19.1	21.2
5	11.5	16.5	26.7	15.2
6	12.2	78.6	32.1	20.0
7	3.5	49.1	25.3	21.8
8	0.2	32.6	24.1	23.9
9	7.0	35.0	35.0	28.0
10	4.3	30.2	30.2	25.8
11	0.4	27.1	27.0	26.6
12	6.0	43.2	34.0	28.0

Id	Depth (m)	2019RL (m)	Final RL (m)	PreMine RL (m)
13	3.5	43.2	28.0	24.5
14	9.9	44.8	33.6	23.7
15	3.9	34.2	25.9	22.1
16	-1.7	36.3	22.3	24.0
17	9.8	18.8	28.6	25.3
18	-3.1	33.7	28.6	31.7
19	4.2	43.2	30.1	25.9
20	5.7	43.2	29.7	24.0
21	0.2	32.1	32.1	31.9
22	9.0	43.2	37.0	28.0
23	4.4	27.4	31.8	31.5
24	2.5	24.4	27.0	27.0

Figure 5-76: Depth of rock over natural soil

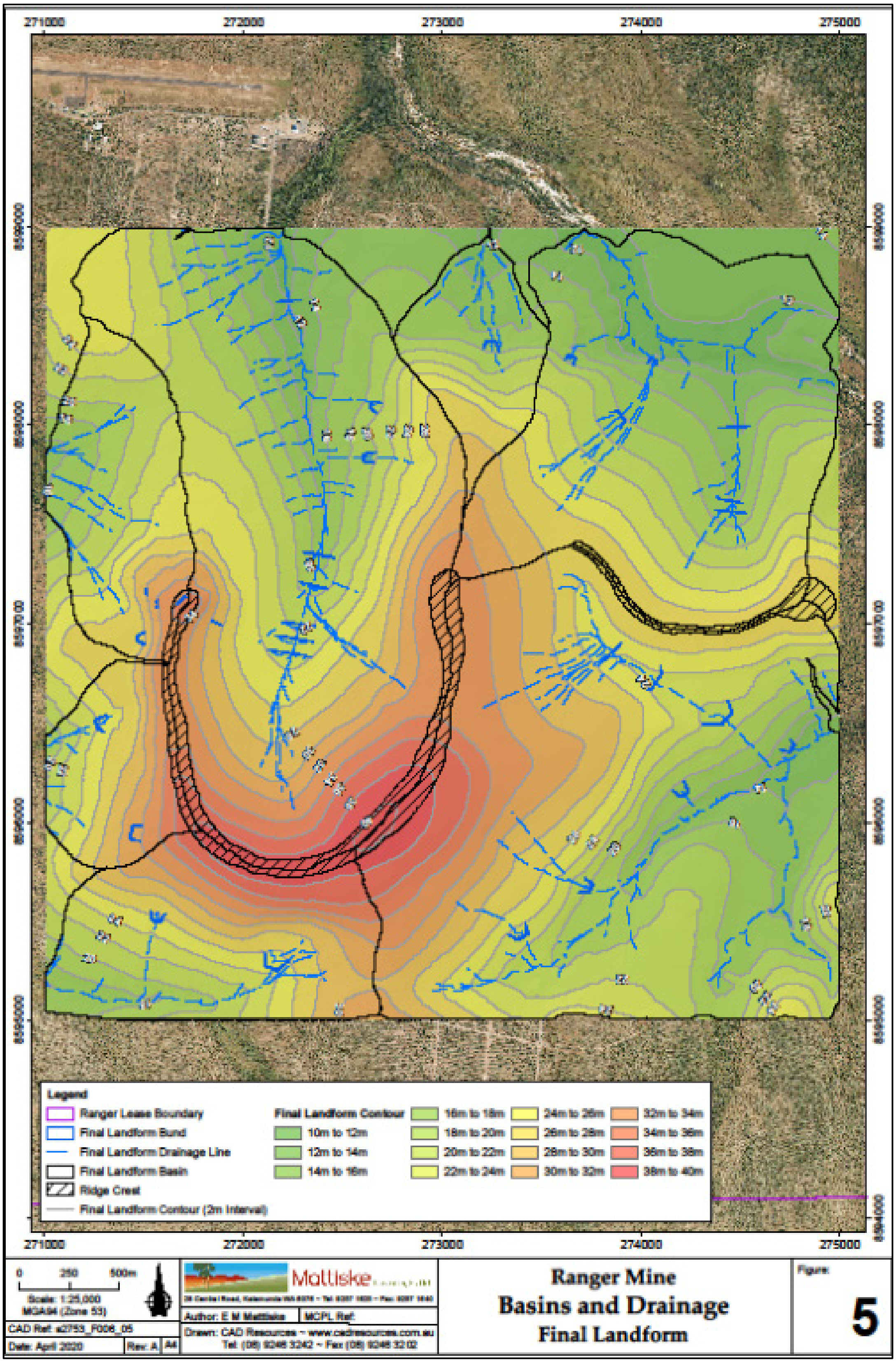


Figure 5-77: Basins and drainage features of the final landform.

Slope and aspect

Whilst slopes and aspects can be significant influences in some mine rehabilitation scenarios, at Ranger Mine almost all slopes are less than 5° and do not require any particularly drastic revegetation treatment. Surface ripping of areas with steeper slopes is allowed for, which should mitigate against any potential erosion risks.

5.4.1.3 RPA and surrounding environment survey history

Part of the Ranger Ecosystem Establishment Strategy has been to identify and describe vegetation types that are ecologically, culturally and technically realistic target endpoints, for different facets of the final landform, based on the likely physical and chemical environments that will be created (Appendix 5.4). The final landform is being designed to resemble, and behave in a manner similar to, landforms of the surrounding area, while still providing for the long-term protection of the environment (refer landform section above). Based on the likely low-rocky rise features of this landform, most research to date has focussed on identifying and characterising natural ecosystems occurring in comparable landscape locations, for use as appropriate reference ecosystems. There is a range of vegetation community types in areas outside the mine footprint that represent the spectrum of environments likely to be found across the rehabilitated final landform and RPA. By understanding the environmental features that are associated with the normal range of native vegetation community types, the conditions required to support these communities and/or the community types that best suit particular environmental conditions of the Ranger Mine final landform, can be identified (Humphrey *et al.* 2009).

There has been substantial surveying and monitoring of the terrestrial flora across the RPA and surrounding Kakadu NP over the past few decades. These were performed to obtain quantitative data on the surrounding environment to inform revegetation planning and management, as well as performance objectives and assessment methods (in terms of closure criteria) (e.g. Hollingsworth and Meek 2003, Brennan 2005, Hollingsworth et al. 2007b, Humphrey 2013, Humphrey & Fox 2010, Humphrey et al. 2009, Humphrey et al. 2011, Humphrey et al. 2008, Humphrey et al. 2012; Table 5-38).

Table 5-38: Vegetation survey data collected in the Alligator Rivers Region (adapted from Erskine *et al.* 2019)

Reference	Sites	Date	Design	Plot size and methods	Plots within 10 km radius of Ranger
Conservation Commission (White *et al.* 1985)	77	1979-1981	Unknown	Vegetation present within 50 m radius of soil sampling site. Understorey not collected	36%
Brennan (2005)	20	1991-1993	Stratified Random	Two assessments based on height >1.5m = Ten 20m x 20m randomly placed in 1ha (4000m^2); <1.5m = 20 x 5m x	35%

Reference	Sites	Date	Design	Plot size and methods	Plots within 10 km radius of Ranger
				5m quadrats (400m^2) 25 understorey (0.71m x 0.71m (12.5m^2)	
EWLS (Hollingsworth & Meek 2003)	20	2002	Stratified Systematic	For trees and shrubs >2m; 320m x 20m plots (total of 1200m^2) at each site stratified by ecosystem types. 10 understorey x 1m x 1m (10m^2)	100%
Cyclone Monica (Saynor *et al.* 2009)	31	2006	Stratified Random	For trees & shrubs >2m 30m x 30m plots (900m^2) Understorey not collected	67%
Hollingsworth *et al*. (2007a)	38	2007	Stratified & mixture of random and systematic	Data from Hollingsworth and Meek (2003) and Brennan (2005)	100%
2010 Survey (Humphrey *et al*. 2012)	54	2010	Stratified Random	For trees & shrubs >2m 20m x 20m plots (400m^2) plots except site A53 (25m x 20m) Understorey not collected	100%
2019-2020 (Supervising Scientist 2019b)	12	2019-2020	Stratified and Random	For Trees and Shrubs: >1.5m , <1.5m on Transects in 1ha. Density of Stems and % Cover Understorey presence absence and cover. SSB S1 to SSB S10 from within 10km radius of the Ranger mine and SSB G1 and SSB G2 from part of the Georgetown area south-east of RPA.	100%

5.4.1.4 Potential substrate factors influencing vegetation community variability

Early work by the Supervising Scientist (Needham *et al*. 1973) and NT Land Conservation Unit (Uren 1992) identified a number of locations in the Alligator Rivers Region as being weathered hills composed of Cahill formation schists – likely to be natural sites where both topography and rock type were similar to that expected on the Ranger final landform. Referencing this work, a later Supervising Scientist study by Brennan (2005) compared vegetation found at areas adjacent to the Ranger site and those further afield (but within Kakadu NP). As Brennan (2005) states:

The concept of site revegetation based on the characteristics of adjacent or pre-existing plant communities has much popular appeal a clear statement of intent to restore disturbed sites to their previous undisturbed state. However, there is a potential problem in applying this concept to guide revegetation on the Ranger Waste Rock Dump (WRD) ... The basis of the problem is that the landform and substrate of the WRD are not related to the pre-existing landforms, or to substrates adjacent to it. The WRD is composed of metamorphic, Cahill-formation schists whereas adjacent substrates belong to a geologically unrelated entity known as the Koolpinyah- surface (Needham et al. 1973, Wells 1979). Given these striking geotopographic differences it seemed reasonable to suggest that native vegetation communities immediately adjacent to the WRD might not contain the most appropriate species for revegetating this area.

There has been a lot of research on what drives community types in the region. A key finding from Brennan (2005) was that floristic heterogeneity (among the hill sites) was due to the dissimilarity of their substrates or parent-rock types. A later study by Humphrey, Fox and Lu (2008) looked at previously surveyed vegetation communities and soil factors associated with sites, including soil chemistry, PSD, soil water retention properties, soil morphology, surface drainage classes and soil permeability. Generally, no relationship was found between underlying soil properties and community composition and structure based on statistical analyses performed (Humphrey et al. 2008). It may be that these contrasting conclusions resulted from difference in scales at which the studies were undertaken.

A review of the drivers of vegetation structure in northern Australian savannas concluded that water availability, particularly during the dry season was the major determinant of tree structure (Cook et al. 2020; Murphy et al. 2015). As part of the long-term Kapalga experiment in Kakadu NP, it was found that soil depth, most likely through the mechanism of water availability during the dry season, is a major driver of tree stand structure, and that evergreen trees increased in basal area as soil depth increased, but deciduous trees showed no significant variation with soil depth (Figure 5-78) (Cook 2021).

Key drivers of vegetation structure in woodland and forest savanna ecosystems are summarised by Cook (2021):

Both fire and water limitations expressed through seasonal water deficits lead to tree death, and this leads to the development of multi-age and multi-size tree stands in the savannas (Cook et al. 2020; Cook et al. 2016). Mortality rates from both causes are greater in woodlands (2.7% per year) than open forests (2.15% per year) (Cook et al. 2020). Larger trees in these systems may be several centuries old. The open forests dominate on deeper loam to sandy loam soils while woodlands dominate on shallower soils with greater water limitations. Fire in these systems has a secondary role compared to that of soil and landscape position. In riparian zones, high water availability can favour fire sensitive species, but frequent fire can greatly reduce the number of woody species along ephemeral streams in the region (Douglas et al. 2003). Further, the density of riparian vegetation is reduced with frequent fires.

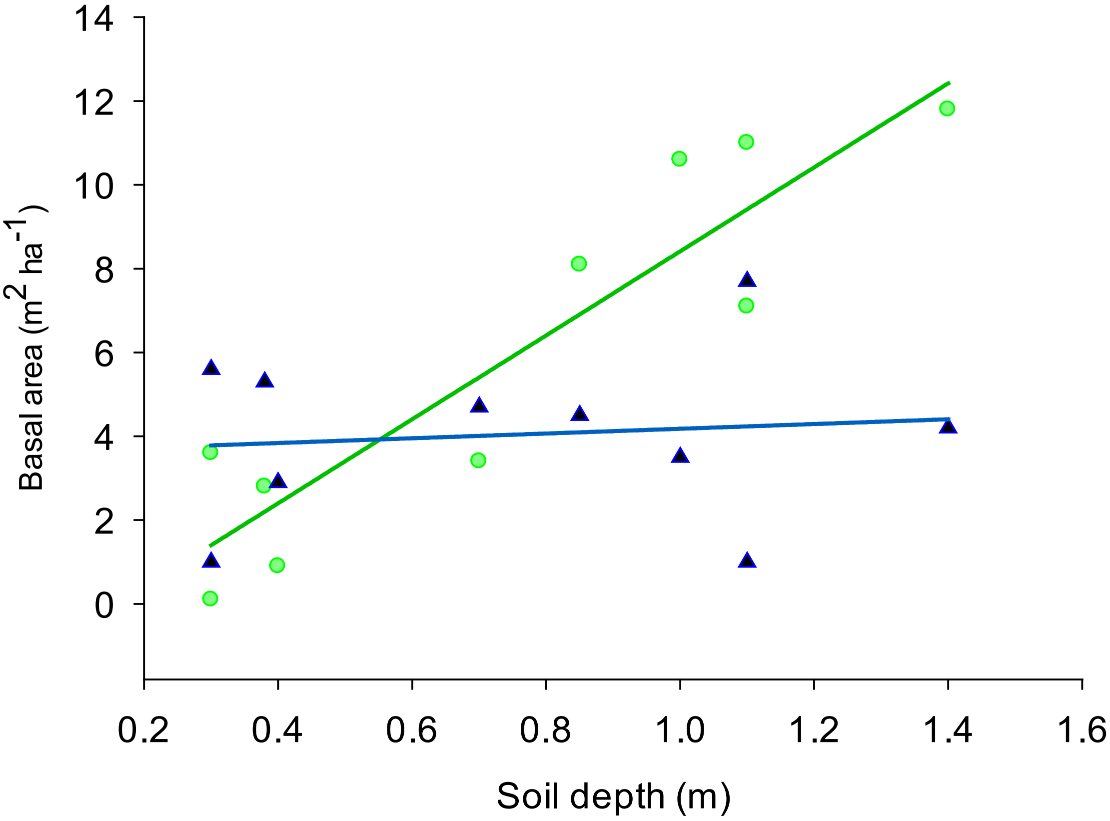


Figure 5-78: Variation in the basal area of evergreen trees (●) and deciduous trees (▲) in relation to soil depth along downslope catenary sequences at Kapalga in Kakadu National Park (Cook *et al* 2020).

5.4.1.5 Identifying suitable natural reference sites for Ranger rehabilitation

An area of particular focus on the RPA has been the 'The Georgetown Creek Reference Area' (hereon referred to as Georgetown Area, the hexagon in Figure 5-79), chosen because it is representative of nearby Kakadu NP habitats that are considered appropriate for a rocky final landform (Hollingsworth et al. 2003a). Early work focussed on describing the detailed geomorphic and pedological characteristics of different units that were present and on relating these to compositional and structural features of their vegetation cover (Hollingsworth et al. 2003a, Hollingsworth & Meek 2003).

Extensive surveys of the Georgetown Area have been completed, including a 400 ha grid survey (at 200 m spacing) that has shown graphically the natural variability of the vegetation types across the analogue area (Hollingsworth & Meek, 2003; Figure 5-80). Monitoring plots in Figure 5-80 are coloured according to vegetation type:

- Pink: Tall *Eucalyptus tetrodonta* open forest
- Yellow: Tall *Corymbia bleeseri* and *E. tetrodonta* mixed open woodland

- Blue: Mid-high *Melaleuca viridiflora* open woodland
- Green: Tall *E. tetrodonta*, *E. miniata* and *E. tectifica* open woodland
- White: Tall *E. tetrodonta, E. miniata*, *C. dunlopiana*, and *C. porrecta* open forest
- Brown: Tall *C. foelscheana*, *E. tetrodonta* and *C. disjuncta* mixed open woodland
- Red: Mid-high *C. disjuncta*, *E. tectifica* and *C. foelscheana* open woodland

The soils in the Georgetown Area vary in their drainage status and are typically gravelly and less than one metre deep to parent rock. The variation in the plant communities is typical of the lowland regional surface (Russell-Smith 1995) and there is a strong response to drainage and water supply (Williams et al. 1996). The structure and composition of the Georgetown Area vegetation is likely to be governed principally by water availability and plant available nutrients, typical of northern Australian savanna (Williams et al. 1996). Key geomorphic features (including parent material, slope, effective soil depth etc.) may also be important. However, more subtle variations in the vegetation composition and structure are likely to be the result of interplay between historic factors, proximity and context (i.e. the surrounding vegetation types) and discrete, often localised, disturbance events.

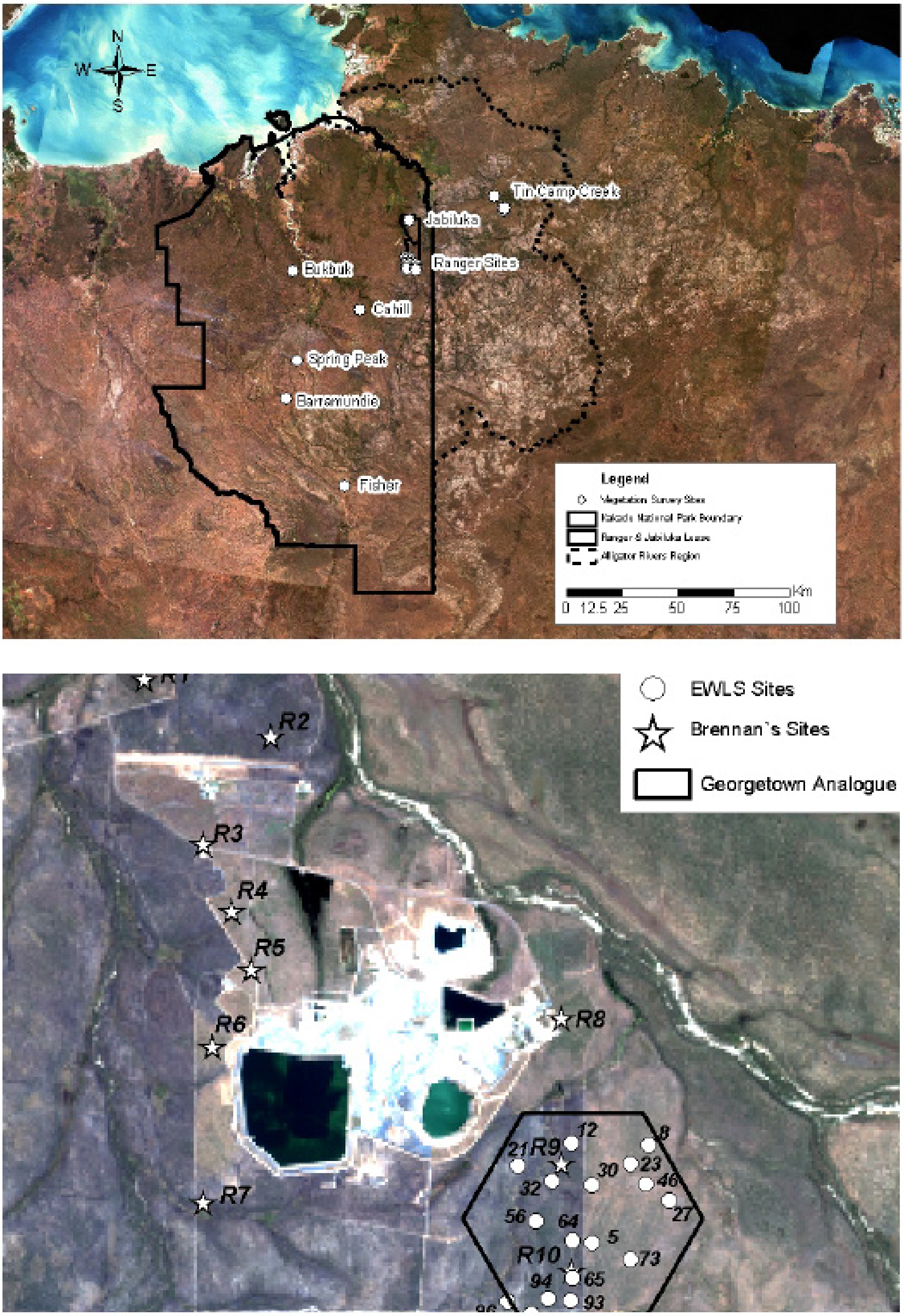


Figure 5-79: Maps of plant analogue sites surveyed by Brennan (2005) (top and bottom) and (Hollingsworth *et al.* 2003a) (bottom)

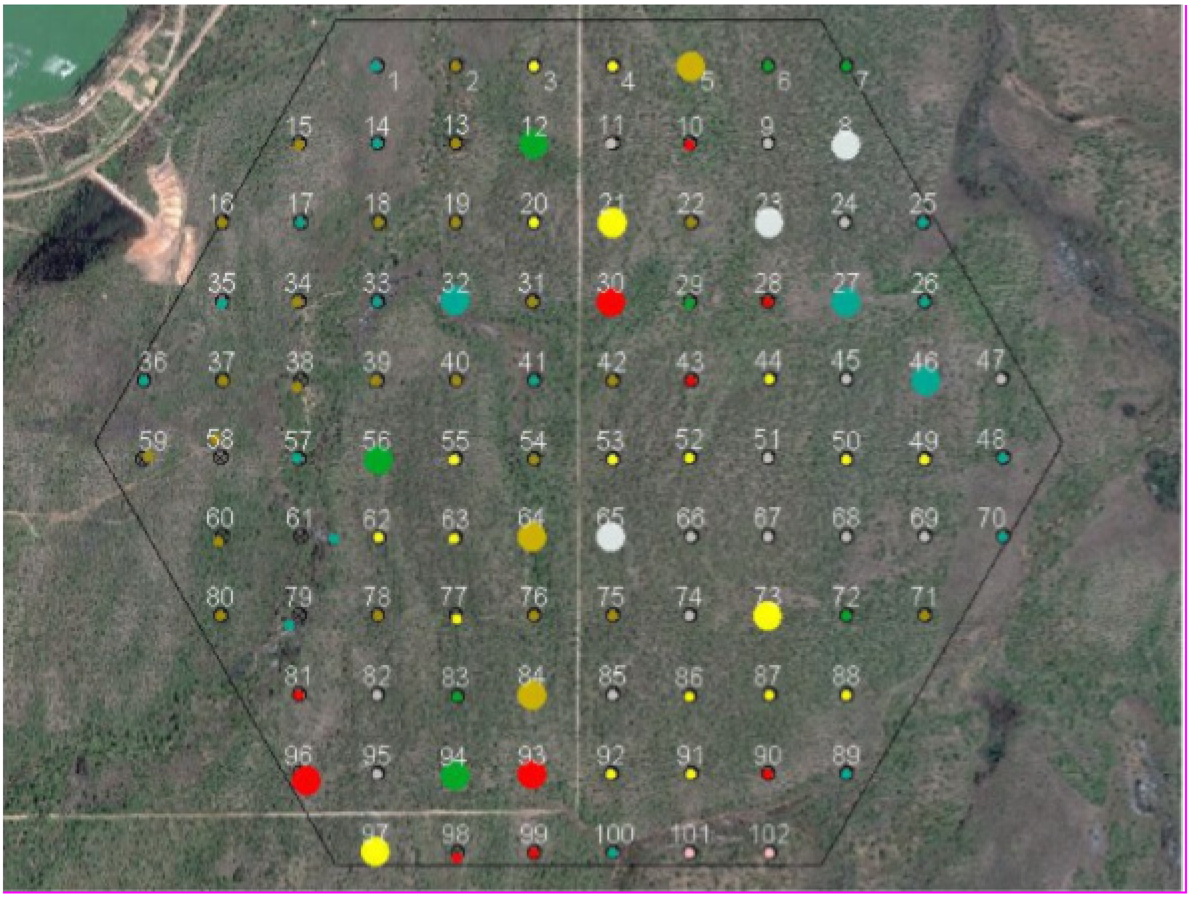


Figure 5-80: Georgetown Creek Reference Area vegetation type variation across monitoring sites

From 2018 - 2019, SSB surveyed 12 one-hectare vegetation reference plots (including two sites within the Georgetown Area) from within a 10 km radius of the mine site. In 2021, a further two one-hectare sites were surveyed in the Georgetown Area.

Four intermittently flooding savanna ecosystems were also surveyed by SSB in 2019 and 2020, in recognition that some areas of the Ranger final landform may have impacted surface hydrology and subsurface hydrogeology, including impeded drainage, seasonal flooding etc. The data from these sites are considered preliminary, and stakeholder discussion on seasonally inundated sites is ongoing. Future iterations of the RMCP will include updates on this work as it progresses.

5.4.1.6 Proposed conceptual reference ecosystems for ERA Ranger Mine

Due to the permanent and irreversible changes to the site, particularly in terms of topography, hydrology and substrate of the final landform, ecological conditions will be different to the pre-mining environment and no real analogue exists in the natural surroundings. In the absence of a natural reference ecosystem with a similar substrate, a nearby natural reference ecosystem can be adopted but adjusted to accommodate changed or predicted environmental conditions (SRG SERA 2021). The target ecosystem(s) in the case of Ranger Mine will be a conceptual ecological model, also referred to as a conceptual reference ecosystem (CRE). The CREs will be synthesised from numerous appropriate reference sites, revegetation trials, cultural values and historical and predictive records (e.g. potential modifications for predicted climate change or substrate limitations, Prober et al. 2015).

ERA is collaborating with key stakeholders to define appropriate CRE(s), and develop agreed closure criteria (Section 8), for the rehabilitation of Ranger Mine. As work on this has progressed, a clearer pathway towards development of an agreed CRE model for Ranger Mine revegetation has appeared, as outlined below:

- ensure a shared understanding of clear and specific objectives;
- understand the ideal environmental conditions for the target post-mine land use and, as far as practicable, consider these in the design and execution of the rehabilitated landform; and
- understand any constraints (and opportunities) to vegetation establishment imposed by the post-mining conditions.

In late 2019, ERA commissioned Dr Libby Mattiske, a renowned expert in the field of mine site rehabilitation, monitoring and assessment, to review the available vegetation data for Ranger Mine, compare these to benchmarked approaches from other operations and jurisdictions, and recommend an updated method to develop CREs for ERA. This work built on many years of research efforts with an emphasis on the current local and regional values that may influence the selection of appropriate species and communities for the rehabilitation areas predicted on the Ranger site. It also placed such information into the context of the constraints to the values on the post-mining site conditions with regard for current industry practices for rehabilitation management and objective setting.

The data sets from the various studies to date were integrated and a series of analyses undertaken on the representative subsets of data to clarify a potential way forward to maximise the use of the datasets (Mattiske & Meek 2020). Surveys analysed included ten of the SSB 2018/19 surveyed woodland sites, as well as the data sets from Humphrey et al. (2012), Saynor et al. (2009), and Hollingsworth and Meek (2003). The survey data was integrated with a reliance particularly on stem numbers of the overstorey and midstorey species due to the greater consistency between researchers and the need to concentrate on these species for the initial revegetation works on the Ranger Mine. This initial focus also avoided the constraints of variations in seasonal conditions at the time of samplings and the complexity of different lifeforms (Mattiske & Meek 2020).

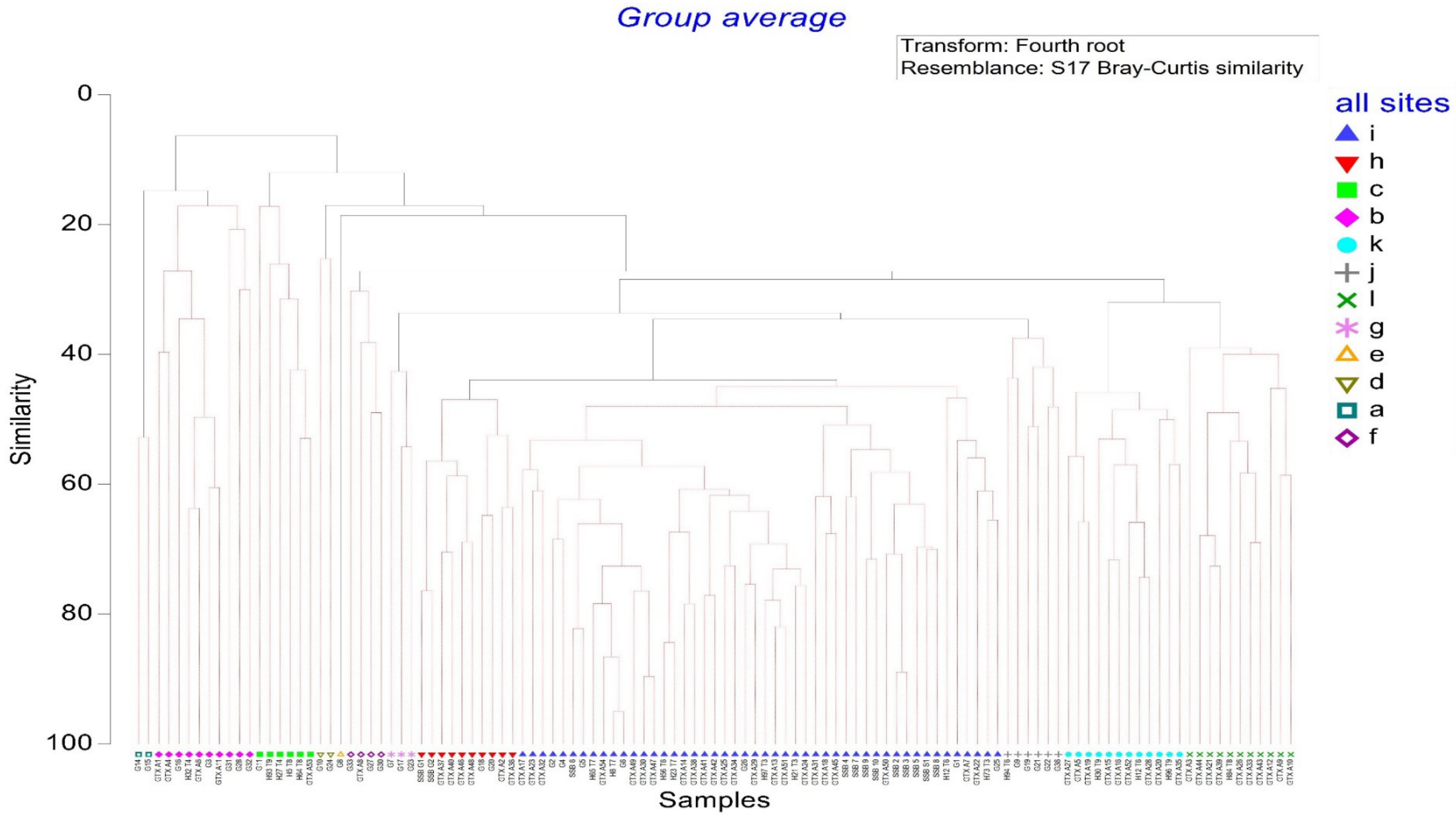


Figure 5-81: Dendrogram illustrating similarity of SSB sites near Ranger (2019/2020 data) and all of Saynor et al. (2009) and Georgetown (Hollingsworth & Meek 2003, Humphry et al (2012) using stems/ha overstorey/midstorey species (Mattiske & Meek 2020).

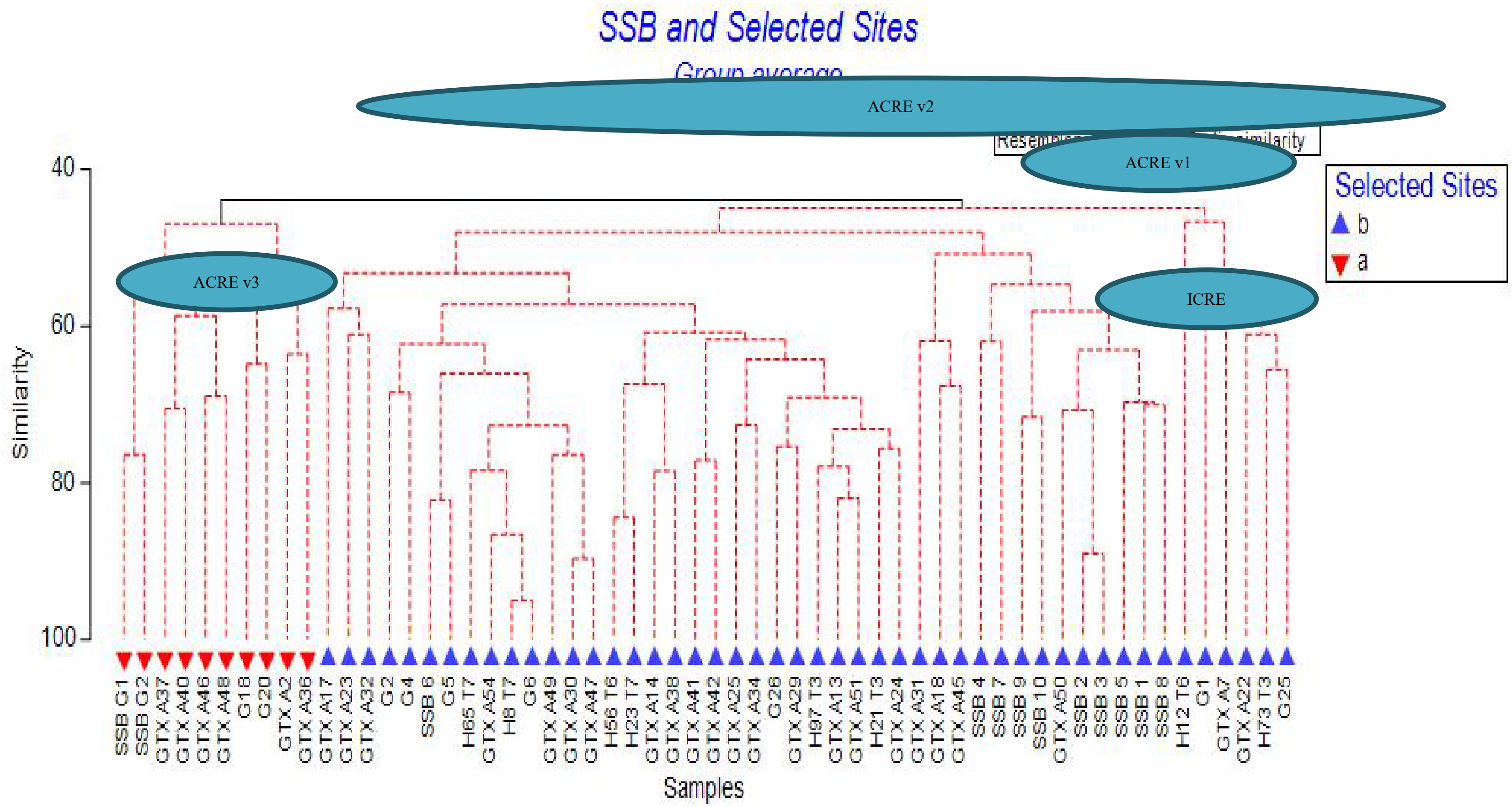


Figure 5-82: Dendrogram illustrating similarity of a subset of SSB sites near Ranger (2019/2020 data), Saynor et al. (2009) and Georgetown (Hollingsworth & Meek 2003, Humphry et al (2012) using stems/ha of overstorey/midstorey species (Mattiske & Meek 2020).

The data was analysed using Clarke and Gorley (2015) Primer version 7.0.13 using Bray – Curtis similarity. As indicated in the dendrogram (Figure 5-81) the data from some Georgetown woodland sites align with the SSB Eucalypt woodlands. Consequently, it was seen that the results supported a combination of the SSB sites with other selected sites from within and near the RPA, to broaden the coverage of natural variations within the local woodland. The report proposed that the ten SSB 2018/19 sites represent an 'Initial Conceptual Reference Ecosystem' (ICRE), and that three versions of potential alternative CREs (ACREs) in Table 5-82) be considered based on a combination of SSB 2018/19 data and the other surveys. These included ACREv1 as a slightly modified ICRE, ACREv2 which included species and communities wider in representation, and ACREv3 which allowed for the inclusion of what was considered 'drier site tolerant species'.

There was general agreement from stakeholders that the proposed alternative CREv2 formed a suitable basis for a CRE. In particular, the inclusion of a number of Georgetown survey sites (20x20 m quadrats) expanding the overstorey species array for *E. tetrodonta / E. miniata* dominated savanna than that which was contained in SSB one-ha 2018/2019 reference plots. However, two key issues where raised for consideration:

- the disturbance history of reference sites / plots, and whether 'impacted' sites should be included in developing the CRE; and
- given the mix of scales, different survey methods and disproportionate (over)representation of Georgetown survey sites, implications for (i) use of the alternative CREv2 site data in deriving a species and stem density list for ecosystem establishment, (ii) demonstration and scenario testing, and (iii) future monitoring of the reference ecosystem going forward.

Following from this assessment, it was agreed that two of the SSB sites surveyed in 2018 not be included in the CRE due to their recent disturbance histories, and that two additional one-hectare surveys be performed in the Georgetown Area. The selection of the two new Georgetown sites was done with consultation between ERA, SSB, NLC and Traditional Owners. The two survey plots were established in *E. tetrodonta / E. miniata* dominated savanna that had a greater representation of overstorey species present, including *E. tectifica.* The CRE as of early 2022 consists of ten one-hectare sites (Figure 5-83);

- S1, S2, S3, S6, S7 and S8 – surveyed in March and April 2018;
- S9 and S10 – surveyed in March 2019; and
- S11 and S12 (expanded from previously surveyed 20x20m Georgetown quadrats) – surveyed in March 2021.

The sites are highly variable in regards to species richness, stem densities (total and species-specific), and cover % (Figure 5-84 and Figure 5-85). This supports the degree of local variation in the sites and communities near the Ranger operations that have been apparent in previous studies.

There are however concerns that the dominance of certain species is potentially driven by undesirable and inappropriate fire regimes, in particular annual *Sorghum* and *Acacia mimula.* This prompted discussions on the functional role collective groups of species' play, rather than individual species, particularly with understorey which can be very ephemeral and variable within the same woodland on a year-to-year basis. It was decided that a 'functional understorey approach' be considered for the CREs. A dedicated workshop was held to develop this approach on the 24th of June 2021, which involved relevant ERA, SSB, NLC personnel, as well as experts from Charles Darwin University and Kakadu Native Plants Pty Ltd (draft report Bellairs, 2021). This functional group approach has also been adopted for the understorey composition closure criterion (*Section 8*).

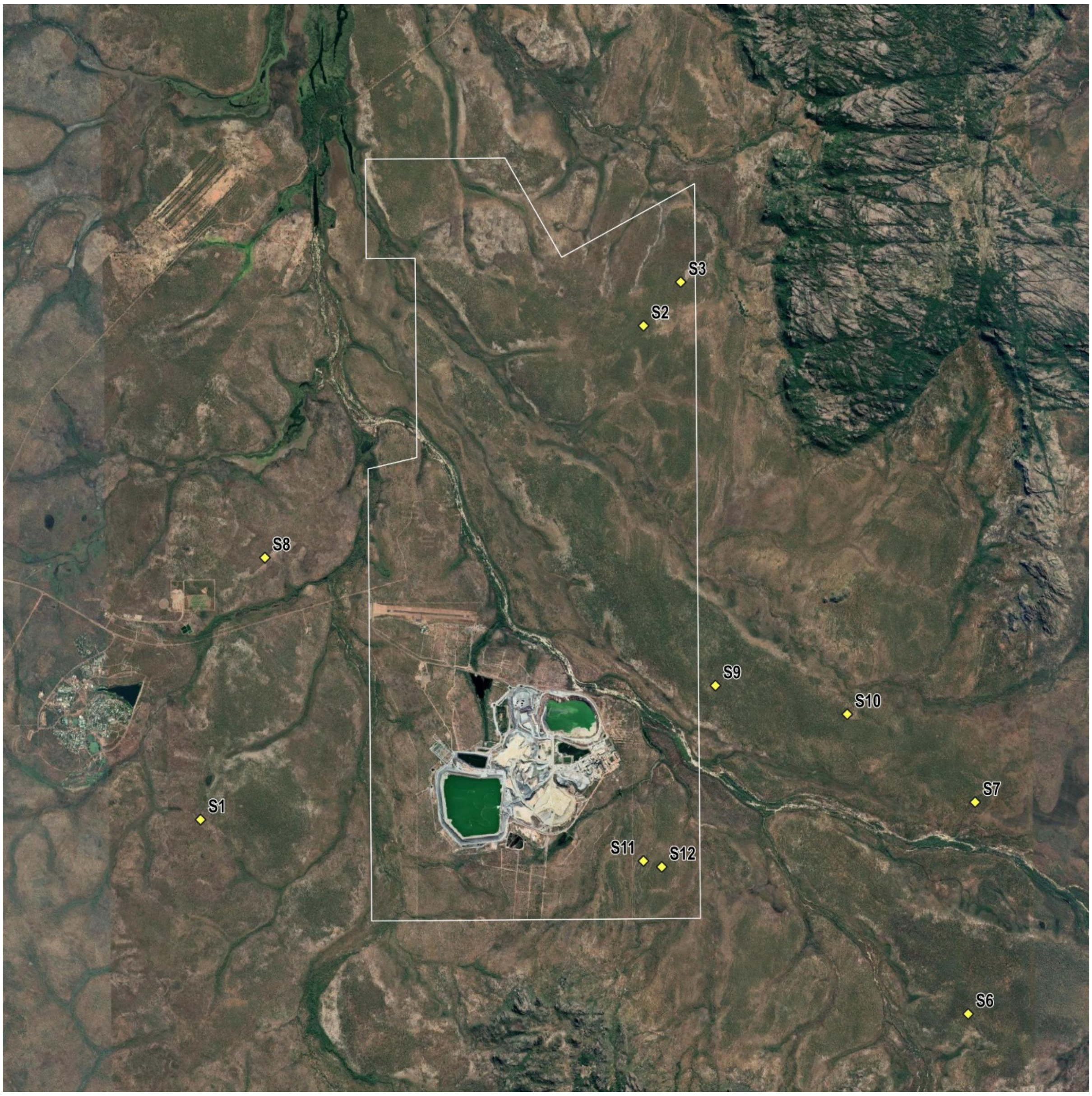


Figure 5-83: Location of conceptual reference ecosystem sites in relation to the Ranger Project Area

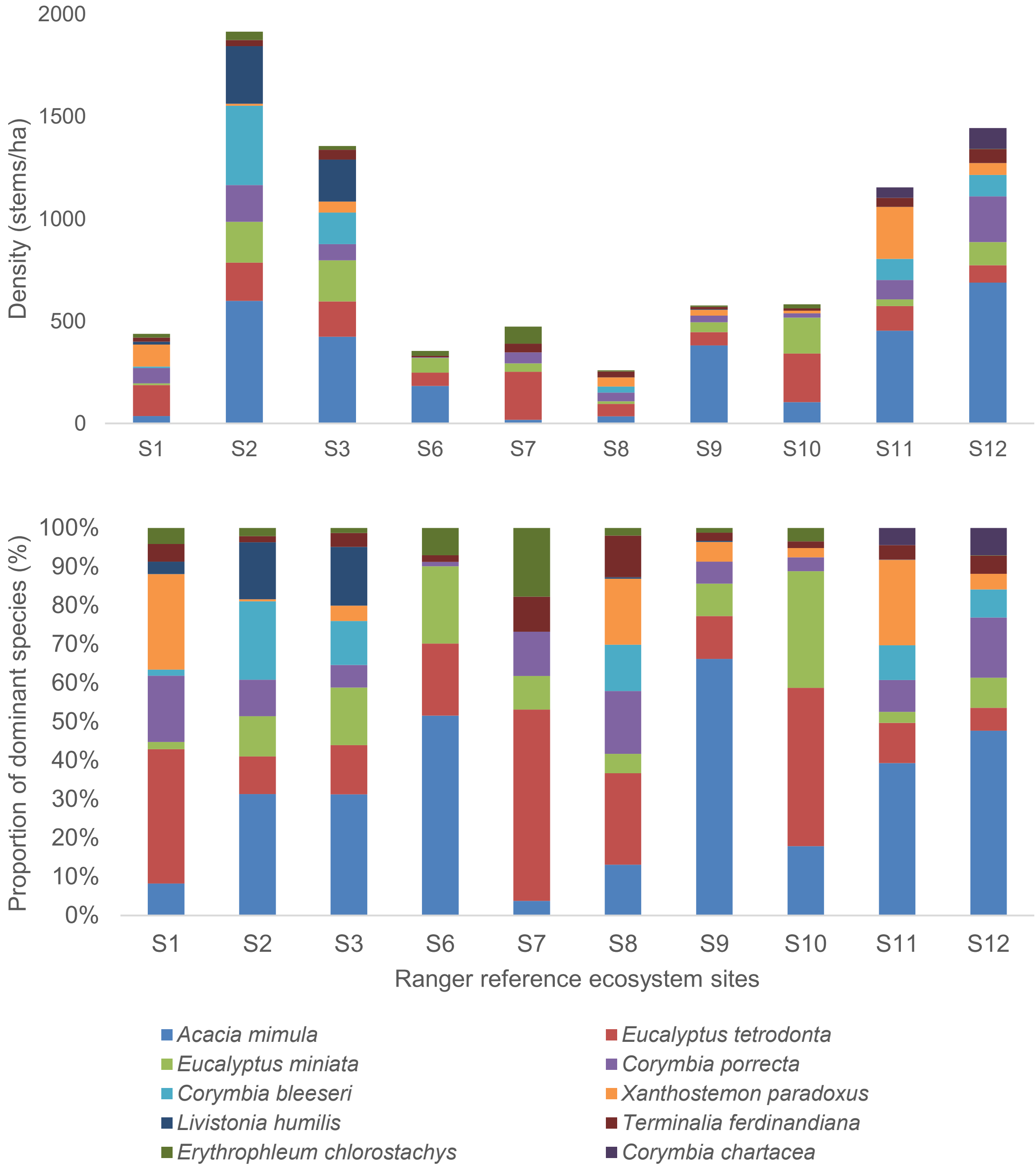


Figure 5-84: Stem density and species composition of the dominant ten shrub and tree species present in the CRE sites

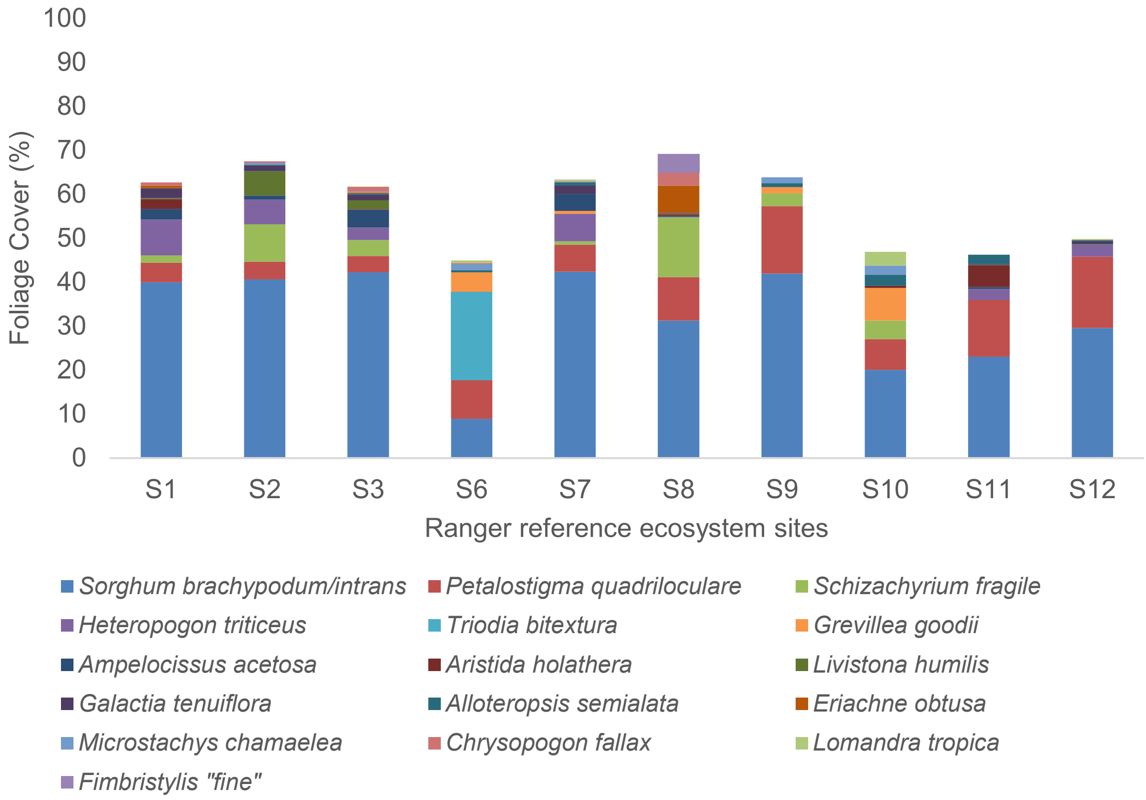


Figure 5-85: Dominant understorey species (> 0.4% average) vegetation cover in the CRE sites

5.4.1.7 Future work on the conceptual reference ecosystem(s)

The CRE project has significantly progressed in 2021 and 2022 and is nearing finalisation. Topics identified for continued work/discussion include:

- Continued consultation with the Cultural Reconnection Working Group on FLF features. For example, potentially increasing densities of desired species along long-term tracks and roads, or creating localised habitat/cultural features (rocky sites, drainage-lines, groves etc.).
- Further stakeholder discussion on particular species' dominances, whether they are appropriate for the CRE (eg. Acacia mimula dominance being potentially driven by undesirable fire regimes), and how some species' may be considered at a genus level, or other grouping, instead.
- Further stakeholder discussion to clarify different scale options for the CRE and for monitoring the ecosystem closure criteria (Section 8 and Section 10). For example, it is acknowledged that canopy cover should be considered at a landscape-scale rather than a per hectare scale.
- Continued development of an ecosystem rehabilitation plan for seasonally inundated / drainage areas on the RPA, driven by stakeholder consultation.

5.4.2 ESR7 Understanding the effect of waste rock properties on ecosystem establishment and sustainability

KKN title	Question
ESR7. Understanding the effect of waste rock properties of ecosystem establishment and sustainability	ESR7A *What is the potential for plant available nutrients (e.g. nitrogen and phosphorus) to be a limiting factor for sustainable nutrient cycling in waste rock?*
	ESR7B *Will sufficient plant available water be available in the final landform to support a mature vegetation community?*
	ESR7C *Will ecological processes required for vegetation sustainability (e.g. soil formation) occur on the rehabilitated landform and if not, what are the mitigation responses?*

5.4.2.1 Final landform material properties

Weathering and soil development

Developing waste rock 'soil' to a level able to sustain native vegetation is a result of complex interactions between the waste rock, plant roots, leaf litter, a range of microbial organisms and other environmental and climatic factors. Production of rock fines through weathering forms an important component of this process, as does generation and infiltration (illuviation) of organic matter (Tony Milnes, pers. comm. 2019).

Weathering of the waste rock over time increases both the proportion of fines in the soil profile as well as water holding capacity. General observations indicate the Run-of-Mine (ROM) waste rock on the TLF have been breaking down since its initial placement as a consequence of physical, chemical and biological weathering processes, vegetation establishment and litter accumulation, and decomposition by microbial activity in the substrate. The increased proportion of fines will provide a suitable substrate to support understorey development. Natural establishment of understorey species in the waste-rock-only section of the TLF began considerably increasing approximately10 years after revegetation, supporting the theory.

Johnston and Milnes (2007) reviewed various Commonwealth Scientific and Industrial Research Organisation (CSIRO) investigations of waste rock 'soil' formation to inform the Ranger revegetation strategy. Some of these early studies identified rapid weathering of exposed Pit 1 waste rock on the surface of the stockpiles; however it has since been recognised that this is more isolated and associated with certain rock types. Fitzpatrick *et al* (1989) recognised colour mottling from increased hydromorphy, variations in soil texture due to water erosion of fines material, structure development, decreasing pH from pyrite oxidation and sulfate weathering occurred within two years of waste rock stockpile construction.

- A number of distinct 'minesoil' types were recognised on the waste rock stockpiles. (Fitzpatrick 1986). Fitzpatrick noted that K and S released during weathering of waste rock were 'sufficient' for plant growth in minesoils, and 'sufficient' P was available to support deep-rooted vegetation. However, the very high ratios of Mg to Ca in the minesoil solution could affect the nutrition of some plants.

Table 5-39 and Table 5-40 show the edaphic properties measured for the rehabilitated waste rock landform and the analogue natural landform (Hollingsworth 2010).

Table 5-39: Rehabilitated waste rock landform properties

Depth	Rock content	Soil texture	Dry bulk density	Infiltration rate	Saturated hydraulic conductivity	Plant available water content	Soil penetration resistance
	%		$kg.m^{-3}$	$mm.hr^{-1}$	$mm.hr^{-1}$	$mm.m^{-1}$	MPa
				Soil			
0 – 0.5 m	>60	Sand	1.4 – 2.3	1 - 10	1,000	10	>3
0.5 < 1.5 m	50 < 60	Sandy loam	>1.6		1 - 10	50	
>1.5 m					>1,000	10	
Landform	**Recharge rate**	**Runoff coeff.**	**Relief**	**Catchment area**	**Slope**		
	10 – 25% of rainfall	>50%	<5 m	11 ha	0 – 3%		

Table 5-40: Analogue landscape properties

Soil depth	Gravel content %	Soil texture	Dry bulk density $kg.m^{-3}$	Infiltration rate $mm.hr^{-1}$	Saturated hydraulic conductivity $mm.hr^{-1}$	Plant available water content $mm.m^{-1}$	Soil penetration resistance MPa
0 – 0.5 m	>60	Sand to sandy loam	1.1 – 1.7	300 – 4,800	1,000	10	>3
0.5 < 1.5 m	50 < 60	Sandy loam – sandy clay loam	>1.6		60 – 4,500	50	
1.5 – 2.0 m	>60	Sandy loam	>1.8		0.4	50 – 100	
2.0 – 3.0 m					0.08	50 – 100	
Landform	**Recharge rate**	**Runoff coeff.**	**Relief**	**Catchment area**	**Slope**	**Leaf area index**	
	5 – 10% of rainfall	>20%	<30 m	1,500 – 5,000 m^2	1 – 5%	0.8 – 1.6	

Waste rock particle size distribution

A key parameter to assess water holding capacity of the growth media (waste rock), is the percentage (%) of the fines smaller or equal to 2 mm (≤2 mm) in size. Typically, only this portion of the material is considered able to store water for plant use.

Waste rock particle size is also an important parameter in landform evolution modelling. Studies and data on PSD related to landform are provided under KKN LAN3.

As discussed under KKN LAN3, during the TLF construction in 2009 PSD sampling was conducted. One pit in each of the 1A and 1B TLF subsections were constructed from waste rock material only. Samples were taken in triplicate from the surface and at depths of one, two, three and four metres (m) from these pits. The samples were sieved to determine weight of the fraction of material greater than 2 mm (>2 mm) and less than 2 mm (<2 mm). Sub-samples of the fine earth fraction (i.e. <2 mm) were provided to the University of Melbourne for particle size analysis using the Bekham Coulter LP13320 laser sizer. Particle sizes were grouped into sand, silt and clay fractions according to United States Department of Agriculture (USDA) size classes. It should be noted that this early sampling work did not follow the Australian Standard for PSD measurement.

PSD results from the TLF section 1A profile are presented in Table 5-41. Note the sand, silt and clay fractions make up 100 % of the fine earth fraction (i.e. particles <2 mm), termed '*fines*'. The rock content (i.e. particles >2 mm) range from 61 to 73 % averaging 67 % consistent with SSB observed 70 % rock content (Mike Saynor, *pers. comm.*).

A breakdown of the fines content is shown in Table 5-41, with similar values published by Saynor & Houghton (2011) and provided under KKN LAN3; describing the determination of the particle size statistics of the surface material from different areas of the TLF.

Table 5-41: Particle size distribution data from TLF 1A section at construction in 2009

Depth (cm)	Total volume of material (rock and fines)		Classification and breakdown of fines portion (particles <2 mm)		
	Rock %v/v	Fines %v/v	Sand %	Silt %	Clay %
0	66.2	33.8	83.8 ± 1.4	14.9 ± 1.3	1.3 ± 0.2
100	68.0	32.0	82.8 ± 2.5	15.8 ± 2.4	1.3 ± 0.2
200	63.8	36.2	82.9 ± 1.2	15.7 ± 1.1	1.4 ± 0.1
300	73.0	27.0	83.6 ± 0.3	15.0 ± 0.2	1.4 ± 0.1
400	61.6	38.4	82.9 ± 2.1	15.7 ± 1.9	1.3 ± 0.2

Hollingsworth (2010) measured PSD, water content and water potential from 24 core samples from the northern Ranger Mine experimental waste rock cover comprised of the Pit 3 materials. The substrate contained 36% of fines (<2 mm) and 64% of gravels/rocks (>2mm).

A CSIRO study (Emerson and Hignett, 1986) on revegetated waste rock dumps at Ranger, identified rock fractions (> 2 mm) of samples taken from the trenches in three rock piles of Pit 1 materials were 'surprisingly' uniform with means of 61 %, 54 % and 57 %, respectively (Emerson & Hignett, 1986). These rock contents are lower than but comparable to the TLF finding of 67 %. These findings also suggest that Pit 3 stockpile materials in the TLF, combined with the Hollingsworth (2010) findings and the Pit 1 (Emerson & Hignett 1986) and Pit 3 waste rock materials are similar in terms of their fines content.

In 2013 the University of Queensland and Charles Darwin University (CDU) conducted a small-scale excavation of section 1A of the TLF at Ranger mine. Particle size analysis was conducted to assess particle size distribution. A slight increase in fines was observed and compared to measured proportions taken during initial construction of the TLF in 2009 (Figure 5-86, Figure 5-87).

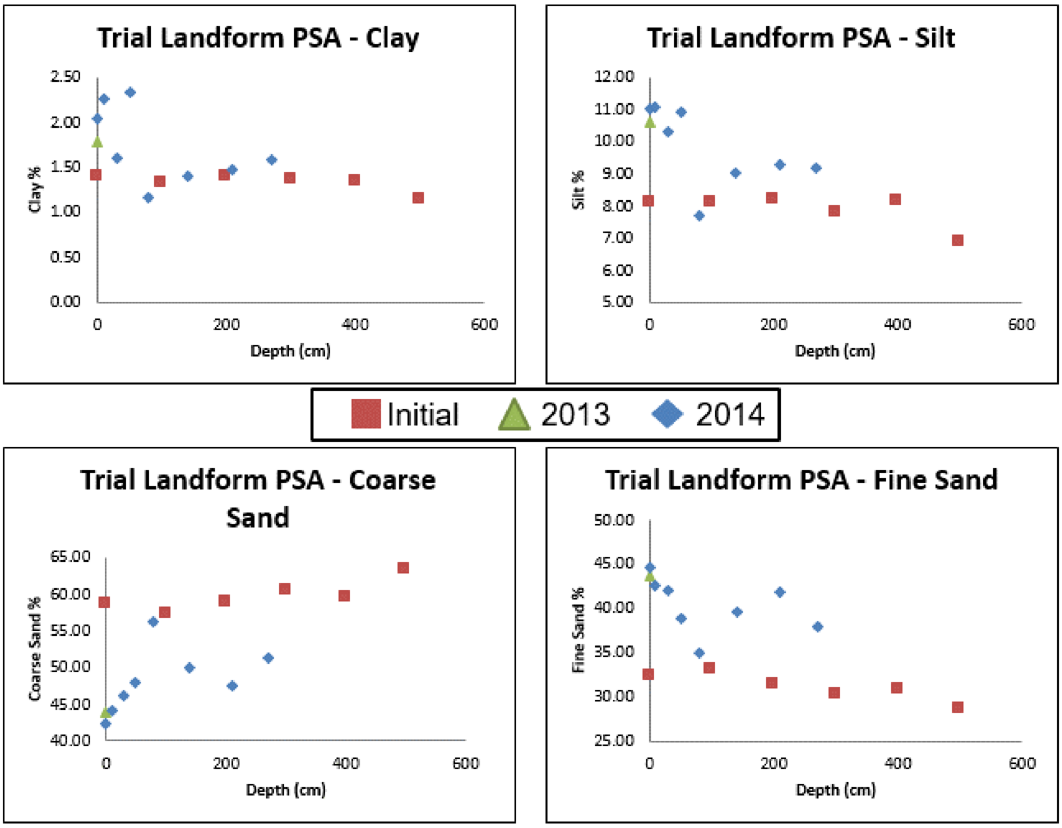


Figure 5-86: Changes in PSD on TLF from 2009 to 2014 inclusive

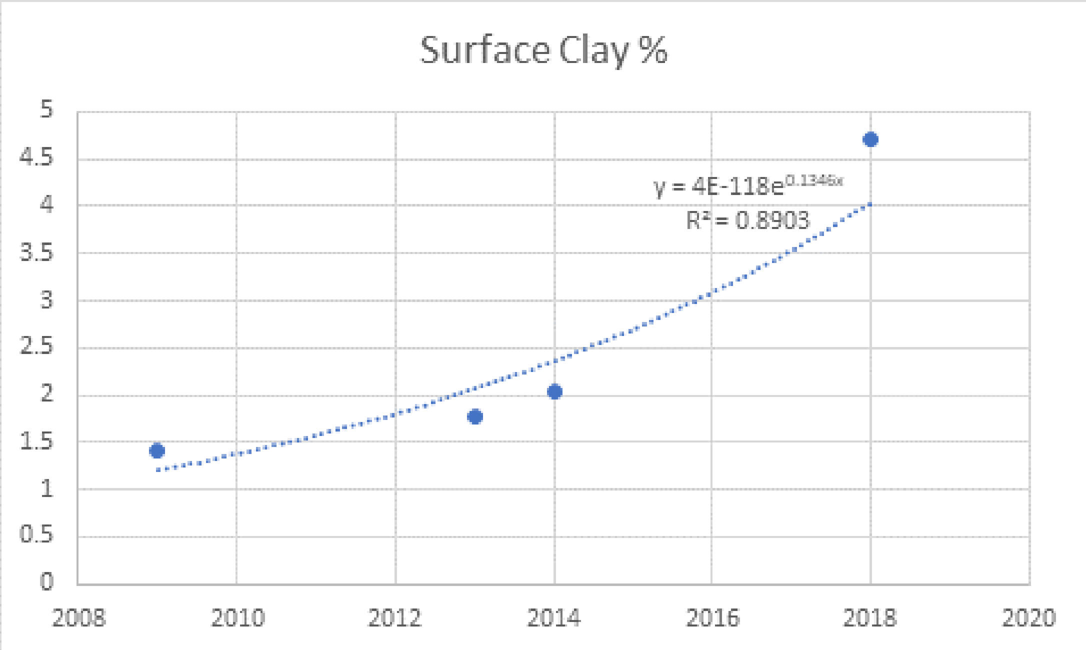


Figure 5-87: Changes in PSD on TLF1A (including 2018 surface soil samples) at 5 cm depth

During the construction of the Pit 1 final landform layer (top 6m, described in Section 9) ERA engaged Douglas Partners Geotechnical & Environmental Consultants to develop an appropriate PSD sampling method based on the Australian Standard and conduct monitoring across the pit as it was being constructed. A total of 82 samples were collected across the two final landform construction layers; the upper layer (U; 1.5 m) and lower layer (L; 1.5 m to 6 m). An average and a median PSD curve for both the upper layer material and lower layer material were calculated using all the sample results (Figure 5-88). There is an approximate ten percent difference between the average and median value of the fine fraction for the lower layer, indicating material characteristics of the lower layer potentially present a more heterogeneous form in the fine size fractions compared to that in the upper layer materials.

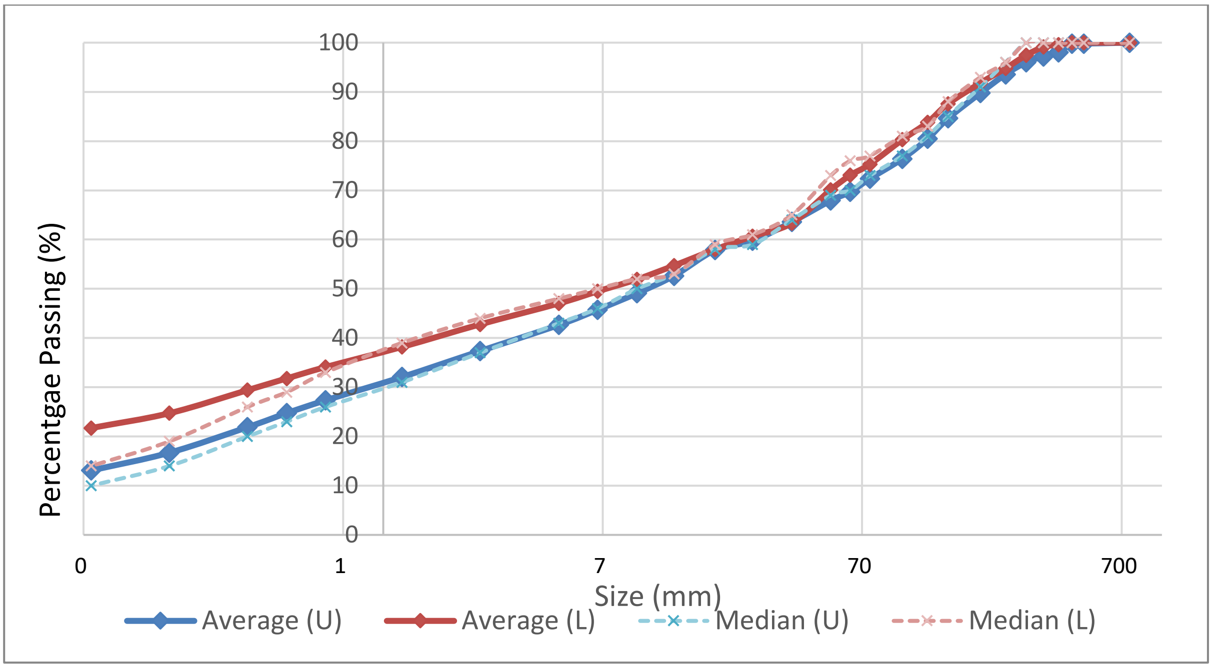


Figure 5-88: PSD result average and median for upper and lower layer

5.4.2.2 Plant available water studies

Ranger Mine is located in the seasonally wet-dry tropics of northern Australia, where approximately 95 % of rainfall occurs between November and April. The most important factors shaping the landscape which determines savanna ecosystem type are soil water availability and vegetation survival during the dry season. This also presents the most critical challenge for Ranger Mine site revegetation post-mining, with soils often lacking structure or containing large amounts of rock fragments that reduces water holding capacity.

To address the critical question of whether the waste rock substrate of the Ranger Mine final landform can supply sufficient plant available water (PAW) to sustain a range of sustainable vegetation communities similar to those in Kakadu National Park, ERA has undertaken extensive research over the past three decades, particularly the two decades (Hollingsworth 2010, Lu 2017, Lu *et al*. 2019). These studies are summarised in this section and include long-term ecohydrological studies in the Georgetown Creek Reference Ecosystem area since 2008 and extensive soil water dynamics and vegetation performance studies on the Ranger Mine TLF since 2009.

PAW Modelling

From 2011, ERA engaged CDU to undertake a modelling approach to understand the TLF water balance. The hydrologic characteristics of the waste rock substrate combined with results from the ecohydrological studies informed the CSIRO Water, Vegetation, Energy and Solute (WAVES) model (Zhang & Dawes 1998). The model focussed on estimating required PAW in the waste rock surface layer to meet the predicted demand to sustain the rehabilitated ecosystem (ERA 2019).

PAW is the amount of available water that can be stored in soil within the rooting zone available for growing plants. The Ranger waste rock growth media often lacks structure or may contain large amounts of rock fragments and macropores which reduces water holding capacity compared to natural soils.

In 2021, ERA engaged Okane Consultants Pty Ltd (Okane), a world leader in water balance studies of waste rock cover, to undertake further modelling, using updated input data, to re-evaluate PAW for the Pit 1 final landform. Okane completed modelling in two phases using Geostudio Flow Model Software and the WAVES Model to evaluate PAW for several modelling scenarios. Phase 1 work was completed to validate the WAVES model using the Geostudio Flow 2021 software suite. Phase 2 modelling involved the application of WAVES and Geostudio modelling to evaluate three Scenarios.

- Scenario 1 – Assessment using material properties and vegetation inputs within the previous WAVES modelling (TLF) coupled with new climate data acquired since the previous modelling.
- Scenario 2 – Assessment using Pit 1 final landform material testing results completed in 2019/2020 and the same climate sequence and vegetation inputs as Scenario 1.
- Scenario 3 - Assessment using Pit 1 final landform material testing results completed in 2019/2020 and the same vegetation inputs as modelling Scenario 1 and 2 using a 'dry' rainfall climate.

A summary of the work completed to date is provided below. Once completed final reports will be issues to stakeholders for review and updates will continue to be provided in this MCP.

Phase 1 Modelling

Phase 1 involved a validation exercise for the WAVES model using 1D Geostudio Flow 2021 software suite (GeoSlope, 2021). Previous model inputs (material properties, vegetation and climate) developed in the WAVES calibration modelling program were used in the Geostudio soil-plant-atmosphere (SPA) and WAVES. The results of the 1D models provided validation that the WAVES software used for previous assessments performs similarly to the globally recognised and accepted Geostudio software. Geostudio SPA modelling resulted in similar predictions of water balance parameters to that of the WAVES model.

Phase 2 Modelling

Scenario 1 - Trial Landform Modelling

Scenario 1 modelling was completed to compare estimated PAW results to those discussed in the previuos modelling (ERA 2019). Okane completed 1D SPA modelling using Geostudio Flow Models and WAVES Models. Results obtained by the Geostudio Models were similar to those of the WAVES Model thus validated the use of this method to evaluate PAW.

Similar to previous modelling, PAW was evaluated for various waste rock thicknesses and varying material fines content. Okane used their proprietary Inverse SPA Model to estimate material properties for the waste rock materials using field measured volumetric water content data. Material properties representative of 10-20%, 20-30%, and 30-40% range of fines content were developed based on material characterisation data from the waste rock and soil-moisture measurements from the TLF.

Results of the Scenario 1 modelling indicated a similar trend to those discussed in ERA (2019). Increased coarse content of the material requires a thicker waste rock layer to maintain a lower net negative PAW balance. To maintain a net negative PAW balance of less than 5% under high (Georgetown reference Site 21) evapotranspirative demands a minimum waste rock thickness of 5 m is required with a fines content greater than 33%. However, if the waste rock thickness is increased to 6 m, a fines content of 25% or greater would be sufficient. This result is similar to those in ERA (2019).

Scenario 2 – Final Landform Modelling and Sensitivity Analysis

Scenario 2 modelling was completed for the final landform based on Pit 1 material investigations completed between 2019 and 2020 (Miller, 2020a, 2020b; Okane, 2021). A range of material properties were evaluated for the low (less than 20%) and high (greater than 40%) fines materials. As expected, material with lower fines stored less water when compared to the higher fines material. However, the lower fines material was still capable of maintaining a net negative PAW balance of no more than 5% under high (Site 21) evapotranspirative demands and a waste rock depth of only 5 m. The influence of waste rock thickness on PAW was the same as Scenario 1 in that PAW increases with increasing waste rock thickness. The higher fines material was able to maintain a 0% net negative PAW balance regardless of waste rock thickness (>= 5 m) or evapotranspirative demands.

Scenario 3 – Final Landform Modelling with ‘Dry Climate’

Modelling completed for Scenario 3 replicated that of Scenario 2 with the exception of the rainfall model input. The 100-year climate database used to evaluate Scenario 3 was provided by SSB and is considered to be representative of a ‘dry climate’.

Net negative PAW balance was evaluated for a 5 m thick waste rock layer for both the lower and higher fines material. The higher fines materials resulted in a 0 % net negative PAW balance for both evapotranspiration demand regimes. However, the lower fines material resulted in a 5 % and 7 % net negative PAW balance for Site 30 (lower evapotranspirative demand) and Site 21 (higher evapotranspirative demand), respectively.

Ecohydrology of natural tropical savanna ecosystems

As discussed previously, a particularly strong influence on vegetation survival in the wet-dry topics is water availability. Plant adaptations have evolved to survive in their particular environment including physiological responses to cope with a broad natural range of scenarios. In the seasonally wet-dry tropics, survival strategies range from extremes of inundation or ‘drought’ to more-nuanced variations such as length of dry season, or timing of the wet season onset. In the dry season, plant survival is dependent on water balance especially towards the end of the dry season when the soil water stress is highest. Strategies to survive these periods of low water availability include stomatal closure, loss of leaves, and development of a progressively deeper root system.

A key strategy to avoid catastrophic cavitation of the water-conducting xylem system is to balance canopy water loss with root absorption. As soil moisture reduces, trees minimise their water loss initially by stomatal closure, followed by sacrificing non-vital, peripheral organs (i.e. leaves, twigs, branches and above ground stems). These adaptations slow down water loss and soil water depletion increasing chance of survival in times of drought (Tyree and Sperry 1988). Most plants, including evergreen trees notably *Eucalyptus miniata* and *Eucalyptus tetrodonta*, shed their leaves to reduce transpiration (water loss from tree canopy). This maintains a balance between root water uptake and canopy water loss (Thomas and Eamus, 1999). These adaptations assist plant survival when soil PAW is very low.

Another key strategy to reduce water stress as the dry season progresses is to develop roots that can access PAW as it retreats down the soil profile. Root soil water extraction is energy driven; water is pulled by a tension gradient created between the leaf surface to the root tips. Roots first extract the soil water from nearer the soil surface where water is mostly readily available (water potential is high or less negative) thereafter accessing water progressively deeper in the ground as the upper soil profile dries out. Plants will not generally establish roots to a depth below a layer that has already provided sufficient soil-water. That is, if soil-water is available in the top four or five metres of the soil profile, plants will typically not require roots deeper than this. If water is more readily available below this depth, i.e. the plant can spend less energy accessing water at depth than from the upper dryer soil layer, the plant will extend its root system into the deeper layer providing the level of hydraulic tension within the plant xylem vessels does not reach a catastrophic level that will kill the plant (runaway of xylem embolism, Tyree and Sperry 1988). In this way plants have evolved to maintain the balance of water demand and supply to avoid this catastrophic result (Tyree and Sperry 1988).

The trees of the savanna woodlands typical of Kakadu NP and the revegetation target at Ranger, typically have the majority of their root system in the upper one metre of the substrate to access water during the wet season when growth rates are at a maximum (Janos *et al*. 2008; Hutley 2008). This is partly due to the ferricrete layer (duricrust) that occurs approximately 1 to 1.5 m below the soil surface throughout the region (Figure 5-89). This layer limits root development further down but enables penetration by deeper-tapping roots through macropores (Werner and Murphy 2001; Hutley 2008; Hutley *et al*. 2000). Many important top end savanna species can root to depths up to five or six metres (Hutley *et al*. 2000; Kelley *et al*. 2002; Kelley *et al*. 2007)

Hutley (2008) summarised the key features of savanna vegetation water use and carbon allocation strategies for vegetation adaptations to Top-End monsoonal seasons (Figure 5-90). During the wet season, trees maximise their growth and water uptake from the nutrient rich shallow soils. During the dry season the shallow soil water is quickly depleted, and trees cease growing, instead accessing water from deeper in the soil to maintain photosynthesis and, under more severe conditions, maintain the viability of vital organs. For plants, water uptake (use) from deeper in the soil is very low and the nutrients are very limited, where sub-soil water storage is critical to survival.

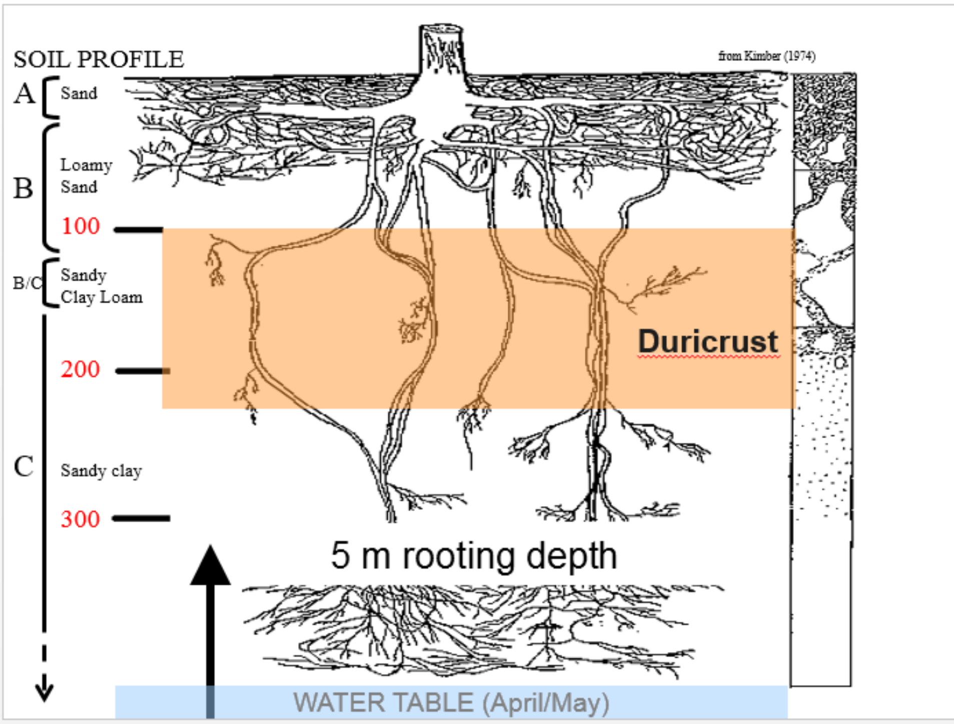


Figure 5-89: Rooting pattern of the savanna woodland trees in the Top-End (Source: Hutley 2008)

Features of savanna water use carbon allocation

- Dual root systems – maximise carbon and water uptake in seasonal climate
- Wet season, 0-1 m depth
  - Surface fine roots – water and nutrient uptake
  - Stem increment possible
- Dry season, 2-5 m depth
  - No surface soil moisture, limited nutrient availability, no stem growth possible
  - Account for dry season ET using soil water balance
  - **Trees using up to 5 m of soil for dry season water requirements**
  - Sub-soil water storage critical
  - Photosynthesis maintained
  - Carbon partitioned into maintenance of deep roots, storage in lignotuber and reproduction
- Partitioning of soil water usage
  - grasses: 0 - 0.5 m (wet)
  - trees: 0 - 5 m (wet and dry)
- competition with grasses limited or avoided

Figure 5-90: Key features of savanna vegetation water-use and carbon allocation strategies adapted to the Top-End seasonality (Source: Hutley 2008)

Plant growth rate and water demand decline as the wet season ends and the dry season progresses. The fine root mass diminishes with the receding soil-water reserve, where the cost to the plant of maintaining these fine roots during the dry season with little or no return is too great. (Janos *et al*. 2008). Any residual water demand must be met by the ability of plants to use deeper roots to access the remaining soil-water reserve.

Soil moisture extraction patterns at the Ranger's Georgetown Creek Reference Area (Site 21) demonstrates soil water is extracted from between 5.5 to 5.8 m below the surface in the late dry season. (See *Groundwater table and soil water dynamics* section under this KKN)

Canopy cover dynamics

Long-term canopy cover measured by Leaf Area Index (LAI) of woodlands monitored at four ecohydrological study sites have shown significant seasonal variability (refer to Figure 5-91). The LAI is highest during the wet season and lowest during the dry season. The seasonal reduction is approximately 50%, but is higher in some dry years (Lu *et al* 2019).

Site 21 has the densest canopy (highest LAI) and the highest seasonal variation of all sites. The LAI reduced by about 70% over the extended dry period leading into the late 2015-16 wet season. Whole-tree sap flow measurement demonstrated that Site 21 has the highest annual transpiration. Site 21 has a species composition dominated by the overstorey species *E. tetrodonta* and *E. miniata* and basal area of 8 m^2 ha^{-1} similar to tropical savannas across northern Australia (Hutley *et al*. 2000).

Plants will shed more leaves earlier during the driest part of a dry season if water is beyond reach of the roots, observed at reference sites 21 and 30. Site 30 is a drier site regarding substrate-type, where plants shed more leaves earlier and more rapidly than species at Site 21 reflected in the seasonal dynamics of the LAI (Figure 5-92). In the worst-case scenario, if PAW is less than the target, trees that survive the dry season regrow during the wet season.

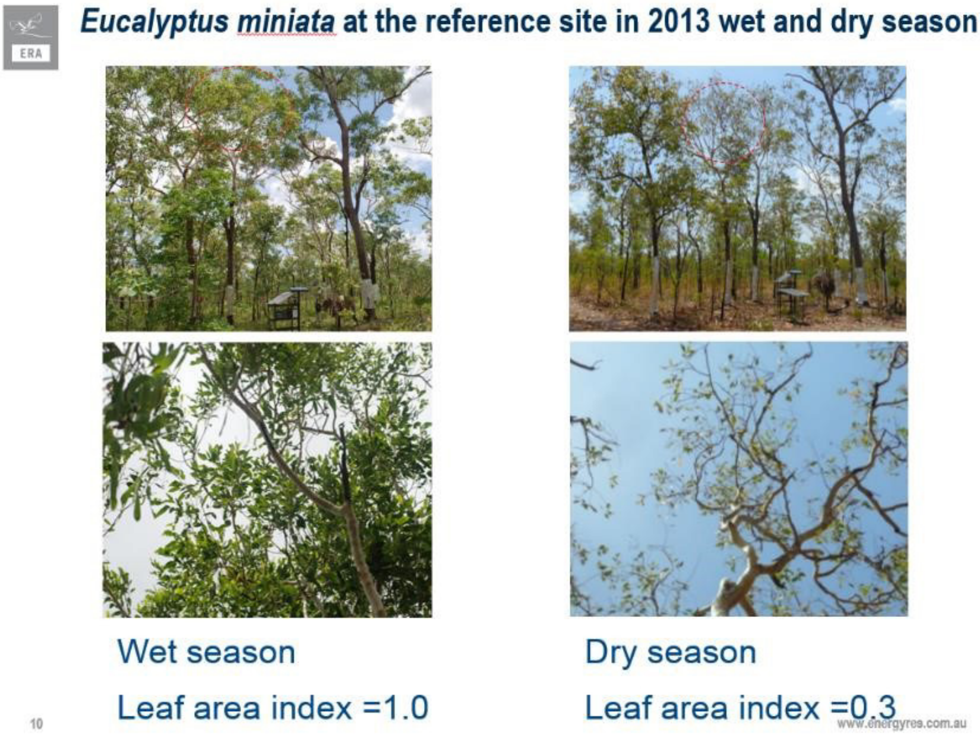


Figure 5-91: Seasonal change in leaf area index at the Georgetown Creek Reference Area (Source: Lu *et al*. 2018)

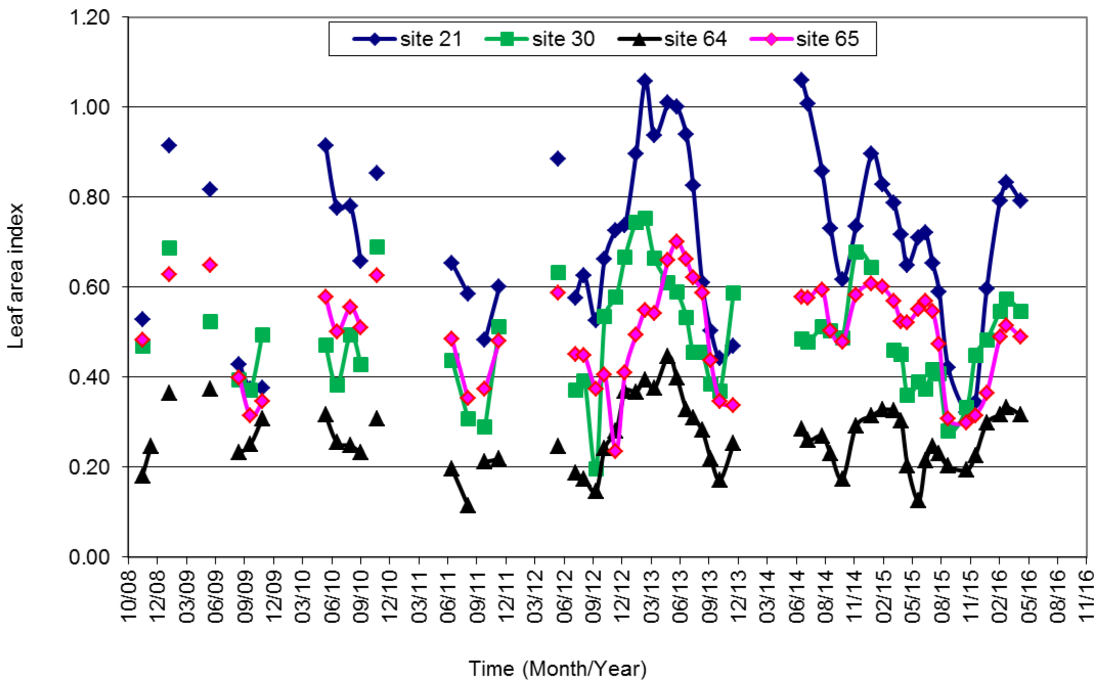


Figure 5-92: LAI dynamics at the four ecohydrological study sites (missing data during the wet season due to site inaccessibility)

Total water requirements of the vegetation during dry season

Total water requirement for vegetation is typically measured by evapotranspiration (ET), the sum of overstorey transpiration, understorey transpiration, and soil evaporation (Figure 5-93). Other closely related processes shown in Figure 5-93 are runoff and groundwater recharge.

In the Top End of Northern Australia, during the dry season, woodland vegetation water use is dominated by the overstorey and midstorey vegetation. The understorey dries rapidly at the beginning of each dry season where its contribution to ET is negligible compared to tree and shrub water use (Hutley 2008, Hutley *et al*. 2000).

Stand transpiration measured from the woodland near Ranger site was estimated based on tree stem xylem sap flow measurements at Site 21 (Figure 5-94, Figure 5-95). Lu *et al* (2019) details measurements of sap flow and stand transpiration. Tree water use peaks towards the end of wet season and/or the beginning of the dry season (April to June) when the soil water availability is high, days are sunny, the air is dry, evaporative demand and LAI are high (Figure 5-92). Transpiration decreases during the dry season as the soil dries out and LAI decreases (Figure 5-92). It reaches its minimum at the end of the dry season right before a significant rainfall event. In the early wet-season transpiration increases as the soil water availability and canopy LAI increase, but has not reached it maximum rate due to rainfall.

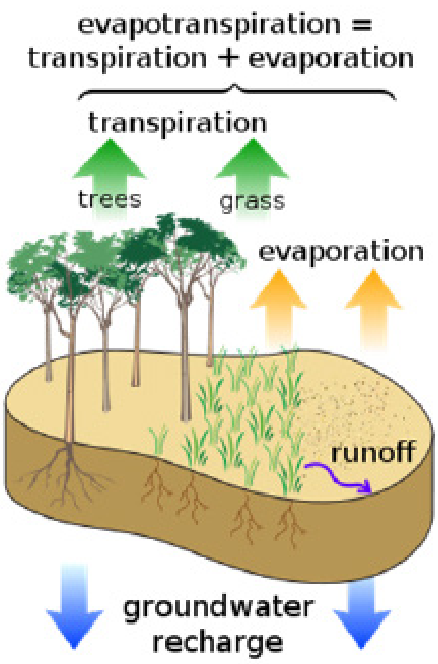


Figure 5-93: Evapotranspiration and its components

Figure 5-94: General view of an instrumented study site

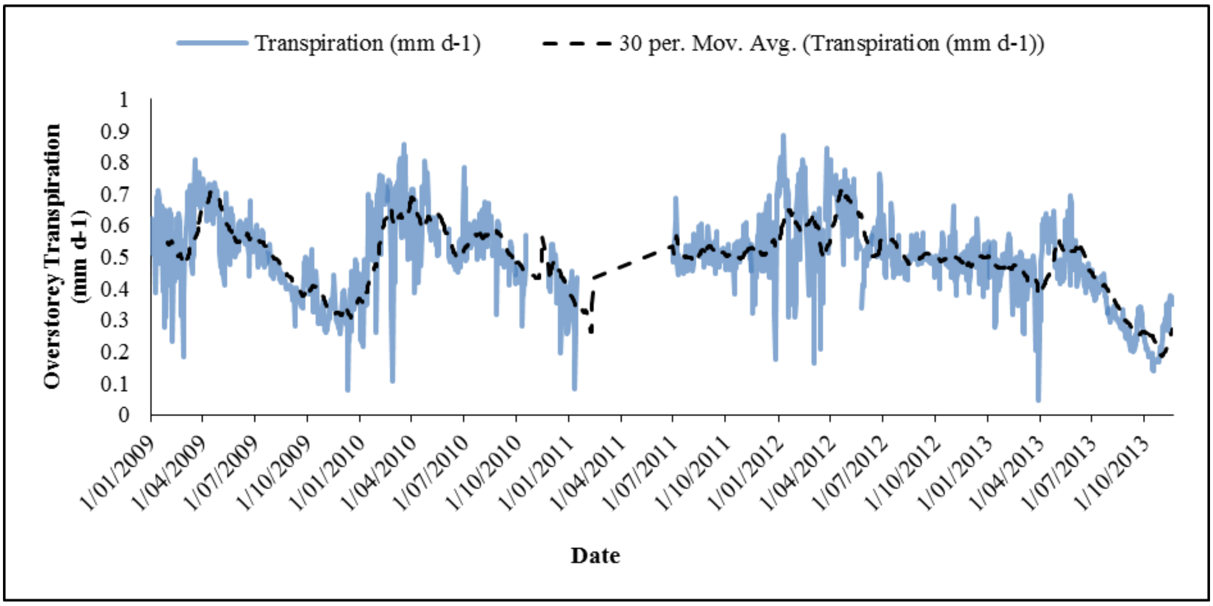


Figure 5-95: Annual dynamics of over storey tree transpiration at Site 21

Canopy cover (LAI) is directly and highly correlated with vegetation water use (Baumgartl *et al*. 2018). Site 21, which has the highest LAI and therefore the highest vegetation water use, is the reference site for modelling. Comparison of dry season natural vegetation water requirement with PAW supply in the final waste rock landform at this site presents a conservative target for the vegetation water requirement (Baumgartl *et al*. 2018) with an upper envelop of the average dry season transpiration of 0.5 mm○day^{-1} adopted for the WAVES modelling.

Groundwater table and soil water dynamics

At Site 21, the groundwater table level is dynamic (Figure 5-96). The shallow groundwater system is very transient during the wet season, where water levels reached within 0.5 m of the soil surface and peaks, then subsiding rapidly after heavy rainfall ceases. During the dry season the groundwater table drops 10 m below the soil surface. These characteristics are typical of a groundwater system with a low hill topography comprised of porous shallow ground material.

Note that the bore hole depth is slightly deeper than 10 m and the cable length of the hydrostatic pressure transducer was set to 10 m. When the water level drops below 10 m the transducer (logged) gives a maximal 10 m depth afterwhich a manual dipper can provide a reading until the bottom of the borehole is dry. Groundwater and soil moisture measurement details can be found in Lu *et al* 2019.

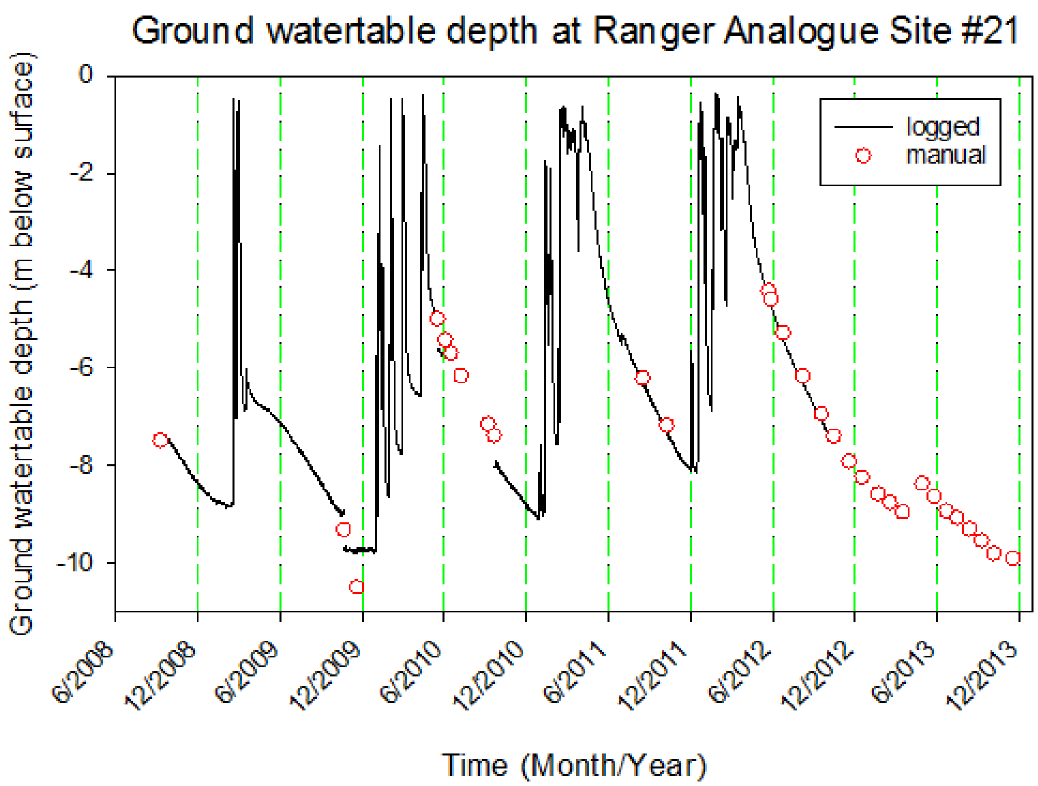


Figure 5-96: Temporal dynamics of the groundwater depth at Site 21

A comparison between soil water dynamics defined as relative extractable water content (REW) from varying depths below ground surface and the groundwater table level (GWT) at Site 21 is shown in Figure 5-97. The data shows maximum REW for the whole soil profile occurred late in the wet season. As the dry season progressed, soils quickly dried out within one month near the surface and in depths up to 1 m. Following drying of the shallow soil, water was progressively extracted from deeper levels, up to 5.8 m. By November 2012, extractable water in the entire 5.8-metre thick profile was almost depleted. Measuring sap flow suggests trees maintain a substantial level of transpiration (Figure 5-95) during this period demonstrating that tree root systems exploit soil water from deeper soil.

The depth to the ground water table decreased progressively with, but faster than the decreasing REW. The depth difference between the REW and the ground water table depth broadly corresponds to the capillary fringe height.

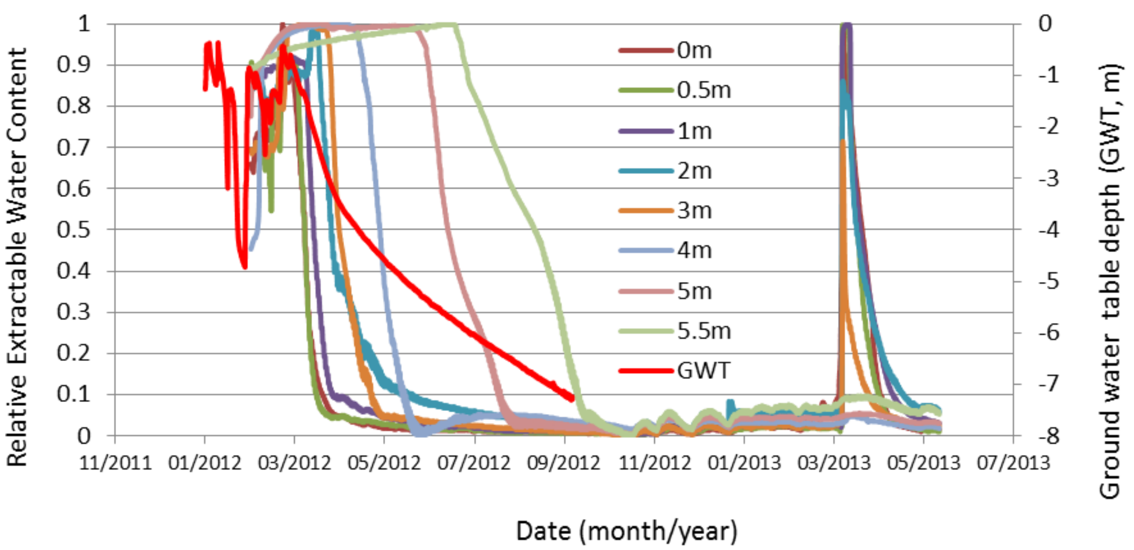


Figure 5-97: Relative extractable water contents measured at different depths and ground water table depth (GWT, in Red) at Site 21

Plant water uptake patterns can often be inferred from soil water depletion pattern (Knight 1999). From Figure 5-97 it is evident that as the dry season progresses, extractable water was progressively depleted from the surface to deeper depths reaching depths of 5.5 to 5.8 m. This suggests that the natural savanna trees at the Ranger Georgetown Creek reference site are able to extract water at depth close to 6 metres below ground level consistent with the findings by Sharma *et al*. (1987) where a significant amount of soil water extraction in Eucalypt forests in Western Australia occurs to a depth of at least 6 m.

Soil evaporation and under storey transpiration are highly dependent on the shallow soil water content. Based on the soil moisture results shown in Figure 5-97 it is reasonable to expect that the evapotranspiration from the soil and understorey would decrease to near zero within a couple of months after the dry season starts. Therefore, the major component of evapotranspiration during the dry season is over and midstorey transpiration. This is consistent with other evapotranspiration studies in the Top End of the NT (Hutley 2008).

Despite the dry season understorey ET and soil evaporation being negligible and not directly measured at the Ranger reference site, they were simulated using the locally calibrated WAVES model discussed earlier in this section to obtain the total dry season vegetation ET (Dawes *et al*. 1998, Zhang & Dawes 1998, Segura 2016)

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5.4.2.3 Chemical characteristics and nutritional processes

Chemicals in substrates play a vital role in revegetation success, including as a limiting nutrient, a toxicant above a threshold effects level, a modifier or facilitator of other chemical processes/interactions or a combination (Bayliss 2018).

It is important to have site specific and species-specific information on the nutrient requirements and toxicity risks for target species for rehabilitation of the Ranger Mine final landform. Some findings and observations may obscure specific effects resulting in sub-optimal vegetation establishment and development.

Waste rock material at Ranger Mine differs from natural soils by having higher pH, EC, CEC, Magnesium (Mg), total Phosphorous (P) and Sulfate (SO_4) concentrations, and lower levels of nitrogen (N) and extremely low organic carbon (C) at the beginning of landform establishment where the materials are run-of-mine without topsoil (Ashwath *et al*. 1993, Gellert 2014,Table 5-42**)**.

It is noted that compared to waste rock from other mines in the ARR, or natural soils, the Ranger Mine waste rock has higher total, exchangeable and water soluble Mg, and higher total P (Ashwath *et al*. 1993). Ashwath *et al*. (1993) also found that C:N ratio is significantly higher in Ranger waste rock (58:1) than in natural soils (19:1). The presence of high ratio of C:N in mine waste rock may restrict the net release of N to plants and soils.

Chemical toxicity

Bayliss (2018) assessed the potential chemical effects on seedling plant growth and survival relating to toxicity thresholds reported in the literature for species or genera that will be used in revegetation at the Ranger Mine, and their potential roles as either limiting nutrients, toxicants or chemical facilitators, concluding:

“In summary, the potential chemical risks from poor pH range (for ectomycorrhizal fungi at least) and low values of N, Ca and Mg can be discounted in the assessment given that TS can be enhanced at planting with fertilisers (e.g. broadcast or directed application) and water crystals whose effects may last up to 14 months (Daws & Gellert 2011; Gellert 2012). Additionally, Fe was discounted as a potential toxicant given the higher concentrations found on the Miniata and Heritage analogue sites, albeit closer to the minesite compared to Georgetown. Hence, in our assessment, risks to revegetation from mine-derived chemicals is assumed zero and, needless to say, a more thorough screening process needs to be undertaken of potential effects on seedling growth and survival to test that critical assumption. This may require experimental in situ research and pot trials to fill knowledge gaps.”

ERA presented to ARRTC (May 2018) results of vegetation growing in the waste rock on the TLF and other areas around the mine site exposed to pond water (waste rock runoff and leachate). The observations and studies of the LAAs, irrigated with pond water for over a decade, indicate there are no observed negative effects on vegetation from waste rock contaminants.

Investigations into the effect of magnesium sulfate salinity on the germination of seeds of twenty plant species native to the Kakadu NP (Malden *et al*. 1994) found that the presence of magnesium sulfate salinity severely decreased the final germination percentages and decreased the rate of germination of most species. Whilst use of tubestock planting can decrease these specific germination impacts, these effects may impact subsequent growth or impact the subsequent establishment of mid storey and under storey species from seed. Thus, as discussed at ARRTC (May 2018), studies on plant establishment and growth rates for specific species may inform future management practices that could mitigate nutrient and toxicity effects. These studies are currently being undertaken by SSB in collaboration with the National Environmental Science Program (NESP) and CDU and will be summaried in this MCP once completed.

Table 5-42: Chemical analysis of waste rock samples taken in January 2010 compared to natural soils (source Gellert 2014)

	Section 1A TLF	Analogue sites
paste pH	8.0 (±0)	6.3 (±0.1)
paste EC (uS/cm)	260 (±49.2)	14.4 (±2.2)
Organic C (%)	0 (±0)	0.54 (±0.08)
P (ppm)	410 (±6.6)	0.2 (±0.1)
Total P (mg/kg)	460 (±25)	64.8 (±12.6)
Total S (%)	0.03 (±0.02)	0.02 (±0.01)
NO2-N (mg/kg)	Below detectable limit (BDL)	0.28 (±0.05)
NO3-N (mg/kg)	0.64 (±0.48)	0.24 (±0.08)
paste NH3-N (mg/kg)	0.07 (±0.01)	1.27 (±0.30)
Total N (mg/kg)	45.1 (±14.0)	422 (±20.5)
Ca (mg/kg)	85.8 (±23.8)	0.8 (±0.1)
K (mg/kg)	20.3 (±1.9)	4.9 (±0.0)
Mg (mg/kg)	61.7 (±18.3)	BDL
Na (mg/kg)	17.0 (±3.8)	1.2 (±0.1)
CEC	5.3 (±0.5)	3.2 (±0.2)
Al (me/100g)	0.4 (±0.1)	1.8 (±0.1)

Nutrient cycling

The diversity and sustainable growth of revegetated plants is closely related to nutrient cycling in soil-plant systems, driven by functional microbial communities in litter, surface soil and the rhizosphere. Microbial driven processes are critical to *in situ* litter decomposition and N/P mineralization in soil and plant uptake.

Rehabilitated sites rapidly redevelop nutrient pools in the soil, litter and understorey vegetation, but the pool contained within trees takes longer to develop. Litter accumulates rapidly in rehabilitated sites, sourced mainly from eucalypt and legume species. At bauxite mines in WA, rehabilitated areas have accumulated the same amount of litter within three to five years as unmined forest sites after the same period of time following burning (Ward 2000). Surface roughness provided by scarification or ripping aid these processes by ensuring that resources such as water, leaf litter and nutrients are captured and used *in situ* or recycled. The furrows also concentrate the litter, allowing decomposition processes to commence earlier.

Research by Grant *et al.* (2007) found that a critical aspect of re-establishing a self-sustaining jarrah (*Eucalyptus marginata*) forest ecosystem to mined areas is to ensure that vital ecosystem functions such as litter decomposition and nutrient cycling are returned. Significant research has been undertaken over the past twenty years relating to litter decomposition and nutrient cycling. Studies have shown that litter accumulates rapidly in restored areas (1–4 t/ha/a) and the accumulated litter tends to be richer in nitrogen due to intentionally elevated densities of nitrogen-fixing species. This leads to a lower carbon:nitrogen ratio (60:1 compared to 130:1 in unmined forests) that may promote mineralization of organic nitrogen to inorganic forms in restored areas. The major nutrient store in the unmined forest is in the soil and returning soil during the rehabilitation process largely conserves this resource, particularly in relation to phosphorus. Short-term plant macronutrient requirements for growth are readily restored by fertilizer application. Studies on the re-accumulation of nutrient pools in the successional development of restored areas have shown that pools equivalent to the unmined forest are established within ten to twenty years. Ongoing research is focusing on the rates of cycling processes in burnt and unburnt restored areas and comparing these to the unmined forest to ensure that key functions have been re-established.

ERA commissioned a study (Huang & You 2018, Huang *et al*. 2020) of nutrient cycling in revegetation of the TLF compared to Georgetown Creek reference sites. The 2018 study compared TLF-1A and Georgetown Site 21 while the 2019 assessed TLF-1A and Georgetown Site 30, where soil is more gravelly and shallower. The key findings of the 2018 study are summarised in Table 5-43.

Huang and You (2018) suggest low mineralisation rates in the 9 year-old revegetated TLF soils may be attributed to combined abiotic stress selection, solar radiation associated heat stress, rapid evaporation and water deficit in the surface “soil” – fine fractions of weathered rock and organic matter debris at the surface due to low ground cover vegetation and/or litter. Water deficit may be a key factor limiting microbial growth and soil functions.

The study assessed key microbial and nutrient cycling attributes of litters and surface soils from 10 year-old revegetated waste rock (TLF-1A and 1B) compared to the natural vegetation reference Site 30 (Huang *et al*. 2020). The investigation characterised litter properties including elemental and organic compound composition and a range of key soil molecular microbial, chemical and biogeochemical indicators to assess the potential capacity of organic carbon decomposition and nutrient cycling processes in surface soil of the TLF (1A and 1B).

The litter collected from the sites contained 40-50% organic carbon and low concentrations of N and P. The organic compounds within the litter were dominant by carbohydrate, followed by protein (especially the C=O amide I) and lipids. The differences of litter chemistry were not statistically significant between the reference and TLF sites (Table 5-44).

Compared to the rehabilitated waste rock sites, surface soil at the reference site was more fertile though (Figure 5-98) slightly acidic and associated with relatively high levels of organic matter (4.5% organic C) and N (>20mg/kg), especially in the form of ammonium-N. This might be attributed to long-term organic matter decomposition and humic compound accumulation, as a high density of understorey annual/perennial plant species was present. Surface soil at the reference site had the highest diversity of bacteria and fungi, particularly with abundant actinobacteria associated with N enrichment and fungi genera associated with woody and later stage organic matter decomposition. Metagenome prediction and *in situ* enzymatic activities showed that bacterial communities from the reference sites also had the highest capacity to drive organic matter metabolism as an indicator of nutrient cycling.

The TLF surface soil is slightly alkaline and less fertile than the reference site; comprised of freshly formed/weathered rock fines and decomposed organic matter. The organic matter levels of TLF soil samples were approx. one third of the reference site, with much lower levels of total nitrogen (<5mg/kg). Microbial communities in the surface soils were highly diverse and dominated by organoheterotrophs across all sampling sites. Bacterial and fungal communities from reference site soils showed the highest diversity. The microbial communities in the reference site appeared structurally different to other sites. Some Actinobacteria associated with N enrichment as well as fungi associated with later decomposition stage were abundant in the reference site soil. The soils from TLF-1A and TLF-1B sites were enriched with microbes well adapted to habitats of low moisture and infertile soils.

The surface soil from the reference site also showed the highest capacity of microbial driven organic matter decomposition and N metabolism among the sites sampled. The metagenome prediction and induced metabolic activities suggested that microbial communities from the reference site had the highest capacity to metabolise simple carbohydrate. The activities of selected enzymes involved in cellulose, hemicellulose and protein decomposition were not significantly different among the sampling sites.

The TLF soil microbial communities expressed a lower potential capacity of organic matter decomposition, especially for simple carbohydrates (e.g. sugar). Enzymes involved in cellulose, hemicellulose and protein decomposition were at similar level as the reference site. As sugar metabolisms are usually associated with opportunistic bacteria requiring moist habitats, enhancing the water availability and the accumulation of organic matter with favourable C:N ratios (eg. understorey plant biomass) is critical to enhance the microbial functions and coupled nutrient cycling.

The 2018 and 2019 findings collectively point to the importance of establishing productive understorey species including N2-fixing leguminous species to increase labile organic matter (biomass residues and root debris) and N inputs. This is critical to restore nutrient pools and maintain biological functions in surface soil. Importantly, the increased understorey vegetation provides shading effects helping alleviate radiation heat and drought stress in the surface soil of the TLF sites in future, favourable for soil microbial activities and nutrient cycling.

Table 5-43: key findings of 2018 nutrient cycling study (TLF-1A and Site 21)

Area	Finding
Nutrient status in litter and surface soil	After 9 years of revegetation, litter accumulated in the trial landforms showed relatively higher levels of nutrients concentrations than those collected from the analogue. Soil in the trial landforms showed lower level of nutrients concentrations than those in the analogue.
Characteristics of bacterial and fungal decomposers	Microbial communities in both litter and surface soil of the three sites were dominated by heterotrophic bacteria. Bacterial and fungal communities in trial landforms appeared to be more diverse than those in the analogue soil, however seemed to be under selection pressure which constrained their functions. Some N-fixing and plant growth-promoting bacteria were 3 times more abundant in the analogue soil than in TLF. TLF soils had abundant bacteria colonizing nutrient limiting environment, and Rozellomycota associated with early stage of soil development. Also, there was a smaller portion of stress response stain assigned to class of Bacillus enriched in soils from TLF-1A than the analogue site.
Nutrient cycling processes in surface soil	As is expected for a ‘new soil’, the microbial functions related to C and N cycling in the surface soil of trial landforms were constrained, compared to the soil from the analogue site. The TLF surface soil exhibited significantly lower levels of net mineralisation rates and higher levels of metabolic quotient (representing lower carbon utilization efficacy) than those of analogue site in the wet season when microbial biomass was supposed to be significantly boosted with increased moisture and availability of C and N.

In summary, 10 years after the revegetation, the TLF growth media has significantly improved their nutrient level compared to the initial stage of the revegetation. The microbial communities in the surface soils were highly diverse, similar to the reference site. The TLF soil microbial communities expressed a lower potential capacity of organic matter decomposition, especially for simple carbohydrate (eg. sugar), due mainly to relatively dry surface material, and relatively low accumulation of organic matter with favourable C: N ratios (eg. understorey plant biomass).

To improve the TLF nutrient status and cycling, it was recommended to:

- minimize surface drought and heat;
- enrich high quality organic matter through understorey growth; and
- improve N-supplying capacity by introducing diverse deep-rooting understorey legumes.

Table 5-44: Elemental composition in the litter among sites

Element	Reference site	TLF-1A	TLF-1B
OC (%)	42.3	47.8	42.9
N (%)	0.71	0.68	0.78
P (g/kg)	0.30	0.27	0.31
K (g/kg)	0.72	0.76	0.97
Ca (g/kg)	14.19	13.36	13.80
Mg (g/kg)	1.86	2.95	5.69
Fe(g/kg)	8.70	0.68	3.28
Al (g/kg)	2.51	0.85	4.02
S (g/kg)	0.63	0.74	0.69
Mn (g/kg)	0.38	0.12	0.15
Cu (mg/kg)	7.8	4.4	10.2
Zn (mg/kg)	18.5	16.4	20.6

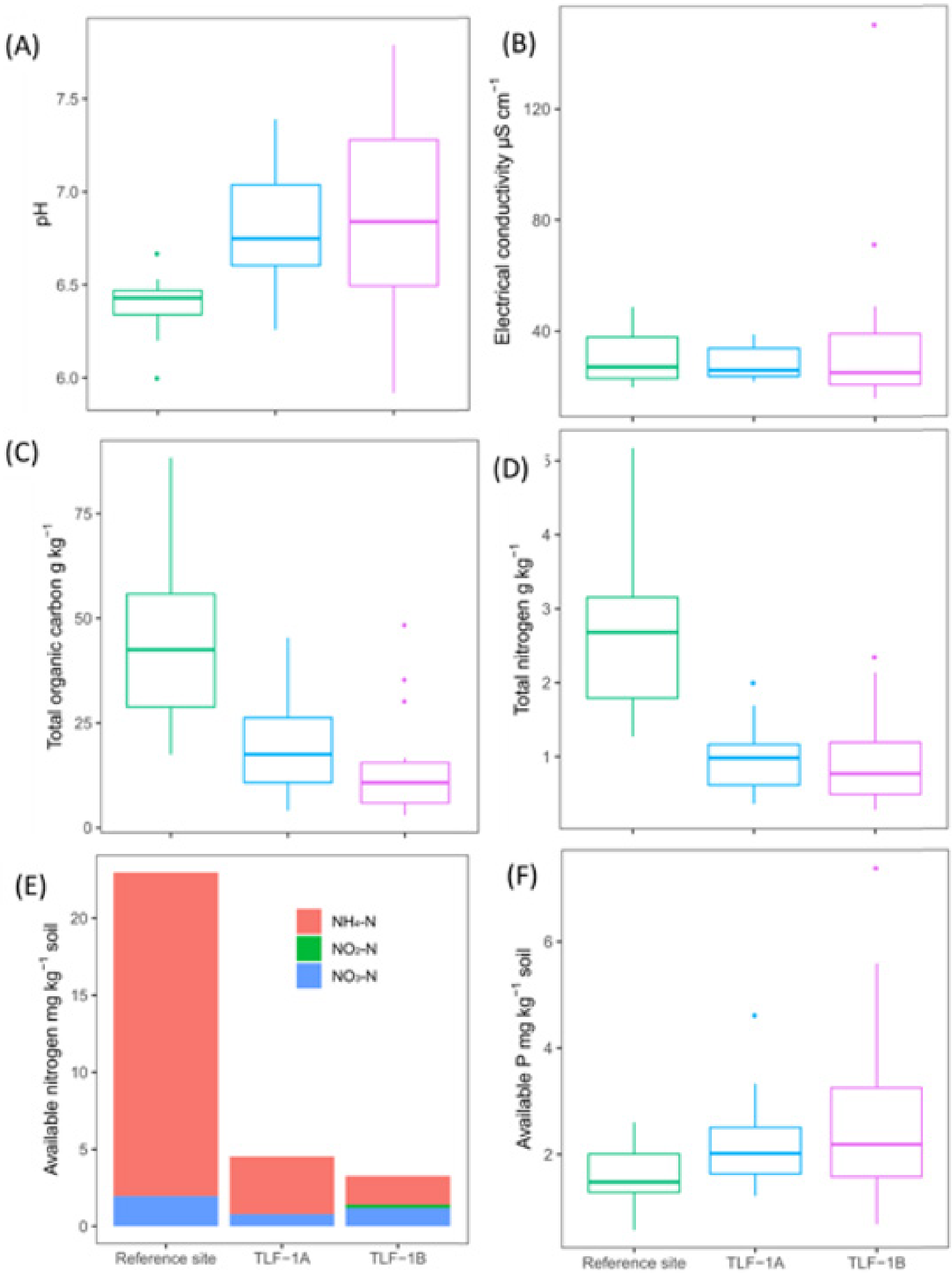


Figure 5-98: Selected soil chemical properties pH (A), EC (B), and nutrient availability, including total organic carbon (C), total nitrogen (D), Available N in the form of NH4+-N, NO2--N and NO3--N (E) and Available P (F) among reference Site 30, TLF-1A and TLF-1B.

5.4.3 ESR3 Understanding how to establish native terrestrial vegetation, including understory species

KKN title	Question
ESR3. Understanding how to establish native terrestrial vegetation, including understory species	ESR3A *How do we successfully establish terrestrial vegetation, including understory (e.g. seed supply, seed treatment and timing of planting)?*

5.4.3.1 Mine rehabilitation and revegetation methods

The establishment methods for revegetating most species on previously mined land generally include a combination of topsoil return, direct seeding, tubestock planting and/or volunteer colonisation. Which revegetation method/s are used often depend on the type of mine (eg. strip versus hard-rock), location and climate, the characteristics of the planting substrate available, the amount of seed available and/or allowed to be collected, and final land use objectives.

Vegetation is reintroduced to most strip-mines in the wet-dry tropics by both transport of propagules in fresh topsoil and by direct seeding, using a range of methods (from hand broadcasting to tractor mounted seeders to aerial sowing). Occasionally ‘enrichment’ planting of nursery-grown stock is used to increase the density of important species. The success of direct seeding at these strip-mines can be variable, but in general, with good topsoil handling techniques (minimising weed presence in the transported seed bank) and the use of appropriate seed mixes, good early establishment results have been obtained.

In contrast, on some hard-rock mines, direct seeding has been more problematic and unreliable compared to tubestock planting for establishing important, dominant species (Gordon *et al* 1995; Reddell and Hopkins 1994; Reddell & Spain 1995; Reddell & Zimmermann 2002). Hard-rock mines, such as Ranger, often do not have access to topsoil and are required to revegetate on mined substrate that can be barren and coarse, with near zero organic matter or fungi/microbial presence (*Section ESR7*). These characteristics combined with extreme and variable climatic conditions on the substrate surface, including high reflectance, ambient temperatures and fluctuating moisture levels, create a challenging environment for successful seed survival, germination and seedling persistence. Another limitation with direct seeding is the amount of seed required to establish vegetation at appropriate densities. Considering establishment from seed in the field is often very low (<10 % reported in Merritt & Dixon 2011), a significantly greater quantity of seed is needed for direct seeding as compared to tubestock planting. This can present another obstacle for mining operations where seed must be sourced from relatively small local provenances.

Tubestock planting can also accelerate the speed of ecosystem development. Revegetated plants need to quickly capture space and other resources, reach a certain size to be fire resilient, and have sufficient roots established at a depth to support better survival through harsh conditions. If plants are slow to establish and capture the site, resilience to weed invasion and fire can be significantly delayed, incurring greater maintenance requirements and costs.

Another passive establishment method that is common in mining revegetation is the 'volunteer colonisation' of species from surrounding environments, usually through dispersal by insects, animals and wind. These species often include grasses and fruiting species.

5.4.3.2 Historical Ranger ecosystem rehabilitation research

Over more than thirty years, numerous small-scale rehabilitation trials have been undertaken at Ranger Mine by ERA, SSB, CSIRO and other parties in relation to final landform morphology, revegetation and ecosystem establishment. All this research has culminated in an extensive body of applied techniques, designed to give confidence that the Ecosystem Establishment Strategy proposed for the closure of the RPA will result in a self-sustaining, long-term ecosystem.

A myriad of revegetation trials were undertaken at Ranger Mine between 1982 and 2002 (refer Table 5-45 and Figure 5-99). Almost all of these trials were discontinued at various stages, due to research programs finishing or the need by operations for additional waste rock storage areas as mining progressed. However, these trials enabled important lessons to be learned early and in turn influence subsequent trials. This historical knowledge and experience was used to inform the first Ranger Revegetation Strategy (Reddell & Meek 2004, Appendix 5.4). In 2001, Reddell and Zimmermann (2002) completed a comprehensive assessment of 11 earlier waste rock revegetation trials and identified a number of examples of success and failure, and addressed key issues that were highly relevant to ERA's revegetation strategy.

Table 5-45: Small-scale revegetation trials conducted on the RPA (1982 – 2002)

Project	Location	Date
First revegetation – germination trials	Waste rock piles	1982
Irrigation using RP2 water to 35 hectares of mature savanna woodland, along with fire exclusion	Ranger Mine lease	1984-1995
Fire trial	Waste rock piles	1986
1:5 slope erosion trial	Waste rock piles	1986-1987
Constructed wetlands experiments and aquatic plant transplantation	North-west seepage collector	1987-1988
Slope erosion trial	Waste rock piles	1988-1991
Wetland filter trials using RP4 water directed through 3 hectares of Djalkmarra Creek catchment	Djalkmarra Creek catchment	1988-1991
Topsoil spread. Hydroseeded (grass and fertiliser ± eucalypt seed). *Pandanus basedowii* planted	Waste rock piles	1988-1995
Topsoil trials ± fungi	Waste rock dump	1989
Revegetation trials and rainfall simulation	Waste rock piles	1990-1993
Direct seeding via tractor spread of 3 ha with pasture grasses	Northern waste rock dump	1991-1992
Hydromulching, tree and grass seed spreading, and aquatic plant transplantation (*Eleocharis, Nymphaea*	RP1 wetland filter	1991-1992

Project	Location	Date
and *Azolla*)		
Tubestocks ± inoculation. Various seed mixes, grass, aggressive and non-aggressive acacias. Planting on angle of repose batter west of plots	Ecological islands	1992
Topsoil trial	Waste rock piles	1992
Topsoil spread	RP5	1992
Application of hydromulch and grass seed to batter slopes facing Pit 1	Pit 1	1992
Tubestock planting, seedling and fungi trials	Northern waste rock dump	1992
Native seed and tubestock planting at tailings seepage sumps	North-western, north-eastern and southern seepage collectors	1992-1993
Tubestock and native tree seedling planting	VLGS (stockpile, north-west of the TSF)	1992-1994
Tubestock planting and fungi and varied density of nitrogen-fixing acacias. Inoculation of different seed mixes	RP4 irrigation	1992-1994
Seeded (grass and fertiliser with broadcaster)	Northern waste rock dump	1993
Log shelter/baits, termite baiting, pitfall trapping and casual soil fauna collecting	Northern waste rock dump	1993-1994
Native tubestock	VLG (west of Pit 1)	1993-1995
Native tubestock planted (grown by ERA and Djabulukgu Association)	Southern waste rock dump	1993-1997
Rhizobia trial	Waste rock piles	1994-1995
Effect of seed imbibition mulch, fertiliser *Scleroderma* and eucalypt applications rates	Southern waste rock dump	1994-1995
Angle of repose and 1:3 batter slopes. Randomised block hydromulched seed and *Pisolithus ectomycorrhizal* fungi	RP5	1994-1995
Establishment and growth on waste rock and magnesite to determine rate of self-thinning in high density eucalypt and non-aggressive acacias and slow release fertiliser	RP5	1994-1995
Effect of mulch type on germination and early growth	Waste rock piles	1994-1995
Native tubestock planting	Waste rock piles	1994-1996
RP1 wetland filter expansion and aquatic plant transplanting (*Nymphaea* and *Eleocharis*)	RP1 wetland filter	1995
Effect of mycorrhizal associations on survival and growth of *Eucalyptus miniata* seedlings.	RP5	1995
Direct seedling fertiliser and tubestock planting	Sleepy Cod Farm Dam walls	1995-1996

Project	Location	Date
Transplanting native tree root section trials	Southern waste rock dump	1996
Irrigation with RP4 water, introduced grasses (*Chloris gayana*), tubestock and seed mix trials	Waste rock dump	1996
Large-scale planting (seed and tubestock) composition, density, irrigation, mulch, fungi, fertiliser	Waste rock and Retention Pond	1996-1997
Hydromulch and native grass trials ± fertiliser	Northern waste rock dump	1996-1997
Elevated wetland trials, tubestock, seed and herb transplanting	Southern waste rock dump	1997
Measure indicators of rehabilitation success on the RPA. Fauna surveys and landscape function analysis	Ranger Mine lease	1997
Direct seeding	Old light industrial area road	1997-1998
Hydromulch with native grass seed and fertiliser applied to 3 kilometres of table drain	Main access road	1997-1998
Direct seeding, tubestock and fertiliser application	Northern waste rock dump	1997-1998
Hydromulch with native grass seed and fertiliser application	TSF waste rock dump	1997-1998
Direct seedling, tubestock and fertiliser application	Southern waste rock dump	1997-1998
Direct seeding and tubestock planting following deep ripping	Borrow pit north-west of Pit 3	1998
Seed (*Grevillea* spp.) under erosion control matting	RP5	n.d.
Removal and remediation/rehabilitation of road infrastructure. Tubestock and direct seeding trials of native woodland species on freshly cultivated waste rock	Various roads, tracks and former low-grade ore stockpiles	1998 - 1999
Grass direct seeding trials with and without fertiliser	Borrow pits	1999 - 2002

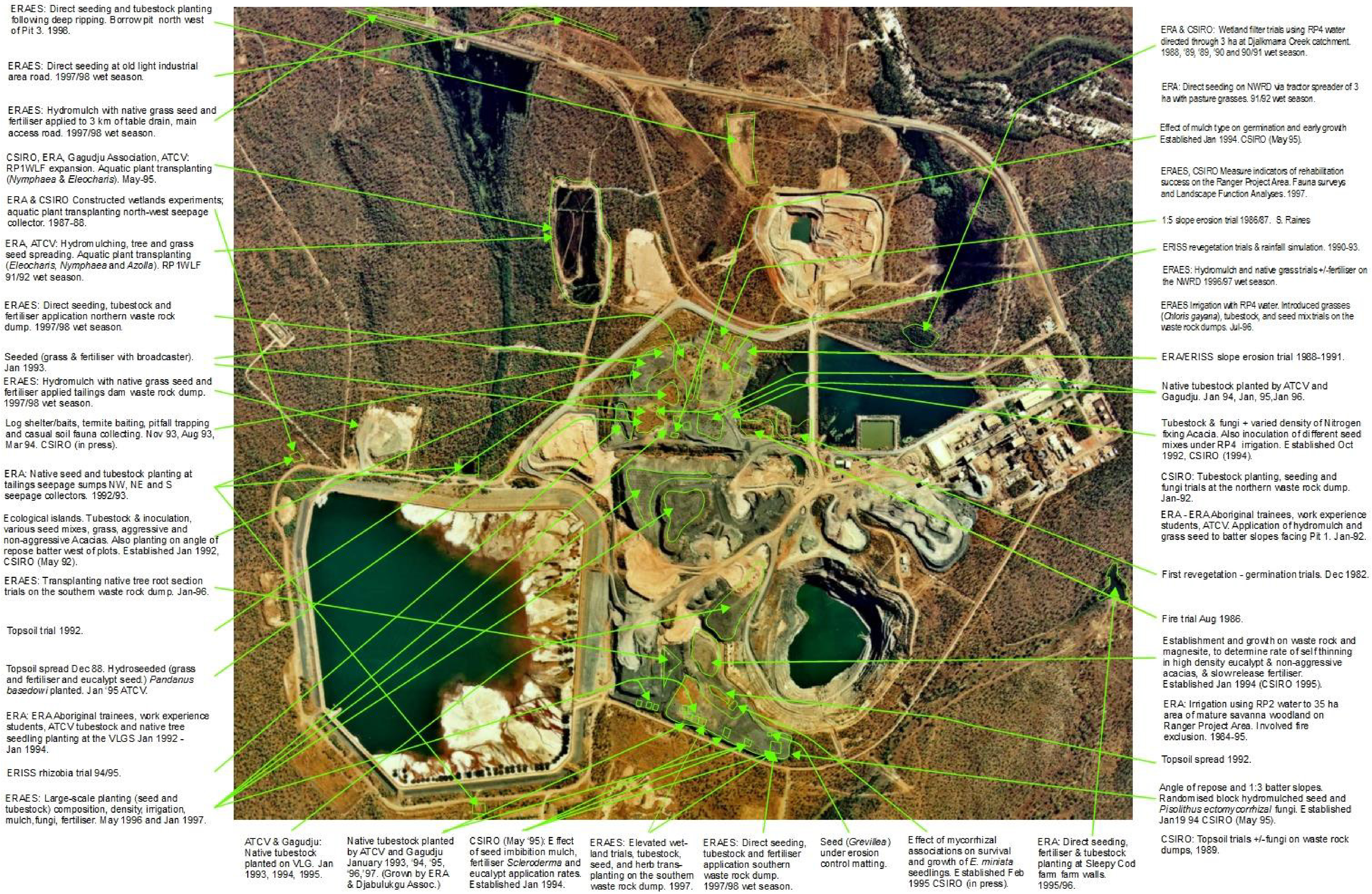


Figure 5-99: Revegetation conducted on Ranger Mine (1982 – 1998)

5.4.3.3 Ranger species establishment research program

In more recent years, the focus has been to expand on local species-specific knowledge as part of a Species Establishment Research Program (SERP). The SERP has been developed to systematically work through all of the potential revegetation species and identify the best way to establish them in the rehabilitation of Ranger Mine; it is informed by experience and a series of progressive trials to determine the most efficient and effective establishment method for each species (or for an indicative species for a group of related or similar species). The SERP is continuously working to improve understanding of practical aspects of species establishment. This knowledge has been captured in a SERP database and includes overarching themes of:

- seed management - including species phenology and seed collection, storage longevity, viability and germinability;
- propagation strategies - including seed treatments, potting materials, inoculation, plant growth, seasonality of propagation and alternative propagation methods; and
- revegetation and ecosystem development - including initial and intermediate establishment phases.

The revegetation species list has been considerably developed and modified over the last 15 years. In 2007, reference sites were used to develop a species list with relative densities for the revegetation of the TLF by ERA in collaboration with SSB, which and was provided to GAC for consultation in 2014 (Lu 2014). In 2015, the Mirarr developed a list of culturally important flora based on various criteria that pertain to an end use continuum, including but not limited to whether the plant is used as a cultural resource (e.g. for food, medicinal, aesthetic, material culture and/or ritual purposes), provides faunal linkages, and promotes biodiversity (Garde 2015). In March 2016, the flora and fauna closure criteria technical working group reached a consensus on a Ranger Mine revegetation tree and shrub species list, which was developed based on:

- previous analogue vegetation studies in undisturbed RPA and surrounding areas by SSB and ERA (125 studied analogue sites, including 10 sites from Kakadu NP with a land surface similar to the Ranger Mine final landform);
- culturally-important plant species, as identified by the Mirarr Traditional Owners in Garde (2015); and
- learnings from progressive revegetation activities and in particular the learnings from the TLF.

Over the last six years, the species list has further evolved based on consultation with CDU researchers and bininj ecology experts (Lu *et al.* 2017; Dr Sean Bellairs and Peter Christophersen *pers comm.* 2019) and recent reference site surveys. The ERA SERP database currently comprises 165 species (mostly terrestrial), including 21 overstorey tree species, 74 midstorey tree and shrub species, and 70 understorey species (or genus). The species included in the database will continue to be refined as outcomes from ongoing CRE work, revegetation trials, risk assessments, expert elicitation and further consultation with Traditional Owners are completed (including appropriate formal review by stakeholders).

To help focus research efforts, priority has been placed on tree and shrub species that are common and dominant in the surrounding landscape, therefore resulting in the majority of stems per hectare during initial revegetation, and on species that have been identified by Traditional Owners as important for re-establishment (Garde 2015, Cultural Reconnection Working Group *pers comm.* 2021, 2022). There is also a lot of research underway on how and when is best to establish understorey species, considering the important ecosystem services they provide and their significant contribution to species richness in the surrounding woodlands. Progress on the ERA SERP was presented during ARRTC46 in February 2021.

ERA has been working and collaborating with Kakadu Native Plants Pty Ltd (KNPS), a wholly bininj owned and operated business, for over 17 years on the progressive revegetation that has occurred both at Ranger Mine and Jabiluka. This supplier has extensive expertise on local ecosystems and plants, which has been invaluable for the seed collection, tubestock propagation and revegetation programs at Ranger (Section 9). The knowledge and expertise that has been shared by KNPS form an integral component of the SERP, particularly the seed and propagation knowledge base.

5.4.3.4 Seed knowledge

Provenance and use of seed collected within Kakadu NP

The use of seed collected only from within Kakadu NP ensures that the genetic make-up of the revegetation is consistent with locally adapted populations of each species and provides a buffer for adapting to future global change (Zimmermann 2013). To this end, a ‘conservative provenance zone’ has been adopted based on assessment of environmental factors, species distributions, taxonomy, present and past gene flow and species traits known to influence genetic variation in plants (Zimmermann & Lu 2015).

In 2011 to 2013, ERA conducted an extensive study investigating the provenance boundaries of the Ranger Mine in order to possibly extend the 30 km seed collection zone (Zimmermann 2013, Zimmermann & Lu 2015). The usefulness of genetic and non-genetic methods was assessed, and a non-genetic approach, based on the methods developed by FloraBank, Greening Australia and other experts in the field, was adopted. The method assessed environmental factors, gene flow and species traits known to influence genetic variation in plants and identified zones of least likely genetic variation. The resulting zones match the eco-geography of the Ranger Mine area and hence maintain the 'home site' advantage of local plants. Some genetic diversity that may be present in more distant seeds is welcomed, as it may allow plant populations to respond to environmental changes such as climate change (e.g. Prober et al. 2015). This 'composite provenancing' approach ensures increased genetic diversity whilst reducing the risk of genetic pollution and outbreeding depression.

The Atlas of Living Australia was identified as the most suitable and accurate environmental modelling tool, in the absence of fine-scale regional soil, vegetation and climate data. Environmental layers relevant to plant species distribution in the Top End (mean annual evaporation, annual precipitation, mean annual temperature, annual drainage, and topographic wetness index) were combined to predict a zone with a similar environment to the Ranger Mine, representing the Ranger Mine 'environmental provenance zone'. Investigations into revegetation species distributions found that each is well represented within the conservative provenance zone.

An assessment of potential gene flow indicated that there are no major geographic barriers within the Top End that may hinder the exchange of genetic material. As far as is known, there were no historical barriers in the Top End in the more recent geological past and the evolution in climate and vegetation was most likely uniform. Pollination takes place for the large majority of the investigated species not only by insects, but also by birds and bats, with most birds being generalists and hence being able to use other species as stepping stones between populations. Dispersal mostly takes place within 1 km of the source, but birds and bats can carry seeds over longer distances (e.g. 100 km).

Considering the abundance of birds, a continuous vegetation cover and that most revegetation species are common and widespread across the Top End, genetic exchange is likely to happen over large areas, if not the entire region. Any localised environmental variations that could cause genetic variation were eliminated by composite provenancing, which identified the 'environmental provenance zone' eco-geographically similar to the Ranger Mine. This was further narrowed by applying the conservative provenance zone. Seed collection guidelines further define and match the vegetation community and local environmental characteristics with the disturbed and created environments to be revegetated.

The seeds collected within the proposed conservative provenance zone (Figure 5-100) should be well adapted to the current conditions of the Ranger Mine, as well as provide sufficient genetic diversity to reduce inbreeding, promote the plants' adaptive potential and increase the resilience of the revegetation areas against moderate changes in climate. However, larger changes in climate may require seeds to be sourced from environments currently dissimilar to the Ranger Mine area, with the risk that they may not perform well under the current environmental conditions at the mine. The scope of changes in climate and associated risks for revegetation has a high degree of uncertainty at this point in time and should be reassessed in the future.

The outcomes of this study were presented to ARRTC and submitted to the GAC Board for endorsement. The GAC advised that "… after long and careful consideration… [the GAC Board] …are comfortable with seeds being collected for rehabilitation only within the borders of Kakadu" (Melanie Impey 2015, *pers. comm.*, 12 August). This makes provision for harvesting seeds from the southern part of Kakadu NP, where edaphic conditions are closer to the future conditions at the Ranger Mine under global climate change scenarios.

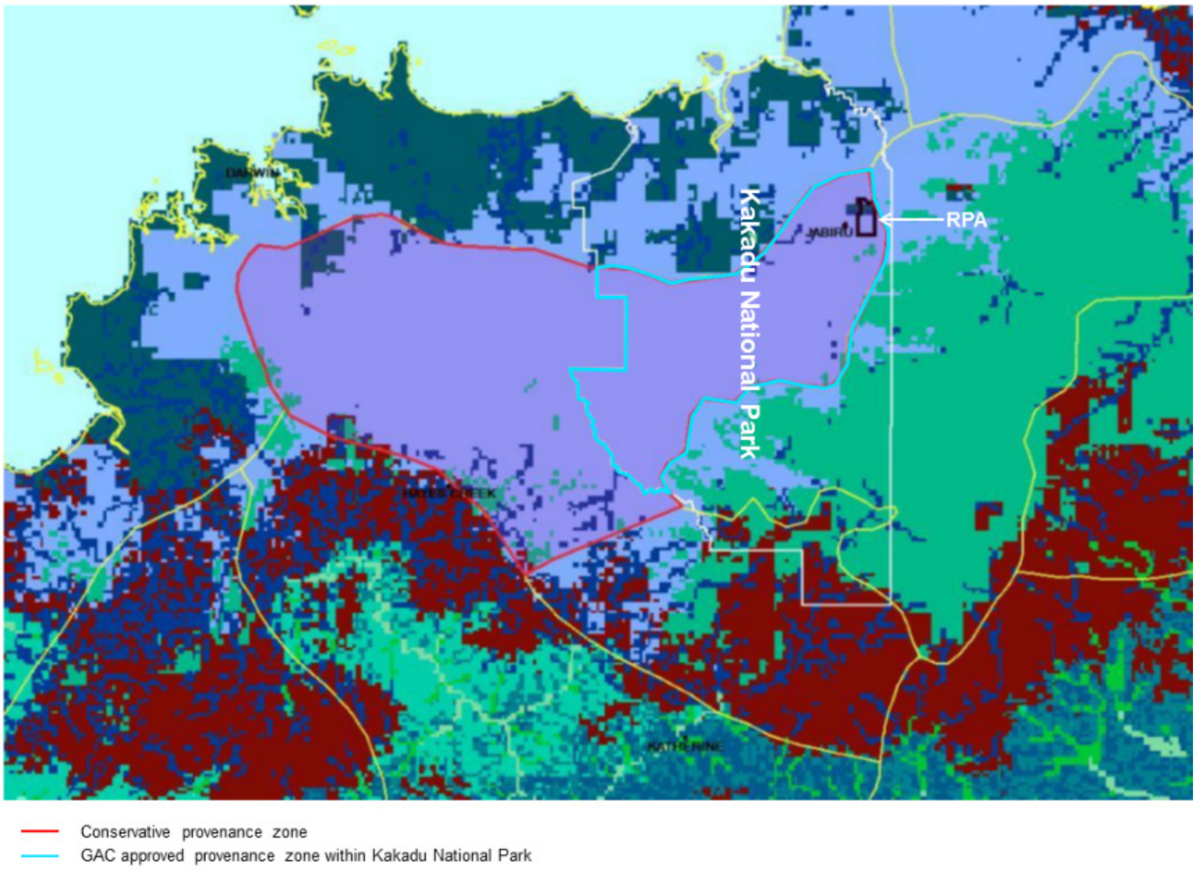


Figure 5-100: Proposed conservative provenance zone (bordered by the red line) and the GAC approved provenance zone within Kakadu NP (bordered by the blue line)

Species phenology and seed collection

Species flowering and fruiting periods are comprehensively documented in literature and field guides (Brock 2001; Crowder & Saggers 2010; Dunlop et al. 1995; Flora NT 2021; Fox & Garde 2018). However, many local species in Kakadu NP are variable seeders, some being highly reliable with year on year seeding whereas others only having ‘good’ seeding every few years (Brennan 1996; KNPS 2021 pers. comm). Another important consideration is when to time seed collection. If collected too early the seed can be immature and not fully developed, and if collected too late seed can be lost to natural dispersal, herbivory, insect or pathogen infection, or simply be too old. These factors can change annually depending on the prevailing weather and fire history, and some local species are more vulnerable to seed spoilage than others (KNPS per comms.). Carefully timed collection can ensure optimised seed quality and longevity (Pedrini et al. 2020). This is why knowledge on seeding behaviour (eg. extremely brief periods of ripe seed, extended periods of progressively maturing seed etc.), and local vegetation communities (eg. stands even relatively nearby can have different seeding times) is critical. KNPS use traditional knowledge, which is continuously developed by spending time on country and by performing reconnaissance surveys and *in situ* seed cut tests, to ensure that seed is collected at the best possible time.

Seed processing, storage, viability and germinability

Sub-optimal preparation of seed can impact viability and storage longevity (Frischie et al. 2020). After collection, seed lots are carefully processed (e.g. cleaned, purified, dried etc.) so that excess material is removed and moisture content is reduced. This ensures that potential vectors for seed spoilage, such as pests and fungi, are minimised, whilst also simplifying the storage and later seed management process. Each species has a specific processing method guided by current literature and standards, and further developed by KNPS from years of experience. Once the seeds are processed they are given to ERA, at which time the seed is generally dried a second time in a climate-controlled room prior to storage.

It is well understood that seed longevity in storage is highly dependent on seed moisture content and storage temperature (De Vitis et al. 2020). ERA have invested in two secure, climate-controlled storage rooms, as well as a short-term storage room for species that are generally used within a year (eg. grasses). The specific conditions of storage have been based on industry best practice and historical seed storage experiments. A small portion of the revegetation species are considered recalcitrant, with seed that is unsuitable for storage; this seed, deemed ‘perishable’, requires propagation immediately after collection for optimal germination.

ERA have periodically commissioned seed testing to help determine the viability, germinability and storage life of the revegetation species and individual seed lots (Figure 5-101). Some of this testing has been to interpret direct seeding trial success (e.g. TLF in 2008, understorey trials in 2018 and 2020 etc.), and others have been for targeted research, quality control and/or risk management purposes. A comprehensive research project was conducted by CDU (Bellairs & McDowell 2012), titled *Seed biology research to optimise germination of local native species to support the rehabilitation of the Ranger mine site 2006 -2011.* The project investigated viability, germination, dormancy and storage longevity of over 70 native species that were being considered for revegetation at the time; it also aimed to develop protocols for species that had been identified as being difficult to germinate. The majority of species studied were native understorey, because of “the death of seed biology information available for shrubs and ground cover species compared to the greater information available for trees” (Bellairs & McDowell 2012).

At the end of 2019, ERA commissioned CDU to perform viability (through tetroazolium chloride staining) and germination testing on over 80 seed lots from 49 species to assess the quality and longevity of their stored seed. Generally, the species that will make up the majority of stems in future Ranger revegetation (*Corymbias, Eucalyptus* and *Acacias*) maintained viability and germinability for well over five years in storage, with some thirteen year old seed lots still achieving 94% germination. Other important species such as Kakadu Plum (*Terminalia ferdinandiana*) were still achieving high germination after three years in storage, but not after eight. This comprehensive testing confirmed that the ERA storage facility conditions are appropriate for preserving seed longevity of key, dominant revegetation species. It also provided updated metrics to enter into the Seed Management and SERP databases. ERA is in the processes of setting up an ongoing, periodical seed testing campaign.

During propagation, germination data is carefully recorded for each seed lot and is fed back into the Seed Management and SERP databases. This ensures that seed quality and longevity knowledge is continuously developed and updated, and that each seed can be used optimally.

Figure 5-101: Replicate from seed testing germination trials (*Heteropogon triticeus*)

Seed management and SERP databases

Each seed lot has information recorded and stored in the *ERA Seed Management Database*. Collection information includes an identification code, date, location (including GPS coordinates), collector, method, and amount of seed collected. Seed quality information includes mean individual seed weight, purity, viability and laboratory germinability (if tested), and nursery germinability. This information is then used to quantify the approximate amount (by weight or individual seeds) of total, viable, and germinable seed in storage.

Species-specific seed knowledge captured in the SERP database includes:

- flowering and fruiting periods;
- seeding behaviour (including annual variability and seed maturing periods);
- vulnerabilities to spoilage (eg. weevils, mould, cockatoos etc.);

- optimal period for seed collection;
- collection method(s);
- quantities generally collectable in one effort;
- collection ease and risks;
- processing method;
- seed storage longevity;
- general viability; and
- general germinability.

5.4.3.5 Propagation knowledge

Potting materials

ERA are currently investigating the potential use of plantable, biodegradable pots (biopots) as an alternative to traditional nursery tubes at Stage 13.1 and Pit 1, for reasons outlined below.

Standard plastic nursery tubes

Nursery tubes were used at Ranger for all tubestock planting pre-2017, including the TLF. The obvious benefit of using nursery tubes is that they are the commercial standard, meaning there is a wealth of knowledge, experience, research and published literature involving the use of nursery tubes. Additionally, KNPS have well over a decade's worth of experience growing tubestock for ERA using nursery tubes. However, there are still concerns that nursery tubes may not be the best option for the large-scale revegetation of Ranger mine.

Issues with root growth in nursery tubes is well documented, some of which are associated with the impermeable nature of the pot sides (eg. root circling, even in square pots). Many of these root development issues can be exacerbated by prolonged bench time. Although the full-scale revegetation of Ranger is carefully planned and scheduled, unexpected delays or interruptions can occur (as has been demonstrated by the COVID-19 outbreak). When TLF construction was delayed for two months due to material sourcing difficulties and road inaccessibility, the tubestock were held in the nursery for longer than anticipated. By the time the TLF was ready for revegetation, many of the tubestock were pot-bound and some plants had to have portions of their roots removed to facilitate depotting, as the roots had grown through the bottom of the tube (Daws & Gellert, 2010). Conversely, if an area of the final landform is available ahead of schedule it may be advantageous to plant tubestock earlier than planned. There is a risk with nursery tubes that if the roots are underdeveloped, they may not hold the potting material adequately and loss of material may occur during planting.

There are also potential overheating issues with traditional nursery tubes. They are black which absorbs heat and have solid sides, which although improves water efficiency, does not allow for evaporative cooling of the potting substrate. These factors can cause the substrate in nursery tubes to heat up. Root growth stops when temperatures exceed species-specific thresholds, and root death can occur if exposure to these temperatures is prolonged. The risk of pots overheating is very real at Ranger mine; it is not uncommon to have > 40 °C days during the October – December period. The most dangerous time for nursery tubes to overheat is during planting when the pots are sitting exposed on the waste rock surface, which can reach well over 50 °C (Daws & Poole, 2010).

The process of removing the plant from the nursery tube can be time consuming, particularly given the care that needs to be taken to ensure the plant is not damaged. Although depotting ideally only takes an additional few seconds, this still equates to a significant amount of time when extrapolated for over 1 million stems. Additionally, the process can often take longer depending on the species and how long the plant has been in the pot. Even when performed carefully, depotting can lead to loss of roots and potting material. Given the extreme conditions of the waste rock final landform, tubestock need to be in the best condition possible to ensure their survival. High levels of transplant shock have been observed historically at Ranger mine when depotting was performed incorrectly by inexperienced planting crews (per comms. Dr Ping Lu).

Lastly, although it is not a factor that impacts the revegetation success of Ranger mine, another consideration is the excessive plastic involved when using nursery tubes. The tubes can be reused to some extent, however given that hundreds of thousands of plants will need to be grown at the same time during peak revegetation, reuse will be limited.

Biodegradable pots

Plantable biopots can be made from a wide range of organic materials, such as rice straw and hulls, peat and wood fibre, coconut husk, paper, poultry feathers and cow manure. In theory, plantable biopots are an attractive option for large-scale tubestock revegetation as they eliminate many of the risks outlined above. However, the use of biopots introduces new factors that need considering such as their durability, water retention, impact on plant growth, rate of field decomposition and plant field performance (Evans et al. 2010; Sun et al 2015). Furthermore, revegetation of mine waste rock in the wet-dry tropics using biopots is (at this stage thought to be) unprecedented. The majority of research conducted on biopots concerns the production of agricultural and horticultural species planted into natural soil; therefore, the performance of native savanna species in waste rock substrate will inherently be different.

The plantable biopot that has been sourced for trials at Ranger Mine is a slotted, square rice-hull pot. Wood fibre pots were also briefly investigated, however those trials have discontinued due to their lack of durability and wet strength during nursery propagation.

Pots need to be durable enough to last 2 – 6 months on a nursery bench, where they are frequently watered and handled. They also need to survive transport to the planting site. Solid, compostable rice-hull pots have been found to be amongst the strongest types of biopot, with vertical and lateral strength (dry and wet) comparable to plastic nursery tubes (Evans et al 2010). The plantable rice-hull pots are still highly durable, but differ to the solid rice-hull containers in that they use a less resilient binder and contain slots, which allows them to decompose in the field (Cypher & Fulcher 2015a; Summit Plastic Company 2020). For the purposes of Ranger Mine revegetation, the slotted rice-hull pots have been found to be suitably durable for nursery propagation and planting.

Most plantable biopots have either porous or slotted sides which aid field decomposition. Although this has an advantageous cooling effect, it also means the potting substrate has a faster rate of drying than nursery tubes. Depending on the type of biopot, they can require up to three times the amount of nursery irrigation as plastic tubes (Cypher & Fulcher 2015a). Slotted rice-hull pots are considered to have moderate water requirements, needing similar or slightly more water than nursery tubes depending on the species that are being grown (Cypher & Fulcher 2015b). At Ranger, the nursery irrigation needs of plants in plastic and biopots has been found to be similar. However, plants in biopots have been disproportionally impacted by nursery irrigation failure incidents that occurred at the end of 2019 and mid-2021, so much so that considerable biopot stock was unsalvageable after both events. This was likely due to the biopot substrate drying faster than the solid-sided plastic pot substrate because of their slotted-sides and smaller size.

Studies comparing biopots to nursery tubes in regards to plant growth have had mixed results depending on the pot type and species being grown; however overall, biopots and nursery pots generally appear to have similar results in regards to plant growth (Conneway 2013; Cypher & Fulcher 2015a; Nambuthiri et al 2015). A wide range of local species have been grown at the ERA nursery since 2019, with no obvious differences in seedling condition and growth between the two pot types when grown under optimal conditions. However, during irrigation incidents (as discussed above) or when planting was delayed and seedlings spent additional time on the nursery benches, biopot plants were in poorer condition than same-aged plastic pot plants.

Field decomposition is an important component of what makes biopots truly ‘plantable’. Slow decomposition post-planting may cause restricted movement of water and nutrients, poor root formation, and impede the plant’s ability to anchor and perform (Nambuthiri et al 2015). The different type of materials used to create biopots can impact their rate of field decomposition. Biopots high in cellulose, such as cow pat, have been found to decompose faster than biopots high in lignin, such as coconut fibre (Evans et al 2010; Sun et al 2015). It has also been suggested that the high levels of nitrogen present in cow pat containers may increase microbial activity, thereby increasing decomposition (Evans et al 2010). Slotted rice-hull pots have been found to have amongst the lowest rates of field decomposition (Conneway 2013; Sun et al 2015).

The location where biopots are planted can also significantly influence rate of decomposition, in some cases more than the material of the biopot (Sun et al 2015). Temperature, rainfall, soil pH and moisture, and microbial activity can highly impact biopot decomposition rates (Cypher & Fulcher 2015a; Evans et al 2010; Nambuthiri et al 2015; Sun et al 2015). The plant species grown in the biopot may also influence rate of decomposition (Conneway 2013; Sun et al 2015).

There is no known available information on field decomposition rates of biopots in mine waste rock. ERA has used rice-hull biopots for infill planting of understorey species on the TLF in 2018 and 2020, where opportunistic excavation of some plants showed significant pot decomposition. However, this planting was conducted on a 10-year-old revegetated waste rock landform, which has considerably different conditions (eg. increased shade and organic matter) to a newly formed landform. The species infilled were also predominately grasses, which have fibrous roots rather than taproots, therefore could easily spread and establish through the slotted biopot sides. Being aware of the potential risks to root formation from slow biopot decomposition, a step was added to planting procedures to 'crack' the biopot once it is in the planting hole, before substrate is infilled, to minimise potential root restriction. Stage 13.1 and Pit 1 provide opportunities to investigate biopot decomposition rates and root formation.

Despite the difference in decomposition rates, plant establishment and growth post-transplant have been found to be relatively similar across different biopot types, and compared with control plants grown in nursery tubes (Conneway 2013; Sun et al 2015). Preliminary field results from Stage 13.1 and Pit 1 are discussed in the revegetation section below.

Seed treatments, germination and growing seedlings

There has been several extensive research projects investigating treatments to improve seed germination of native species for Ranger revegetation (Ashwath et al. 1994; Bellairs & McDowell 2012). A variety of treatments were examined depending on the species, including different medias (filter paper, sand and vermiculite), heat (submersing seed in water at various temperatures), smokewater, soaking or leaching, sulphuric acid (H_2SO_4), gibberellic acid ($C_{19}H_{22}O_6$), nitrate (NO_3), scarification (including nicking, drilling, rubbing on sandpaper, and mechanical stirring of seed with sand), cleaning (removal of mesocarp), partial or full endocarp removal, as well as combinations of treatments. This historical research has been the foundation of seed germination trials at Ranger, with treatments further refined and developed by KNPS using traditional knowledge.

Until recently, propagating and planting of tubestock has only been performed for revegetation in the wet season, which is standard industry practise. A unique challenge for Ranger Mine is the requirement for year-round revegetation during peak rehabilitation periods (originally 2024 / 2025 before reforecast). Efforts over the last three years have been focussed on 'unseasonal trials', to familiarise with germinating seeds and growing species during different times of year (eg. during dry, cooler months when seed germination and plant growth are typically very slow, or completely dormant). Two years of unseasonal propagation trials found that some species significantly benefit from being placed in a greenhouse (Figure 5-102), either for the initial germination period or for the entire growing season, during certain months of the year. Other species simply require sowing a few weeks earlier than usual, and many are not impacted at all by unseasonal propagation.

Figure 5-102: Greenhouse tunnel trials at the ERA Nursery

Other work that is being undertaken is refining optimal growing times for each species. Previous experience has shown that prolonged nursery bench time can result in 'leggy' seedlings that are root bound, nutrient stressed and more prone to parasites, herbivory and fungal attacks. Other times, seedlings that were initially considered 'young' and small actually performed better than standard aged seedlings, likely because of a better root-shoot ratio which decreased the seedling's initial water demand after planting (Dr Ping Lu 2019 *pers comms*). This concept of 'standard-aged verses younger' seedlings is being investigated at the large-scale revegetation trial on Pit 1. If younger seedlings are found to perform similarly or better than standard-aged seedlings there is the added benefit of freeing up nursery bench space during peak revegetation, potential helping take pressure off the schedule.

Tubestock grown at the Ranger Mine nursery are fully exposed to the sun and wind during the entire propagation process. This has resulted in 'hardy' plants better suited to the harsh moonscape environment of the waste rock FLF. ERA have trialled 'hardening off' the seedlings further by slowly reducing irrigation in the weeks leading up to planting, however this has had unpromising field results (discussed in revegetation section below).

Tubestock inoculation

Microorganism inoculation has become standard practice in many commercial nurseries due to the vital role microbes perform in plant nutrient acquisition. The importance of symbiotic microorganisms for the revegetation of post-mining land has been well documented (Johnson & Milnes 2007; Chandrasekaran et al. 2000; Corbett, M 1999). Mycorrhizal and Rhizobium inoculation of tubestock has been found to alleviate nutritional problems and promote plant growth during early establishment (Reddell & Zimmerman, 2002). *Eucalyptus miniata* tubestock had significantly improved establishment on Ranger waste rock when inoculated with *Pisolithus* and *Laccaria*, or when 'locally contaminated' by *Nothocastoreum* (Gordon et al. 1997; Reddell et al. 1999). Inoculated seedlings had significantly greater shoot growth and leaf phosphorous concentrations than uninoculated seedlings, and seedling dry weight was found to increase consistently with levels of fungi colonisation (Reddell et al.1999). Hinz (1997, as reported in Corbett M 1999) also found that *Nothocastoreum* mycorrhizal associations were important for *E. tetrodonta* growth and development at Gove mine. Inoculation of Rhizobium has also been found to alleviate Acacia seedlings' nitrogen deficiencies when growing on Ranger waste rock (Reddell & Milnes, 1992).

From their review of revegetation research at Ranger Mine, Reddell and Zimmermann (2002) concluded that "inoculation of framework species with spores of ectomycorrhizal fungi would seem a very cheap and effective way of partially alleviating nutrient limitations to seedling establishment on the waste rock stockpiles" (note: 'framework species' are species that are ubiquitous in the *Eucalyptus tetrodonta-miniata* dominated savanna woodland, that generally will be actively introduced at higher densities across the whole Ranger Final Landform). Tubestock used for the revegetation of the TLF and Jabiluka were inoculated using locally collected fungi, and all tubestock in the last four years have been inoculated using local and/or commercial microbes, other than at Stage 13.1A where a combination of different inoculation treatments were explored (Table 5-46).

Alternative propagation methods

As discussed previously, a small portion of the revegetation species have perishable seed and require immediate sowing after collection (typically during early wet season); this presents a challenge for year-round revegetation. ERA have been working with KNPS to develop alternative propagation methods for these species. One of these alternatives has been to hold the seedlings longer in the nursery, repotting into larger pots as needed to minimise stress and allow the plant to continue developing as normally as possible. Species that have been propagated and planted at Stage 13.1 and Pit 1 using this method include bushfoods such as Bush Apples (*Syzygiums*), Cocky Apple (*Planchonia careya*), White Currant (*Fluggea virosa*) and *Breynia cernua*.

SERP database - Propagation

Species-specific propagation information summarised in the SERP database includes:

- seed treatments;
- general nursery germinability, with consideration of different seasons;
- required growing times, with consideration of different season;
- propagation issues (e.g. susceptible to herbivory, low germination in the dry season, perishable seed); and
- controls (e.g. insecticide, greenhouse germination in the dry season, older plants in larger pots).

Table 5-46: Stage 13.1A propagation treatments and rationale

Treatment		Rationale
1- 4	Different sources of microbes [1] local microbes [2] no microbes [3] commercial only [4] combination of local and commercial microbes	These treatments are to assess whether tubestock seedlings have improved growth/survival when inoculated with microbes from different sources. Commercially produced microbial additives for potting mix are becoming routinely used by nursery and horticultural industries. Locally sourced microbes may perform better than commercial microbes because they are adapted to the environmental conditions of Kakadu and have evolved with the plant species that are being used for revegetation. However, there is concern that inoculation with a local microbe mix sourced from inside the RPA (which historically has been frequently disturbed by fire) will not have sufficient quantities or diversity of micro-organisms. It may be that a combination of local and commercial microbes are needed for improved plant growth and survival.
5	Plastic nursery tubes (50 x 120 mm)	Although nursery tubes are the commercial standard for revegetation, past experience at Ranger suggests biodegradable pots may be a preferable option as they eliminate the need to depot and will speed up planting.
6	Irrigation “hardening off”	By slowly reducing the frequency of watering a few weeks before transplanting, the tubestock may be better adapted to ‘cope’ with the harsh field condition of the final landform.

5.4.3.6 Revegetation

The revegetation trials conducted over the last decade have continued to reinforce many aspects of the first ARRTC-endorsed Ranger Revegetation Strategy (Reddell & Meek 2004, Appendix 5.4), which was first formed over 15 years ago based on research conducted in the 80s, 90s and early 2000s. However, the current ERA Ecosystem Establishment Strategy continues to evolve from further propagation and revegetation experience. Some of the key learnings from recent revegetation trials (discussed in greater detail in the following sections) include:

- The final landform growth medium layer will be predominately waste rock material with no purposely mixed laterite incorporated as was previously considered (over a decade ago). This is due to: 1) a lack of suitable laterite material of sufficient quantity for the final landform; 2) vegetation performing well on waste rock only substrates in terms of survival and establishment; and 3) areas with high proportions of laterite material showing higher risk of weed infestation;
- The majority of revegetation will be performed through tubestock planting. In almost all cases, tubestock areas have out-performed direct seeded areas in terms of plant survival, growth, stem density, species diversity, production of flowers and fruit, and recruitment; and
- Irrigation with be installed prior to revegetation to ensure seedlings can be watered during the first few months following planting, regardless of season, as initial plant survival on waste rock is significantly influenced by water availability.

Trial Landform

The TLF has been continually monitored for over a decade to assess revegetation performance and ecosystem development on waste rock-only and waste rock/laterite mix substrates (Figure 5-103 and Table 5-47). A range of trials and management actions have been undertaken on the TLF during this time (Table 5-48).

Table 5-47: TLF Permanent Monitoring Plot details

Plots	Substrate Type	Establishment Method
0 – 4	Waste rock only	Tubestock
5 – 9	Laterite mix (5m depth)	Tubestock
10 – 14	Laterite mix (2m depth)	Tubestock
15 – 19	Waste rock only	Direct seeding
20 - 24	Laterite mix (2m depth)	Direct seeding
25 – 29	Laterite mix (5m depth)	Direct seeding
30 – 34	Waste rock only	Tubestock & Direct seeding
35 – 39	Laterite mix (2m depth)	Tubestock & Direct seeding
40 - 44	Laterite mix (5m depth)	Tubestock & Direct seeding

Figure 5-103: Trial Landform layout from northwest to southeast are sections 1A & 1B (waste rock only) and 2 & 3 (waste rock / laterite mix). Includes 15 x 15m permanent monitoring plot locations

Table 5-48: Vegetation establishment activities conducted on the Ranger Mine TLF, 2009 – 2020, not including routine weed management

Month/Year	Action	Details	Reference
March 2009	Tubestock planted on the TLF	1473 tubestock planted in section 1A, 3029 planted in section 3 – each with 21 g slow release fertiliser tablet	Daws & Gellert (2010)
July 2009	Direct seeding of TLF (irrigated sections)	Seed mixes, made up of 31 species, sown at a rate of 3 kg ha^{-1} in sections 1B and 2	Daws and Poole (2010)
December 2009	Direct seeding of TLF (unirrigated sections) Fertiliser application	Direct seeding of the northern edge in sections 1B and 2, using the same sowing rate and species mix as the previous areas 50 kg ha^{-1} of Osmocote Plus to whole landform – applied at the base of tubestock and broadcasted in direct seeded areas	Daws and Gellert (2011)
January 2010	Infill tubestock planted	699 tubestock planted in section 1A, 1317 planted in section 3 – each with 21 g slow release fertiliser tablet	
November 2010	Fertiliser application	50 kg ha^{-1} of Osmocote Plus to whole landform – applied at the base of tubestock and broadcasted in direct seeded areas	
January 2011	Infill tubestock planted	1449 tubestock planted in section 1B, 2432 planted in section 2 – each with 21g slow release fertiliser tablet	Gellert (2012a)
January 2011	Understorey trials	Five grass species were sown in section 1A and 3	Gellert (2012b)
January 2012	*Xanthostemon* tubestock planted	Approximately 300 planted in the track between sections 1A and 1B; 75 planted in section 3	Gellert (2013)
November 2012	Understorey trials Fertiliser application	Seven grass species were sown in section 1A Small handful of Osmocote applied to each of the Jan-2011 infill planted tubestock. Smaller amount applied to direct-seeding plants on an ad-hoc basis	Gellert (2013; 2014)
May 2016	Burn	Cool burn of the laterite mix sections (2 and 3)	Wright (2019a)
April 2018	Understorey direct seeding trial	Five understorey species were sown in sections 1A and 1B with six amelioration treatments	Parry et al (2022)
June 2018	Understorey tubestock trial	Five understorey species were planted in sections 1A and 1B	
January 2019	Understorey planting in 'islands'	Nine understorey species that were grown in 2018 nursery trials were planted in 'islands' on sections 1A and 1B – some with litter	NA
June 2019	Burn	Cool burn of the laterite mix sections (2 and 3)	Wright (2019b)

Month/Year	Action	Details	Reference
February 2020	'Secondary' introductions	Eighteen species tubestock planted (10x understorey and 8x midstorey/overstorey), and seven understorey species seeded in patches with and without added mulch (21 species total, mostly 1A and 1B)	TLF Research and Monitoring Plan 2020 – 2026
February 2020	Understorey direct seeding trial	Twelve understorey species were sown in section 1A in plots with and without naturally occurring organic matter	
December 2021	*Xanthostemon paradoxus* direct seeding trial	Approximately 300 seeds per site at 40 sites across sections 1A and 1B	NA

Overstorey and midstorey species

Survival and establishment

Plant mortality is often highest in the first few months following planting, as the seedlings recover from any transplant shock and adjust to the new, harsher field conditions. At the TLF, initial mortality of the 2009 tubestock was very high. Overall survival after six months was 40% in section 1A and 36.3% in section 3 with irrigation; this was still significantly greater than the non-irrigated areas, which had 13% and 22.7% survival in 1A and 3 (Daws & Gellert 2010). It should be noted that there were issues in the 2009 planting relating to tubestock quality and irrigation reliability that may have contributed to this high initial mortality. Overall initial survival was considerably better for the tubestock planted in January 2010, with 73.6% and 55.3% survival in the irrigated areas of 1A and 3 eight months after planting (Daws & Gellert 2011). Surprisingly, survival in the non-irrigated areas was not significantly different to the irrigated areas; this is presumably because of the high and consistent rainfall between January – April in 2010, which was 16 % above the mean for that period (Jabiru Airport, Bureau of Meteorology 2020) (Figure 5-104) (Daws & Gellert 2011). Over 109% more rainfall was delivered in March and April 2010 compared to the same period in 2009 (Jabiru Airport, Bureau of Meteorology 2020). These results clearly demonstrate that annual rainfall variability can have a significant impact on initial tubestock survival, and that irrigation is critical to avoid complete revegetation failure in the event that Jabiru experiences a poor wet season.

Initial results from the TLF direct seeding appeared promising. Although sowing was performed during the dry season, a considerable number of seedlings emerged in both sections of the TLF (approximately 25% greater density in the waste rock only substrate). Interestingly, the irrigated seeding in July 2009 was significantly more successful than the non-irrigated seeding in December 2009, despite the above-average rainfall over the 2009/2010 wet season (Daws & Gellert 2011). It's possible that the lower temperatures experienced in July were actually beneficial for germination, as the waste rock substrate surface can reach well over 50°C in the heat of the day during the build-up. However, it is likely that the consistent irrigation also contributed to the initial success of the July seeding.

Whilst the TLF direct seeding seemed successful in the first year due to the high initial stem density, species compositions were skewed due to the different rates of germination. In both sections *Acacia sp.* and *Terminalia* were amongst the more 'successful', with many of the framework Myrtaceae overstorey species germinating at lower rates (Daws & Gellert 2011). Within 18 months of seeding, infill planting was required to improve both sections' species compositions and stem densities.

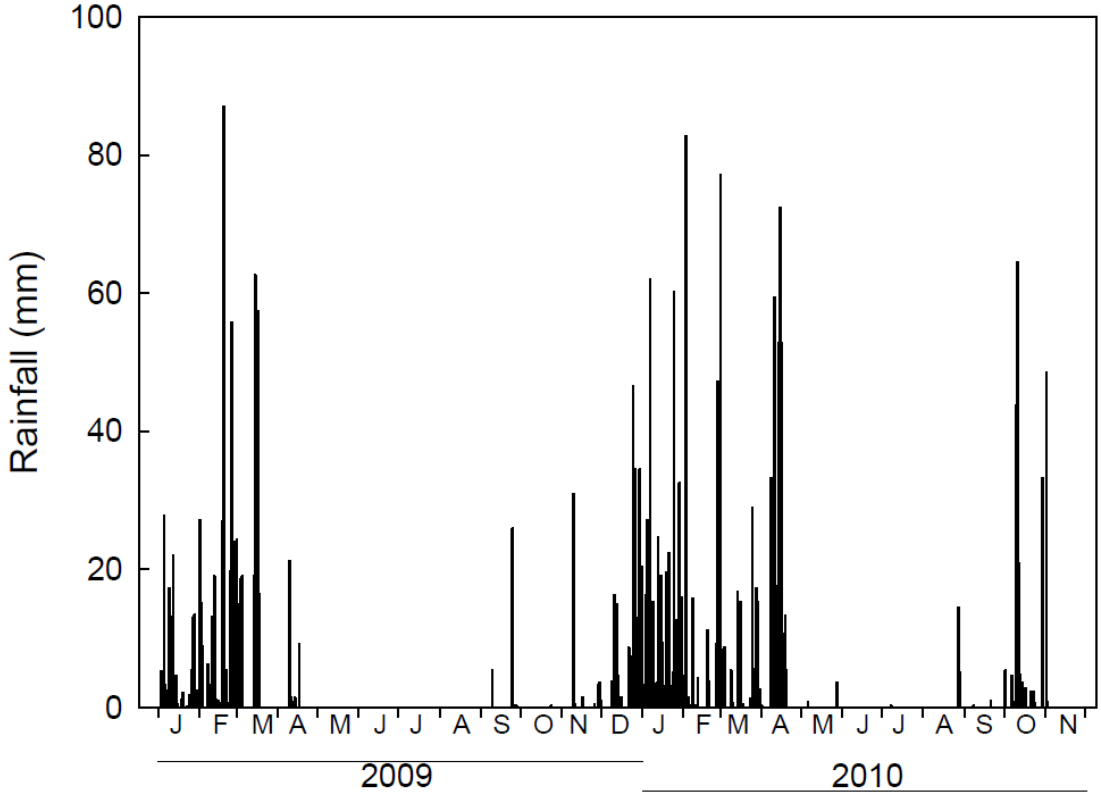


Figure 5-104: Daily rainfall for 2009 – 2010. Data up to 17 April 2009 from Jabiru Airport (Bureau of Meteorology): subsequent data from the TLF.

Overall, 39 of the 42 tree, shrub and palm species that were planted or direct seeded on the TLF are still present in 2022. Two of the species which completely failed to establish, *Erythrophleum chlorostachys* and *Stenocarpus acacioides,* were only direct seeded; *E. chlorostachys* germinated in section 2 but failed to persist beyond two years, and *S. acaciodes* seed failed to germinate despite the seed having ~94% viability (Daws & Gellert 2011). The other species that was actively introduced that is no longer present is *Grevillea pteridifolia,* which initially established really well but began dying out in 2018; the last large adults died in 2021, and although some small recruits were observed for this species, they failed to persist through the dry season. *Grevillea pteridifolia* typically occur in low lying and seasonally inundated areas, or near permanent freshwater streams, so it is likely that the harsh conditions on the TLF were not suitable for this species. All of the other midstorey and overstorey species actively introduced are still present on the TLF, however some have disappeared from one or more sections of the landform over time, and others have persisted but with very few individuals (*Jacksonia dilitata*, *Petalostigma pubescens* and *Owenia vernicosa*).

The full TLF survey in 2019 found that mean survival after ten years in the tubestock planted areas is relatively low (32 ± 4.4% in section 1A; 18 ± 3.3% in section 3) (Figure 5-105). This is partly due to the high initial mortality rates of the 2009 tubestock and the shorter-lived species senescing in recent years (e.g. some of the *Acacias* and *Grevilleas*). One of the species that had particularly low survival during the revegetation of the TLF was *Xanthostemon paradoxus.* Mortality was extremely high in the six months following planting (over 95 %) which prompted a master's research project. It was found that *X. paradoxus* tubestock survival and growth was significantly improved with shading, likely due to less light and reduced heat stress (Gellert 2014). These results indicate that this species may be better suited for introduction once the overstorey has had time to develop canopy and provide shade, therefore it has been delegated to a 'secondary introduction' species.

The species with the greatest survival on both sections of the TLF is *Eucalyptus tintinnans*. This species naturally grows on rocky ridges and appears well adapted to the Ranger waste rock media. *Eucalyptus tintinnans* does not occur within a 10 km radius of the mine unlike the currently proposed CRE sites. However, it is native to Kakadu NP and is on the agreed list of species for revegetation of Ranger by the flora and fauna closure criteria technical working group. Because of this, it has continued to be trialled at Stage 13.1 and Pit 1. ERA are conscious of unintentionally creating an inappropriately 'mixed' vegetation community on the final landform (Brady et al 2021); therefore, further Traditional Owner consultation has begun on the inclusion or removal of this species from the SERP.

Stem Density

Throughout the life of the TLF, stem densities have consistently been greater in the waste rock sections compared to the laterite mix sections due to better germination and/or survival of the trees and shrubs (Figure 5-106). A survey of the entire TLF in 2019 found that section 1A had the greatest stem density (plants >1.5m) at approximately 727 stems/ha^{-1}, followed by 1B, 3 and 2 at 534, 354, and 200 stems/ha^{-1} respectively (Table 5-49). Self-recruitment was also highest in 1A, with approximately 290 recruits, followed by sections 3, 1B and 2 with approximately 146, 98 and 75 recruits respectively.

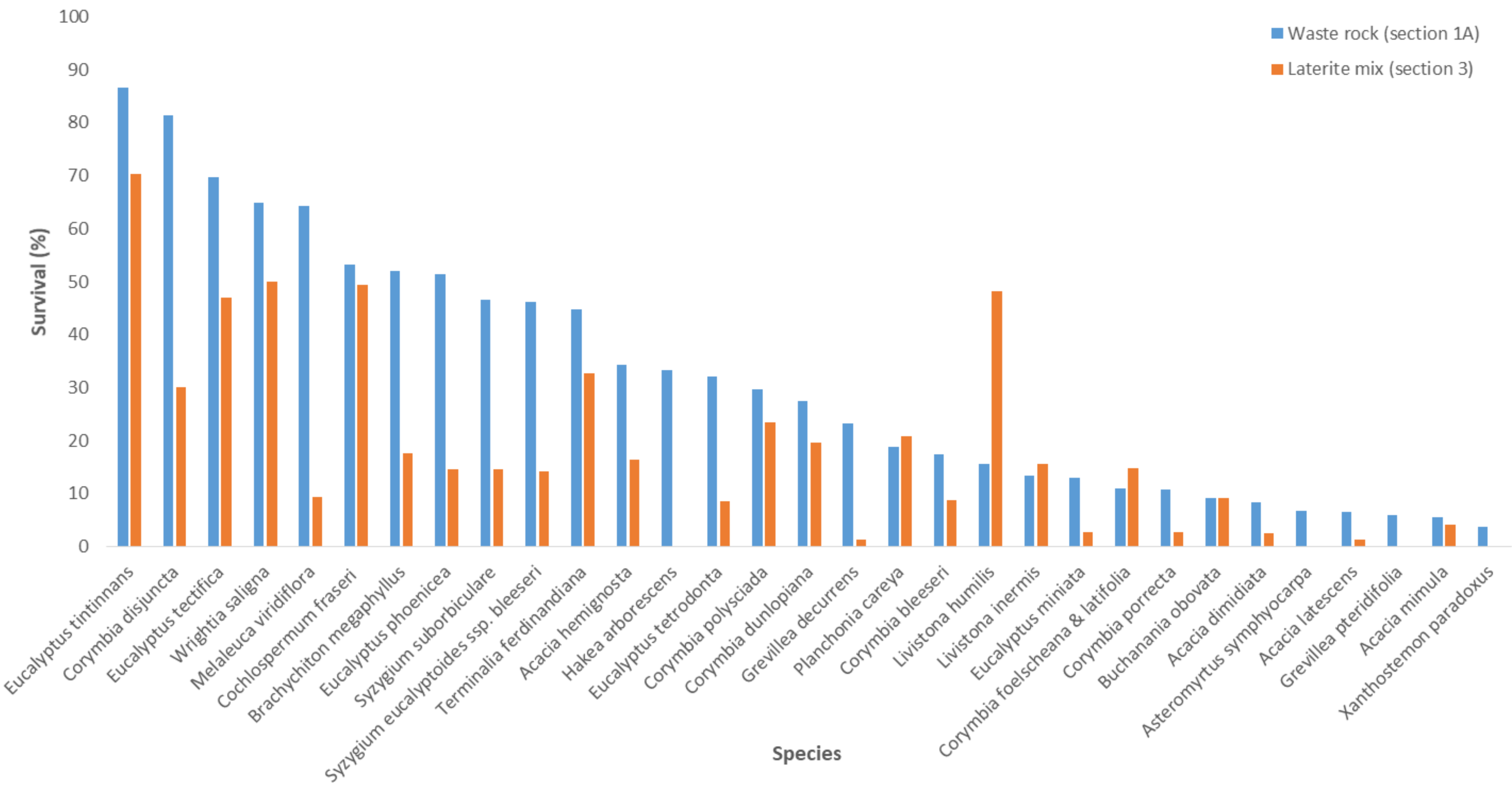


Figure 5-105: Tubestock Survival on 1A and 3 after ten years.

Calculated = (# of non-recruits present in 2019 / # planted in 2009 + 2010) * 100

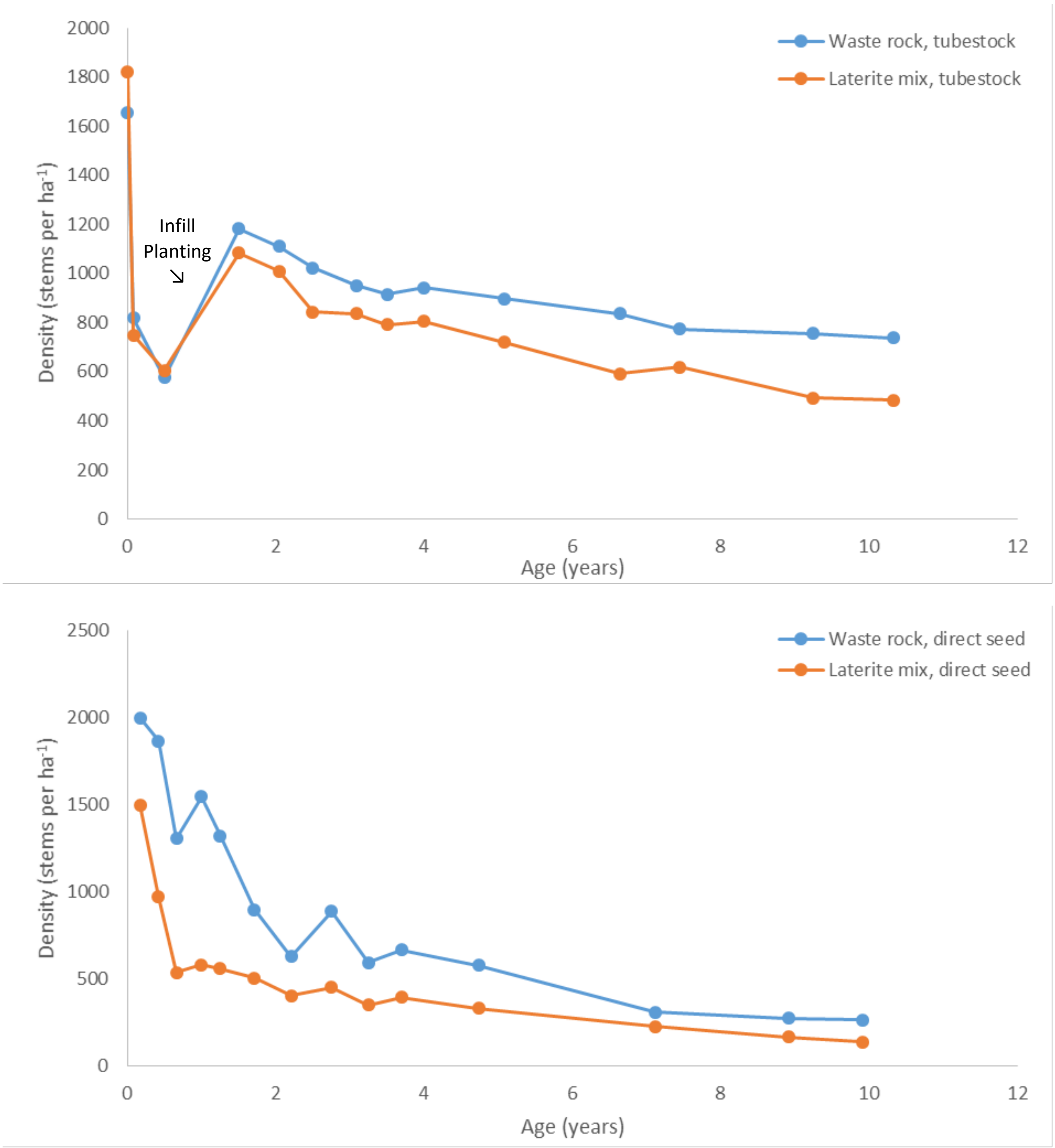


Figure 5-106: Longitudinal plant density (stems per ha^{-1}) based on the tubestock only (0 -14) and direct seeding only (15 – 29) Permanent Monitoring Plots on the TLF, not including recruits.

Note: Density is based on all introduced individuals inside the permanent monitoring point regardless of height. Density before 0.5 years was calculated using the total number of seedlings in each section (estimates for direct seeded areas); the direct seeding densities do not include infill planting. It is believed that the increases in density in the directly seeded areas during the first few years were likely due to ongoing germination of the broadcast seed.

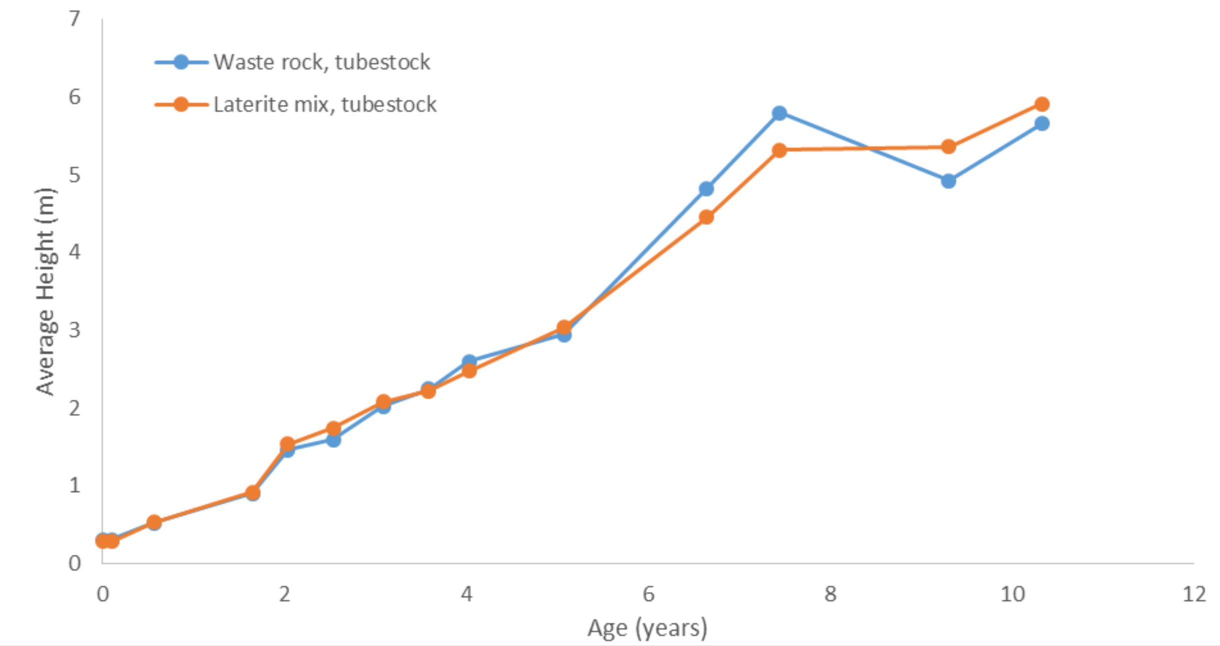
Table 5-49: Approximate total overstorey and midstorey stems on the TLF in 2019, including recruits.

	Total # of individuals (approx.)	Total # of individuals >1.5 m	Stems per hectare (>1.5 m)
1A	967	727	727
1B	863	534	534
2	564	400	200
3	864	708	354
Total	3258	2369	296

Plant Growth

Plant height on the TLF has not varied significantly by substrate in the tubestock areas (Gellert & Lu 2015, Parry 2019 unpublished data; Figure 5-107). In the first five years, mean height in the waste rock and laterite mix tubestock sections was almost identical, with around 60 cm of plant growth per year. Mean height almost doubled in the following 2.5 years, reaching a peak average height of 5.8 m in the waste rock section in August 2016. Cyclone Marcus brought heavy destructive winds to the area in March 2018, disproportionately effecting the waste rock end of the TLF. This combined with tall Acacias reaching the end of their natural life-span, accounts for the reduction in height between August 2016 and June 2018. Diameter at breast height (DBH) is slightly greater in the laterite mix substrate, with a mean DBH of 8.6 ± 0.4 cm in section 3 compared to 8.05 ± 0.46 cm in 1A (based on 2019 permanent monitoring point data).

Growth differences between the substrates is more pronounced in the direct seeded areas of the TLF, with lower mean plant height in the waste rock section. Plant DBH is also lower in the waste rock, with a mean DBH of 6.11 ± 0.8 cm in 1B compared to 7.73 ± 0.92 cm in section 2 (based on 2019 permanent monitoring point data). The considerable differences in growth between the two direct seeded areas are likely due (at least partially), to a greater proportion of taller species in section 2 (Gellert 2013). It is also possible that the TLF's mean plant height and DBH has been somewhat skewed towards larger plants in the laterite mix areas (particularly the direct seeded section), considering a greater proportion of smaller plants died in the 2016 burn conducted on those areas (discussed in Section ESR8).



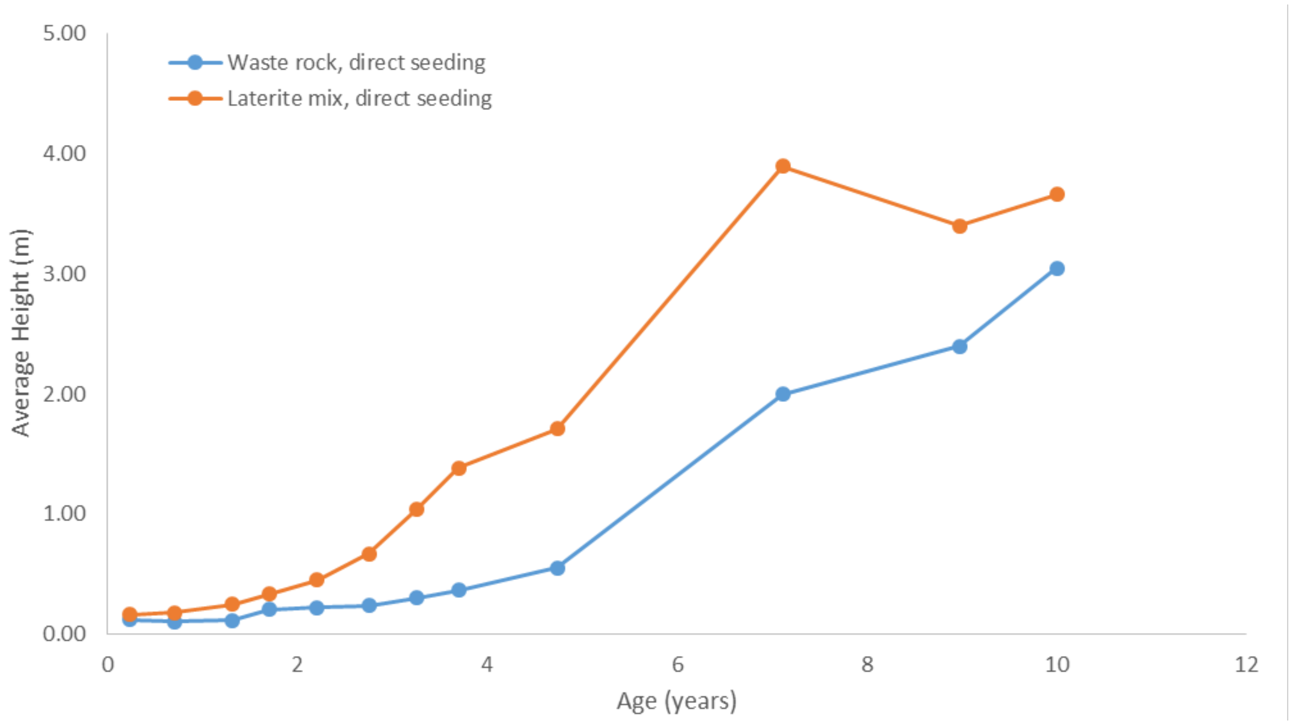


Figure 5-107: Longitudinal plant growth (height) based on the tubestock only (0 -14) and direct seeding only (15 – 29) Permanent Monitoring Plots on the TLF, not including recruits

Flowering, fruiting and self-recruitment

Of the 40 overstorey/midstorey species that were introduced on the TLF between 2009 and 2011 and are still present today, 37 have flowered and fruited at least once since September 2018 (when regular walk-through monitoring began, see Section 10). Over half of the species have flowered and fruited in every section that they are still present, including the majority of *Corymbia* and *Eucalyptus* (Table 5-50, Figure 5-80). The three species that have not flowered and fruited at all include *Gardenia megasperma*, *O. vernicosa* and *Pandanus spiralis*, which have grown very slowly (most <1 m) and are generally still too small to flower and fruit.

Over three-quarters of the overstorey/midstorey species on the TLF have self-recruited, either via seed and/or vegetative reproduction (suckering). Although the majority of the overstorey/midstorey species have had at least one observed instance of self-recruitment, most seedlings survive for a few months before disappearing, typically towards the end of the dry season. Only nine of the TLF species, many of which began self-recruiting within five years (Gellert 2014), have obvious recruits that have survived for over twelve months.

The species with the greatest levels of self-recruitment are *Acacia hemignosta* and *Cochlospermum fraseri*. It appears that *C. fraseri* in particular is very suitably adapted for the waste rock only substrate, with almost one hundred recruits greater than 1.5 m in section 1A (Parry 2019 unpublished data). Not only does this significant level of recruitment contribute to 1A's high stem density, it also skews the section's species composition, which Gellert (2014) predicted may occur. It appears that the head-start the species received being tubestock planted rather than direct-seeded, combined with the rocky substrate, allowed *C. fraseri* to thrive and aggressively recruit.

Fire also appears to be an important factor influencing self-recruitment. *E. tetrodonta* and *W. saligna* in particularly have considerably more recruitment in the laterite mix sections compared to the waste-rock only sections, with the recruitment being almost entirely through vegetative reproduction (suckers) in section 2 and 3, compared with mostly seed in sections 1A and 1B.

Overall, section 1A has had the greatest number of species self-recruit. This section has also had the most species fruiting and the highest density of shrubs and trees, therefore more individuals to potentially drop seed and recruit. Section 1A also has greater canopy cover and ground litter than the other sections of the TLF; although in natural systems shade and litter may impede recruitment, it is possible that on the harsh conditions of the TLF they provide a beneficial microclimate for early seedling establishment (Parry et al 2022). Lastly, section 1A has never had a dense weedy groundcover, unlike sections 2 and 3, which can outcompete young emerging recruits.

Table 5-50: Flowering, fruiting and self-recruitment of tree, shrub and palm species present on the TLF

Species	Flowering and Fruiting	Self-recruiting
Acacia dimidiata	At least 1 section	At least 1 section
Acacia hemignosta	All sections species is present	All sections species is present
Acacia latescens	All sections species is present	All sections species is present
Acacia mimula	At least 1 section	At least 1 section
Asteromyrtus symphyocarpa	All sections species is present	Not observed
Brachychiton diversifolius	At least 1 section	Not observed
Brachychiton megaphyllus	All sections species is present	At least 1 section
Buchanania obovata	All sections species is present	All sections species is present
Cochlospermum fraseri	All sections species is present	All sections species is present
Corymbia bleeseri	All sections species is present	At least 1 section
Corymbia disjuncta	All sections species is present	At least 1 section
Corymbia dunlopiana	All sections species is present	At least 1 section
Corymbia foelscheana	All sections species is present	At least 1 section
Corymbia latifolia	All sections species is present	At least 1 section
Corymbia polysciada	All sections species is present	All sections species is present
Corymbia porrecta	All sections species is present	At least 1 section
Eucalyptus miniata	All sections species is present	All sections species is present
Eucalyptus phoenicea	All sections species is present	At least 1 section
Eucalyptus tectifica	All sections species is present	At least 1 section
Eucalyptus tetrodonta	All sections species is present	All sections species is present
Eucalyptus tintinnans	All sections species is present	At least 1 section
Gardenia megasperma	Not observed	Not observed
Grevillea decurrens	All sections species is present	At least 1 section
Grevillea pteridifolia	All sections species is present	At least 1 section
Hakea arborescens	All sections species is present	At least 1 section
Jacksonia dilatata	All sections species is present	Not observed
Livistona humilis	At least 1 section	At least 1 section
Livistona inermis	At least 1 section	At least 1 section
Melaleuca viridiflora	All sections species is present	All sections species is present
Owenia vernicosa	Not observed	Not observed
Pandanus spiralis	Not observed	Not observed
Petalostigma pubescens	At least 1 section	All sections species is present
Planchonia careya	All sections species is present	At least 1 section
Syzygium eucalyptoides	At least 1 section	At least 1 section

Species	Flowering and Fruiting	Self-recruiting
ssp. bleeseri		
Syzygium eucalyptoides ssp. eucalyptoides	At least 1 section	Not observed
Syzygium suborbiculare	At least 1 section	At least 1 section
Terminalia carpentariae	All sections species is present	At least 1 section
Terminalia ferdinandiana	All sections species is present	All sections species is present
Wrightia saligna	All sections species is present	All sections species is present
Xanthostemon paradoxus	At least 1 section	Not observed

Figure 5-108: Flowering and fruiting on the Trial Landform. Top left to bottom right: *Brachychiton megaphyllus, Jacksonia dilatata, Eucalyptus tectifica, Cochlospermum fraseri*

Understorey species

Between September 2018 and August 2022 there have been approximately 100 native understorey species observed on the TLF. Over the almost four-year period of regular monitoring, 84 species were observed on Section 1A, 51 species on 1B, 36 species on section 2 and 28 species on section 3. This diversity is predominately driven by natural colonisation, with some species introduced via tubestock planting and/or direct seeding.

Direct seeding

All attempts at direct seeding grasses on the TLF in the first few years following construction were ultimately unsuccessful. The grass trials either had minimal seed germination (Gellert 2014), or when germination did occur, seedlings failed to recruit and persist for longer than a year (Gellert 2012b). It's likely that irrigation and/or fertiliser would have improved the outcome of these trials. The 2012/2013 wet season was particularly dry and warm, with 21% less rainfall than normal and December - February being in the 95th temperature percentile (December 2012 the hottest on record) (Jabiru Airport, Bureau of Meteorology). During a 1993 directly-seeded grass trial, some native understorey cover was able to establish and persist on an old waste rock dump capsite (Gray & Ashwath 1994). However, multiple factors likely contributed to this trial's success, including:

- A favourable study site – the trial was conducted on a 'substantially weathered' section of the dump located below the upper level batter slope. The site was ripped and graded, and each plot was raked to remove as many rocks with a >20cm diameter as possible.
- Irrigation – substantial irrigation was provided throughout the first few months of the trial.
- Favourable microsite conditions – shade cloths were secured over the experimental plots during germination and early establishment of the seedlings (for up to two months). This was to protect against seed loss from wind, but it also would have provided shade, which likely reduced irradiance, surface temperatures and soil water evaporation.

Direct seeding on the TLF has been somewhat more successful in recent years. In the 2018 section 1A trial, mean emergence from germinable seed ranged from 0 – 19 % for all species with the exception of *Galactica tenuiflora* in the surface litter treatment, which had 46 % emergence from germinable seed (Parry et al 2022). All the species had greatest emergence and number of surviving seedlings in the surface litter treatments, likely because the litter improved the seedlings microclimate by retaining water and reducing surface temperature. The surface litter may also have protected the seeds/seedlings from rain wash or uprooting, and predation. A corresponding shade house trial was also conducted in 2018; interestingly, treatments with fertiliser were the most successful in terms of growth and onset of flowering and fruiting. This suggested that under well-watered shade house conditions, waste rock nutrient deficiency was the factor limiting understorey establishment (Parry et al 2022).

The TLF direct seeded plants experienced considerable mortality during the first build-up after irrigation was stopped, however generally, seedlings that survived until the end of the following wet season have since persisted with most having low levels of self-recruitment. The best performing direct seeded plots had fertiliser, surface litter, or a combination treatment (Figure 5-109). One exceptionally successful plot was *G. tenuiflora* in a combination treatment. What likely contributed to the success was a large Acacia being blown over the plot, which provided shade and pinned down the surface litter that had been applied so that it did not get washed away. The *G. tenuiflora* stems have regrow with more vigour each year, and in 2022, over 28 self-recruits were observed within 2 m of the original plot.

The same species were also direct seeded without any amelioration treatments (controls) on section 1B in 2018, which was considerably more open than 1A with virtually no canopy. However, there was minimal germination with no seedlings surviving after a few months.

Figure 5-109: Directly seeded *Galactica tenuiflora* in a mixed treatment plot with fallen tree, March 2022

During a rainy period in February 2020, twelve understorey species from different genera were direct seeded in section 1A without irrigation; they were sown onto areas where organic matter/humus was naturally present, as well as bare areas (TLF Research and Monitoring Plan 2020 - 2026). All species had seed that germinated within a year of sowing; however, five species had very low germination (<5 seedlings total) and two of the species failed to persist after the first year. The most successful species have been *Cymbopogon bombycinus* and *Heteropogon triticeus*, which both had greater germination in the bare plots but larger, more vigorous seedlings in the organic matter plots (

Figure 5-110). Also interestingly, the grasses in the organic matter plots began flowering and fruiting in 2022, whereas the grasses in the 'bare' plots are yet to reach that maturity. It should be noted that many plots that were considered 'bare' in February 2020 had accumulated some litter within two months of sowing.

Figure 5-110: Directly seeded *Heteropogon triticeus* in an 'organic matter' plot in February 2021 (left) and March 2022 (right)

Tubestock planting

As part of the 2018 understorey trial, the same five species were also tubestock planted on sections 1A and 2. Tubestock planting overall was considerably more successful that direct seeding, resulting in a great number of larger, more robust seedlings (Parry et al 2022). Most seedlings that survived until the first wet season have persisted over the last four years. All three grasses began self-recruiting within the first year, with many plots now having three generations of recruitment that has spread over 10 m away from the original planted plots (Parry 2022 unpublished data). Successful self-recruit of the two legume species was observed during surveys in March 2021, with considerably higher levels evident in March 2022. In January 2019, plants from the 2018 shade house trial were planted in 'islands' on sections 1A and 1B and are still thriving three years later (Figure 5-111).

Figure 5-111: Understorey 'island' on section 1A of the TLF

Species colonisation

Native colonisation from external sources has been closely monitored on the TLF since September 2018. During this time, close to 100 native species have been observed to colonise, with approximately 80 identified to a genus level and 48 to a species level. Nine of these species are overstorey and midstorey species, five of which colonised many years ago and are now several metres tall (including *Acacia difficilis, A. oncinocarpa, Alstonia actinophylla, Ficus racemosa and Lophostemon lactifluus*). Understorey species with the greatest abundance include *Blumea, tenellula, Boerhavia coccinea*, *Brachyachne convergens*, *Crotalaria brevis, Ectrosia leporina, Eragrostis sp.*, *Indigofera linifolia, Phyllanthus sp., Sporobolus australasicus* and *Tacca leontopetaloides*. Much of the understorey diversity, particularly in 1A, comes from annual grasses, sedges and herbs, however an increasing number of perennial species are also appearing.

Section 1A has had considerably greater diversity than the other sections (Figure 5-112). Over the four-year monitoring period, a total of 82 species colonised 1A compared to 46 on 1B, 38 on section 2 and 31 on section 3. This is likely due to a more favourable microclimate for seed germination at 1A (increased shade and organic matter) and the section having minimal weedy groundcover (therefore more open area, less competition, and requiring minimal herbicide application).

The rate of recruitment has generally increased on all sections over the four years of monitoring, with seasonal fluctuations. This would support the theory that species richness, particularly the understorey, will increase over time as the ecosystem develops (e.g. soil formation, nutrient cycling, overstorey canopy etc). Section 1A has consistently had the highest levels of colonised species richness over the four-year period; however, the other waste-rock only section,1B, has also shown an increase in the number of species recruiting, particularly over the last two years as the diversity becomes increasingly similar to that seen at 1A. Interestingly, the levels reached in 1B in the wet season of 2021 are similar to the levels reached in 1A during the wet season of 2019. The roughly two-year delay in colonisation between the two sections likely stems from 1B being initially tubestock planted rather than direct-seeded, with follow-up tubestock infilling two years later. The two laterite mix sections' rate of native colonisation is also increasing, however more slowly than the waste rock only sections.

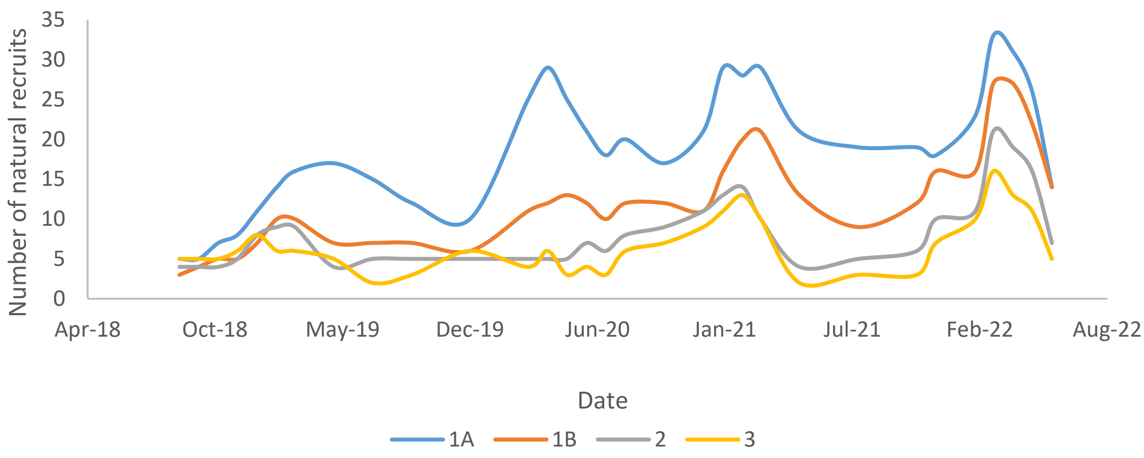


Figure 5-112: Rate of native understorey species naturally colonising the TLF since September 2018

Figure 5-113: Natural colonisation of species, including multiple *Brachychiton megaphyllus, Livistona sp.,* and *Tacca leontopetaloides* individuals underneath a large tree on Section 1A, February 2021.

Stage 13.1

Stage 13.1 Areas A and B have served as pilot studies for the large-scale Pit 1 revegetation trials (Figure 5-114). A key learning from this area has been that 'finer' waste rock exists underneath certain stockpiles, and that careful substrate preparation is needed to avoid significant depressions. In areas where depressions and saturated substrate may be unavoidable, it could be strategic to introduce more 'waterlogging-tolerant' species, such as Melaleuca and Pandanus. In addition, appropriate weed management is critical throughout the revegetation execution process, including pre-emergent herbicide prior to planting, and consistent follow-up management during the initial plant establishment phase.

Figure 5-114: Stage 13.1 revegetation. Research trial area A (0.52 ha) planted in April 2020, research trial area B (1.18 ha) planted in November 2020, and progressive revegetation area C (2.37) planted in August 2021 and infill planted January 2022.

Survival and Establishment

Stage 13.1A was planted in April 2020. Unfortunately, tubestock health was not optimal at the time of planting due to a nursery irrigation failure incident at the end of 2019 and unanticipated planting delays due to the COVID-19 pandemic. Despite this, seedlings had reasonable survival during the first few weeks. After two months mean survival was 89.9 ± 1.4% then over the following four months it slowly dropped further and appeared to stabilise around 70%. However, in the eight months that followed, at 14 months post-planting, survival was down to 56 ± 2.8 %. Much of this mortality appeared to occur during the first few months of the wet season, when areas of the substrate became waterlogged for extended periods of time. Many E. miniata and E. phonecia in particular appeared to be impacted by saturated substrate; after closer inspection of standing dead or dying individuals, the roots appeared to be ‘rotting’ in anerobic conditions (Figure 5-115). One year later, at 25 months post-planting, survival appeared to have again stabilised at 52 ± 2.8 %.

Overall, six of the twenty-two planted species in Area A had a survival less than 40 % and two species had a survival less than 20 % (Figure 5-116). The poorest performing tree species, E. phoenicea, is naturally found on sandstone escarpments and rocky rises which are generally well drained habitats unlike the finer saturation prone substate seen at Stage 13.1. Although some species experienced high mortality, none of the species planted at Area A completely failed to establish.

Some species have performed well in Area A, such as *M. viridiflora* and *H. triticeus* which had greater than 85 % survival at 25 months post-planting. It is unsurprising that *M. viridiflora* has been the overstorey/midstorey species with the greatest survival, as this species naturally grows in a wide range of seasonally flooded habitats and hence is not sensitive to 'wet feet'.

Figure 5-115: Dead *Eucalyptus* in saturated substrate at Stage 13.1A

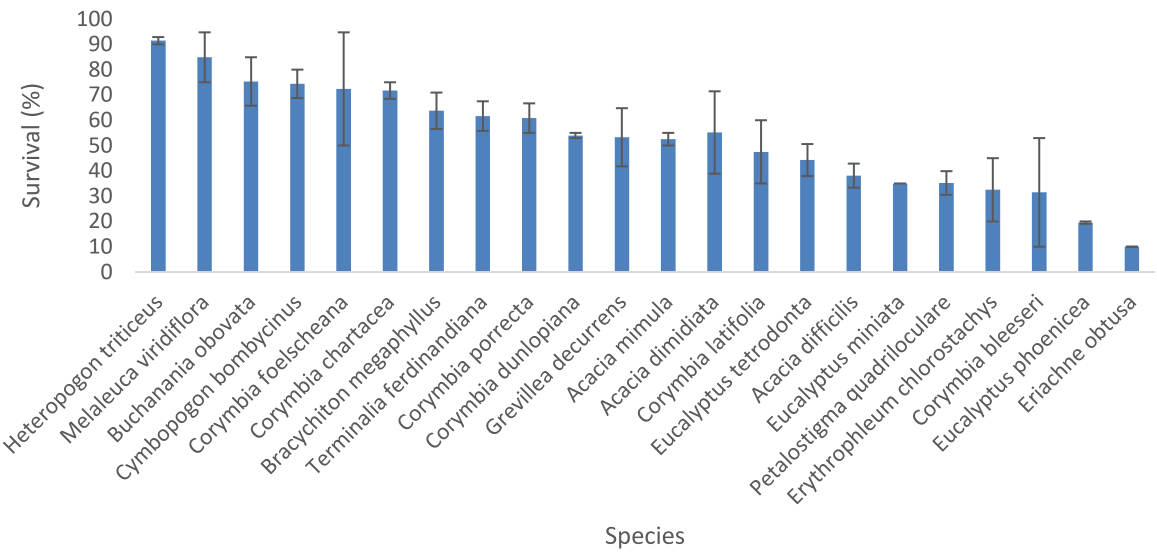


Figure 5-116 Average species survival on Stage 13.1 Area A after 25 months.

Area A also investigated seven different propagation and planting methods with the aim of optimising plant survival and establishment (see Table 5-46 in the propagation section above). All seven treatments were trialled on three species, *E. tetrodonta, Terminalia ferdinandiana* and *Petalostigma quadriloculare*. Four of these treatments were trialled on an additional three species, *Brachychiton megaphyllus*, *Buchanania obovata* and *Grevillea decurrens,* and the final two treatments (puffball and combination microbe) were trialled on all species. Unfortunately, due to COVID-19 staffing issues in April 2020 when planting was performed the treatments were not properly randomised. This should be taken into account when interpreting the effect of treatment on seedling performance.

When comparing the survival of the three species with the full treatment suite, the plastic pot method produced the best average survival (65 ± 9.4 %) (Figure 5-117). The poorest performing treatment was the commercial-only microbe treatment with an average survival of 34 ± 5.2 %.The plastic pot method was also generally most successful for the species that were trialled with four treatments, achieving an average survival of 71 ± 9 % compared to the other three treatments which all achieved an average survival of around 50% (Figure 5-118). The plastic pot method obtained the greatest survival for four of the six species.

It is still unclear from the species only trialled with the two treatments whether solely native microbes or a combination of native and combination microbes are optimal for species establishment. Half of the species had better survival with the puffball treatment and the other half with the combination microbe treatment (two species had equal survival) (Figure 5-119). Although species with the puffball treatment generally had a higher survival, this could be due to, at least in part, topography and location conditions rather than treatment. With the inappropriate level of randomisation in the field trial it will be difficult to determine actual treatment effects with the other confounding factors.

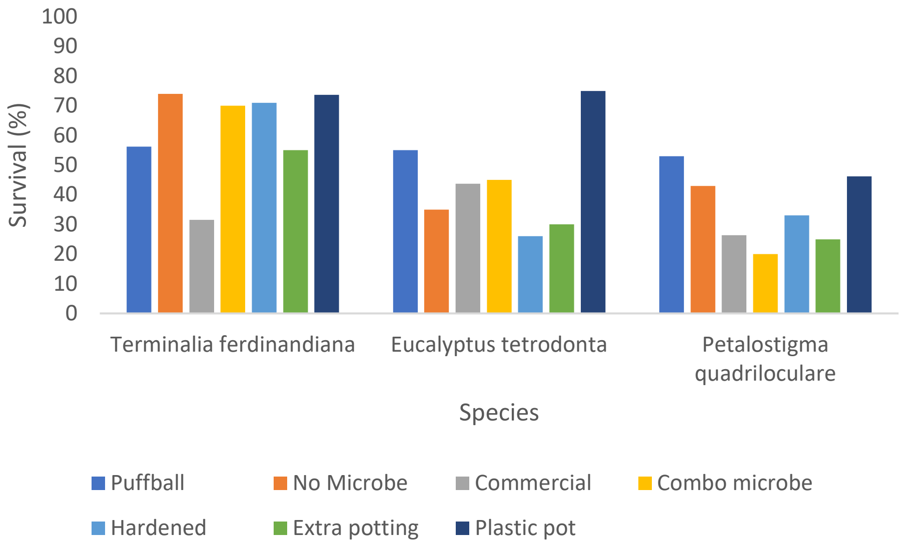


Figure 5-117 Species survival on Stage 13.1 Area A after 18 months for the full suite of treatments

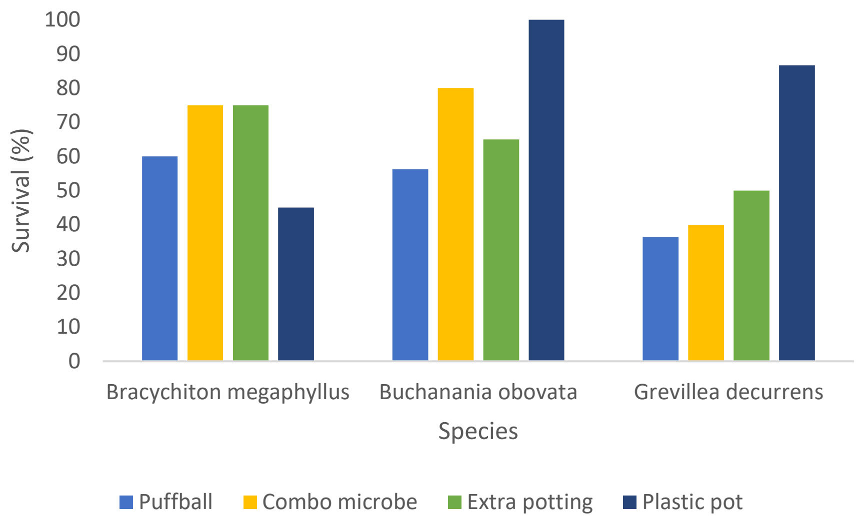


Figure 5-118 Species survival on Stage 13.1 Area A after 18 months for the partial suite of treatments

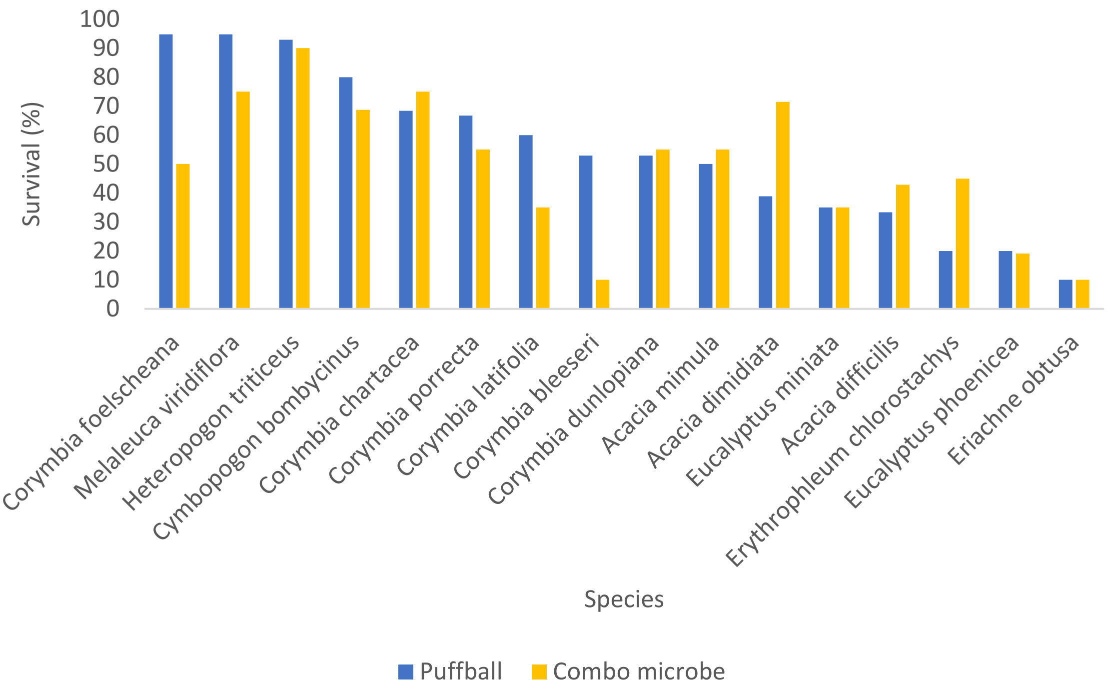


Figure 5-119 Species survival on Stage 13.1 Area A after 18 months with puffball and combination microbe treatments

Stage 13.1B was planted in November 2020. The seedlings were the first to be propagated at the ERA nursery during the dry season and as a result, some were small and/or stressed. That, combined with planting at the hottest time of the year, followed by heavy rainfall flooding and washing away seedlings or burying them in sediment, resulted in high initial mortality. After six months, mean survival was 64 ± 3.6 %. It again was apparent that surface conditions can have a significant impact on plant survival. The first four rows of Stage 13.1B only had 36 % survival compared to 68 % in the remaining area (Figure 5-120 and Figure

5-121); this dramatic difference is likely due to the significant depressions and water pooling present in that section, where waterlogged plants appeared to 'cook' in a manner of days during a warm period in January. Over the following 12 months survival dropped only slightly to 61 ± 3.5 % at 12 months post planting and then again to 58 ± 3.5 % at 18 months post planting, slightly higher than the survival in Area A at a similar age.

Three species had a survival less than 20% including Acacia dimidiata and Haemodorum coccineum and one species, Stenocarpus acacioides, failed to establish (Figure 5-121). Like the poorer performing species in Area A, it appears that the finer substrate found at Stage 13.1 is not well enough drained for Stenocarpus acacioides which generally grows on rocky soils. Despite the challenges, several species have performed well in Area B. Overall, 22 % of the planted species had a survival greater than 80 % and 4 species had 100 % survival; these were Corymbia polysciada, M. viridiflora, Acacia gonocarpa and H. triticeus, noting that only two individuals were planted for A. gonocarpa and four for C. polysciada.

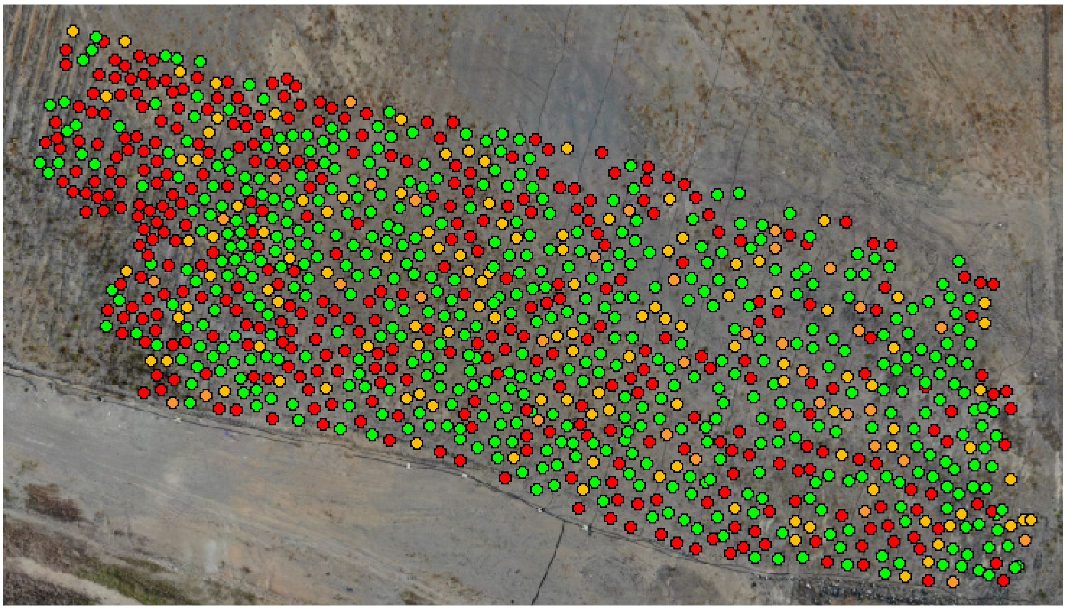


Figure 5-120: Seedling survival and health at Stage 13.1B at six months after planting when substrate impacts became apparent. Green is an alive seedling, yellow is a stressed seedling, and red is a seedling that appeared dead.

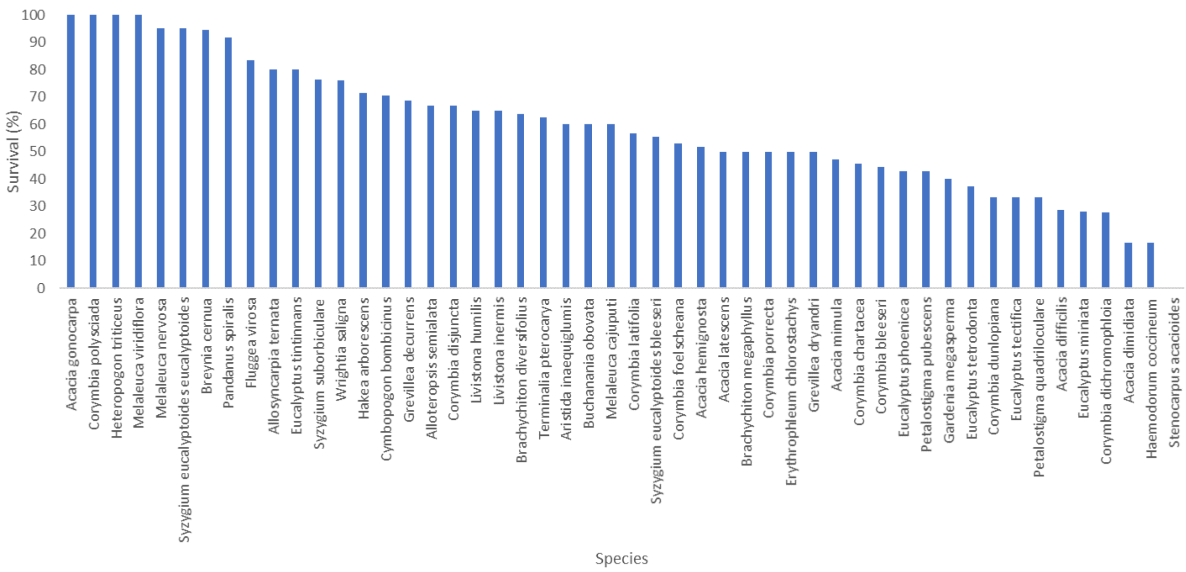


Figure 5-121: Overall species survival on Stage 13.1 Area B after 18-months

Stem Density

Stem density on Stage 13.1 differs greatly between Area A and Area B, predominantly due to the significantly higher initial planting density in Area A. The seedlings were planted at approximately twice the standard planting density due to issues in surface preparation and a smaller than anticipated area being suitable for planting at that time. As Stage 13.1 was a pilot study for Pit 1 with the main focus being on initial seedling establishment, it was decided that the trial go ahead, noting that competition issues will likely become apparent as the seedlings mature.

As of May 2022, Area A still had a considerably higher stem density than Area B, despite also experiencing higher mortality (Figure 5-122). The stem density of all midstorey and overstorey species regardless of height at Area A was 1015 stems/ha-1, more than double Area B's density of 413 stems/ha-1 (Table 5-51). For stems over 1.5 m, the density is more similar between the areas with Area A at 425 stems/ha-1 compared to Area B at 341 stems/ha-1 (Table 5-51).

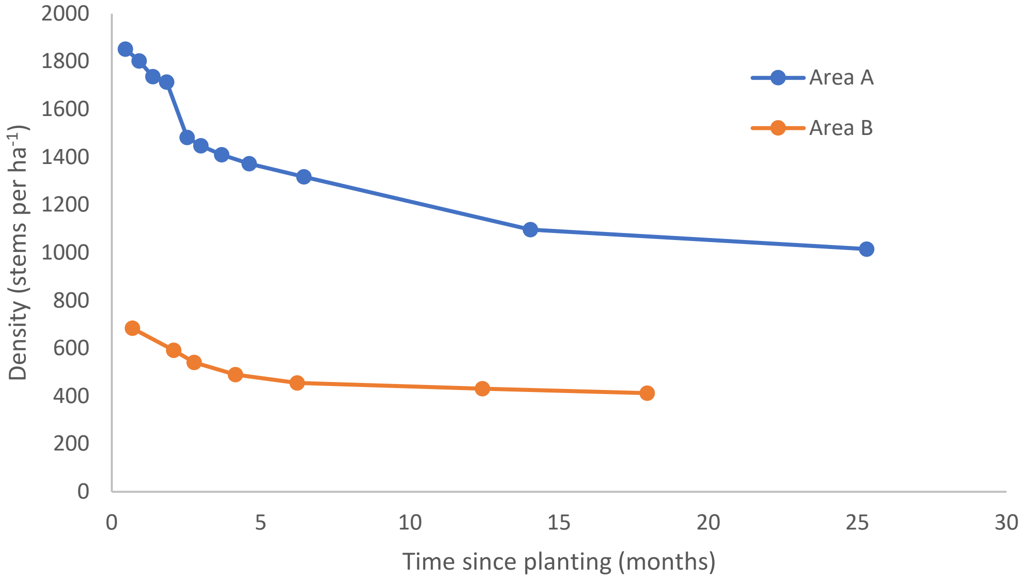


Figure 5-122: Plant density (stems per ha^{-1}) based on all midstorey and overstorey individuals on Stage 13.1 Area A and B regardless of height, not including recruits.

Table 5-51: Total overstory and midstory stems on Stage 13.1, excluding recruits.

	Total # of individuals	Stems per hectare	Total # of individuals >1.5 m	Stems >1.5 m per hectare
Area A	528	1015	221	425
Area B	487	413	403	341

Plant Growth

Despite the challenging conditions at Stage 13.1 the seedlings on Area A had a mean height of 47 cm at six months post planting. Over the next year and a half, the seedlings grew at an approximate rate of 55 cm per year, reaching a mean height of 133 cm at 25 months post planting. In comparison, the TLF had a slightly higher average plant growth rate of 60 cm per year in the first 5 years post planting, however, this rate was not linear over the 5-year timeframe and the species composition at TLF differs to Stage13.1.

At Area B the mean growth in the first 6 months was similar to Area A, reaching a height of 45 cm. Over the next year, the mean growth increased to 93cm at 18 months post planting, slightly lower than the growth at Area A when it was the same age (Figure 5-125). Although, it should be noted that when comparing Area A and B the species composition varies (Table 1).

The species with the greatest growth at Area A was *E. phoenicea*, which had a mean height of 2.4 m at 25 months post planting. Species *Grevillea decurrens* and *E. tetrodonta* also performed well with both reaching mean heights over 2 m (Figure 5-123). The species with the least growth was *Erythrophleum chlorostachys* which had a mean height of only 40 cm.

At Area B, *E. tintinnans* grew fastest reaching a mean height of 2.2 m at 18 months post planting (Figure 5-124). Like in Area A, *E. chlorostachys* was slow growing in Area B reaching a mean height of 30 cm. The sand palms, *Livistona humilis and L. inermis*, had the least growth, reaching 25 cm and 23 cm respectively. These three species are known to be slow growing

At both areas some Corymbia species had seedlings which appeared to be stunted in growth. At Area A, several *C. porrecta* and *C. latifolia* individuals were stunted and both species had average heights less than one metre. Stunted *C. porrecta* individuals were also observed at Area B.

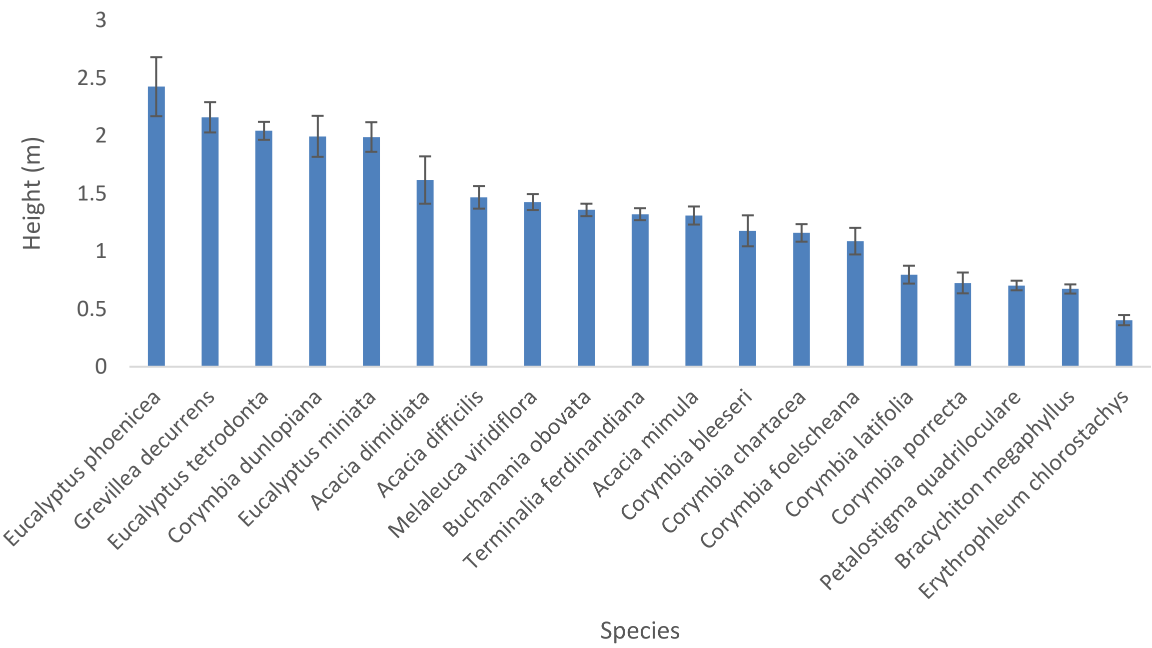


Figure 5-123: Species average height at Stage 13.1 Area A after two years

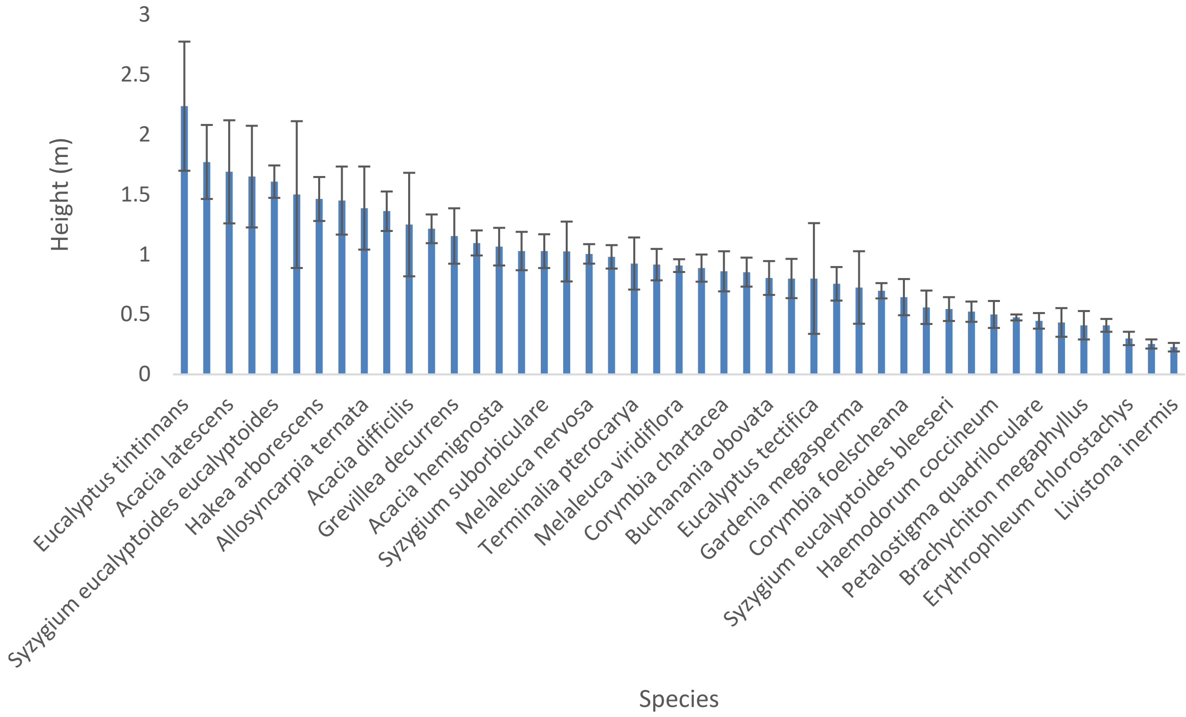


Figure 5-124: Species average height at Stage 13.1 Area B after 18-months

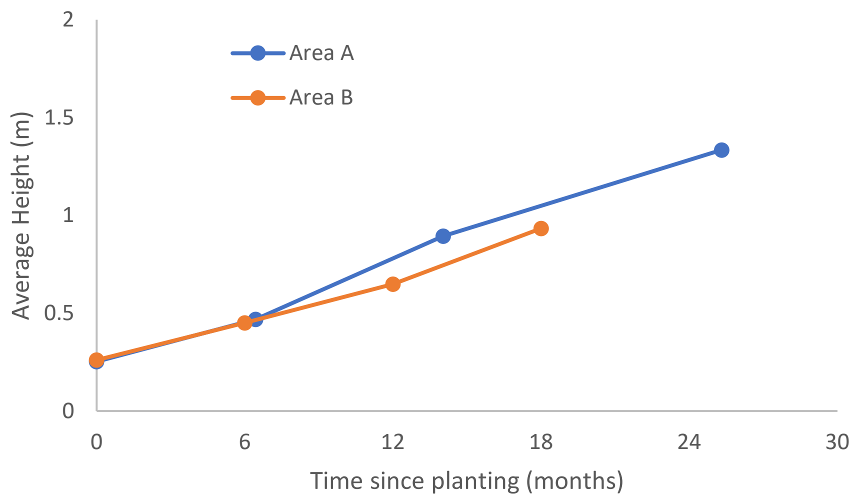


Figure 5-125: Plant growth at Stage 13.1 Areas A and B over two years.

Flowering, Fruiting and Self-recruitment

At Area A, 7 of the 22 species have been observed to flower and fruit in the two years since planting. All four understorey species have flowered and fruited as well as three midstorey species – *A. dimidiata*, *B. megaphyllus* and *G. decurrens*. At Area B, 10 of the 50 planted species have flowered and fruited in the 18 months since planting. This includes all understory species (excluding *Acacia gonocarpa*), and three midstorey species – *Acacia dimidiata*, *Flueggea virosa* and *Terminalia pterocarya*.

All four understory species have self-recruited at Area A. However, no self-recruitment has been observed at Area B. More species may have flowered, fruited and recruited on Stage 13.1 A and B since planting, however observations were only recorded during set monitoring times. It may be that the flowering and fruiting seasons of some species were outside of the periods that were monitored. It is also possible that species had seed germinate, but that the small recruits did not survive until the next scheduled survey. This is where monthly walkthrough monitoring, such as those performed at TLF, can be beneficial. Before the end of 2022 this type of monitoring program will be deployed at Stage 13.1 and Pit 1.

Species colonisation

In the two years since planting, 23 native species have been observed naturally colonising at Area A. The majority of these were understorey species, dominated by *B. convergens*, *E. leporina*, *S. australasicus* and including *B. coccineum*, *Eragrostis sp.*, *Oldanlandia sp.*, *Scoparia dulcis* and *U. reptans*. Three overstorey/midstorey species have also colonised the area, *C. fraseri*, *L. lactifluus* and *Melaleuca sp*.

At Area B, 16 native species have naturally colonised, including two overstorey/midstorey species – *B. megaphyllus* and *M. viridiflora*. Similar to Area A, the understory species are dominated by *E. leporina*, *S. dulcis* and *S. australasicus* followed by *B. convergens* and *Fimbristylis sp.*

Pit 1

Three research trial areas were established on Pit 1 in 2021 with the objectives of (ERA, 2021c):

- determining if revegetation can be performed all-year-round whilst minimising remediation actions required;
- determining specific methods and materials used for revegetation to optimise initial survival (first 2 years after planting); and
- gaining experience establishing species that have not been investigated previously.

Three variables were investigated; planting season (Wet, Dry and Build-up), seedling age (‘older’ and ‘younger’) and pot type (standard nursery tubes and biopot). Each research area was divided into three strata. The four treatments, older biopot, older plastic, younger biopot and younger plastic, were randomised into subplots within each stratum (Table 5-52). The rest of Pit 1 was progressively revegetated in May and December 2021, and January 2022.

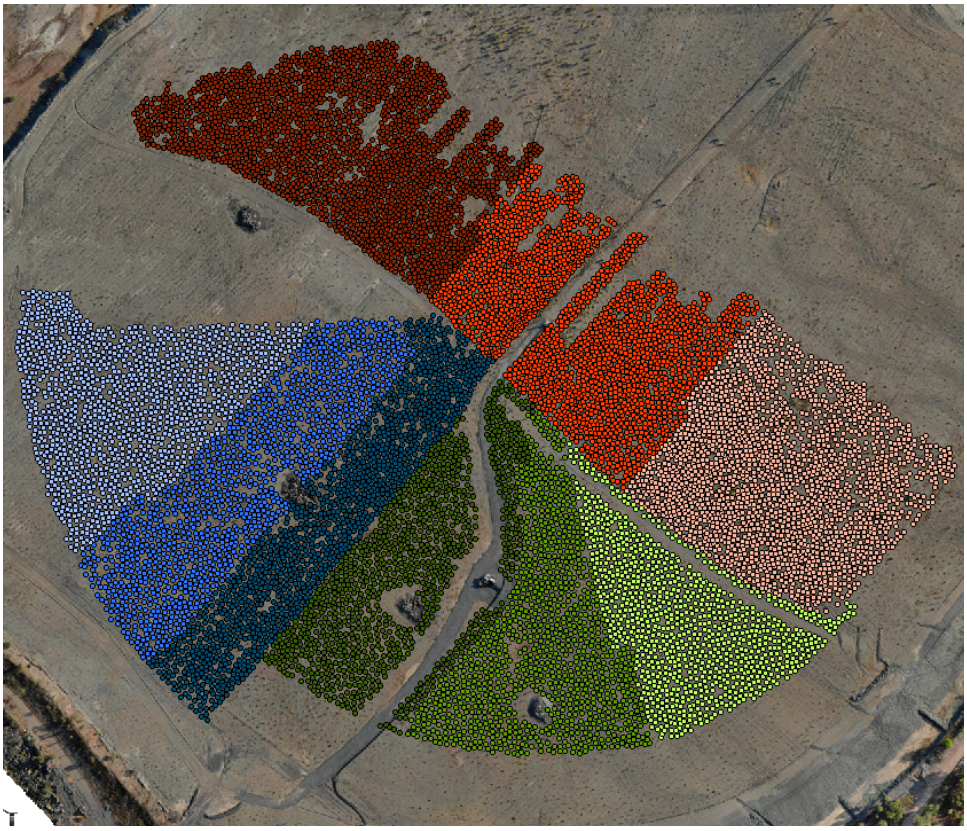


Figure 5-126: Pit 1 research areas: March 2021 ‘Wet season’ planting (6.6 ha), July 2021 ‘Dry season’ planting (3.8 ha) and October 2021 ‘Build-up’ planting (3.1 ha)

Table 5-52: Overstorey/midstorey (OS) and understorey (US) species investigated in the Pit 1 research trials

Species	Strata	Mar	Jul	Oct	Species	Strata	Mar	Jul	Oct
Acacia dimidiata	OS			Y	*Erythrophleum chlorostachys*	OS	Y	Y	Y
Acacia gonocarpa	US	Y	Y	Y	*Eucalyptus miniata*	OS	Y	Y	Y
Acacia lamprocarpa	OS	Y	Y		*Eucalyptus phoenicea*	OS	Y	Y	Y
Acacia mimula	OS	Y	Y	Y	*Eucalyptus tectifica*	OS	Y	Y	Y
Acacia oncinocarpa	OS	Y		Y	*Eucalyptus tetrodonta*	OS	Y	Y	Y
Alloteropsis semialata	US	Y	Y		*Eucalyptus tintinnans*	OS	Y	Y	Y
Ampelocissus acetosa	US	Y			*Galactia tenuiflora*	US	Y		
Aristida holathera	US	Y			*Gardenia fucata*	OS	Y		
Austrodolichos errabundus	US	Y			*Gardenia megasperma*	OS	Y		
Banksia dentata	OS	Y			*Grevillea decurrens*	OS	Y	Y	Y
Brachychiton megaphyllus	OS	Y	Y	Y	*Haemodorum coccineum*	US	Y		

Species	Strata	Mar	Jul	Oct	Species	Strata	Mar	Jul	Oct
Buchanania obovata	OS	Y	Y	Y	*Heteropogon triticeus*	US	Y	Y	Y
Calytrix exstipulata	OS	Y			*Indigofera saxicola*	US	Y		
Cartonema spicatum	US	Y			*Livistona humilis*	OS	Y	Y	Y
Cayratia trifolia	US	Y			*Livistona inermis*	OS	Y		
Chrysopogon latifolius	US	Y	Y	Y	*Melaleuca viridiflora*	OS	Y		
Cochlospermum fraseri	OS	Y			*Petalostigma quadriloculare*	US	Y	Y	Y
Corymbia bleeseri	OS	Y	Y	Y	*Planchonia careya*	OS	Y	Y	Y
Corymbia chartacea	OS	Y	Y	Y	*Stenocarpus acacioides*	OS	Y		
Corymbia disjuncta	OS	Y			*Syzygium eucalyptoides ssp. bleeseri*	OS	Y	Y	
Corymbia dunlopiana	OS	Y			*Templetonia hookeri*	OS	Y		
Corymbia foelscheana	OS	Y		Y	*Tephrosia subpectinata*	US	Y	Y	
Corymbia polysciada	OS	Y			*Terminalia ferdinandiana*	OS	Y	Y	Y
Corymbia porrecta	OS	Y	Y	Y	*Terminalia pterocarya*	OS	Y	Y	Y
Dolichandrone filiformis	OS	Y			*Uraria lagopodioides*	US	Y		
Eriachne obtusa	US	Y	Y	Y	Total		50	26	25

Overall survival

Pit 1 revegetation has been the most successful in recent Ranger history. Post-planting surveys performed in the immediate weeks following planting found overall tubestock survival rates of 99.1 %, 95.5 % and 93.3 % for the Wet, Dry and Build-up trials respectively (Figure CC). It was expected that the post-planting survival rates for the Dry and Build-up trials would be lower than the Wet season trials, as the seedlings were propagated and planted during more challenging times of year, either when plants are typically dormant or when temperatures are extremely high.

The first three months after planting is when highest mortality is typically experienced as seedlings overcome initial planting shock and begin establishing in the waste rock. Overall survival dropped by 14.9 %, 17.9 % and 12.7 % for the Wet, Dry and Build-up respectively during this time. It is unsurprising that the Dry season seedlings experienced the highest mortality, considering they were planted whilst relatively dormant then spent the next three months heading into harsh build-up conditions.

At the six-month survey, overall survival for the Dry and Build-up trial areas remained at similar levels to the three-month survey. The Dry trial survival dropped 3.1 %, sitting at 74.6 %, and the Build-up trial survival dropped 2.1 %, sitting at 78.5 %. The Wet season trial area had higher mortality at the six-month survey, with survival dropping an additional 8.0 % between June 2021 and November 2021, sitting at 76.2 %. As discussed, this is the harshest time of year. Comparatively, at similar timeframes post-planting, Stage 13.1A and Stage 13.1B had 66.9 % and 62.1 % overall survival respectively Figure (CC).

At 12-months post-planting, the Wet season trial overall survival reached 70.6 %; the Stage 13.1 trials at similar ages were at 55.4 % and 58.6 % for Area A and B respectively (Figure 5-127). It is expected that Pit 1 research trials' mortality rate will reduce and generally stabilise during the second year post-planting, as has been observed in Stage 13.1A and 13.1B (Figure 5-122).

It should be noted that it is not necessarily meaningful to compare the overall survival of the five research areas, particularly between Pit 1 and Stage 13.1, because the treatments and species compositions are very different.

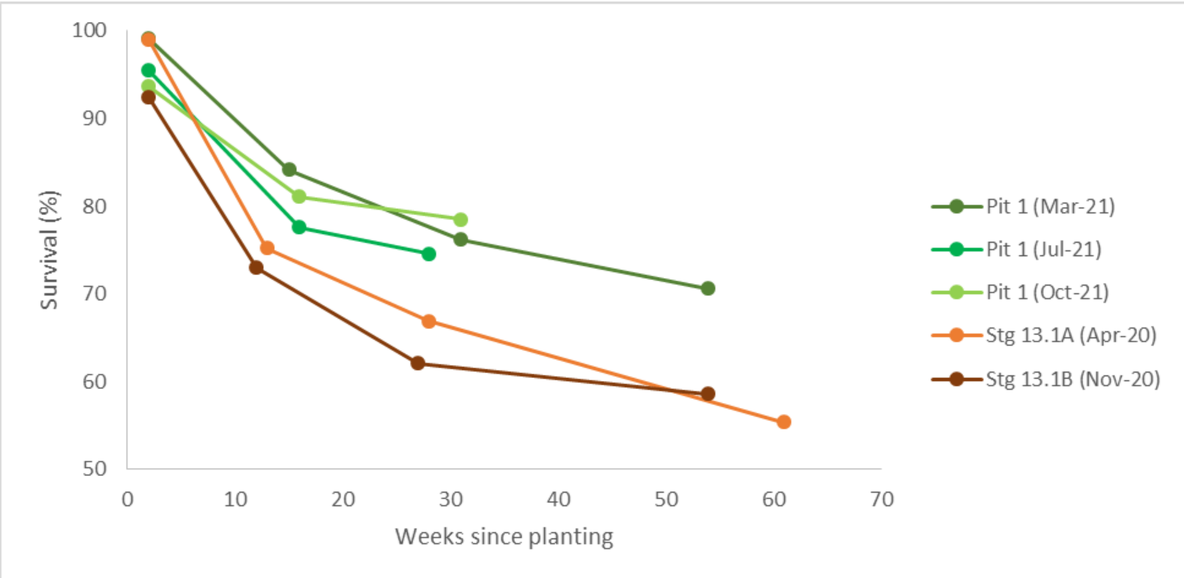


Figure 5-127: Overall tubestock survival of the research trial areas on Pit 1 and Stage 13.1 within approximately one year of planting

Location was found to impact tubestock mortality on Pit 1. Most notably, high mortality was experienced around a large depression in the Wet season trial area (Figure 5-128). During planting, obvious depressions were avoided as it has been established from previous revegetation experience that many of the savanna woodland species do not tolerate any waterlogging. However, as the Pit was still experiencing subsidence from waste rock infill, the area of depression continued to develop a few months after planting. This resulted in seedlings that were planted around the original depression to become waterlogged. This sort of subsidence issue will be unavoidable for large, infilled sections of the FLF, and will likely also occur in some areas on Pit 3. Management options for depressions will be to 1) not plant directly into an obvious depression, 2) avoid planting waterlogging-intolerant species around the edge of depressions, then 3) introduce waterlogging-tolerant species (such as *Pandanus*) into the area in the following wet season once subsidence has stabilised and the extent of the depression is understood. It is possible that there are more factors influencing the high mortality in that specific area of the Wet season trial, for example high levels of surface salts. Substrate testing will be conducted to investigate this possibility further.

There is no obvious topography or location impacts on tubestock survival for the Dry season trial area. Potentially there is a small effect in the Build-up trial area where there has been preferential water flow in the third strata. That area also did not receive a pre-emergent herbicide spray due to the planting area shape being changed prior to planting (due to damage to the pivot irrigation system the week earlier). Therefore, there could also be slightly higher mortality in that area due to small seedlings competing with weeds, which were visible in that section during the initial post-planting survey.

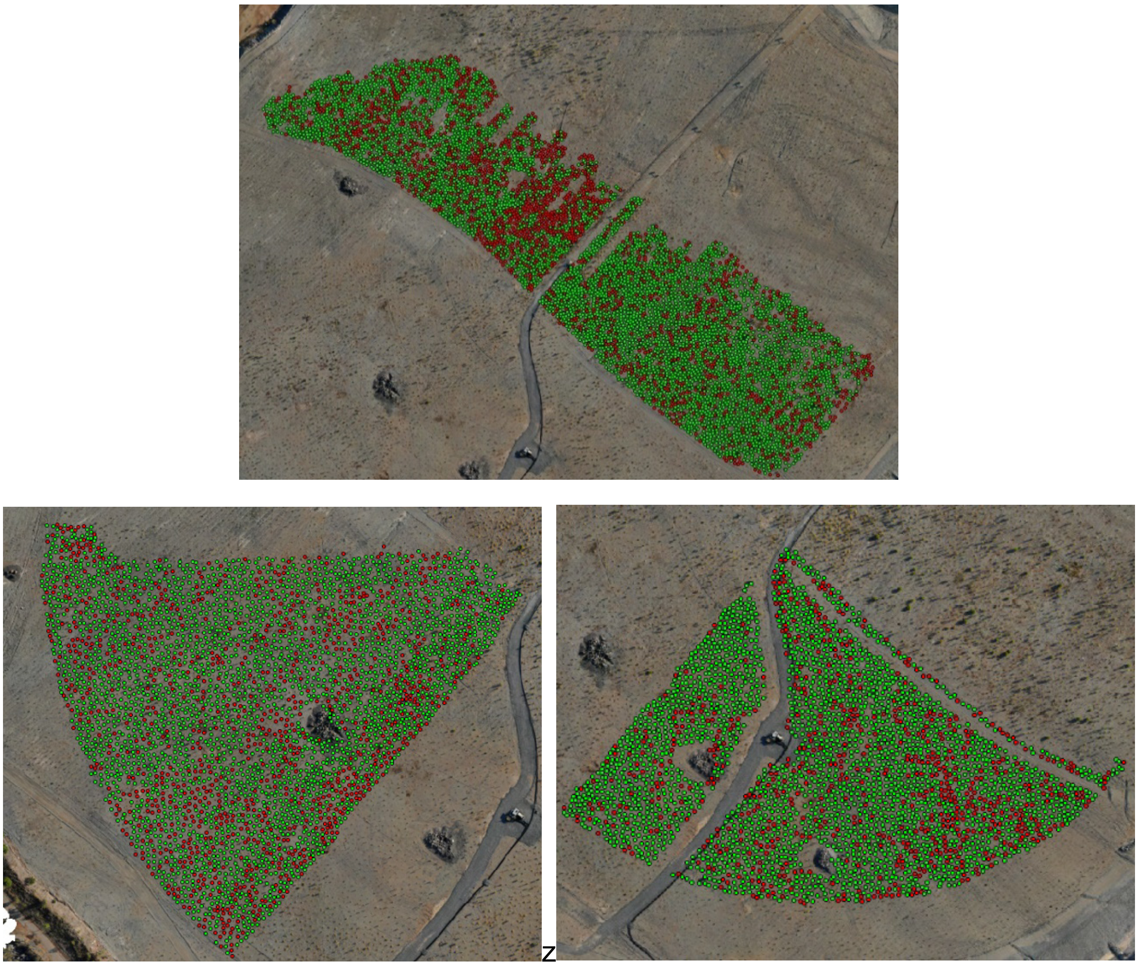


Figure 5-128: Survival maps at 12-months for the Wet season trial (Mar 2022, top), and 6-months for the Dry season trial (Feb 2022, left bottom) and Build-up trial (May 2022, right bottom). Green is an alive seedling and red is a seedling that appeared dead.

Five new midstorey species were tubestock planted for the first time in the Wet season trial area. Most of the species have established well, with the exception of *Banksia dentata* at 44 % survival. *Banksia* typically occur in moist or seasonally flooded low areas, so even this level of survival on waste rock substrate is unexpectedly high. It would not be surprising if this species fails to properly establish over the next few years due to dry conditions on the landform. *Banksia dentata* is a traditionally important species (Garde 2015, Fox & Garde 2018) so it is desirable that it be included in the revegetation of Ranger Mine. However, it may be that this species is only suitable for specific locations on the FLF, such as drainage areas.

Seven new understorey species were also tubestock planted for the first time in the Wet season trial area. Most of the species had above 60 % survival, exceptions being *Austrodolichos errabundus, Cartonema spicatum* and *Tephrosia subpectinata* (42 %, 11 % and 43 % respectively at 12-months post planting). *Tephrosia subpectinata* is a weak perennial species so the tubestock are expected to start senescing within the first year or two; encouragingly, many seedlings have already self-recruited, indicating that the introduction of the species can be self-sustaining. *Austrodolichus errabundus* has an annual stem and therefore may actually have higher survival than what was observed during the survey periods; this species has also successfully self-recruited. *Cartonema spicatum* has had very poor survival on Pit 1 (4 % in older biopots and 18 % in older plastic pots), possibly because it is not suited for the harsh, open conditions of initial revegetation. During a Cultural Reconnection Working Group visit, Traditional Owners suggested this species as well as *Haemodorum coccineum,* another understorey species that has had low survival in Ranger revegetation, should be planted in sandy areas with soft ground (*pers. Comm.* 30th June 2022). Preferential planting of these species in specific types of substrate will be explored in future revegetation.

Two ‘perishable’ fruited species, *P. careya* and *Syzygium eucalyptoides ssp. bleeseri* were held in the nursery over 2021, repotted as needed, and introduced in the unseasonal research trials as larger plants. Preliminary results show this method to be highly successful, with 98 % - 100 % survival of *P. careya* tubestock in the Dry and Build-up trial areas, and 96 % surival of *S. eucalyptoides ssp. bleeseri* in the Dry season trial (there were not enough available stock for this species to also be trialled in the Build-up). Being able to introduce these low density, but important species during initial revegetation instead in the following wet season when seed becomes available will help reduce infill requirements and reduce additional disturbance in a revegetated area.

Treatment effect on survival

Preliminary results suggest that for overstorey and midstorey species, plastic pots will generally result in similar or higher seedling survival than biopots. Out of the midstorey and overstorey species trialled with both types of pots, 28 of the 31 species in the Wet season trial (Figure 5-129 and Figure 5-130), 13 of the 16 species in the Dry season trial (Figure 5-131), and 17 of the 19 species in the Build-up trial (Figure 5-132), had the same or higher suvival in a plastic pot treatment. Almost all of the ‘older biopot’ seedlings were unable to be included in the Build-up revegetation trial due to their high mortality or poor condition after an irrigation failure incident in the nursery.

The effect of age on overstorey and midstorey seedling survival has been less clear. Out of the species trialled with different ages, the majority of the Wet season species had better survival with older plants (11 out of 15, Figure 5-130), whereas in the other two areas, younger plants generally had higher survival (12 out of 16 for the Dry trial, 12 out of 19 for the Build-up trial). Further investigation and data interrogation is needed to determine optimal seedling age for propagating and planting during different seasons.

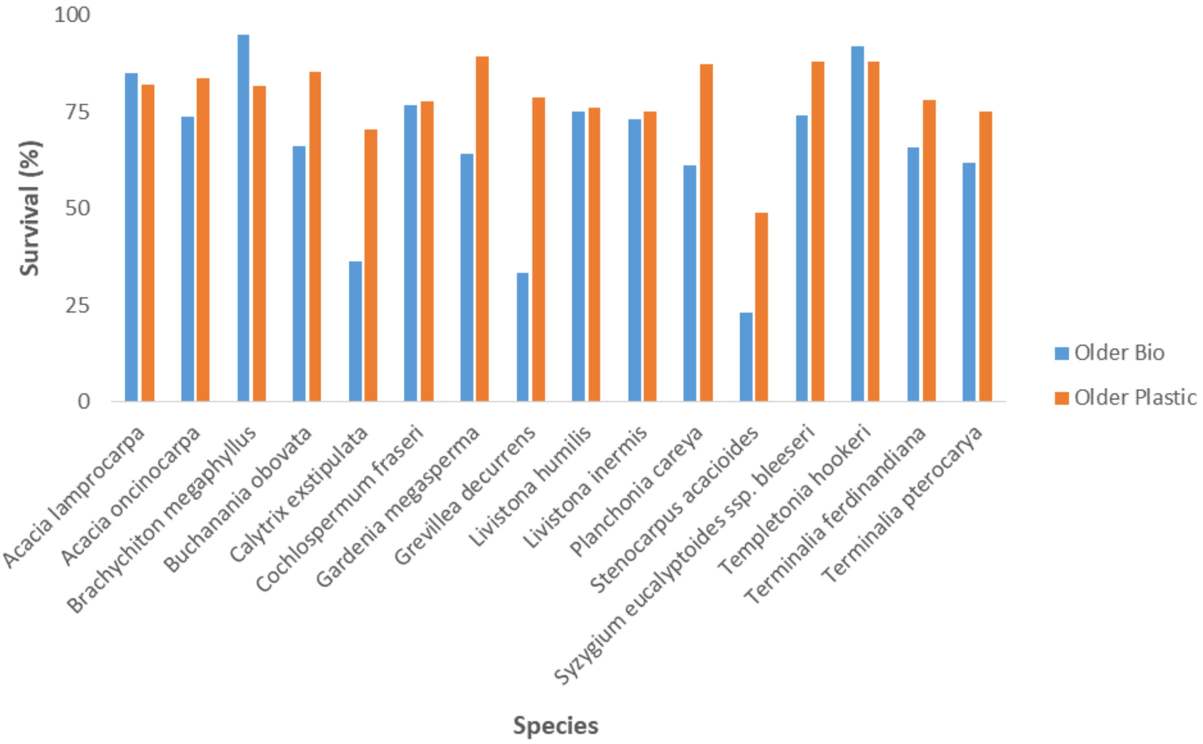


Figure 5-129: Survival of overstorey and midstorey seedlings with only ‘older’ treatments in Pit 1 Wet season trial 12-month survey

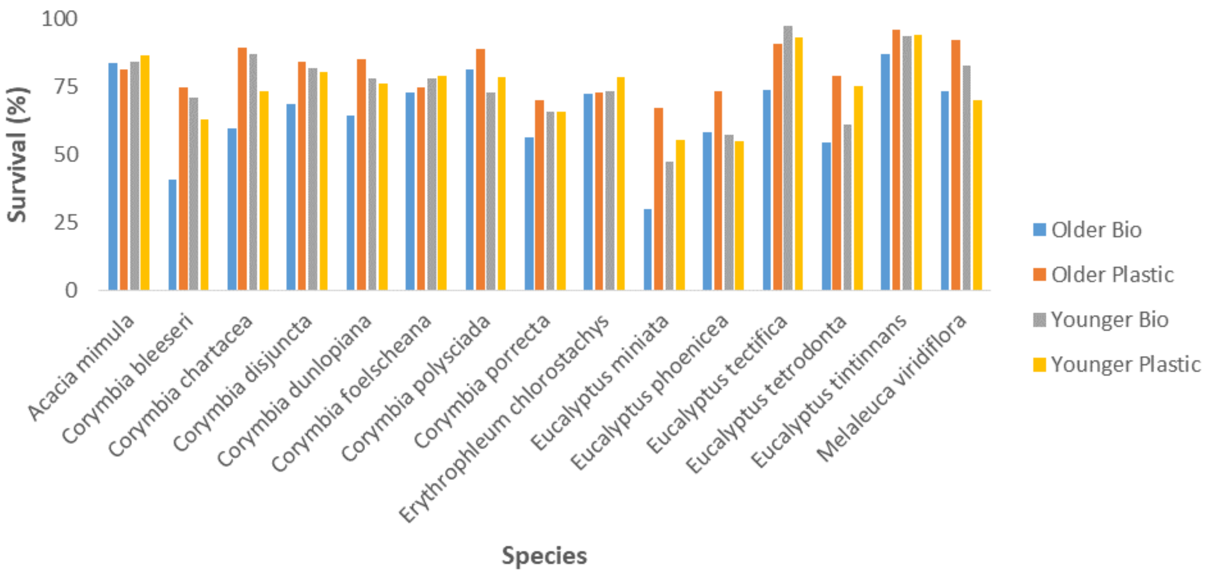


Figure 5-130: Survival of overstorey and midstorey seedlings with all four treatments in Pit 1 Wet season trial 12-month survey

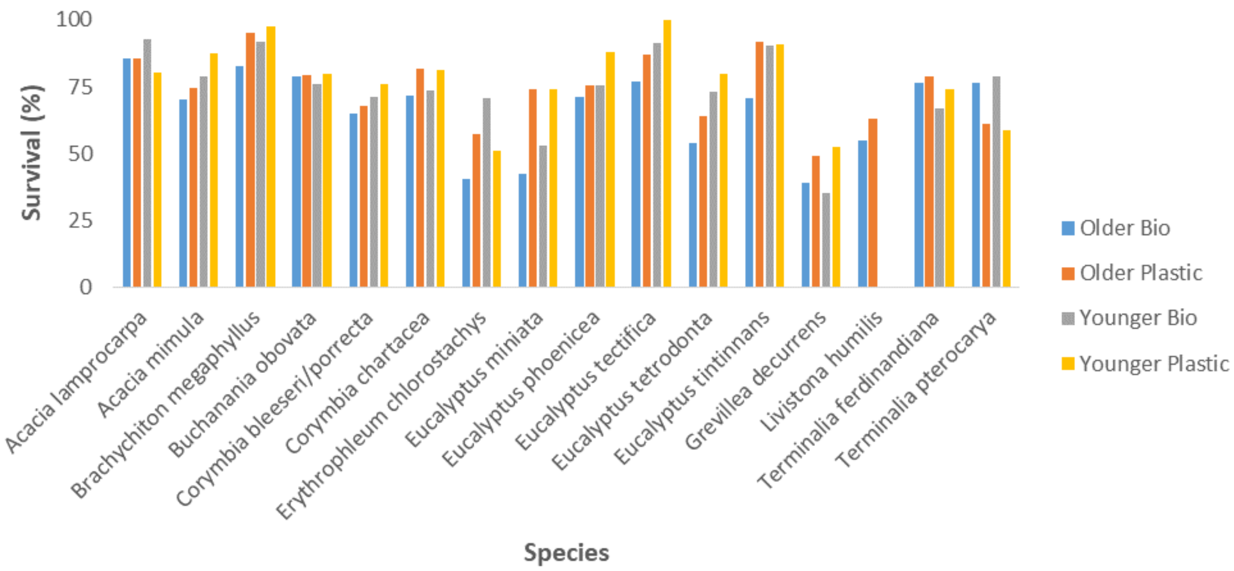


Figure 5-131: Survival of overstorey and midstorey seedlings with multiple treatments in Pit 1 Dry season trial 6-month survey

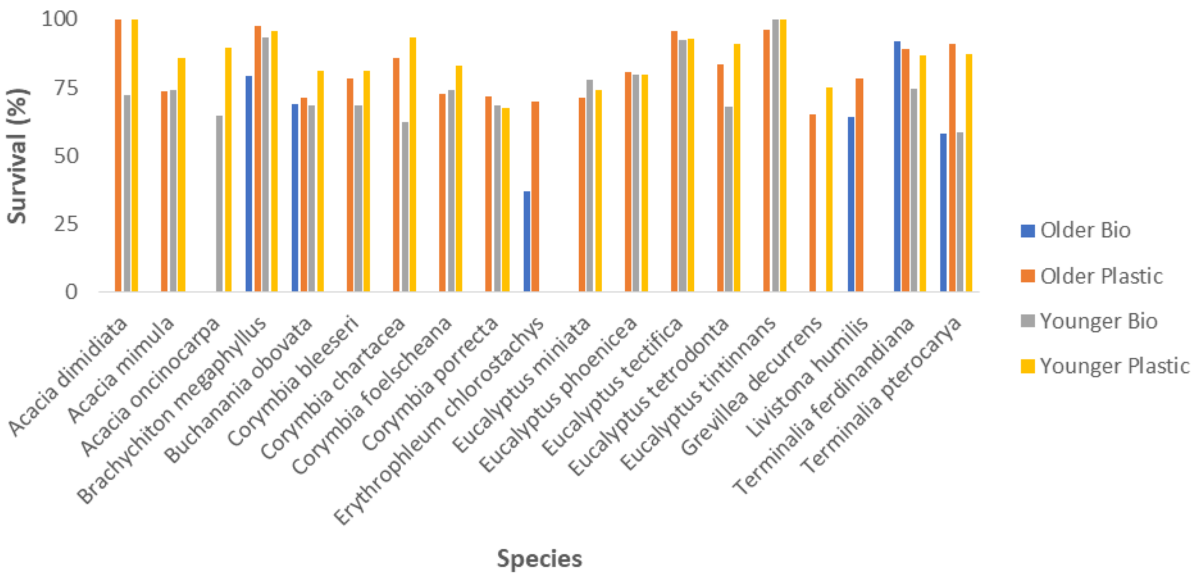


Figure 5-132: Survival of overstorey and midstorey seedlings with multiple treatments in Pit 1 Build-up trial 6-month survey

Preliminary results for the understorey species also suggest that plastic pot seedlings will generally have similar or higher survival than biopot seedlings regardless of propagation and planting season (Figure 5-133, Figure 5-134 and Figure 5-135). Similarly to the overstorey species, the younger understorey seedlings also generally had higher survival than the older seedligns in the Dry season and Build-up trials. The majority of the understorey species in the Wet season trial did not have an age treatment, but of the ones that did, older seedlings generally perferred similarly or better. Some species, such as *H. triticeus,* had high survival regardless of season, age or pot type (92 – 100 % survival across all three trials).

It should be noted that the data collected from the Pit 1 trials is yet to undergo statistical analysis, and that the findings in this iteration of the MCP are based on high level data interrogation. Whether any treatments have had a statistically significant impact on species survival will be reported in the 2023 MCP.

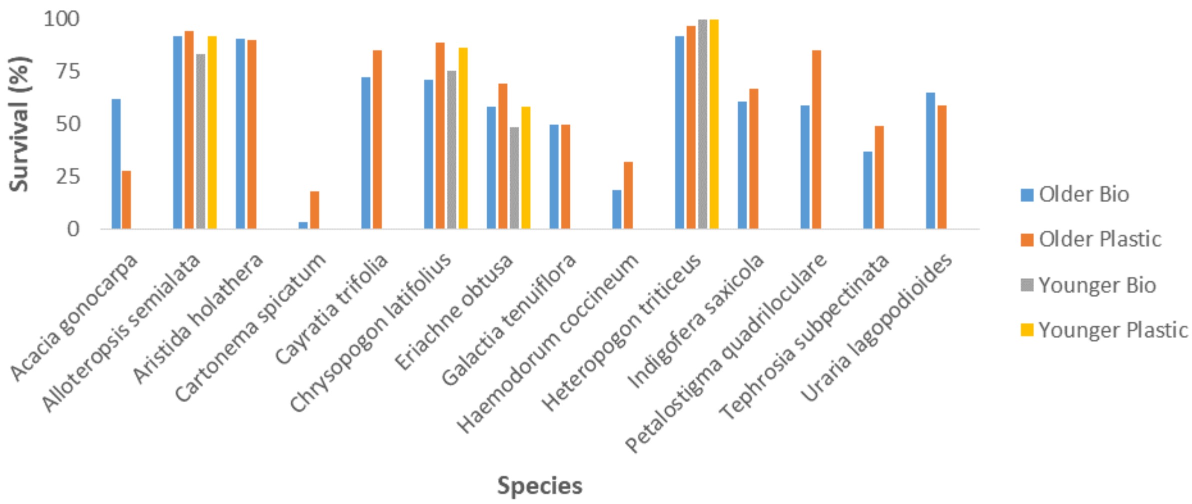


Figure 5-133: Survival of understorey seedlings with multiple treatments in Pit 1 Wet season trial 12-month survey

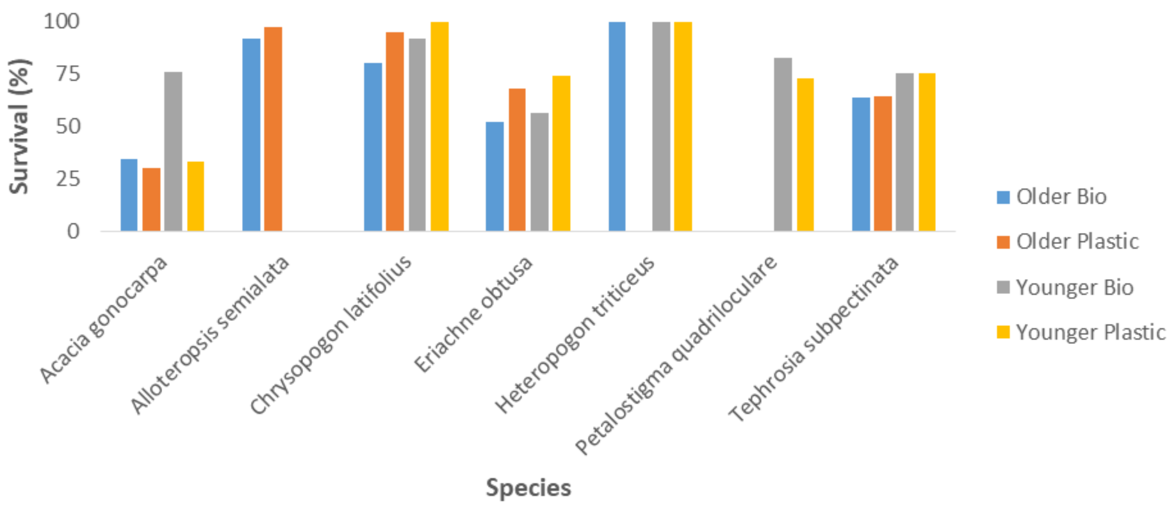


Figure 5-134: Survival of understorey seedlings with multiple treatments in Pit 1 Dry season trial 6-month survey

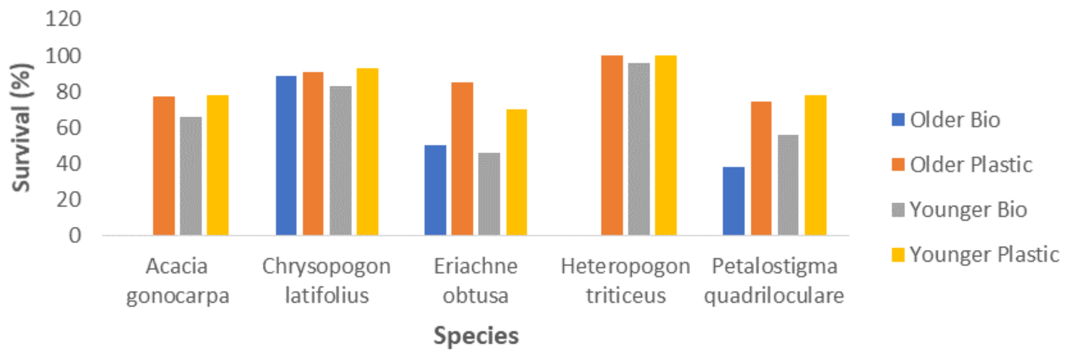


Figure 5-135: Survival of understorey seedlings with multiple treatments in Pit 1 Build-up trial 6-month survey

Flowering, fruiting and recruitment

All of the understorey species in all three trial areas have been observed to flower and fruit, and most of them have also self-recruited. *Terminalia pterocarya* has also flowered and fruited in all three areas. Other midstorey species that have been observed to flower and fruit include *Calytrix exstipulata, Templetonia hookeri, C. fraseri* and *Dolichandrone filiformis*, all of which were only planted in the Wet season trial area. A few individuals of *Syzygium eucalyptoides ssp. bleeseri* and *B. megaphyllus* have also flowered, however this appeared to be a stress response as the plants were very small.

5.4.3.7 SERP database - revegetation

Species-specific revegetation information summarised in the SERP database includes:

- whether a species has naturally colonised on waste rock, with references to where and if known, when (e.g. TLF after ten years, waste rock dumps etc.);
- history of research trials and/or progressive revegetation where species has been actively introduced onto waste rock, with specific reference to trial and/or area;
- whether the species has been successfully introduced (in this case, the species being present two years after introduction) via tubestock planting, direct seeding or other methods (eg. mulch islands). Level of success is categorically ranked from highly successful (eg. >90 % tubestock survival) to low success (eg. <3% emergence and persistence from viable seed);
- comments on initial (<2 years), early-intermediate (2 – 6 years), mid-intermediate (7-15 years) and long-intermediate (16 - 25 years) species establishment;
- whether a species has been observed to flower, fruit and recruit on waste rock, with consideration of appropriate age based on lifeform (e.g. a midstorey shrub species flowering within 1 month of planting at 20 cm height is likely a sign of stress). Type of recruitment observed (e.g. from seed or vegetative suckers) is noted where identifiable; and

- comments on any establishment concerns, e.g. Species senescing without recruitment, species particularly susceptible to termites etc.

5.4.3.8 Future work on establishing native terrestrial vegetation

Projects identified for continued work, the progress of which will be incorporated into future iterations of the Ranger MCP, will include:

- ongoing monitoring of the TLF, Stage 13.1, and Pit 1, with further and more detailed interrogation of results in relation to treatment effects, surface conditions, optimal species establishment methods and ecosystem development;
- targeted programs for important species that have been difficult to establish thus far; and
- begin SERP for species that may be better suited for seasonally-inundated areas, drainage features etc. on the final landform.

5.4.4 ESR8 Understanding fire resilience and management in ecosystem restoration

KKN title	Question
ESR8. Understanding fire resilience and management in ecosystem restoration	ESR8A *What is the most appropriate fire management regime to ensure a fire resilient ecosystem on the rehabilitated site?*

5.4.4.1 Background

Fire is a major exogenous feature of Australian eucalypt-dominated ecosystems, especially subtropical savanna woodlands (e.g. Gill 1981; Bradstock *et al*. 2002; Russel-Smith & Whitehead 2015). Fire is the key disturbance that influences vegetation composition, structure and function in the northern savanna woodlands and forests of Australia. Fire can be natural (eg caused by lightening at the end of the dry season when fuel loads are cured and ready to burn) but is more commonly anthropogenic, having been used for thousands of centuries by Traditional Owners as part of managing the land and more recently by land managers such as Parks Australia and various ranger groups.

5.4.4.2 Fire regimes in natural surrounding woodlands and their influence on species composition and community structure

Fire regimes consider the intensity, frequency and timing of fires, which are all important factors that impact on the influence fires have on the environment (Gill 1981; Bradstock *et al*. 2002; Woinarski *et al*. 1999). Intensity is often related to timing, for instance late dry season burns are usually more intense as fuel is very dry, but can also be influenced by the type of fuel (e.g. fire-promoting grasses such as Gamba grass). Deliberately lit fires usually occur earlier in the dry season than wildfires, and therefore are generally less intense and less destructive to vegetation. Tropical savannas worldwide are intentionally burnt every 1 to 3 years (Andersen *et al*. 1998),

The RPA is surrounded by the eucalypt savanna dominated landscape of Kakadu NP. High annual wet season rainfall promotes extensive vegetation growth, particularly from annual grasses dominated by Sorghum. The subsequent curing of the vegetation during the long dry season results in a highly flammable landscape, where fire is an annual event (Russell-Smith *et al*. 1997) and a major force in shaping and altering the natural landscape (Edwards *et al*. 2003). Risk of fire becomes especially severe in September to November due to a combination of low humidity, average maximum temperatures above 35 °C and low soil moisture (Gill *et al*. 1996). Kakadu NP experiences high fire frequency with 2.7 – 7 fires per decade (Table 5-53). Changes to fire management practices in Kakadu NP since the late 1980s have resulted in more frequent early dry season fires and fewer late dry season fires (Russell-Smith *et al*. 1997). Fire is estimated to occur over 55 percent of the park annually (Russell-Smith *et al*. 1997, Lehmann *et al*. 2008 and NAFI 2015) .

The fire management plan for Kakadu NP from 2016 to 2026 aims to reduce the area impacted by large fires and the risk of wildfires entering, spreading, or leaving the park; it also plans for reduced frequency of large severe fires and reduced average fire patch size (Director of National Parks 2016). The management plan also identifies the importance of maintaining long-unburnt patches for vegetation regeneration and wildlife habitat (Director of National Parks 2016).

Table 5-53: Published fire frequencies for the region surrounding Ranger Mine (from Cook 2021)

Location	**Reference**	**Fire Frequency (fires per decade)**	
		All fires	Late fires
High rainfall Open Forest (National) 1988-2018	Cook *et al.* (2020)	2.66	1.85
High rainfall Woodland with mixed grass (National) 1988-2018	Cook *et al.* (2020)	3.62	2.22
Kakadu NP	https://firenorth.org.au/nafi3/ NAFI InfoNet report Kakadu NP 2000-2019	5.4	1.6
Kakadu NP 1980-2015	Gill *et al.* (2000)	4.6	1.6
Kakadu NP Lowlands (1980-2015)	Gill *et al.* (2000)	7	2
Kakadu NP savannah (1995-2009)	Russel-Smith *et al.* (2012)	2.68	1.48
WALFA area Savanna (1995-2009)	Russel-Smith *et al.* (2012)	4.11	2.56
WALFA area (1995-2004)	Russel-Smith *et al.* (2013)	3.96	3.2
WALFA area (2005-2011)	Russel-Smith *et al.* (2013)	3.18	1.09

Despite the adoption of early dry season burning by management agencies, total fire frequency (which includes both early and late dry season fires) has been shown to have a deleterious impact on the environment (Andersen *et al*. 2005, Lehmann *et al*. 2008). A higher early dry season fire frequency increases grass fuel levels, which in turn encourages higher intensity fires. Such a fire regime may have a similar negative impact on flora and fauna as infrequent late dry season fires (Woinarski *et al*. 2010) and frequent fire has adversely affected sensitive flora species in sandstone escarpment habitats (Russell-Smith *et al*. 1998). Further to this, a high fire frequency has been shown to have a propensity for producing a grass-fire cycle (D'Antonio & Vitousek 1992), resulting in an increase in the presence of annual grasses, particularly *Sorghum* spp. (Peter Christophersen *per comms.,* February et al. 2013; Parr et al. 2014; Scott et al. 2012; Werner 2012), that can eventually replace trees and shrubs. The presence of grassy weeds such as Mission grass and Gamba grass can exacerbate the effects of a grass-fire cycle (Rossiter *et al*. 2003).

Two major research projects in the NT, Munmarlary and Kapalga, have examined savanna dynamics in relation to different fire regimes at landscape scales (e.g. Bowman and Panton 1995; Andersen *et al*. 1998, 2003, 2005). Sites at Kapalga that had been unburnt for a number of years were found to have less grass cover (7% in November and 13% in March) than sites that had been burned annually (for 5 years) in the early or late dry season (Setterfield 2002). These previously-burned sites had 11% and 15% grass cover, respectively, in November and over 25% for both by the end of the wet season in March.

Frequent fires tend to simplify vegetation structure leading to the presence of a dominant tree layer and an understorey of grasses and resprouting shrubs and trees (Cook 2021). By contrast, a regime of less frequent fires will provide greater opportunities for saplings to escape the flame zone and for a mid-stratum to develop (Freeman et al. 2017; Setterfield 2002). Many species can persist and reproduce sexually or asexually in the long-term as woody resprouts; these facultative trees only enter the mid-stratum or overstorey rarely (Freeman et al. 2018). Resprouts make use of existing root systems to quickly recover after above-ground damage due to fires (Cook 2021). Their development arises from frequent fires, but are restricted from growing into the canopy from those frequent fires along with competition for light and water from overstorey trees (Fensham and Bowman 1992; Prior et al. 1997).

5.4.4.3 Vegetation adaptations and resilience to fire

The structure and composition of Australian savannas has developed under a regime of anthropogenic fires for many tens of thousands of years. As a result, native savanna vegetation is largely resilient to fires through a range of mechanisms that develop over time, and community dynamics such as structure and recruitment are heavily influenced by fire. Vegetation attributes that enable resilience to single fires can include (Lawes et al. 2011b):

- the ability to protect growing points from heat damage such as through thick bark; placement in tall canopy above common flame and scorch height; placement below ground; placement in moist bark or leaves; and/or
- the ability to recruit following fires through asexual reproduction or protection of seed.

For vegetation experiencing regular fires, the ability to restore protections damaged in one fire before the next fire, and the ability of top-killed plants to produce seed or asexual propagules before the next fire, become important. Most of the species planned for revegetation at Ranger Mine have fire resilient mechanisms (Table 5-54).

Table 5-54: Fire resilience mechanisms in natural ecosystems and 25 year old developing revegetation (Cook 2021)

Fire resilience mechanism	Mature, natural ecosystem	25 year old developing revegetated ecosystem
Recruitment processes	Asexual recruitment dominates for most woody and herbaceous species. Although herbaceous species may be able to develop strong tubers within the first year of growth, woody lignotubers of tree species may be decades to centuries old (Fensham and Bowman 1992). The establishment of woody species from seed is rare (Setterfield 2002), and little studied.	Little is known of the development of tubers of tropical herbaceous species or of woody species. It is unlikely that woody lignotubers will have developed to the density, size or diversity that occur in natural systems, but they may be on a trajectory towards it. Direct measurement of lignotuber development will be challenging, but could be inferred from resprout growth. The relative roles of seeding recruitment and asexual recruitment from lignotubers and root suckers (*Eucalyptus tetrodonta* and *Erythrophleum chlorostachys*) may be different to natural ecosystems because of incomplete development of the lignotuber population.

Fire resilience mechanism	Mature, natural ecosystem	25 year old developing revegetated ecosystem
Avoidance of heat from flames e.g. perennial grasses with deep growing points: *Chysopogon fallax, Alloteropsis semialata*. Annual grasses with buried seed: *Sorghum intrans, Aristida spp*. Herbs with tubers: *Galactia tenuiflora, Haemodorum spp*. Most Woody species with lignotubers	Grasses and herbaceous species are able to evade fire impacts through buried seed and growing points that allow rapid growth in the wet season (Scott et al. 2010a; Scott et al. 2010b). For woody species, lignotubers provide protection from heat and resources to support rapid post-fire growth (Freeman et al. 2017). Many woody species can flower and fruit within the understorey and do not need to become mid or overstorey trees to sexually reproduce (Freeman et al. 2018). Thick bark confers protection from fire to above-ground growing points of woody species (Lawes et al. 2011a)	Grasses and herbaceous species in revegetation should respond similarly to fire as those in natural systems. Many species of eucalypts in southern Australia can develop lignotubers capable of resprouting after fires within one to two years of germinating (Gill 1997), and this is likely to be the case in northern Australia for eucalypts as well as other genera of trees. The process of development of lignotubers and of resprout populations over time since germination and the consequent fire resistance is largely unknown (Fensham and Bowman 1992; Fensham et al. 2008). Even in small trees, mortality after a fire is low and topkill uncommon (Lawes et al. 2011b). Species with thicker bark will have greater ability to not be topkilled by fire, but eucalypts can survive, despite thinner bark due to deeply embedded epicormic sprouts (Lawes et al. 2011a).
Root suckering after topkill of mature individuals: *Eucalyptus tetrodonta, Erythrophleum chlorostachys*	Mature trees exist in canopy as well as in ground stratum. With adequate fire-free gaps suckers can recruit above flame zone. A semi-log distribution of tree sizes (Cook et al. 2020b) across the savanna zone indicates that trees are continuously recruiting into the canopy.	Many individual young trees still have potential to be top-killed by fire, but this should encourage root suckers to develop (Fensham and Bowman 1992). It is likely that the pool of root suckers will be less than that in mature, natural ecosystems – it will require more time and cycles of growth of saplings and topkill to develop pool of root suckers. The even-age stand that will develop may, for many decades, preclude recruitment of new canopy trees from root suckers.
Growing tall rapidly so that growing points above flame zone: *E. tetrodonta, E. miniata*	Multi-strata, presence of a fire-suppressed community of plants to rapidly take the place of topkilled plants. Mortality rate in Eucalypt open forest across all size classes from seasonal drought and fire is about 1 to 2% per year. A proportion of most woody species occurs as mature tall individuals with their canopy > 4 m and up to about 25 m.	Possibly still simple stratification, with a lack of recruits in ground layer and mid-storey. A multi-size pool may develop slowly. Mortality rate will be driven by the interaction of water use by the growing trees and the ability of the soil developing on the waste rock to store and provide that water. Trees will still be growing vertically, and none are likely to have reached their maximum height.

Fire resilience mechanism	Mature, natural ecosystem	25 year old developing revegetated ecosystem
Fire tolerant Corymbia and woodland *Eucalyptus spp*., more tolerant of shallow soils and not as strong growing as *E. tetrodonta and E. miniata:*	Mortality rate across all size classes from seasonal drought and fire = 2.7 % per year possibly reflecting harsher environments on shallower soils.	Mortality rate across all size classes may be lower because system not at carrying capacity. It is likely that the relative abundance of shorter stature Corymbia and tall growing *E. miniata and E. tetrodonta* will reach an equilibrium with soil conditions that will be difficult to predict. Allowance should be made in seedling mixes to provide for differential responses to substrate variability and the complex interactions with fire.
Production of seeds that can survive fires: *Acacia spp*.	Plants recruit from seed and occasionally from resprouting. Plants typically short-lived (5-7 and some longer years?).	Plants recruit from seed after fires and occasionally from resprouting. Plants typically short-lived (5 years?). A bad outcome would occur if these become dominant because they would outcompete framework species and could provide ladder fuels to carry fire into developing canopy.
Wide variety of responses to stresses and disturbances through overall species composition	High species richness ensures community has a wide range of responses to disturbances and stresses. In areas with a low frequency of less severe fires, the following species or groups of species may be present in the shrub or midstorey in higher density: monsoon forest species, mid-storey savanna species (e.g. *Erythrophleum chlorostachys, Terminalia ferdinandiana*). Higher fire frequency may lead to an absent mid-storey or support a high density of fast growing acacias.	In areas with a low frequency of less severe fires, the following species or groups of species may be present in the shrub or developing midstorey in higher density: monsoon forest species, mid-storey savanna species (e.g. *Erythrophleum chlorostachys, Terminalia ferdinandiana*). Higher fire frequency may lead to an absent mid-storey or support a high density of fast growing acacias.
Growing point protected by thick leaf bases and thick trunk: *Livistona spp., Pandanas spiralis*	Livistona and Pandanas trees in a range of size classes, able to persist and remain reproductive under most fires.	Livistona and Pandanas trees in even age (25 yr) stand, able to persist and remain reproductive under most fires. Some new recruitment from seed occurring.
Investing in thick bark and rapid regrowth from epicormic shoots or lignotubers if burnt: *Melaleuca spp.*	Usually survives fire and most commonly grows in wetter parts of landscape.	Usually survives fire and most commonly grows in wetter parts of landscape.

Fire resilience mechanism	**Mature, natural ecosystem**	**25 year old developing revegetated ecosystem**
Ability to persist and reproduce sexually in flame zone: *Buchanania obovata, Planchonia careya, Petalostigma quadriloculare, Planchonia careya, Terminalia ferdinandiana, Brachychiton spp*.,	Although often stated to be fire sensitive, these species can persist, flower and fruit at high densities within the flame zone. Occasional individuals may escape to become components of the mid-stratum.	Some individuals may be approaching mid-stratum (8 – 15 m), but many may be persisting in ground layer which is similar to a mature, natural system.
Ability to resprout rapidly from lignotubers and reproduce in one season: *Grevillea dryandra, G. goodii*.	An occasional component of understorey able to persist by regrowing each wet season, and survive in absence of fire.	An occasional component of understorey able to persist by regrowing each wet season, and survive in absence of fire.
Fire-proofing the stand through exclusion of most grasses: *Calytrix exstipulata, Dodonaea hispidula.*	On sites often with shallow soils, Calytrix stands can exclude most fires through reducing grass growth and persist (Scott et al. 2009).	Calytrix stands may be able to develop and persist on revegetation areas with shallow soils. Dodonaea may become aggressive and outcompete Framework species. In dense stands, they can exclude fires from rehabilitating savanna and alter trajectories.
Nutrient cycling and soil development	Mixture of biological and pyrogenic pathways for mineralisation of dead organic matter supports vegetation growth in nutrient poor soils (Cook 1994; Rossiter-Rachor et al. 2008) Termite and earthworm activity recycles dead organic matter (Dawes-Gromadzki 2008).	Slow establishment of decomposer populations may have led to excessive litter loads, creating a fire hazard. Careful implementation of burning may have mineralised dead organic matter (Cook 2012). Disturbance reduces the activity and diversity of termites and earthworms and reduces the soil forming activity of these groups (Dawes 2010a). Bare soil or a lack of termite activity may reduce recycling of organic matter and thereby fail to develop soil porosity, water storage and plant growth (Dawes 2010b). Provision of mulch and organic matter as islands may increase colonisation by termites

5.4.4.4 Rehabilitated ecosystem responses to fire

As outlined by Dr Gary Cook, a renowned expert in fire ecology that has been commissioned by ERA to support their work addressing KKN ESR8 (Cook 2021):

Developing ecosystems have a different structure and composition to natural ecosystems in which many plants are decades to centuries old. Although the same species may have been planted in rehabilitated landscapes as adjoining natural landscapes, they may take a long time to develop resilience to fire at both an individual and a population scale. Compared with natural ecosystems, there have been few published studies about rehabilitating ecosystems in Australia's savanna zone and fewer that focus on fire. It is likely that fire will impact developing ecosystems differently to natural systems.

On the waste rock / laterite mix sections of the TLF, trees greater than 2.5 m tall and 4 cm DBH were more likely to survive a fire than those less than this threshold (discussed further below, Wright 2019b). However, even if the majority of individuals in a reconstructed ecosystem have reached a size where they are likely to survive one or two fires, does not mean the ecosystem is resilient enough, or that it is desirable, to implement a fire regime similar to the surrounding Kakadu National Park.

5.4.4.5 Fire and nutrient cycling

Nutrient cycling in tropical, fire dependent ecosystems, such as the eucalypt-dominated woodlands of Kakadu NP, is driven by this disturbance regime (Cook 1994). Annual litter accumulation can be significant (depending on vegetation composition and structure), especially due to grass, fallen leaves and branches. In the humid wet season, this organic material is rapidly decomposed by soil micro-organisms, providing significant nutrient input, much of which is available to plants at the precise time they are growing most rapidly and require it. As the dry season progresses and soil moisture is depleted, and with the removal of the accumulated litter and grass biomass layer by fire, microbial activity declines (Cook 1994). Combustion of dead organic matter produces char and ash that has a high content of plant nutrients. These nutrients are highly available and provide for plant growth along with the first rains of the following wet season (Cook 1992; 1994); however, may contribute to nutrient movement in surface water run-off (Townsend and Douglas 2000).

Although fire has an important role in the cycling of nutrients in natural, established savannas, considering the novel waste rock substrate that will be used for revegetation of the Ranger FLF, future fire management must also carefully consider pedogenesis. The development of a litter layer has been seen as beneficial for soil development in natural and re-establishing ecosystems (Tongway and Hindley 2003; Tongway and Hindley 2004), and the removal of this organic matter through fire may delay or even set-back this process during the early and possibly intermediate stages of ecosystem establishment. Burning may also cause losses of nutrients, particularly nitrogen through atmospheric transfers and erosion of deposited ash (Cook 2021).

5.4.4.6 Burns on the TLF

A weed control burn was conducted in 2016 in laterite mix sections 2 and 3 of the TLF to reduce the cover of weedy species (Wright 2019a). Key findings from this report were that trees greater than 2.5 m height and 4 cm DBH are more likely to survive fire and other natural threats (Figure 5-137 and Figure 5-138). Further, planted species *E. tetrodonta, W. saligna* and *A. hemignosta* observed high rates of recruitment following fire. Density of *A. holosericea* was particularly documented to be impacted by fire, however left unmanaged rapidly bounced back.

A second controlled burn was planned and executed in June 2019, to again reduce weed loads. The burn was preceded by a thorough application of herbicide to initially reduce the seed bank and cure existing material. The fuel load prior to burning was visually estimated at 2-3 tonnes per hectare, which in dry season conditions was considered suitable to carry fire without allowing critical damage of larger trees. The burn was conducted under cool conditions and a southeast prevailing wind of 10-15 km/h. It was performed slowly and carefully against the wind to achieve a low, slow burn and concentrate intensity at the ground level.

Data was collected pre-burn and one month post-burn in affected permanent plots for height, DBH, health/condition for each woody stem or tree, as well as ground cover composition and extent. From this data the main findings were:

- Scorch height (height of leaf browning) averaged 2-3 m.
- Except *A. holosericea* (which has a narrow stem and less natural protection from fire) the large majority of trees above 2.5 m height and 4 cm DBH survived and showed signs of regeneration. From over 100 stems, only two large *A. holosericea* shrubs (>3.5 m height) actually showed signs of survival, and these were somewhat protected by fire due to their position on a very rocky area that did not burn (Figure 5-136).
- Weed-dominant groundcover was reduced from 48-98 % to 0-10 %.
- Of all the planted *Acacia* species, those above 2 m survived and many were responding by reshooting.
- Some small *T. ferdinandiana* and *C. fraseri* (<1.3 m) were destroyed.
- A few stunted original *C. disjuncta* and most *E. tetrodonta* and *W. saligna* suckers below 1.4 m were damaged, but showed signs of early regeneration.
- Some slow growing small plants such as *O. vernicosa* and *P. pubescens* (<0.8 m) appeared to be destroyed, however routine monitoring of the TLF has since shown them to have recovered.

It was intended to introduce native understorey in the following wet season, however this opportunity was not capitalised on and early rains contributed to a dense weedy covering by January 2020. The groundcover composition however was changed; pre-burn the ground layer was dominated by Buffalo Clover whereas after it was predominately *Urochloa reptans*, a more manageable weedy native species.

Figure 5-136: *Acacia holosericea* exposed to fire (top) and protected from fire (bottom), four months after 2019 June burn.

Figure 5-137: Recovery of the revegetation from a prescribed burn in May 2016. View of the burnt vegetation on the trial landform 12 days post fire (left) and 6 months post fire (right)

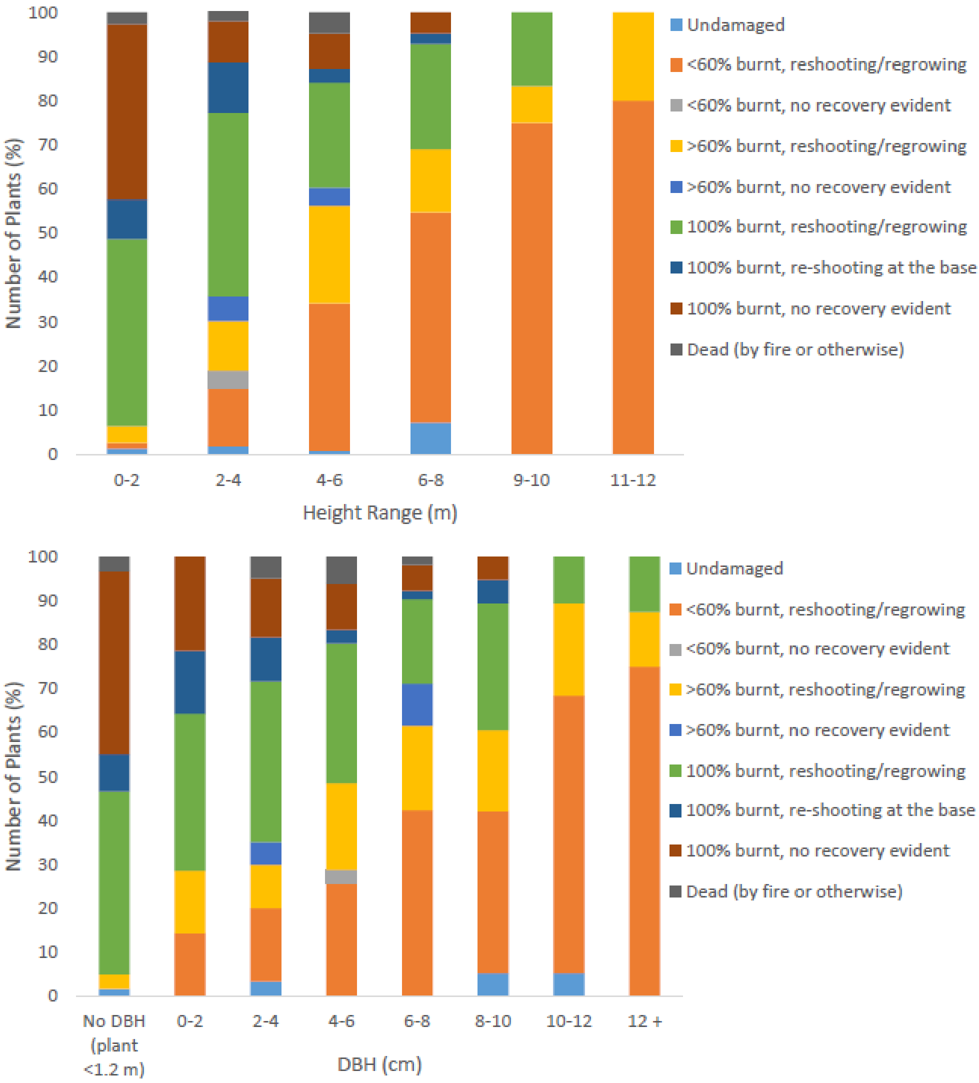


Figure 5-138: Height and DBH ranges and associated health classes after the 2016 burn on laterite mix areas of the TLF (Wright 2019a)

5.4.4.7 Fire implementation on rehabilitated landforms at Ranger

The current strategy for Ranger Mine is to completely exclude fire from developing revegetation areas until, at a very minimum, the majority of individuals from the majority of species have reached a size where survival is likely. Adaptive management trials can be used to help inform when a fire can and should be implemented with consideration of risk management and soil development. In the longer term, a fire regime will gradually be introduced with a focus on purposeful burns and desired burn patterns, rather than on timing exclusively. It is essential that this is undertaken in partnership with Traditional Owners and Traditional Knowledge.

5.4.4.8 Future work on fire resilience and fire implementation on rehabilitated ecosystems

ERA will continue to develop their understanding on how fire on revegetated waste rock landforms may impact key indicators of the ecosystem closure criteria, specifically:

- flora species composition and abundance;
- community structure;
- species flowering, fruiting and recruitment;
- nutrient cycling and soil development; and
- fauna colonisation.

This will help inform and develop the ERA Fire Implementation Plan. ERA will also investigate fire, the risk of deviated states and fire management actions to redirect ecosystems onto a desired development trajectory. This will be achieved though ongoing expert elicitation, stakeholder engagement and ongoing, targeted, adaptive management trial burns.

5.4.5 ESR4 Incidence and abundance of introduced species (flora and fauna)

KKN title	Question
ESR4. Incidence and abundance of introduced species (flora and fauna)	ESR4A What is the incidence and abundance of introduced animals and weeds in areas adjacent to the mine site, and what are the factors that will inform effective management of introduced species on the rehabilitated mine site?

5.4.5.1 Background

A weed is an exotic or native species that colonises and persists in an ecosystem in which it did not previously exist. These invasive plants typically produce large numbers of seeds and are excellent at surviving and reproducing in disturbed environments. Weeds potentially reduce biodiversity by competing with or displacing endemic species and may also affect natural processes such as fire intensity and stream flows. The restriction to recreational movement of people may also result from weed infestations.

One of the most significant threats to the natural and cultural values of the Kakadu NP is weeds (Director of National Parks 2016). Compared to other national parks in the region, Kakadu NP has a low proportion of weeds. However, there are still significant impacts by invasive weeds to some of the landscapes within the national park.

The RPA has been surveyed by ERA annually for weeds since 2003, and approximately 80 species have been recorded during this time. Weeds of National Significance (WoNS) are categorised under the Federal *Environment Protection and Biodiversity Conservation Act 1999* (*EPBC Act).* Gamba Grass (*Andropogon gayanus*) is the only WoNS previously recorded in the RPA with the recorded presence historically restricted to isolated plants on roadsides, in the vicinity of the Jabiru Airport. In 2022 there was a suspected sighting of one individual plant on a ramp entering Pit 1 from the mine, which was immediately removed and reported to stakeholders. It is possible that the seed was brought in on a vehicle as there are no known sources of gamba grass in the immediate surrounding areas. There are significant sources of gamba grass along the Arnhem highway, so good weed hygiene (including vehicle wash-downs and inspections) and continued weed awareness is required to ensure no populations develop on the RPA. There are five grass species listed as Key Threatening Processes to Australia's biodiversity also under the *EPBC Act*. Gamba Grass is one of these, whilst the other four species have not been recorded on the Ranger Mine.

The Northern Australia Quarantine Strategy (NAQS) was established in 1989 to manage the risks of biosecurity particular to northern Australia due to the proximity to neighbouring countries. The NAQS is administered by the Federal Department of Agriculture. No weeds listed within the NAQS have been recorded within the RPA. There are also six weed species listed under the Tropical Weeds Eradication Program (DAF 2019) which, to date, have not been recorded on the RPA.

In the NT, the *Weeds Management Act 2001* is administered by the Department of Environment and Natural Resources. Six species listed under this legislation as Class A/B/C (eradicate/growth and spread to be/not to be introduced into the NT) have been recorded within the RPA. In addition, there are a further nine weed species that have been identified by ERA as requiring active treatment and/or removal when detected on the RPA (Table 5-55).

An un-identified plant was observed on the RPA in 2019. A sample was submitted to the NT Herbarium for identification, and it was identified on 17 April 2019 as *Spigelia anthelmia* (Indian Pinkroot). The identification of *Spigelia* at the Ranger Mine is the first known occurrence of this weed in Australia. External stakeholders were notified. *Spigelia* is native to the tropical and sub-tropical Americas and is known to have spread to parts of Africa and South East Asia (including Thailand, the Philippines and Papua New Guinea). Since identification the RPA has been comprehensively surveyed. *Spigelia* was detected in a number of locations and all located plants were treated. ERA aims to eradicate the *Spigelia* infestation. A timeframe to achieve eradication is 5-6 years given that *Spigelia* seed may remain viable for at least 3 years.

Twelve introduced fauna species have been recorded in the RPA, the most recently being the browsing ant (*Lepisiota frauenfeldi*), and an additional eight species have been recorded in Kakadu NP

Table 5-56). Three species recorded in both the RPA and Kakadu NP (pig, cat and cane toad) are listed under the *EPBC Act* as key threatening processes to environmental, natural heritage and cultural heritage values.

Table 5-55: Actively Managed Weeds in the surrounding RPA

Scientific name	Common name	*Weeds Act 2001* (NT) listing
Andropogan gayanus	Gamba Grass	Class A, Class C and Weed of National Significance
Calopogonium mucunoides	Calopo	–
Cenchrus pedicellatus	Annual Pennisetum	–
Cenchrus polystachios	Mission Grass	Class B, Class C
Chamaecrista rotundifolia	Wynn's Cassia	–
Crotalaria goreensis	Rattlepod	–
Hyptis suaveolens	Hyptis	Class B, Class C
Ipomoea quamoclit	Cupid's Flower	–
Macroptilium atropurpureum	Siratro	–
Senna obtusifolia	Sicklepod	Class B, Class C
Sesamum indicum	Sesame	–
Sida acuta	Spinyhead Sida	Class B, Class C
Sida cordifolia	Flannel Weed	–
Spigelia anthelmia	Indian Pinkroot	–
Themeda quadrivalvis	Grader Grass	Class B, Class C

Table 5-56: Feral fauna species known to occur in Kakadu NP and the RPA

Type	Common name	Scientific name	RPA	Kakadu NP
Mammal	Dog	*Canis lupus familiaris*	Y	Y
Mammal	Banteng	*Bos javanicus*		Y
Mammal	Buffalo	*Bubalus bubalis*	Y	Y
Mammal	Cattle	*Bos taurus*		Y
Mammal	Cat	*Felis catus*	Y	Y
Mammal	Donkey	*Equus asinus*		Y

Type	Common name	Scientific name	RPA	Kakadu NP
Mammal	Goat	*Capra hircus*		Y
Mammal	Horse	*Equus caballus*		Y
Mammal	Black rat	*Rattus rattus*	Y	Y
Mammal	House mouse	*Mus domesticus*	Y	Y
Mammal	Pig	*Sus scrofa*	Y	Y
Mammal	Rusa Deer	*Cervus timorensis*		Y
Mammal	Sambar Deer	*Cervus unicolour*		Y
Bird	Rock pigeon	*Columbia livia*		Y
Fish	Mosquito fish	*Gambusia holbrooki*		Y
Insect	Ginger ant	*Solenopsis geminata*		Y
Insect	Pharaoh's ant	*Monomorium pharaonis*		Y
Insect	Singapore ant	*Monomorium destructor*		Y
Insect	Ghost ant	*Tapinoma melanocephalum*		Y
Insect	Big-headed ant	*Pheidole megacephala*		Y
Insect	Browsing ant	*Lepisiota frauenfeldi*	Y	
Insect	Black crazy ant	*Pratrechina longicornis*		Y
Insect	Tropical fire ant	*Solenopsis geminate*		Y
Insect	Yellow crazy ant	*Anoplolepis gracilipes*		Y
Insect	Cockroach	*Periplaneta spp.*	Y	Y
Insect	European honey bee	*Apis mellifera*	Y	Y
Insect	Salvina weevil	*Crytobagous salviniae*		Y
Insect	Sida Beetle	*Calligrapha sp.*		Y
Amphibian	Cane toad	*Rhinella marina*	Y	Y
Reptile	Flower-pot snake	*Ramphotyphlops braminus*	Y	Y
Reptile	House gecko	*Hemidactylus frenatus*	Y	Y

5.4.5.2 Exotic and weed species in revegetation areas

Weeds have been an ongoing issue on the TLF. In May 2009, the waste rock/laterite mix section had a weed density of 7,083 +/- 1,828 weeds/ha, whereas no weeds were identified in the waste rock only areas (Daws & Poole 2010). Daws and Poole (2010) concluded that a substantial weed seed bank was introduced with the laterite material used in constructing the landform. In addition, the waste rock only substrate was quite hostile to self-colonisation by weed species. There was still minimal weed cover on the waste rock areas in 2020, however, species have slowly begun colonised from the laterite mix areas into 1B and 1A in recent years. Paradoxically, the high ground cover contributed to higher early landscape function analysis indices on the laterite mix area, albeit confounded due to the high presence of weedy understorey (Gellert & Lu 2015).

Nineteen exotic /weedy species have been observed on the TLF since September 2018. Most of the species present today were growing in the laterite mix areas within two years after the TLF was constructed (Daws & Gellert 2010, 2011; Daws & Poole 2010). Although the number of exotic and weedy species on the TLF is similar across the four sections, the cover is significantly different. Sections 2 and 3 have recurringly dense, groundcovers of weed, whereas 1A and 1B have sparsely scattered weeds with very few dense patches.

Acacia holosericea is generally considered a native/naturalised species in the NT. However, due to their aggressive colonisation and dominance of disturbed areas it is considered a weed on the TLF and across the RPA. Within two years of the TLF construction, *A. holosericea* had germinated, grown, set seed (Gellert 2012), and were cut back at the end of 2010 to manage their spread (Daws & Gellert 2011). The cool burn performed in the laterite mix areas in July 2019 has proven to be a successful management tool for controlling *A. holosericea* and changing the composition of weedy groundcover (as discussed in ESR8).

Stage 13.1 was finished to final level early 2020 with very little weed presence observable. Application of pre-emergent herbicide prior to planting was not prioritised for areas A and B, and due to ongoing disturbance, subsequent earthworks and rainwater run-on from upstream weed sources, weeds began colonising the area by November 2020, particularly *Chloris barbata* (Rhodes Grass) and *Echinochloa colona* (Barnyard Grass). Area C was treated with pre-emergent herbicide four weeks prior to planting in August 2021.

During the two years since planting began on Stage 13.1, fourteen exotic flora species have been observed across the area. There was a targeted effort to reduce weed loads on Stage 13.1 during the 2020-2021 and 2021-2022 weed seasons. Weed status in the area has improved, particularly in 2022, with chemical treatment and physical removal being the main forms of control. There are still ongoing challenges with Rhodes Grass, which is relatively resilient against various herbicides, and *C. pedicellatus* (annual Mission Grass), which has been successfully controlled but continues to be reintroduced due to weed sources in the mine area blowing into Stage 13.1. A multi-year management plan for weeds in the mining area is currently under development and will be executed in the upcoming weed season.

Minimal weeds were observed growing on the Pit 1 surface in the 2020/2021 wet season following completion of backfill, with just relatively small numbers of *A. holosericea*, *Alysicarpus vaginalis* (Buffalo Clover) and annual Mission Grass. These were treated at the end of the wet season, and each planting section was again treated with pre-emergent and knockdown herbicides at least 2 - 4 weeks prior to planting. Learning from the difficulties experience in previous areas, there was significant focus on Pit 1 weed management during the 2021 – 2022 weed season. Current weed status on Pit 1 is promising, especially considering the size of the area (approx. 40 ha). If there is continued effort and resources spent managing weeds on the landform in the upcoming years while trees and shrubs establish and native understorey cover increases, a weed legacy issue is unlikely. Like Stage 13.1, Rhodes grass has been the most difficult to manage due to it's herbicide resilience. Physical removal of individuals is effective, however it is laborious and time consuming.

5.4.5.3 Future work on introduced flora and fauna

ESR4 is a SSB-only KKN, and as such, ERA do not have any specific research programs regarding introduced flora and fauna. However, ERA will continue to:

- comprehensively monitor weeds and exotic fauna throughout the closure period (Section 10); and
- develop their knowledge and experience on weed management options, particularly for revegetation areas.

5.4.6 ESR2 Determining the requirements and characteristics of a terrestrial faunal community similar to natural ecosystems adjacent to the mine site, including Kakadu National Park

KKN title	Question
ESR2. Determining the requirements and characteristics of a terrestrial faunal community similar to natural ecosystems adjacent to the minesite, including Kakadu National Park	ESR2A *What faunal community structure (composition, relative abundance, functional groups) is present in natural ecosystems adjacent to the mine site, and what factors influence variation in these community parameters?*
	ESR2B *What habitat, including enhancements, should be provided on the rehabilitated site to ensure or expedite the colonisation of fauna, including threatened species?*
	ESR2C *What is the risk of introduced animals (e.g. cats and dogs) to faunal colonisation and long-term sustainability?*

5.4.6.1 Species of conservational significance in the region

Kakadu NP contains over one third of Australia's bird species (271), one quarter of Australia's land mammals (77), 132 reptile species, 27 frog species and over 246 fish species recorded in tidal and freshwater areas (Director of National Parks 2016). A significant decline in the abundance of ten small mammal species has been recorded in Kakadu NP since the 1990s, including Northern Brown Bandicoot (*Isoodon macrourus*), Fawn Antechinus (*Antechinus bellus*), Common Brushtail Possum (*Trichosurus vulpecula*), Pale Field-Rat (*Rattus tunneyi*), and Northern Quoll (*Dasyurus hallucatus*). The decline has been attributed to a high fire frequency, feral cats and cane toads (Woinarski *et al*. 2010). The Northern Quoll population particularly has undergone dramatic declines due to ingestion of the toxic cane toad and in many areas of the mainland, such as Kakadu NP, it has become almost extinct.

Many *Environment Protection and Biodiversity Conservation Act 1999* (EPBC) and/or *Territory Parks and Wildlife Conservation Act 1976* (TPWC) listed conservation species have been recorded historically on the RPA and/or in surrounds (Table 5-57). This includes numerous bird species listed under various migratory agreements that are seasonally common and widespread throughout Kakadu NP. A recent analysis of four savanna woodland surveys conducted post-2012 found that the only legislated threatened species recorded in the region across 35 survey sites were Partridge Pigeon (*Geophaps smithii smithii*), Black-footed tree-rat (*Mesembriomys gouldii*), Fawn Antechinus, Northern Brown Bandicoot and Northern Quoll (SLR Consulting 2021).

Table 5-57: Conservation listed species known to occur on the RPA (adapted from Firth 2012)

Common name	Scientific name	*EPBC Act* (Cth) status	*TPWC Act* (NT) status	Preferred habitat
MAMMALS				
Black-footed Tree-rat	*Mesembriomys gouldii*	Endangered	Vulnerable	Tropical woodlands and open forests in coastal areas
Brush-tailed Rabbit-rat	*Conilurus penicillatus*	Vulnerable	Endangered	Tropical woodlands; declined to near extinction since the 1980s
Fawn Antechinus	*Antechinus bellus*	Vulnerable	Endangered	Savanna woodland; tall open forest
Northern Brown Bandicoot	*Isoodon macrourus*	Not listed	Near threatened	Tall grassland, shrubland, savanna and open forest
Northern Quoll	*Dasyurus hallucatus*	Endangered	Critically Endangered	Eucalypt open forests; rocky areas
Pale Field-rat	*Rattus tunneyi*	Not listed	Vulnerable	Found in in the higher rainfall areas of the Top End of the Northern Territory
BIRDS				
Black-tailed Godwit[1-4]	*Limosa limosa*	Marine, migratory	Not listed	Coastal regions
Black-winged Stilt	*Himantopus himantopus*	Marine	Not listed	Freshwater and saltwater marshes, mudflats and the shallow edges of lakes and rivers
Broad-billed Sandpiper[1-4]	*Limicola falcinellus*	Migratory	Not listed	Sheltered coastal, intertidal mudflats
Caspian Tern[3]	*Hydroprogne caspia*	Migratory	Not listed	Coastal sheltered estuaries, inlets and bays
Cattle Egret	*Ardea ibis*	Marine	Not listed	Wet grasslands, wetlands, mudflats
Common Greenshank[1-4]	*Tringa nebularia*	Marine, migratory	Not listed	Coastal and inland wetlands
Common Sandpiper[1-4]	*Actitis hypoleucos*	Marine, migratory	Not listed	Coastal and inland wetlands, billabongs

Common name	Scientific name	*EPBC Act* (Cth) status	*TPWC Act* (NT) status	Preferred habitat
Curlew Sandpiper[1-4]	*Calidris ferruginea*	Critically Endangered, marine, migratory	Vulnerable	Coastal areas, non-tidal swamps, lakes and lagoons, inland ephemeral and permanent lakes, dams
Eastern Great Egret	*Ardea alba modesta*	Marine	Not listed	Range of wetlands, from lakes, rivers and swamps to estuaries, saltmarsh and intertidal mudflats
Glossy Ibis[1]	*Plegadis falcinellus*	Marine, migratory	Not listed	Swamps, flood waters
Great Egret	*Ardea alba*	Marine	Not listed	Wetlands, mudflats, mangroves
Greater Sand Plover[1-4]	*Charadrius leschenaultii*	Vulnerable, marine, migratory	Vulnerable	Sheltered beaches, intertidal mudflats or sandbanks, sandy estuarine lagoons
Green Pigmy Goose	*Nettapus pulchellus*	Marine	Not listed	Coast, tropical freshwater lagoons
Grey Plover[1-4]	*Pluvialis squatarola*	Marine, migratory	Not listed	Coast, inland wetlands
Grey-tailed Tattler[1-4]	*Tringa brevipes*	Marine, migratory	Not listed	Coastal intertidal pools, mudflats and rock ledges
Lesser Sand Plover[1-4]	*Charadrius mongolus*	Endangered, marine, migratory	Vulnerable	Intertidal sandflats and mudflats, beaches, estuary mudflats
Little Ringed Plover[2-4]	*Charadrius dubius*	Marine, migratory	Not listed	Lowland habitats with shallow standing freshwater
Long-toed Stint[1-4]	*Calidris subminuta*	Marine, migratory	Not listed	Shallow freshwater or brackish wetlands
Magpie goose	*Anseranas semipalmata*	Marine	Not listed	Coastal and inland wetlands, billabongs
Marsh Sandpiper/ Little Greenshank[1-4]	*Tringa stagnatilis*	Marine, migratory	Not listed	Coastal and inland wetlands, estuarine and mangrove mudflats
Pacific Golden Plover	*Pluvialis fulva*	Marine	Not listed	Wetlands, shores, paddocks, saltmarsh, coastal golf courses, estuaries and lagoons
Partridge Pigeon	*Geophaps smithii smithii*	Vulnerable	Vulnerable	Lowland woodland
Radjah Shelduck	*Tadorna radjah*	Marine	Not listed	Mangrove flats, swamps, freshwater swamps, lagoons, billabongs
Rainbow Bee-eater	*Merops ornatus*	Marine	Not listed	Open woodlands and forest, grasslands, widespread distribution and habitats
Red-capped Plover	*Charadrius ruficapillus*	Marine	Not listed	Sandflats or mudflats at the margins of saline, brackish or freshwater wetlands

Common name	Scientific name	*EPBC Act* (Cth) status	*TPWC Act* (NT) status	Preferred habitat
Red-necked Stint[1-4]	*Calidris ruficollis*	Marine, migratory	Not listed	Sheltered inlets, bays, lagoons, estuaries, intertidal mudflats and protected sandy or coralline shores
Ruddy Turnstone[1-4]	*Arenaria interpres*	Marine, migratory	Not listed	Coasts including mudflats
Sharp-tailed Sandpiper[1-4]	*Calidris acuminata*	Marine, migratory	Not listed	Fresh or saltwater wetlands
Swinhoe's Snipe[1-4]	*Gallinago megala*	Marine, migratory	Not listed	Coasts, floodplains, rivers
Terek Sandpiper[1-4]	*Xenus cinereus*	Marine, migratory	Not listed	Sheltered coastal mudflats, mangrove swamps
Wandering Whistling Duck	*Dendrocygna arcuata*	Marine	Not listed	Rivers, billabongs, pools and lakes
White-bellied Sea-eagle	*Haliaeetus leucogaster*	Marine	Not listed	Coasts, floodplains, rivers
Whimbrel[1-4]	*Numenius phaeopus*	Marine, migratory	Not listed	Primarily coastal distribution
Wood Sandpiper[1-4]	*Tringa glareola*	Marine, migratory	Not listed	Coasts, floodplains, rivers
REPTILES				
Estuarine Crocodile[1]	*Crocodylus porosus*	Marine, migratory	Not listed	Marine, freshwater
Merten's Water Monitor	*Varanus mertensi*	Not listed	Vulnerable	Creeks and billabongs

[1]Bonn; [2]China Australia Migratory Bird Agreement; [3]Japan Australia Migratory Bird Agreement; [4]Republic of Korea-Australia Migratory Bird Agreement

Although they are not listed in conservation acts, frugivorous and nectivorous birds as a functional group are also recognised by ERA as important for rehabilitation and ecosystem establishment due to their role in pollination and flora species dispersal (Caves et al 2013, Frick et al 2014). Due to these critical ecosystem services, they have been included under external exchanges closure criteria (refer *Section 8*). The frugivorous and nectivorous birds that will potentially occur within the rehabilitated Ranger mine site identified by Dr John Woinarski are listed in Table 5-58.

Table 5-58: Frugivorous and nectivorous bird species that may occur within the rehabilitated Ranger Mine site

Common Name	Scientific name	Importance of fruit*	Importance of nectar*
Australasian Figbird	*Sphecotheres vieilloti*	1	
Banded Honeyeater	*Cissomela pectoralis*		1

Common Name	Scientific name	Importance of fruit*	Importance of nectar*
Bar-Shouldered Dove	*Geopelia humeralis*	2	
Blue-Faced Honeyeater	*Entomyzon cyanotis*	2	1
Brown Honeyeater	*Lichmera indistincta*		1
Channel-Billed Cuckoo	*Scythrops novaehollandiae*	1	
Dusky Honey-Eater	*Myzomela obscura*		1
Eastern Koel	*Eudynamys orientalis*	1	
Great Bowerbird	*Phalacrocorax carbo*	2	
Helmeted Friarbird	*Philemon buceroides*	2	1
Little Friarbird	*Philemon citreogularis*	2	1
Little Shrike-Thrush	*Colluricincla megarhyncha*	2	
Mistletoebird	*Dicaeum hirundinaceum*	1	
Northern Rosella	*Platycercus venustus*	2	
Olive-Backed Oriole	*Oriolus sagittatus*	2	
Red-Collared Lorikeet	*Trichoglossus haematodus*	2	1
Red-Winged Parrot	*Aprosmictus erythropterus*	2	2
Rose-Crowned Fruit-Dove	*Ptilinopus regina*	1	
Rufous-Banded Honeyeater	*Conopophila albogularis*		1
Rufous-Throated Honeyeater	*Conopophila rufogularis*		1
Silver-Crowned Friarbird	*Philemon argenticeps*	2	1
Spangled Drongo	*Dicrurus bracteatus*	2	
Torresian Imperial Pigeon	*Ducula bicolor*	1	
Varied Lorikeet	*Psitteuteles versicolor*		1
White-Bellied Cuckoo-Shrike	*Coracina papuensis*	2	
White-Gaped	*Lichenostomus*	2	1

Common Name	Scientific name	Importance of fruit*	Importance of nectar*
Honeyeater	*unicolor*		
White-Throated Honeyeater	*Melithreptus albogularis*		1
Yellow Oriole	*Oriolus flavocinctus*	1	
Yellow-Throated Miner	*Manorina flavigula*		2

*A value of 1 indicates that most of the diet is fruit, or nectar. A value of 2 indicates that fruit, or nectar is important, but other dietary items are more important.

5.4.6.2 Reference vertebrate monitoring on the RPA and surrounding Kakadu NP

Recolonisation of fauna into rehabilitated areas, in part, depends on the proximity to sources of fauna in surrounding areas. The Ranger FLF will be surrounded by relatively healthy woodland and is therefore close to sources of native fauna.

A variety of fauna surveys in the RPA and surrounds were conducted historically for purposes not specifically related to mine closure. Fauna surveys performed prior to 2010 were reviewed by ENV Australia Pty Ltd (Firth 2012) during the pre-feasibility study for the Ranger 3 Deeps mine development. The literature review synthesised 26 reports that presented results of vertebrate and invertebrate fauna surveys from 1993 – 2010, in addition to flora and aquatic ecosystem surveys (Firth 2012). Although these surveys contain valuable historical baseline data, they no longer represent the current status of fauna in Kakadu NP, particularly in regard to declining small mammal populations. Therefore, these early surveys have not been included in recent considerations for fauna species that have the potential to recolonise the rehabilitated Ranger mine (SLR Consulting 2021).

In 2020, SLR Consulting Australia Pty Ltd. (SLR) were engaged to provide an updated native vertebrate fauna species list for ERA, based on survey data from suitable savanna woodland sites geographically close to the RPA (SLR Consulting 2021). The species list and spatial database was based on four monitoring programs undertaken post-2012 (Eco Logical Australia 2013, Eco Logical Australia 2016b, SLR Consulting 2019, Einoder et al. 2019) (Table 5-59, Figure 5-139). The report identified a total of 177 native vertebrate species across 35 survey sites, including 15 amphibians, 104 birds, 15 mammals and 38 reptiles. These species could be expected to occur on the rehabilitated Ranger FLF. The full list of species is presented in Appendix 5.6.

Table 5-59: Summary of surveys used for SLR Consulting 2021 analysis

Reference	Survey area	Survey techniques
ELA 2014	Within the Ranger Project Area (RPA) between the mine footprint and Magela Creek.	Elliott, cage, cameras and funnel traps, bird census, nocturnal active searches
ELA 2016	Within the RPA, and Kakadu National Park (KNP) up to 11 km from the mine footprint.	Funnel and camera traps, bird census
SLR 2019	Within the RPA up to 5.5 km from the mine footprint, includes sites on the trial landform.	Cage, Elliott, funnel, pitfall and camera traps, nocturnal and diurnal active searches
Einoder et al. 2019	KNP up to approximately 45 km from the mine footprint.	Cage, Elliott and pitfall trap, instantaneous bird census, nocturnal and diurnal active searches

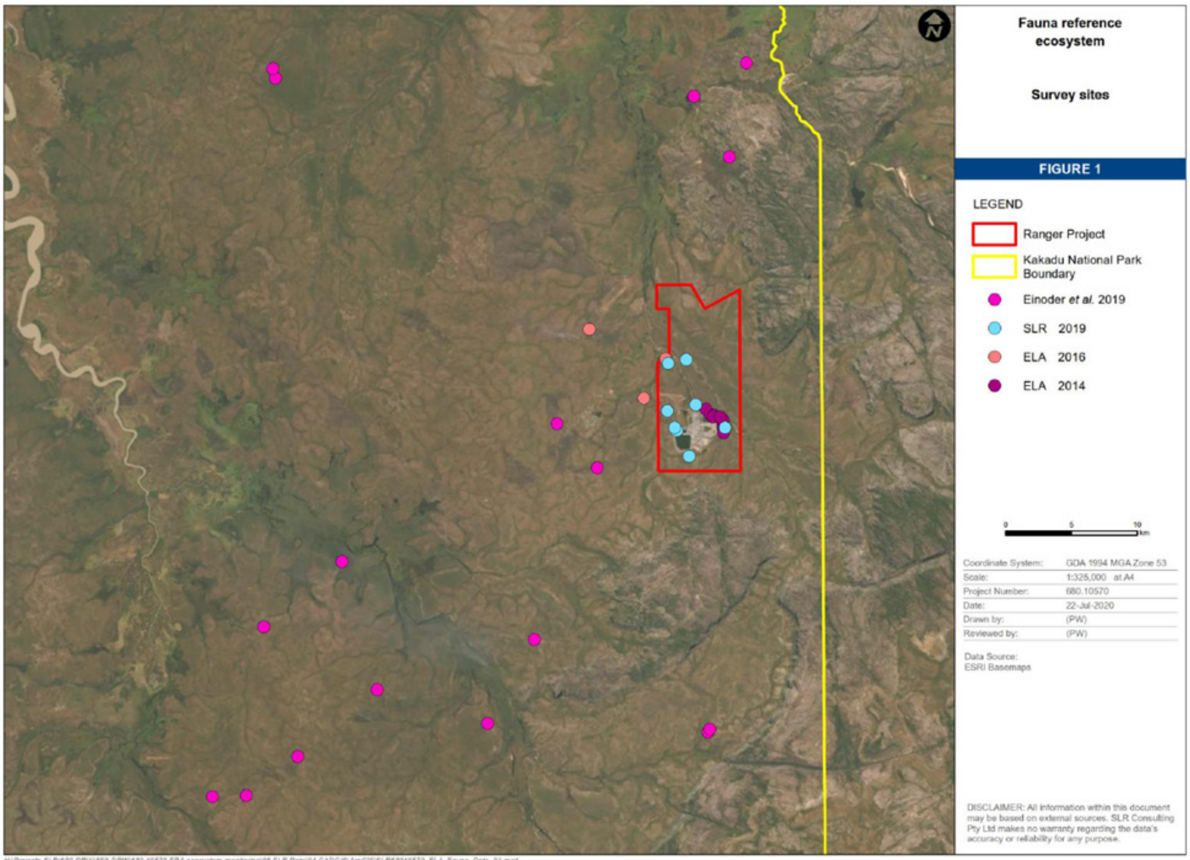


Figure 5-139: Fauna survey site locations across RPA and Kakadu NP (SLR Consulting 2021)

5.4.6.3 Vertebrate colonisation on revegetated waste rock landforms

Extensive fauna studies on historical revegetation trial areas on waste rock dumps in the RPA demonstrated that the array of vertebrate fauna living on the revegetated waste rock dumps was typical to that found in similar habitats of Kakadu NP (Corbett 1999) . One notable exception was the absence of possums and other arboreal groups, which was likely due to the absence of extensive stands of mature trees with hollows (discussed further in later sections). It was hypothesised that one of the major reasons for the relatively high fauna density on the waste rock dump was "… good feral animal control to minimise predator impacts on founder populations" (Corbett 1999).

There were many incidental sightings of fauna on the TLF within the first few years, including visiting dingoes and Agile Wallabies (Macropus agilis). Lizards, frogs and many birds were also observed. Small mammal trapping also found the Common Rock-Rat (Zyzomys argurus) inhabiting the landform (Collier & Hooke 2011). Although the individuals weren't directly observed, Bandicoot tracks/scratchings started appearing after three years. Birds began recolonising and nesting on the TLF in 2013 (Gellert 2014), and excitingly, Partridge Pigeons nested and had offspring in the waste rock only sections in 2015 and 2016 (Figure 5-140). A community of Bush Stone Curlew (Burhinus grallarius) also took up residence for a few years in the laterite mix sections from approximately 2014 - 2017. More regular snake sightings began around this time, particularly in the footage captured from the erosion plot monitoring.

The two tubestock-only sections of the TLF were monitored for vertebrate fauna as part of a larger survey conducted in late wet season 2019 (SLR 2019). The waste rock only site (1A) had 16 native fauna recorded, including 8 birds, 1 mammal and 7 reptiles, and the laterite mix section (3) had 14 native fauna recorded, including 8 birds, 1 mammal and 5 reptiles. Some of the species observed included Common Rock-Rat, Black-Necked Snake-Lizard (*Delma tincta*), Bynoe's Gecko (*Heteronotia binoei*), and Northern Brown Snake (*Pseudonaja nuchalis*). The TLF sites had similar species richness of reptiles and mammals compared to the other RPA sites, but bird richness was lower. No amphibians were observed at the rehabilitated sites during this survey; however, amphibian presence was variable across all the RPA sites (0 – 10 species).

Figure 5-140: Partridge Pigeon on waste rock section of the TLF

5.4.6.4 Invertebrate colonisation on revegetated waste rock landforms

Invertebrates are critically important for a sustainable and functioning rehabilitated ecosystem, as they mediate key ecological processes and are an important food source.

The historical revegetation trials established on waste rock at Ranger Mine in the 1980s were surveyed for ants, in addition to unmined control sites (Andersen 1993). The revegetated sites were first colonised by species of *Iridomyrmex*, with a broad range of species colonising the sites over the initial vegetation establishment phase; however, ant species succession soon stalled due to the dominance of fast-growing Acacias which resulted in heavy litter and considerable shade (Andersen 1993). After eight years, the revegetated sites had roughly a third of ant species compared to the unmined sites (12 compared to 33-35), with the most abundant species being an exotic. Fire management to control the Acacias improved ant recolonisation into the revegetated areas (Andersen 1993).

Insects were incidentally observed on the TLF soon after revegetation. When the ecosystem was nine years old in 2018, invertebrate surveys were performed on the TLF and in natural reference sites surrounding Ranger Mine in the dry season (Andersen & Oberprieler 2019) (Figure 5-141). Species richness was far higher at reference sites compared with the TLF. Surveys from the reference sites yielded 105 ant species from 25 genera, whereas the TLF sites yielded 31 species from 16 genera; the reference sites also collected 37 species of beetle, mutillid wasps and zodariid spiders compared to only 10 at the TLF sites (Andersen & Oberprieler 2019). Species composition was also highly dissimilar. This is to be expected considering the TLF's early stage of revegetation (Andersen & Oberprieler 2019), and encouragingly, the overall ant abundance was similarly high at the reference and TLF sites, with *Iridomyrmex* ants among the most abundant.

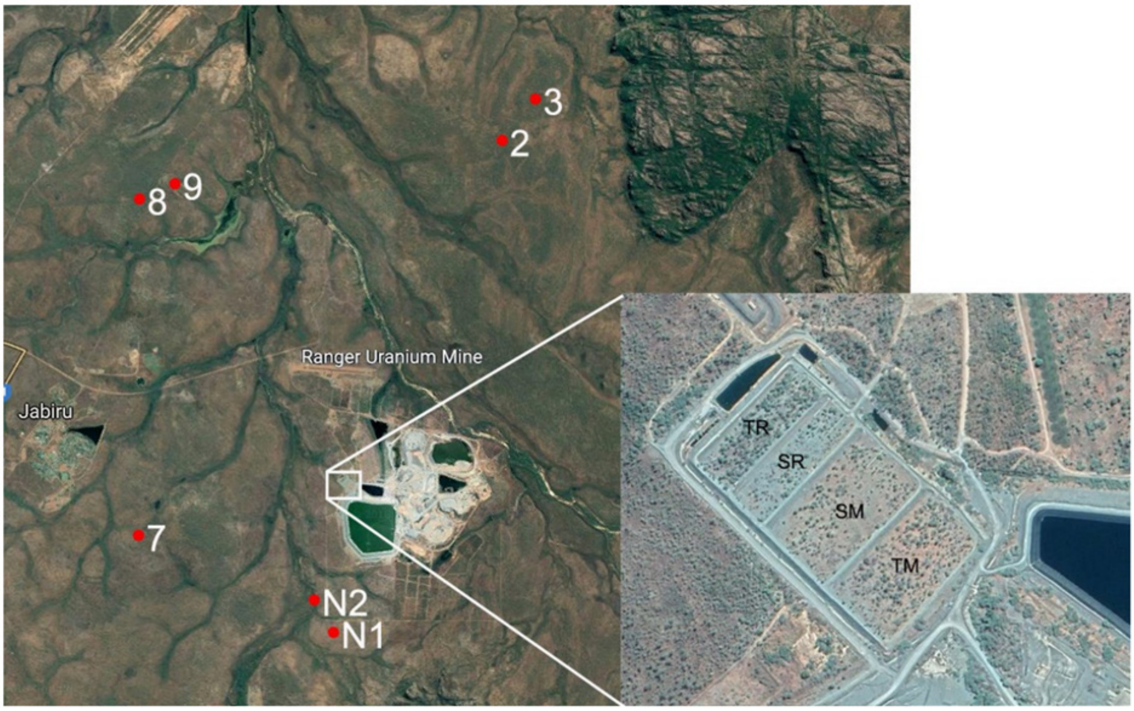


Figure 5-141: Location of the 2018 invertebrate study, with four TLF revegetation sites and seven natural reference sites (Andersen & Oberprieler 2019)

5.4.6.5 Fauna habitat creation

In addition to proximity to sources of fauna, successful fauna recolonisation primarily depends on the presence of suitable habitat for species, with the development of mature vegetation communities correlating with increased species diversity across numerous taxa. The presence of vegetation communities is often used as an indicator of vertebrate recolonisation in mine closure (Cross et al., 2019, Cristescu et al., 2012), although invertebrate recolonisation is typically addressed directly (King et al. 1998, Andersen et al. 2002, Hoffmann and Andersen 2003, Lawes et al. 2017). Important fauna habitat features within vegetation communities include tree hollows, rocks of various sizes, leaf litter, coarse woody debris, and even bushy grasses and palms. Other key considerations are the presence of energy sources (flowers, seed, fruit, leaves, insects etc.) and perching branches for birds. Certain habitat features need to be carefully planned and engineered during the landform construction phase (eg. rocky habitats, discussed in *Section 9*), whereas many other features will develop naturally during the early stages of ecosystem establishment as long as appropriate flora species are introduced.

Tree hollows provide important habitat for various taxa, which include many species that are hollow-dependent (Taylor *et al.* 2003, Goldingay 2009, Goldingay 2011, Lindenmayer *et al.* 2014). Many hollow-forming NT eucalypt woodland tree species/genera (Woolley et al. 2018) are included in the current Ranger revegetation species list (Appendix 5.5). However, hollows can take over a century to form, therefore recolonisation of hollow-dependent species into rehabilitated landscapes is considerably slower than other fauna groups.

ERA began exploring the use of nest boxes in rehabilitated ecosystems in 2019, with the construction of five designs targeting different fauna groups (Table 5-60). The nest box designs were based on advice from Dr John Woinarski and Dr Leigh-Ann Woolley (CDU), as well as Palmerstone Men's Shed. It is recognised that nest boxes cannot replace all the attributes provided by natural hollows; however, they may still provide valuable habitat in rehabilitated areas where no natural hollows are available (SLR 2022a). They can also be used to demonstrate that, with time, rehabilitation areas will become suitable for hollow-dependent species.

In 2021, SLR were engaged to advise on a nest box trial design and implementation plan (SLR 2022a) which was endorsed by stakeholders at the May 2022 ARRTC. The trial will investigate the use of the five nest box designs in three types of sites across the RPA; rehabilitated (on the TLF), modified/disturbed (in the LAAs) and control (in undisturbed woodlands) (Figure 5-142). There will also be 'natural' woodland sites which will only have fauna cameras recording natural hollows as a control for the nest box sites. A ground-truthing, 'reconnaissance' week in June 2022 identified suitable sites and individual trees for camera and nest box installation (SLR 2022b). Construction of additional nest box replicates for the trial is underway and should be completed by October 2022 for installation.

Table 5-60: Nest box design and rationale

Nest Box Type and Rationale	Design
Small arboreal mammal Designed for attracting threatened species such as the Black-footed Tree Rat (*Mesembriomys gouldii*).	
Large arboreal mammal Designed for possums and gliders but may also attract large climbing lizards such as goannas.	

Nest Box Type and Rationale	Design
Small bird Designed for small birds such as finches, particularly if a good ground cover of suitable local native grasses can be established.	
Medium bird Designed for medium size parrots such as the Red-winged Parrot (*Aprosmictus erythropterus*) and Red-Collared Lorikeet (*Trichoglossus haematodus*).	
Microbat Designed to imitate narrow crevices for microbat roosts.	

Figure 5-142: Next box trial site locations (from SLR 2022b)

5.4.6.6 Future work on native fauna

- Full installation of the nest box trial is aimed to be completed before the end of 2022, with ongoing monitoring of the boxes and hollows for at least one year.
- ERA will continue to develop their understanding of habitat requirements for fauna recolonisation of rehabilitated landforms, and potentially undergo more ad hoc, opportunistic trials to encourage faunal establishment.
- Continue to monitor fauna recolonisation into rehabilitated areas, and develop monitoring methods and metrics for closure criteria.

5.4.7 ESR5 Develop a restoration trajectory for Ranger Mine

KKN title	Question
ESR5. Develop a restoration trajectory for Ranger Mine	ESR5A. *What are the key sustainability indicators that should be used to measure restoration success?*
	ESR5B. *What are possible/agreed restoration trajectories (flora and fauna) across the Ranger mine site; and which would ensure they will move to a sustainable ecosystem similar to those adjacent to the mine site, including Kakadu National Park?*

5.4.7.1 Background

State and transition (S&T) models are non-linear conceptual models (that can include quantitative information), which organise information about ecosystem change (Bestelmeyer et al. 2017). A S&T model describing desirable and undesirable transitions along possible rehabilitation trajectories at Ranger mine was developed by scientific, industry and local ecology experts at a workshop in April 2019 (CSIRO, 2020). The development of a S&T model that articulates possible rehabilitation trajectories should lead to better predictions of when rehabilitated sites will move to sustainable ecosystems that no longer require additional management intervention, including articulation of points along the desired trajectory that represent milestones linked to closure criteria (Section 8).

Another key element of S&T models is the development of adaptive management plans for ecosystem rehabilitation that is linked to and guides monitoring and maintenance activities. For ERA these will be detailed within a series of Trigger Action Response Plans (TARPs, discussed in Section 10) (Figure 5-143).

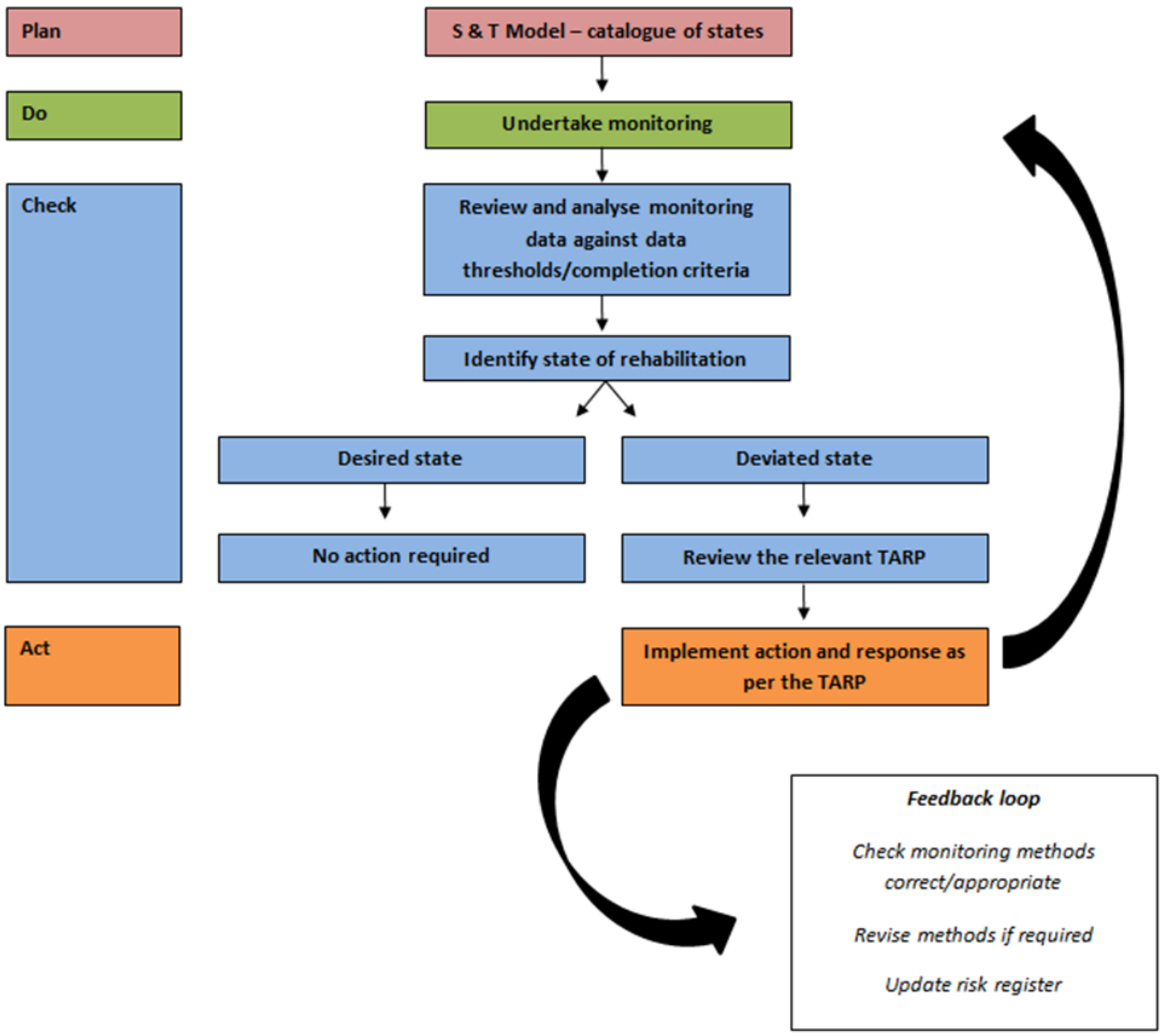


Figure 5-143: Flowchart showing relationship between S&T model and TARPs

5.4.7.2 CSIRO Trajectories Project

As part of the S&T model development process, workshop participants described candidate end states in detail, using the archetype reference dynamic ecosystem model for a wet-dry tropical Eucalypt woodland from the AusEcoModels project as a guide (Figure 5-143). The model was refined and quantified during the workshop. Detailed descriptions of the ecosystem attributes of the five reference ecosystem expressions in the archetype model in Figure 5-144 were developed for the Ranger mine site (CSIRO, 2020). A summary of the S&T model for Ranger mine rehabilitation is shown on Figure 5-145. The axes labels represent qualitative indication of increasing complexity of state attributes over developmental time (ie through the establishment, intermediate and end phases).

The detailed descriptions include descriptions of the three desired end states in the Ranger S&T model (refer to Figure 5-145):

- S1 (Ideal).

- S2 (Ideal_dry).
- S3 (Ideal_function).

Each rehabilitation state is described in CSIRO (2020) using ecosystem attributes related to structure, composition, function, abiotic and landscape characteristics. Each desired and deviated rehabilitation state has been individually modelled to show the potential transitions it could undergo and the resulting states (CSIRO 2020).

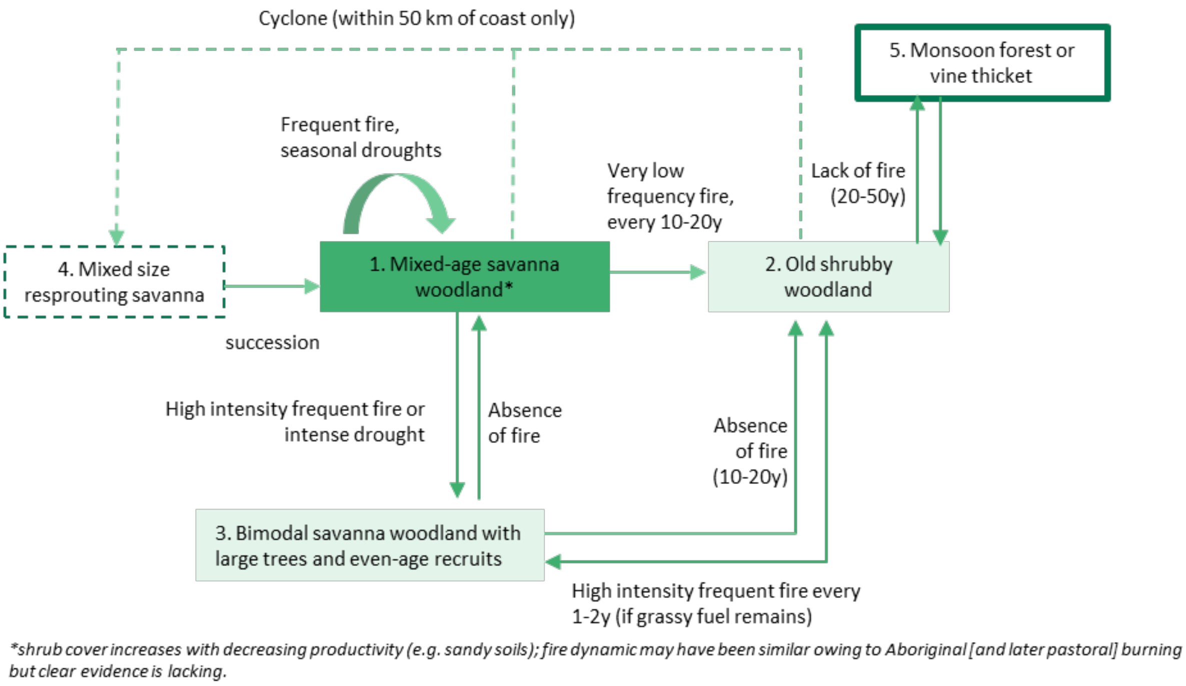


Figure 5-144: Wet-dry tropical woodland archetype reference dynamic ecosystem model (diagram from CSIRO 2020)

The threats (or drivers) of change in rehabilitation state, and management interventions that could be implemented to return rehabilitation states to a desirable trajectory, were identified in the workshop. All possible transitions between rehabilitation states (informed by the list of threats and management interventions), the indicative timeframe for transition to occur, and any pre-conditions (often climate or landscape processes external to the site) were also identified in the workshop (CSIRO, 2020). Transitions are defined as a shift to another state which is not reversible without active management intervention, an extreme event or unacceptably long timeframe.

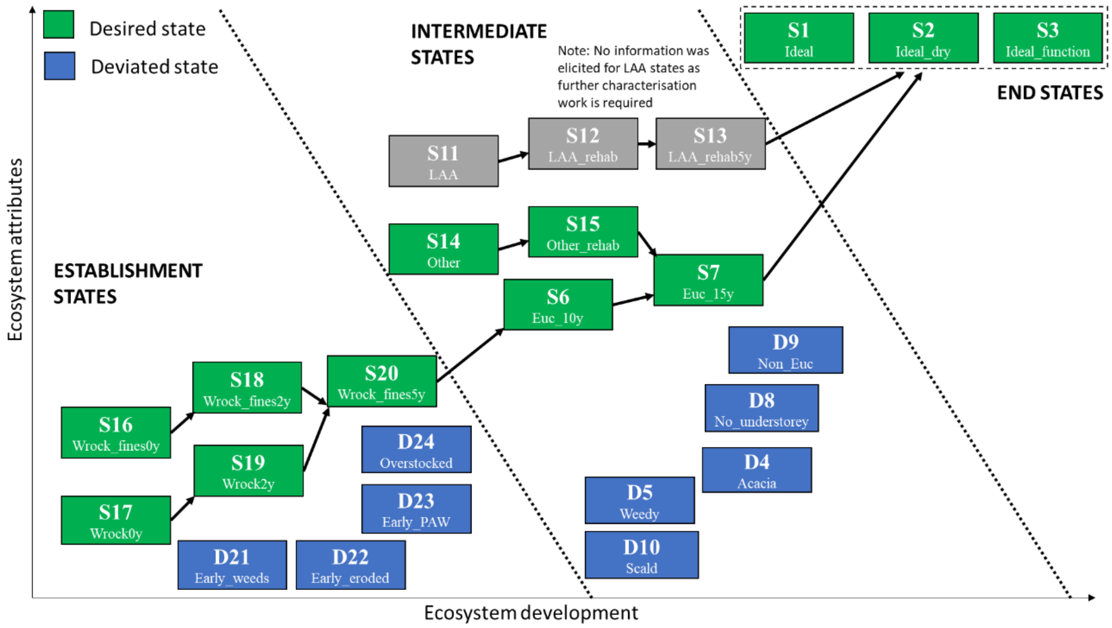


Figure 5-145: Pictorial summary of an S&T model for Ranger mine rehabilitation (diagram from CSIRO 2020)

5.4.7.3 Development of the ERA S&T Model

A first draft of the ERA S&T model report, which builds on the CSIRO (2020) model, was completed April 2021. It included Ranger-specific quantitative and qualitative data derived from previous research and experience on initial and intermediate phase rehabilitated landforms. Themes included: substrate physical, chemical and microbial characteristics (Section ESR7); flora species composition, vegetation community structure, reproduction and recruitment (Section ESR3); and ecosystem resilience (Section ESR8). Unearthed Environment Services Pty Ltd (UES) were then engaged by ERA to critically review and revise the 2021 report. Some key initial observations were (Grant & Grant 2022):

- The form of the S&T model had too many components to meet the ultimate purpose of the model, which is to identify desired and deviated states, aligned to agreed closure criteria to drive maintenance and management activities to facilitate relinquishment.
- Suggest that the model only contains a simplified version of the TARPs, which would reduce the complexity of the model by more than 50% and make it more aligned with the identified purpose.
- That LAAs and 'other disturbed' states be removed from the main S&T model, so that focus can be on waste rock landform rehabilitation. If needed, separate models can be created for the other scenarios.
- Focus on the wholistic characteristics of each state and not the individual abiotic and biotic factors as they were represented in the 2021 report.

- That the short-term focus of the model should be on the ecosystem establishment techniques and identifying early deviated states and the required management activities to bring these back onto the desired successional trajectory. A particular focus should be on early intervention (e.g. monitoring of keystone ecosystem elements at 1-2 years of age).
- There are many more desired states on the desired trajectory, but the focus is on identifiable ecosystem states related to the potential crossing of a management threshold to a deviated state through an undesirable transition.
- That the S&T model development needs to be an iterative process, and revised as more data becomes available over times, particularly for intermediate states. Importantly, the model needs to 'live' through implementation of ecosystem establishment techniques and monitoring and management activities, followed by incorporation of learnings into the S&T model.
- Further data is required to be fitted into the proposed (and agreed) S&T model, which will help to identify knowledge gaps and associated actions to address these.

From this review, UES were reengaged in February 2022 to facilitate the further work required to rapidly develop a 'fit-for-purpose' S&T model, which could be used as a practical management tool to help drive rehabilitated areas along the desired successional trajectory towards the identified end state. A report on the proposed new framework of the S&T model was delivered and presented to stakeholders at ARRTC #50 in May 2022 (Grant & Grant 2022), then feedback was incorporated into a new model framework (Figure 5-146).

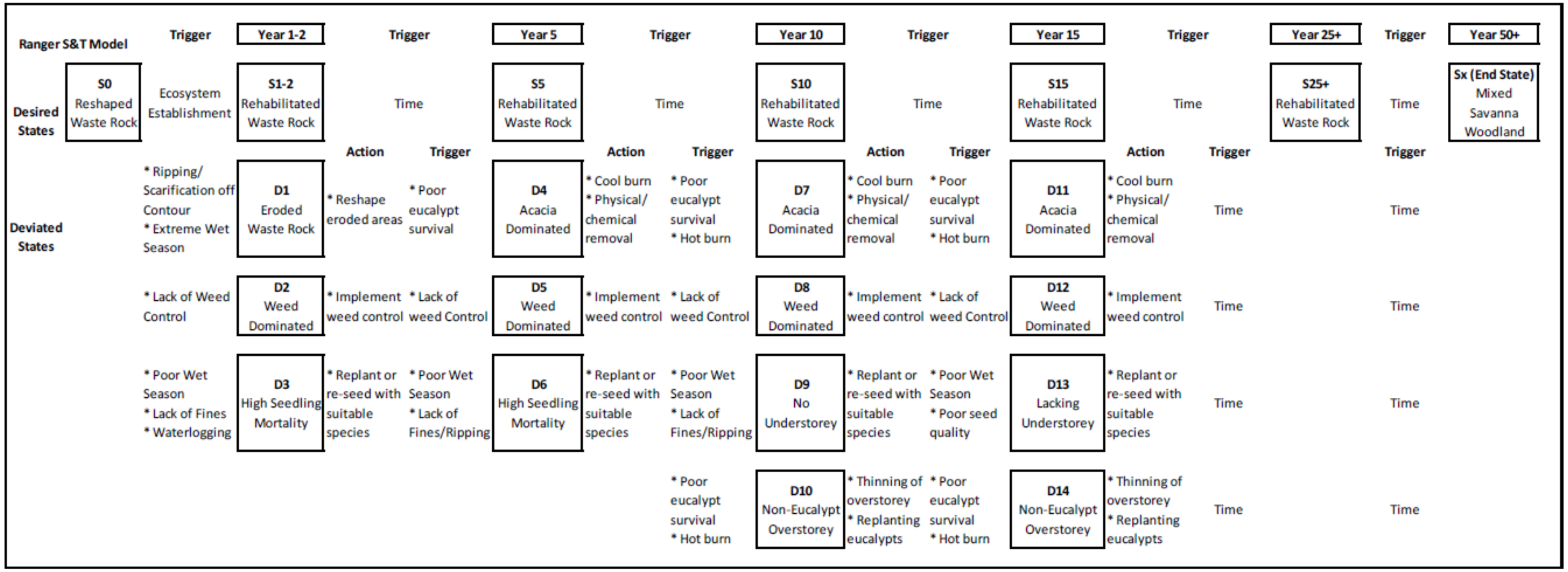


Figure 5-146: Diagram summarizing the updated model for Ranger Mine waste rock rehabilitation

The simplified and more concise version of the Ranger S&T model was developed following the below principles (Grant & Grant 2022):

- Removal of desired and deviated states related to utilization of fines (i.e. laterite) material as this is not a viable broad scale ecosystem establishment technique at Ranger.
- Re-numbering of desired states to reflect the age of the rehabilitated areas (e.g. desired state at year ten is called S10), leaving seven desired states remaining in the model with high level definition of abiotic and biotic characteristics (where available).
- Simplification of a single desired end state of mixed savanna woodland, instead of the five ecosystem types and three climate scenarios previously identified (CSIRO 2020).
- Identification of deviated states for each key time category (i.e. Year 1-2, 5, 10 and 15, 25+ yet to be determined), leaving 14 deviated states in the model with high level definition of abiotic and biotic characteristics.
- Duplication of key relevant deviated states across the time categories (e.g. weed dominated for all key time categories except the end state) and removal of deviated states identified at the 2019 workshop which will not realistically occur on the Ranger Min rehabilitation.
- Identification of key triggers and actions for desirable and undesirable deviations based on the developed TARPs, with further detail provided in an associated spreadsheet.

Some key abiotic and biotic characteristics of the 6 identified desired states and 14 deviated states were populated in the report and associated spreadsheet (Grant & Grant 2022). However, additional sourcing of data was necessary to incorporate into the model to address gaps and uncertainties in the expected trajectories. A week-long 'S&T model intensive' was conducted in August 2022 to source additional data from archives and relevant people. As well as considerable data and report sourcing, the week involved over 15 interviews with various people that currently and/or historically have been involved in rehabilitation research, execution, monitoring and/or management at Ranger mine, the Alligator Rivers Region, and northern Australian.

5.4.7.4 Future Work on the ERA S&T Model

Immediate future development of the ERA S&T model will be focussed on:

- Consolidating and synthesising collected data on abiotic/biotic characteristics of desired and deviated states, and successful management actions, so that they can be populated into model.
- Identify existing gaps and develop standardised monitoring program to fill gaps (where possible).

- Identify any additional sources that may have relevant information where gaps cannot be directly filled with further monitoring.
- Develop a spatial information system (e.g. ArcGIS) to store monitoring data relating to the achievement of identified closure criteria and facilitate identification of required management activities.
- Review and update ecosystem rehabilitation TARPS (Section 10).
- Continued development of the adaptive management plan, including outlining critical uncertainties for key measurable thresholds and deviated state mitigation or reversal scenarios.
- Consider development of separate S&T model for the LAA and other disturbed areas.

5.5 Cross theme

5.5.1 CT1 Assessing the cumulative risks of rehabilitation on-site and to the protection of the off-site environment

KKN title	Question
CT1. Assessing the cumulative risks of rehabilitation on-site and to the protection of the off-site environment	CT1A. *What are the cumulative risks to the success of rehabilitation on-site and to the off-site environment?*

The Phase 1 *Ranger rehabilitation and closure risk assessment* was the problem formulation phase for rehabilitation/closure, an ecological risk assessment for the mine site as well as a landscape scale risk assessment and how the two assessments can be linked. A workshop was conducted for the problem formulation phase to develop initial conceptual models (CM) of potential stressors and pathways around four themes; aquatic ecosystems; terrestrial ecosystems on the RPA; terrestrial ecosystems in the landscape; and people (Pollino *et al.* 2013). The workshop focus included defining endpoints; sources, stressors and values associated with mine closure; developing conceptual models and identifying key knowledge gaps. A report was produced by Pollino *et al.* (2013) which details background material, and the values and draft conceptual models produced during the workshop. The report also recommended adopting the AS/NZS ISO 31000:2009 generic framework to ensure outputs of risk assessments are best practice.

Phase 1 developed CMs identifying potential stressors and consequences to a set of aquatic, terrestrial and human endpoints (Bartolo *et al.* 2013). For the people theme, two conceptual models were developed for cultural landscape and human health. The human health model was considered outside the scope of the workshop to be considered at a later date. For the CMs that remained in scope, close to 100 potential hazards were identified. Whilst many of the hazards were considered important, they were not mine related and/or subject to management through the mine closure process. Some have very low likelihoods of occurrence or insignificant consequences if they were to occur.

Phase 2 was the risk screening phase for rehabilitation and closure. The screening methodology employed used input from 16 key experts and was consistent with ISO risk standards to ensure it defensible and transparent (Pollino 2014). Preliminary screening prioritised efforts for the risk analysis phase, providing spatial context and focus on aquatic and terrestrial systems and human health. Likelihoods were expressed as either probability for long-term (chronic) impacts, or event frequencies with a recurrence interval (Pollino 2014).

Hazard rankings were highest in the RPA, with weeds and feral animals being the highest ranked hazards, followed by sediment and radionuclides. Solutes and metals ranked lower and overall hazards to humans received a low ranking. Risk rankings were also highest in the RPA, with weeds and feral animals again ranked highest, followed by sediment and impacts of vegetation from fire and waste rock. As with hazards, solutes and metals were ranked lower and overall, risks to humans also received a low ranking.

A KKN CT1 project identified weeds as the most significant non-mining threat to the Kakadu landscape and wetlands (Waldon & Bayliss, 2003). This project describes the wetland risk assessment for three weed species, Mimosa (*Mimosa pigra*), Salvinia (*Salvinia molesta*) and Para Grass (*Urochloa mutica*).

Most Kakadu National Park floodplain habitats, including the Magela catchment, are susceptible to extensive mimosa invasion. Salvinia will never be eradicated and is considered a permanent component of Kakadu’s flora (Waldon *et al.* 2012). There are 35 para grass infestations on the Magela floodplain. A significant proportion of the Magela floodplain (~35–50%) could potentially be invaded by para grass in the future. The overall findings of the landscape environmental risk assessment imply that non-mining landscape-scale risks to Magela floodplain should receive the same level of scrutiny as uranium mining risks, including assessing what is needed to manage these risks. Diffuse landscape scale risks are currently several orders of magnitude greater than point source risks to Magela surface waters from the Ranger Uranium Mine, with para grass contributing most to the overall landscape risk.

Compared to climate change timeframes, management and monitoring for the closure prior to site stabilisation and close out has been achieved, found the risk profile for the mine closure was fairly low for climate related risks. A number of impacts are associated with the risks are scenarios beyond 2050 outside of the influence of closure. Risks considered include increased temperatures, and subsequent evaporation impacts on flora and fauna, rising sea levels, erosion and runoff, bushfires. Further detail on these risks is presented in section 5.6.

Climate change implications for mine closure will be actively managed, predominantly related to the revegetation and soil management on site ensuring the site will be in suitable condition for reliquishment. In the longer term, most climate change risks are landscape in nature and will affect the entire park. These risks will require management through local land management practices. Further detail on potential mitigation measures for future climatic conditions is presented in section 5.6.

A cumulative risk assessment (RES-2017-032) combining both Phase 2 (aquatic pathways) as well as qualitative modelling of Phase 1 (on-site risks) is being reviewed (Harford, 2021). Terrestrial and aquatic qualitative models were developed for the Ranger mine-site rehabilitation. Fire and weeds are primary factors that could significantly affect the success of terrestrial ecosystem rehabilitation where effective weed management would offer the greatest benefit. In aquatic ecosystems, higher trophic levels are supported by key aquatic taxonomic groups, indicators that can measure ecosystem health.

Qualitative modelling adds value to current and future risk assessment approaches by confirming importance of identified high risks, reducing system complexity enabling focus on key risks, predicting outcomes of risk interactions, and identifying where mitigations would be most effective.

5.5.1.1 Aquatic ecosystem assessment & framework development

Commonwealth ERs specific to the protection of water quality and the closure of Ranger Mine specify different objectives for waters leaving the RPA and those on the RPA:

- *Waters leaving the RPA do not compromise the achievement of the primary environmental objectives (ER 3.1) related to protection of the people, ecosystem (biodiversity and ecological processes), and World Heritage and Ramsar values of the surrounds (ER 1 and 2).*
- *Impacts on the RPA are ALARA (ER 1.2e).*

The SSB has recommended rehabilitation standards for concentrations of COPC leaving the RPA to protect biodiversity. These are based on ecotoxicity testing of local species, mesocosm studies, field macroinvertebrate and fish studies and are designed to protect 99% of species. Recent studies (Trenfield *et al* 2021) have shown that the individual guideline values for 99% species protection will adequately be protective for downstream ecosystems where there is a potential for exposure mixtures of the contaminants of concern. These apply at the RPA lease boundary to protect biodiversity. Closure criteria for water quality on the RPA is to be based on impacts that are ALARA as described in Sections 6.3 and 8.3.

An understanding of the potential impacts of different concentrations of mine-related COPC on aquatic biodiversity, and the endpoints representing the other primary environmental objectives, ie, ecosystem processes, Kakadu NP World Heritage values (including culturally sensitive species) and Ramsar values is required. This will help to understand what the impacts are and inform an assessment of whether they are ALARA.

ERA contracted BMT Ltd. to develop a practical and transparent framework to assess effects of COPCs on receiving environments within the RPA during the closure phase, with an initial focus on magnesium (Mg). BMT has been working with ERA and stakeholders since 2017 on this three-phase project. The project builds on best practice frameworks for protection of key ecological and community values (CVs), most notably ANZG (2018) and the *National framework and guidance for describing the ecological character of Australian Ramsar wetlands* (DEWHA 2008). The tasks for each of the Project phases are shown in The project phases are shown in Figure 5-147.

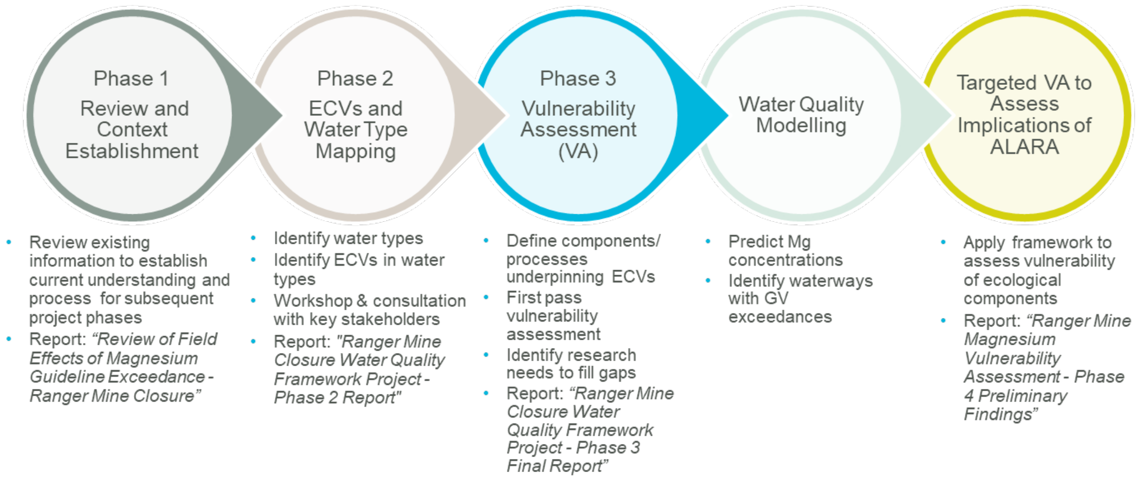


Figure 5-147: Ranger Mine Closure Water Quality Framework Project phases

The Project phases are described in the following sections:

5.5.1.2 Phase 1 (BMT WBM 2017)

This phase provided a review of spatial and temporal patterns in Mg concentrations and aquatic fauna within the waterways of RPA and downstream receiving environments. This Phase provided recommendations on the development of the water quality management framework for mine closure, with consideration given to legislative and policy requirements. Stakeholder feedback on the recommendations helped clarify the scope and role of third phase of the project and its application for future assessments.

5.5.1.3 Phase 2 (BMT 2018)

This phase steps through the initial stages of the ANZECC/ARMCANZ (2000) and ANZG (2018) water quality management frameworks to map and classify waterbody types on and off the RPA and identify CVs relevant to each waterbody type.

5.5.1.4 Phase 3 (BMT 2021)

This final development phase produced the framework to assess the vulnerability of aquatic ecological components underpinning CVs in the RPA to changes in Mg concentrations, and critical periods (i.e. reproduction, migrations, periods of stress) that are important to the maintenance of aquatic ecosystems in the RPA.

Aquatic ecosystems at and adjacent to the RPA support a wide range of biodiversity and cultural values (see BMT WBM 2010; 2017). Biodiversity values, and cultural values that are linked to biodiversity values[11], are composed of a variety of ecological features at different

[11] Note that cultural values not directly linked to biodiversity elements are not included in the scope of this project.

hierarchical levels (i.e. species, assemblages, habitats, ecosystems). These features vary in terms of their sensitivities to stressors such as Mg.

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.

Vulnerability is based on the consideration of following elements (De Lange *et al.* 2010, Weißhuhn *et al*. 2018), depicted in Figure 5-148:

- level of exposure to stressors – which will be predicted by the surface water modelling project (discussed in next project phase below)
- sensitivities to stressors such as Mg, 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, and the structural and functional relationships between the organisms, and the abiotic environment
- capacity to avoid exposure or recover following a perturbation, such as exposure to a contaminant. This is also known as resilience or adaptive capacity

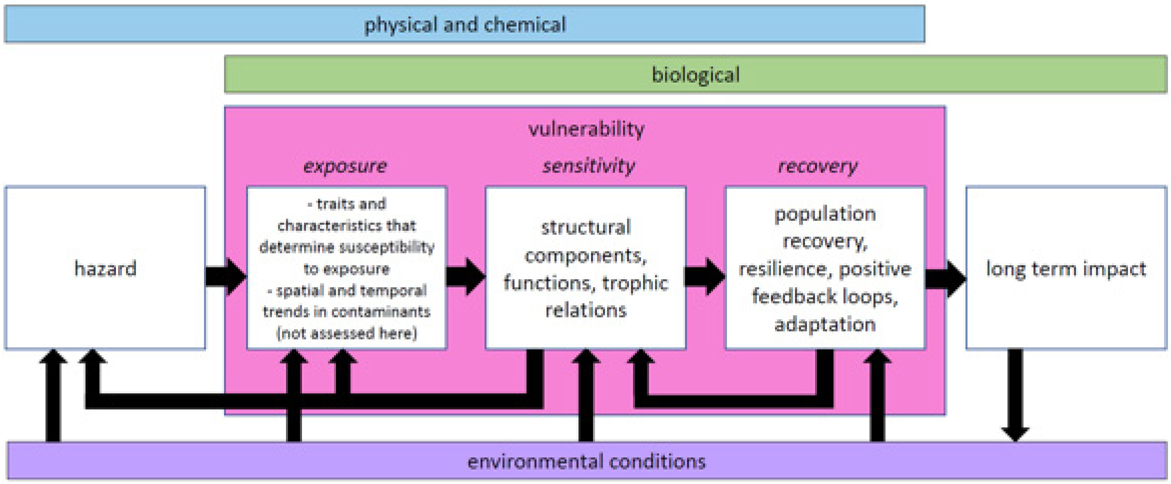


Figure 5-148: Modified version of the generalised ecological vulnerability assessment framework of De Lange et al. (2010)

Ecological vulnerability assessment fills the knowledge gap that exists between laboratory and field effects experiments on a sub-set of species or assemblages (i.e. the information underpinning the recommended SSB Rehabilitation Standards) 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 also trophic and habitat relationships and therefore the potential for indirect flow-on effects.

This phase involved the development of a Vulnerability Assessment Framework (VAF) to aid the interpretation of modelling results, with a focus on the potential effects of Mg on CVs of the mine area. The specific objectives of this third phase were to:

- Describe the key processes underpinning the CVs of the RPA and surrounds, and how these change over seasonal time scales.
- Define the key ecological components [12] underpinning the CVs of the RPA and surrounds, and interactions with underpinning processes.
- Document the salinity (a proxy of Mg) concentrations for which key ecological components have been recorded and undertake a first assessment of the sensitivity of these components to Mg, as inferred from field observations and laboratory studies.
- Determine the sensitivity of key ecological components to changes in habitat and food resources, based on their specificity and the availability of habitat and food resources.
- Assess the capacity of key ecological components to avoid contamination exposure and recover following disturbance (both directly and indirectly from Mg) based on their life history traits.

Then, based on the above:

- undertake a first pass assessment of the vulnerability of ecological components to changes in Mg, and factors affecting vulnerability over time.
- Identify gaps in the knowledge based on aquatic ecological component vulnerability to Mg, and further research needs to fill these gaps.

A large literature review (~200 reports) was undertaken, and scoring matrices developed and tested to assess vulnerability of ecosystem components. This was done with input from a committee of subject matter experts comprised of representatives from ERA, the SSB, BMT and several external specialists. Learnings from this initial assessment (BMT 2019) were used to improve the assessment framework and process. Additional literature and lines of evidence were reviewed, scoring matrices updated and decision trees developed to understand vulnerability based on nine traits concerning exposure, sensitivity, and adaptive capacity. The nine traits are comprised of:

Direct Sensitivity – (1) Direct sensitivity of key species; (2) Sensitivity of species groups (assemblage structure). These attributes consider the Mg sensitivity of ecological components.

Distribution and Habitats – (3) Geographic range; (4) Habitat breadth; (5) Dependency on sensitive bio-physical micro-habitats (macrophytes, riparian vegetation). These attributes consider the resilience of populations and species to perturbations. Species that are range

[12] In the context of this Project, the term ‘ecological components’ is the collective term for key species (those with a high biodiversity and cultural significance) and species groups.

restricted, or are habitat specialists that rely on sensitive habitat resources, have poor resilience.

Movement Capacity – (6) Dispersal traits (recolonisation); (7) Dispersal traits (avoidance). The first of these attributes considers traits that enable rapid recolonisation following perturbation, which should be considered in the context of Reproductive Capacity attribute. The second attribute considers traits that enable organisms to evade sub-optimal water quality conditions, and the potential for avoidance behaviour to impact on the fitness of local populations or species.

Reproductive Capacity – (8) Generation Time/Fecundity. This attribute considers generation time (the average amount of time between two consecutive generations) and number of offspring. Species with short generation times that produce higher numbers of offspring are more likely to produce more genetic variant individuals to trigger adaptation. There are other traits that can influence reproductive capacity including offspring survival, life span and parental care that were also broadly considered if adequate data was available.

Dietary Flexibility – (9) Diet breadth. This attribute considers dietary specialisation. Dietary specialists are more likely to be affected by food resource limitation than dietary generalists.

This phase provided a first pass vulnerability assessment in the absence of water quality modelling to determine ‘exposure’ and also identified key information gaps regarding the vulnerability of biodiversity elements underpinning CVs.

5.5.1.5 Water quality modelling (WS3)

Solute transport modelling predicting the concentrations of COPCs on, and downstream of, the RPA following closure is completed (see WS3). The surface water modelling (WS3) produce predictive estimates of Mg concentrations in receiving environments during post-closure conditions and the vulnerability assessment (Phase 3) provides the tool to interpret the water quality modelling results, i.e. vulnerability of different environmental values should Mg exceed the guideline value. See section WS3 for more information about the water quality monitoring undertaken at Ranger.

5.5.1.6 Targeted Vulnerability Assessment (BMT 2022)

The vulnerability assessment framework (VAF) produced in phase 3 is a tool to understand what type of ecological change might occur at the different contaminant concentrations predicted by the water quality modelling. The first targeted vulnerability assessment was completed in 2021/2022 with a focus on contaminant concentrations as a result of the Pit 3 closure activity (Pit 3 related sources).

An interactive workshop was held in 2021 with key internal and external stakeholders and subject matter experts to:

- Identify target waterbodies and confirm ecological values to be assessed
- 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 and data quality scores
- Identify key knowledge gaps

The targeted VAF undertaken in 2021/2022 focussed on the following subject waterbodies: Coonjimba Billabong, Georgetown Billabong, Georgetown Creek and Magela Creek (end of RPA reporting point).

For the purposes of assessing vulnerability, predicted closure phase Mg concentrations for P10, P50 and P90 loads presented in the surface water modelling and worst-case scenario values were selected. Median (50%), 10% and 1% exceedance values were also provided (BMT 2022).

The operational water quality data as well as seasonal patterns were provided for context and on whether simulated Mg during closure is within or outside the range of operational phase values. Summary statistics (50^{th} , 90^{th} and 99^{th} percentile values) were provided for the period 2006/8 to 2014/18. The metrics were derived from ERA monthly electrical conductivity data converted to Mg based on the equation in Turner et al. (2015).

Seasonal water quality periods were taken into consideration i.e., full flow vs recessional flow. This provides context for evaluating whether the timing of Mg exposure is consistent year-round or is restricted to the recessional period when many important ecological processes occur (BMT 2021).

The species protection levels used in the assessment were based on laboratory ecotoxicity testing conducted by SSB.

Outcomes and further work

The targeted VAF (BMT 2022) reported that At Magela Creek, Georgetown Billabong and Georgetown Creek:

- Sensitive algae and invertebrates may be intermittently affected by Mg (concentrations slightly greater than the 99% water quality guideline value (WQGV)). 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, are considered to have low vulnerability at the individual organism level (and by extension local population level)
- This upper predicted Mg concentration in shallow groundwater at Magela Creek (Djalkmarra Sands location) is close to (but exceeds) the highest concentration tested by Hutley et al. (2001) for which no significant decline in riparian vegetation biomass occurred. The predicted Mg concentration in shallow groundwater at Magela Creek at

the end RPA reporting site was 1-10 mg/L, which is well within the tolerance limits of the tested riparian tree species.

At Coonjimba Billabong (BMT 2022):

- Many algae and invertebrates, and some fish species (including some key species), would be affected by long-term, chronic exposure to Mg concentrations well above the 99% WQGV. While most ecological components have traits that allow rapid recovery from perturbations, ongoing exposure is likely to prevent this. These components are considered to have high vulnerability.
- There is a high degree of uncertainty regarding the response of aquatic macrophytes to Mg concentrations predicted to occur at Coonjimba Billabong. Many aquatic macrophytes species have EC_{MRF} (Maximum recorded field electrical conductivity) values less than the predicted Mg concentrations and are therefore potentially sensitive. However aquatic macrophyte monitoring at Coonjimba Billabong has not detected any change in structure (relative to pre-mining), despite having elevated Mg concentrations similar to (or slightly less) than predicted during closure.
- While most vertebrate fauna are not directly sensitive to Mg, any major shift in macrophyte cover /structure or food resources would be expected to have cascading indirect effects to these groups. These groups are tentatively classified as moderate vulnerability, however further work is required to evaluate this.

It should be noted that this targeted assessment did not consider the capacity of biota to acclimate to changes in environmental conditions, as discussed by BMT (2021).

The workshop and targeted VAF also highlighted areas with potential gaps in information and ERA/BMT and SSB undertook a fieldwork program in 2022 with the aim to address these gaps. The different components of field work were successfully undertaken as a collaboration project between ERA/ BMT and SSB. The components of the field program included Macrophyte mapping, Water quality and Phytoplankton Communities sampling, Periphyton Communities sampling, Aquatic Macrophyte Communities sampling, Aquatic Macroinvertebrate Communities sampling and e-DNA Analysis for Fish, Decapods, Vertebrates and Algae.

The results and report of this field program is being developed and will be reviewed by stakeholders prior to finalisation. The results will also initiate a revised targeted vulnerability assessment to confirm scores in the assessment.

The VAF findings will be used to inform risk assessments and the ALARA process (Section 6.3) for assessing the suitability of the mine closure strategy, apprising the need for mitigation activities, and supporting development of the RPA on-site water quality objectives representing impacts that are ALARA. Section 8.3.2.1 discusses how this work is used to support criteria development in Steps 7 and 8 of the national water quality management framework (ANZG 2018).

5.5.2 CT2 Characterising World Heritage values of the Ranger Project Area

KKN title	Question
CT2. Characterising World Heritage Values of the Ranger Project Area	CT2A. *What World Heritage Values are found on the Ranger Project Area, and how might these influence the incorporation of the site into Kakadu National Park and World Heritage Area?*

5.5.2.1 Aboriginal culture and heritage

There is recent evidence of Aboriginal occupancy of the Kakadu region dating back more than 65,000 years.[13] Central to closure planning are the Mirarr people who are the Traditional Owners of the land encompassing the Ranger and Jabiluka mineral leases. In addition to the mineral leases, Mirarr country extends to the town of Jabiru and parts of Kakadu NP, including the wetlands of the Jabiluka billabong country and the sandstone escarpment of Mount Brockman.

Prior to the 19th Century, the Kakadu region had a population of approximately 2,000. However, the population experienced a rapid decline from the late 19th Century to the early decades of the 20th Century (Taylor, 1999). This was, in part, as a result of European missionary activity, which encouraged a dispersal of the population, and large-scale military activities during the Second World War. At the time of initial uranium exploration at the Ranger deposit in the 1970s, only 44 indigenous Australians were counted as residing in the area in the 1976 Australian Bureau of Statistics Census (cited in Taylor, 1999).

The establishment of the town of Jabiru to service the uranium mining industry was, and remains, a significant factor in the increase in population in the region since the late 1970s. The extent to which the indigenous population has varied during this period is difficult to ascertain due to a paucity of reliable data.

The RPA contains several significant Aboriginal sites, including two recorded sacred sites which lie within designated 'restricted work areas'. One site is located approximately five kilometres north of the mine. The second sacred site, Tree Snake Dreaming, is situated north of Pit 3 and access into the vicinity for operational activity is required on very infrequent occasions. Both sites are listed with the Aboriginal Areas Protection Authority and a Site Management Plan is in place to ensure ongoing protection.

A third site of indigenous cultural heritage significance in the RPA is a cemetery where a small number of local Aboriginal people are buried; this was established prior to mining exploration. This is not a gazetted cemetery, and the burials were contemporary for the period rather than being Traditional Aboriginal burials. There are also restricted work areas on the RPA boundary for two sacred sites that occur outside, but adjacent to, the RPA.

Cultural heritage surveys over the RPA since 2006 have covered 73 percent of the RPA and recorded 99 archaeological sites and 69 archaeological background scatters. There are a

[13] ABC News, 20 July 2017: http://www.abc.net.au/news/science/2017-07-20/aboriginal-shelter-pushes-human-history-back-to-65,000-years/8719314

total of 171 recorded places of indigenous cultural heritage significance in the RPA. One such site (R34), is located adjacent to Pit 3 and is protected within a fenced exclusion zone.

5.5.2.2 World heritage listing attributes

The attributes of the Kakadu NP must not be compromised by the closure and rehabilitation of the RPA. The Kakadu NP was listed under the World Heritage Convention for five of a possible ten criteria, incorporating both cultural and natural attributes (UNESCO 2019). Criterion (i) and (iv) related to the cultural attributes.

In June 2013, the World Heritage Committee adopted the retrospective Statements of Outstanding Universal Value for all World Heritage properties inscribed between 1978 and 2006, prior to the launching of the Second Cycle of Periodic reporting in each region (UNESCO 2013). World Heritage criteria that apply to Kakadu NP, include:

World Heritage criterion (i): The Kakadu art sites represent a unique artistic achievement because of the wide range of styles used, the large number and density of sites and the delicate and detailed depiction of a wide range of human figures and identifiable animal species, including animals long extinct.

World Heritage criterion (vi): The rock art and archaeological record is an exceptional source of evidence for social and ritual activities associated with hunting and gathering traditions of Aboriginal people from the Pleistocene era until the present day.

World Heritage criterion (vii): Kakadu NP contains a remarkable contrast between the internationally recognised Ramsar–listed wetlands and the spectacular rocky escarpment and its outliers. The vast expanse of wetlands to the north of the park extends over tens of kilometres and provides habitat for millions of waterbirds. The escarpment consists of vertical and stepped cliff faces up to 330 m high and extends in a jagged and unbroken line for hundreds of kilometres. The plateau areas behind the escarpment are inaccessible by vehicle and contain large areas with no human infrastructure and limited public access. The views from the plateau are breathtaking.

World Heritage criterion (ix): The property incorporates significant elements of four major river systems of tropical Australia. The Kakadu NP ancient escarpment and stone country span more than two billion years of geological history, whereas the floodplains are recent, dynamic environments, shaped by changing sea levels and big floods every wet season. These floodplains illustrate the ecological and geomorphological effects that have accompanied Holocene climate change and sea level rise.

The Kakadu region has had relatively little impact from European settlement, in comparison with much of the Australian continent. With extensive and relatively unmodified natural vegetation and largely intact faunal composition, the Kakadu NP provides a unique opportunity to investigate large-scale evolutionary processes in a relatively intact landscape.

World Heritage criterion (x): The Kakadu NP is unique in protecting almost the entire catchment of a large tropical river and has one of the widest ranges of habitats and greatest number of species documented of any comparable area in tropical northern Australia. The large size, diversity of habitats and limited impact from European settlement of the Kakadu NP has resulted in the protection and conservation of many significant habitats and species.

5.5.2.3 Kakadu National Park

The area of Kakadu was established as a national park in April 1979, with construction of Ranger Mine commencing in January 1979. Since the original proclamation, the park has been extended to cover an area of almost 20,000 km^2 of the Alligator Rivers Region; the Alligator Rivers Region is as defined in the *Environment Protection (Alligator Rivers Region) Act 1978*). Over half of the Kakadu NP is held by Aboriginal Land Trusts on behalf of the Traditional Owners and has been leased to the Director of Parks Australia North. Kakadu NP is of great significance for its landforms, its variety of fauna and flora and its rich legacy of Aboriginal art.

The park protects an extraordinary number of plant and animal species including over one third of Australia's bird species, one quarter of Australia's land mammals and an exceptionally high number of reptile, frog and fish species. Huge concentrations of waterbirds make seasonal use of the park's extensive coastal floodplains.

5.5.2.4 Ramsar wetlands and sensitive habitat

The entire Kakadu NP is listed as a wetland of international importance under the Ramsar Convention, due to its adherence to the selection of the criteria defining wetlands of international importance (BMT WBM 2010).

Criteria defining Kakadu NP as a site containing Ramsar wetlands of international significance (BMT WBM 2010) are:

- a wetland should be considered internationally important if it contains a representative, rare, or unique example of a natural or near natural wetland type found within the appropriate biogeographic region
- a wetland should be considered internationally important if it supports vulnerable, endangered, or critically endangered species or threatened ecological communities
- a wetland should be considered internationally important if it supports populations of plant and/or animal species important for maintaining the biological diversity of a particular biogeographic region
- a wetland should be considered internationally important if it supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions
- a wetland should be considered internationally important if it regularly supports 20 000 or more waterbirds
- a wetland should be considered internationally important if it regularly supports one percent of the individuals in a population of one species or subspecies of waterbird

- a wetland should be considered internationally important if it supports a significant proportion of indigenous fish subspecies, species or families, life-history stages, species interactions and/or populations that are representative of wetland benefits and/or values and thereby contributes to global biological diversity
- a wetland should be considered internationally important if it is an important source of food for fishes, spawning ground, nursery and/or migration path on which fish stocks, either within the wetland or elsewhere, depend
- a wetland should be considered internationally important if it regularly supports one percent of the individuals in a population of one species or subspecies of wetland-dependent non-avian animal species

The wetlands of Kakadu NP are also part of an East Asian-Australasian Flyway established to protect areas used by migratory shorebirds (BMT WBM 2010). Due to this international recognition of wetlands in the Kakadu NP these wetlands must not be negatively affected by the closure and rehabilitation of the RPA. However, no environments of special significance (such as significant breeding sites, seasonal habitats or wetlands areas) occur within the RPA or the footprint of the Ranger Mine.

One ecological community in the Alligator Rivers Region is listed as Endangered under the (Commonwealth) *Environment Protection and Biodiversity Conservation Act 1999* (*EPBC Act*). However, this Arnhem Plateau Sandstone Shrubland Complex is restricted to stone country and the nearest suitable habitat occurs approximately 1.5 km from the eastern boundary of the RPA.

5.5.2.5 Cataloguing world heritage values

Everett *et al.* (2021) focussed on producing a preliminary catalogue of attributes located within the RPA that would contribute to or complement the natural World Heritage values of Kakadu NP. The three natural criteria contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance; are outstanding examples representing significant ecological and biological processes in the evolution of ecosystems and communities; and contain the most important and significant natural habitats for in-situ conservation of biological diversity. Spatial and other published data sources were collated and analysed to determine the location and extent of attributes associated with each of these criteria for the RPA.

The collation and analyses of data for the broader Kakadu NP and RPA undertaken for this project shows that some attributes representing World Heritage natural values of Kakadu NP are found in the RPA. Where World Heritage natural values in the RPA are found in Kakadu NP, they typically occur more extensively or abundantly in Kakadu NP; and many of the World Heritage natural values of Kakadu NP (threatened, endemic and relict species and ecosystems) are predominantly located in the Stone Country and are not present in the RPA.

In the context of rehabilitation at Ranger mine and long-term ecosystem sustainability, restoration plans should give consideration to maintaining or enhancing values found in

Kakadu NP. This will address the ERs relating to environmental protection of World Heritage values and rehabilitation of the site to a standard such that it could be incorporated in Kakadu NP.

5.6 Future climatic conditions and associated risks

Overall, the state and trend of the environment of Australia are poor and deteriorating as a result of increasing pressures from climate change, habitat loss, invasive species, pollution and resource extraction (Cresswell, Janke & Johnston, 2021). Existing climate patterns affect Australia's environment and communities in regular cycles, with climate change expected to excacerbate the impact of these cycles (Trewin, Morgan-Bulled & Cooper, 2021). Many significant impacts of climate change are due to extreme events (Trewin, Morgan-Bulled & Cooper, 2021). Australian ongoing climate trends include further warming and sea-level rise, more hot days and heatwaves, more rainfall in the north and fewer but more intense tropical cyclones (IPCC, 2022). Climate trends and extreme events have negatively impacted terrestrial and freshwater ecosystems (IPCC, 2022)

Australia's climate varies widely from season to season, year to year, and region to region (Trewin, Morgan-Bulled & Cooper, 2021). Australia currently lacks a framework that delivers holistic environmental management to integrate disconnected legislative and institutionial national, state and territory systems (Cresswell, Janke & Johnston, 2021).

5.6.1 Climate in the Northern Territory

The global climate system is comprised of five interconnected components and their interactions: the atmosphere, the hydrosphere (oceans, lakes, rivers), the cryosphere (ice, snow), the lithosphere (the land) and the biosphere (living things) (NESP ESCC Hub 2020).

The Northern Territory climate is strongly affected by the seasonal migration of the monsoon back and forth across the equator resulting in two distinct climates; a monsoonal wet season typically between October to April followed by a dry season during May to September (Moise *et al.* 2015). The drivers across the Northern Territory which largely influence rainfall include topography, strength (onset, duration and retreat) of the monsoon season, the phase of El Niño Southern Oscillation (ENSO) which influences rainfall, temperatures and tropical cyclones, the occurrence of tropical cyclones, and the strength of the south-eastern trade winds (Moise *et al.* 2015). The timing and strength of the monsoon bursts are further influenced by the Madden-Julian Oscillation (MJO). The Indian Ocean Dipole (IOD) additionally influences rainfall and temperatures (NESP ESCC Hub 2020).

Future climatic conditions globally and in the Northern Territory will be determined by the concentration of greenhouse gases in the atmosphere and how the climate system responds to the change and natural climate variability (NESP ESCC Hub 2020). These future climatic conditions have the potential to influence components of mine closure, particularly given the long-term nature of closure planning.

Potential impacts from climate change within the Northern Territory include:

- Increased exposure of humans and ecosystems to heat stress, disease, extreme rainfall events and flooding,
- Flooding of freshwater wetlands with salty water due to rising sea levels, and
- Less frequent tropical cyclones increasing in proportion of more powerful cyclones, causing more damage to coastal and marine areas.

ERA has completed a number of studies and risk assessments in relation to climate change. In 2012, INTERA facilitated a workshop focussing on Features, Events and Processes (FEPs) that may affect safe storage of tailings in Pit 3. Since 2012, considerable studies have been undertaken by INTERA, refining and revising initial assumptions and updating inputs to the relevant site model (INTERA 2017). A final report identified and evaluated a fully comprehensive list of FEPs that may affect an environmental assessment of a mine facility and associated safety function analysis (INTERA 2017). Climatic processes and effects were identified as a category and evaluated. Potentially deleterious FEPs associated with climatic processes and the risks these present to safety functions were discussed.

ERA have also completed a 'First Pass Climate Change Risk Assessment' to understand how climate change is likely to affect the MCP and determine any additional investigations or actions required to help address identified challenges (BMT 2020). Risk summaries and details of the process undertaken to determine risks are summarised in Chapter 5.2.2.

Climate change is likely to have a significant affect across the entire Kakadu region with most impacts likely to occur beyond 2050. The relatively short period (compared to climate change timeframes) of active onsite management and monitoring for closure expected before the site stabilises and meets close out conditions resulted in a fairly low risk profile for mine closure. In the longer term, most climate change risks are landscape in nature affecting the entire Kakadu region.

5.6.2 Temperature

Climate aspect	Prediction and confidence
Overall temperature	Very high confidence of substantial warming for overall mean, maximum and minimum temperatures
Hot days and prolonged periods of heat	Very high confidence of substantial increase in the temperature reached on the hottest days, the frequency of hot days and the duration of warm spells

Warming temperatures are the clearest manifestation of climate change (Trewin, Morgan-Bulled & Cooper, 2021). Warming of the Australian climate and associated climate system continue unabated, largely driven by increasing concentrations of greenhouse gases in the atmosphere (Trewin, Morgan-Bulled & Cooper, 2021). Emissions that have already occurred will drive futher changes over the coming decades, regardless of the future emissions pathway, where future emissions will have a major effect on the trajectory of climate change in the second half of the 21st Century (Trewin, Morgan-Bulled & Cooper, 2021).

Global surface temperature increases of 1.09 degress Celsius (◦C) in 2011 to 2020 above 1850 to 1900, have at least a greater than 50% likelihood that global warming will reach or exceed 1.5 ◦C in the near term, even for the very low greenhouse gas emissions scenario (IPCC, 2022). Since 1910, mean temperatures have increased in Australia by 1.4 ◦C, over all parts and in all seasons (BOM, 2020; Trewin, Morgan-Bulled & Cooper, 2021) (Figure 5-149).

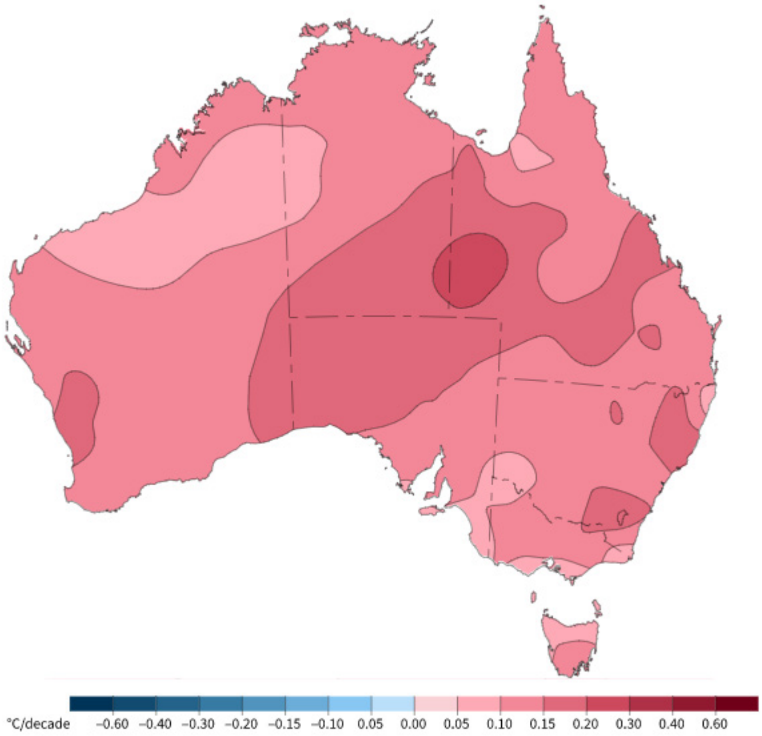


Figure 5-149: Trend in mean temperature, 1910 - 2020 (Source: State of the Environment, 2021)

Indigenous people also experience impacts of rising temperatures leading to extreme cultural change due to biodiversity loss, loss of culture and changed cultural patterns of living and travelling in and across Country (Trewin, Morgan-Bulled & Cooper, 2021). Rising land temperatures can reduce availability and growth of plants used for traditional purposes such as food and medicine, affecting the health of peoples who rely on traditional plants for nutritional and healing properties (Trewin, Morgan-Bulled & Cooper, 2021).

5.6.3 Predictions

Since the middle of last century there has been a clear warming trend with the Northern Territory having warmed by 1.5 °C since 1910 (CSIRO, 2022). Overall, the Northern Territory will continue to get warmer, with the hottest days being hotter and more frequent, and warm spells being longer (NESP ESCC Hub 2020). Future substantial warming for mean, maximum and minimum temperature is projected with very high confidence (NESP ESCC Hub 2020, Moise et al. 2015).

In the Top End of the Northern Territory, the near future (2030) will see warming around 0.5 to 1.4°C compared to the average for the period 1986–2005, with very little difference between emissions scenarios. By mid-century (2050), Darwin is projected to be more like the current climate of Jabiru, with warming ranging from 1.5 to 2.5°C under high emissions with a central estimate of 2.0°C (CSIRO, 2022). Large and sustained reduction in global greenhouse gas emissions reduces the projected warming to around 0.8 to 1.7 °C with a central estimate of 1.1 °C (CSIRO, 2022). Under a high emissions pathway the number of hot days over 35°C will approximately double across various regions of the NT, for example from 86 to 199 days per year in Batchelor (CSIRO, 2022).

5.6.3.1 Risks and possible mitigations

Changes in temperature present the largest risk of impacts to mine closure activities. Increases in frequency and intensity of hot periods could compromise the success of revegetation, present challenges to onsite management activities and impact onsite and receiving waters (BMT 2020). The following potential risks were identified in the Climate Change first pass assessment:

- Increased temperature and long hot and humid conditions may impact health and safety of staff involved in planting, management and maintenance and longer-term monitoring.
- Changing climate may result in conditions unfavourable for target revegetation species and vegetation communities could become unviable.
- Changes to trees species may have flow on effects to fauna. If deciduous trees dominate then following nesting species may be affected by the lower amount of shade that may eventuate.
- Selection of vegetation more tolerant to dry conditions may have flow on consequences e.g. if trees drop leaves to cope with heat stress, ground cover gets impacted by sun and associated heat.
- Temperature and excessive dry weather may affect early survival of revegetation.
- Longer, hotter dry periods impacting understorey growth rates and survival.
- Weed encroachment from the mine site into Kakadu National Park increasing as invasive species have a higher competitive advantage in changing climates.
- Pests or diseases, such as myrtle rust, affecting vegetation of the rehabilitated site.
- Higher temperatures coupled with longer drier periods may impact soil biota and affect nutrient cycling.
- Toxicity of contaminants increasing in higher temperature water.

- Higher temperatures of water bodies may lead to lower levels of dissolved oxygen in the water column which can results in fish kills.
- Increased algal blooms in water ways due to increased rates of production in higher temperatures.
- Longer periods of increased water temperatures can lead to shifting species complexes, favouring thermophiles which are heat tolerant.
- Increased temperatures influencing sex ratios of reptile species such as crocodiles.

Many of the identified risks are not directly linked to mine closure activities, including higher temperatures impacting species complexes and sex ratios. These risks will need to be managed at the landscape scale. A number of potential impacts due to predicted increasing temperature become landscape wide after 2050 and require management in consultation with relevant stakeholders at the landscape scale.

The changing climate was factored into the development of the revegetation plan for the Ranger mine site. Important aspects such as the effect of heat on workers, the selection of vegetation and longer-term management, maintenance and monitoring were considered.

Heat impacts to human health in the context of workers at RPA are not considered a long-term risk because by 2100[14] the period of intense mine closure activities will have passed. Options to manage short to medium-term risk include the use of remote sensing, drones, and other new technology to monitor vegetation, with consideration of night-time planting to reduce heat impacts.

Managing heat impacts on revegetation activities involves a combination of measures undertaken both prior to and after planting has occurred. Climate projections will be monitored over time to ensure that new information is accounted for when selecting plant species for revegetation. Native vegetation that has been removed or partially regrown has reduced ecological integrity (Williams et al, 2021). The extent of ‘remnant’ and ‘regrowth/modified’ native vegetation is not assessed based on its condition; additional information is needed to assess the growth stage and ecological integrity to provide a more comprehensive understanding of the implications for biodiversity and land condition (Williams et al, 2021). The condition of native vegetation is assessed in terms of its integrity or capacity to continue to provide habitat to support Australia’s unique biodiversity (Williams et al, 2021). Condition is quantified by measuring the similarity of a current ecosystem to a historical reference state with high ecological integrity or one that is minimally impacted by people (UNCEEA, 2021).

For savanna overstorey communities to be established at RPA, stakeholders agree that a *Eucalyptus tetrodonta* / *E. miniata* open forest, which dominates the Ranger surrounds, will constitute the community type for establishment. These local species are naturally resilient to high variation in climate variables, ensuring sufficient temperature tolerant plants will be

[14] 2100 is the best available timeframe for long-term projections

planted. Additional factors, such as coarseness of the substrate, will be considered for area-specific revegetation plans. For example, for areas with coarser waste rock, the *E. tetrodonta* / *E. miniata* community may include slightly higher densities of species proven to be well suited to rockier substrate, whereas areas with fine substrate may require slightly more water-logging tolerant species.

Climate change is placing pressure on soils through increased frequency of droughts and extreme weather events, increasing average tempertures which cause soil loss and damage (e.g. Grace et al. 2006, Rabbi et al. 2015, Borrelli et al. 2020, DAWE 2021t). A decline in the amount and health of soil directly affects its ability to provide important ecosystem services that support the natural environment (Williams et al, 2021). Soil rehabilitation may take many decades, and the full range of biodiversity may never be recovered (Williams et al, 2021).

High temperatures combined with drier conditions may result in dieback of establishing and mature plants due to limited water, changes to soil biota and nutrient cycling. Initial plantings will be supported by irrigation measures during the establishment phase. Potential for plant mortality can also be reduced through secondary inductions, with understorey species introduced once the ecosystem has begun to accumulate fines and organic matter, as shade is provided by the initial established species. Further detail on the revegetation implementation is presented in *Section 9 Closure Implementation Chapter 9.3.6*.

5.6.4 Rainfall and evaporation

Climate aspect	Prediction and confidence
Rainfall	Low confidence in models (similar probability of drier and wetter outcomes)
Intensity of heavy rainfall events	High confidence that the intensity of heavy rainfall event will increase
Drought	Low confidence in predictions of the frequency and duration of extreme drought for northern parts of NT
Evaporation	High confidence for increases in evapotranspiration, however despite model agreement there is only medium confidence on the magnitude of these projections
Soil moisture	Medium confidence for overall seasonal decreases in soil moisture
Runoff	Low confidence of a decrease in runoff

Rainfall is generally increasing in the north of Australia (Trewin, Morgan-Bulled & Cooper, 2021). Droughts and periods of extreme fire weather are expected to become common, as are more intense rainfall events (Trewin, Morgan-Bulled & Cooper, 2021). Regional differences may indicate national average rainfall is of limited value as an indicator of climate trend (Trewin, Morgan-Bulled & Cooper, 2021). High levels of decadal variability, particularly in drier parts of Australia, means observed trends in rainfall can be sensitive to start and end dates of the measured trend period (Trewin, Morgan-Bulled & Cooper, 2021).

Extreme rainfall events are projected to become more intense (CSIRO, 2022). High rainfall extremes are expected to increase due to the warmer atmosphere being able to hold more water, with extreme localised events highly variable from year to year, making trends difficult to detect (Trewin, Morgan-Bulled & Cooper, 2021). Increases in both short duration extreme rainfall events and daily totals associated with thunderstorms are most pronounced in Nothern Australia (Trewin, Morgan-Bulled & Cooper, 2021). Heavy rainfall can lead to increased soil runoff, increased risk of landslides and natural hazards, and damage to cultural sites (Trewin, Morgan-Bulled & Cooper, 2021). Inland waterways exposure to these events accelerate bank erosion and over bank flow, movement of sediment into foreign areas and loss of biodiversity in riparian areas, impact cultural heritage sites, as well as affecting level of recovery after an event (Trewin, Morgan-Bulled & Cooper, 2021).

Historical tropical cyclones in the Northern Terriotry include the destruction of much of Darwin during cyclone Tracey in 1974 (Trewin, Morgan-Bulled & Cooper, 2021). The coast is most exposed to damage from wind and storm surges, with heavy rains and flooding extending beyond the cyclone landfall point, with cyclones more common during La Nina years and less common in El Nino years (Trewin, Morgan-Bulled & Cooper, 2021). Cylone numbers have been decreasing in the last 40 years, with studies indicating increases in category (Trewin, Morgan-Bulled & Cooper, 2021).

5.6.4.1 Predictions

As a climatic variable, the projected change in average rainfall for the Northern Territory is unclear, although significant change is possible, where both wetter and drier futures should be considered (CSIRO, 2022). Rainfall can vary a great deal from year to year due to the normal variability of the climate system, and models have high confidence that natural climate variability will remain the major driver of annual mean rainfall changes by 2030 (Moise et al. 2015, NESP ESCC Hub 2020).

For the near future, projections for the dry season in the Top End of the Northern Territory range from 35% drier to 29% wetter than the 1986–2005 average, depending on greenhouse gas concentrations (NESP ESCC 2020). Projected wet season change for the same period ranges from 8% wetter to 7% drier. Towards the end of the century, the projected dry season change ranges from 45% drier to 44% wetter, and for the wet season, the range is 23% drier to 19% wetter (NESP ESCC Hub 2020). Due to the understanding of physical processes, there is high confidence that the intensity of heavy rainfall events will increase, however the magnitude of change, and the time when any change may be evident against natural variability, cannot be reliably projected (Moise *et al.* 2015).

Heavy and extreme rainfall events in the Northern Territory are often the result of tropical cyclones, tropical lows, and long-lived thunderstorms. Tropical cyclones are projected to become less frequent, but with increases in the proportion of the most intense storms due to there being more energy in the climate system (Moise *et al.* 2015, NESP ESCC Hub 2020). As the air becomes warmer it has a greater capacity to hold water vapour, meaning even though changes to average rainfall are unclear, the intensity of heavy rainfall events will increase in the future as a result of increased air temperatures (NESP ESCC Hub 2020).

Similarly, impacts of drought are likely to be more severe in the future due to increasing temperatures (NESP ESCC Hub 2020). The time spent in drought may also increase, with changes seen in both frequency and intensity (NESP ESCC Hub 2020). However, given the relation of drought to rainfall there is low confidence in how the frequency and duration of extreme meteorological drought may change (Moise *et al*. 2015).

Evaporation rates have largely remained unchanged within the Top End, however across the Northern Territory, projections for potential evapotranspiration indicate increases in all seasons (NESP ESCC Hub 2020). In relative terms there are larger increases in the dry season relative to the wet season with the largest absolute rates predicated in the wet season by 2090 (Moise *et al.* 2015, NESP ESCC Hub 2020).

Increases in evaporation rates combined with changes in rainfall can have implications for both soil moisture and runoff. Soil moisture is predicted to have an overall seasonal decrease, predominantly in the dry season due to lower rainfall amounts and high evaporation rates (Moise *et al.* 2015). Runoff is also projected to decrease; however, the projections have low confidence and more detailed hydrological modelling is needed to confidently assess the changes (Moise *et al.* 2015).

5.6.4.2 Risks and possible mitigations

Variability in rainfall patterns and evaporation predominantly present risks to onsite and receiving waters in terms of quantity and quality. The potential for more intense tropical cyclones and droughts can also result in damage to vegetation and landforms (BMT 2020).

The following potential risks were identified in the first pass assessment:

- Cyclone damage to vegetation planted as part of mine rehabilitation.
- Risk that leaf litter may increase as a result of intense winds, increasing bushfire risk and potentially leading to water column deoxygenation if washed into waterways.
- Connectivity of water courses reduced during longer, drier periods and solutes remaining in smaller areas for longer. This could increase exposure of fauna and flora in the water courses which are unable to disperse during periods of little or no connectivity.
- Longer hotter dry periods could dry out billabongs and expose previously unexposed ASS with implications for water quality and release of sediment bound contaminants.
- Increased evaporation leads to an increase in contaminants washed into onsite and receiving water during the first flush. A ‘dry’ wet season could mean greater loads into billabongs which do not then flush out to the ocean.
- Higher evaporation rates may affect shallow billabongs and result in a loss of refuge habitat for species.
- Intense storms damaging the road network.
- Erosion during storm events resulting in minor gullying on land and sedimentation in waterways.

- Increased cyclone damage to riparian zone degrades water quality.

None of these risks are created as a direct result of mining activity. A number of risks will be present across the entirety of the Kakadu NP (for example increased leaf litter from intense storms, loss of refuge from dry out of shallow billabongs) and will require management in consultation with Kakadu NP at the landscape scale. Changes to the waterbodies and hydrology of the system are likely to occur. These will be regional, where local receiving waterways may be affected which may influence the concentrations of received contaminants.

Intense storms and cyclones have the potential to impact directly on mine closure activities, particularly when it comes to revegetation and rehabilitation of areas. Strong winds and heavy rainfall can cause large scale damage to new vegetation. Damage to vegetation can have secondary impacts including increased erosion due to lower revegetation success and potential water quality impacts from increased runoff. Revegetated areas will be monitored with impacts remediated as required during the active management period. The revegetation strategy is tailored to landform elements (e.g. slopes, gullies, etc) to enhance vegetation cover and prevent erosion. The revegetation strategy also involves irrigation to encourage deep root development and subsequent cyclone resistance. Cyclonic activity and a general increase in intense rainfall events can cause significant damage via erosion leading to gullying on land and sedimentation in waterways.

The final landform design and landform evolution modelling will include surface treatments and sediment control features in future iterations. With no steep slopes across the site the potential for gullying on land and risk of flood scour is reduced, where armouring of landform toe-slopes adjacent to Magela Creek is a potential mitigation option. Modelling (Hancock et al. 2017) indicates a high likelihood of gullying across the landscape however not deep enough to expose the buried tailings. A such, whilst the risk of gullying is high the consequence (e.g. exposure of tailings) is low.

Extreme rainfall events are included in the landform evolution models to assess potential tailings exposure over 10,000 years (Lowry 2020). ERA will make minor adjustments to the final constructed landform such that any drainage channels or significant gully formation are mitigated within the shell of the pits. Armoured drainage lines across the pit are also an additional mitigation option. Erosion and gullying that occurs during the management period will be actively managed, with erosion management undertaken by the designated management authority following close-out.

The management of water at RPA makes extensive use of an operational simulation model (OPSIM) to assess the likely change in water inventories over time, taking full account of both climatic and operational influences (Water Solutions 2009). Variations to rainfall patterns are likely to impact both surface water and groundwater on and off-site. The OPSIM is well calibrated and validated, however is application to the task of future forecasts relies on the assumption that historical rainfall is fully representative in future occurrences (Water Solutions 2009). Investigations have been undertaken into methods to assess the likely impacts of changing climatic state on OPSIM based water management techniques used at RPA. The investigation found that specific inclusion of possible changes to rainfall on account of temperature rise was not recommended as there remains uncertainty as to the magnitude of possible changes to rainfall totals and the ‘worst estimate’ impacts are relatively small (Water Solutions 2009). This matter will continue to be investigated as further information becomes available.

A decrease in soil moisture can impact PAW, which is the amount of available water that can be stored in soil and be available for growing plants (within the rooting zone). Water availability on the waste rock final landform cover presents a challenge for ecosystem re-establishment as waste rock growth media often lacks structure or contains large amounts of rock fragments and macropores that reduce their water holding capacity (compared to natural soils). Waste rock PAW depends on the proportion of fines (<2 mm) in the material as well as the total depth available for plant root establishment. Waste rock substrate provides greater rooting depth meaning larger plants will likely be able to access any PAW in this soil and have improved plant-water relations in the late dry season when seasonal stresses (including reductions in soil moisture) are greatest. The construction of the waste rock final landform is carefully designed to optimise PAW as much as possible in the root depth zone.

The Groundwater Uncertainty Analysis (UA) conducted by INTERA incorporates climate variability to the greatest extent possible by treating groundwater recharge rates for surficial HLUs as random parameters to account for uncertainty (INTERA 2021b). The calibration of the UA predictive model was based on 40 years of head change data caused by widely varying rainfalls and consequently, the model appropriately captures the uncertainty in post-closure recharge rates because they reflect the amount of water that can recharge through these materials (INTERA 2021b). If climate change increases rainfall to exceed the observed 40-year span, the physical properties of the materials will likely shed that rainfall as runoff rather than allow it to recharge the groundwater. This means that the wide range of groundwater recharge rates for the landform waste rock used in the model include a wider range than is expected from climate change during the mid to late part of the century when peak loads are expected to occur and likely include all of the recharge rates that may occur from climate change at even later times (INTERA 2021b).

Recent investigations of groundwater and surface water interactions have shown that groundwater discharge does not occur during the last weeks or month of Magela Creek flow, indicating that climate change induced impacts on surface water quality from groundwater will be small (INTERA 2021a). If long term rainfall increased in magnitude or intensity due to climate change, creek flows will increase by a far greater proportion than groundwater recharge (INTERA 2021a). Increase rainfall magnitude and intensity will also likely lead to more rejected recharge when either the subsurface is saturated or the rainfall rate exceeds the infiltration rate. Any excess rainfall as a result of climate change will likely induce greater runoff that effectively decreases COPC surface water concentrations (INTERA 2021a). If future climate change decreases rainfall, then it will also decrease groundwater recharge (INTERA 2021b).

Connectivity of watercourses and provision of associated refuge habitat can be altered by decreases in rainfall combined with increases in evaporation. Assessing the implication and likelihood of reduction in connectivity requires a landscape management approach in order to help understand the issues and process. Long dry and highly evaporative periods may dry out billabongs and expose previously unexposed Potential Acid Sulfate Soils (PASS) and result in the forming of Acid Sulfate Soils (ASS). This has implications if occurring on mine site water bodies and will be a key area of active management during the closure period. It is noted that annual periods of drying are a common and known occurrence in the Northern Territory, which has resulted in local species within and surrounding the RPA adapting to these conditions. A number of projects are currently underway, or have been completed, which assess ASS in and around the RPA.

5.6.5 Fire

Climate aspect	Prediction and confidence
Fire frequency	High confidence of little change to fire frequency

The number of days with higher or above fire danger has generally increased typically from the lengthening of the fire season than from intensification of the peak of the season (Trewin, Morgan-Bulled & Cooper, 2021; Figure 5-150). Increased bushfire events in areas that have not fully recovered will increase nutrient levels in systems, creating unbalanced ecosystems for sustainable biodiversity in both freshwater and coastal regions (Trewin, Morgan-Bulled & Cooper, 2021).

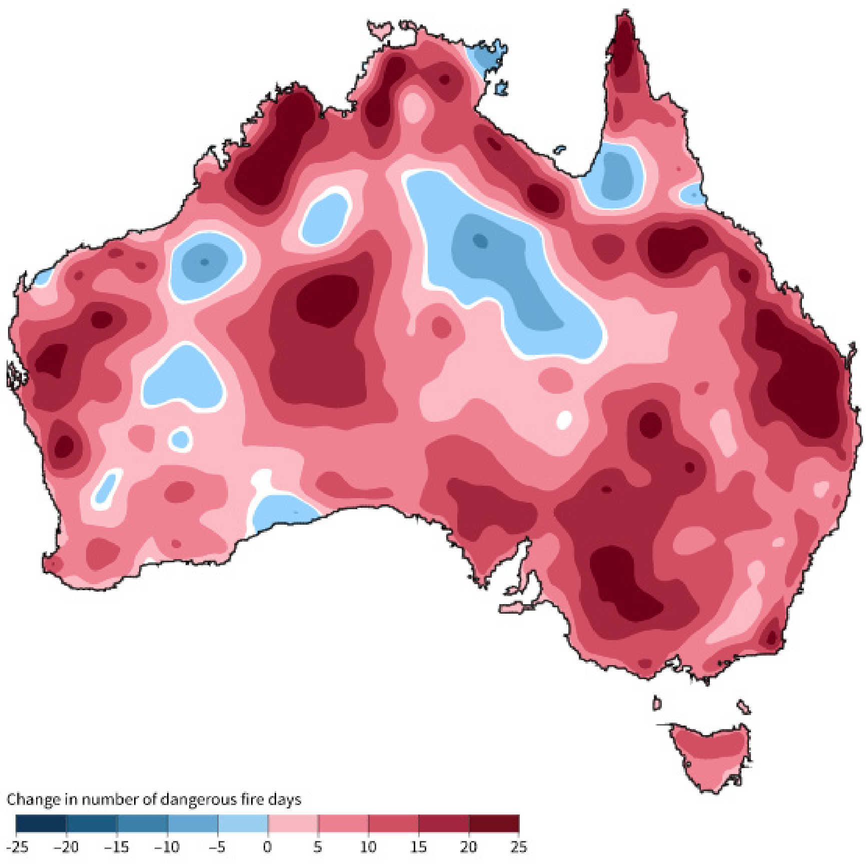


Figure 5-150: Change in number of days with the FFDI above the 90th Percentile, 1950-85 to 1985 - 2020 FFDI – Forest fire danger index (indicator of fire weather in forested or semi-forested areas.

5.6.5.1 Predictions

The occurrence of bushfires is determined by having an ignition source, fuel availability, fuel dryness and suitable fire weather (hot, dry, and windy conditions) (NESP ESCC 2020). Fuel availability in the Northern Territory is largely influenced by rainfall, as abundant rainfall will lead to higher fuel loads (Moise et al 2015). In Northern Australia, the most dangerous fire conditions occur in the dry season when there is an increased fuel load following rainfall from the wet season. Over the past 30 years, the number of days with severe fire weather during the dry season has increased (NESP ESCC 2020).

Rainfall is likely to remain abundant as a result of the monsoonal influence and consequently, there is little change projected to fire frequency within the Northern Territory (NESP ESCC 2020).

5.6.5.2 Risks and possible mitigations

The potential for more extreme fire behaviour presents a significant risk to the success of establishing vegetation across the RPA, both from the risk to humans carrying out activities and the potential for vegetation mortality. The following potential risks were identified in the first pass assessment:

- Climate-driven increased extent of ground cover planted during restoration may increase the fuel load and increase fire risk.
- Exotic grasses may become established following bushfires.
- Vegetation which includes a mix of species better adapted to survival on waste rock sites will be susceptible to fire.
- Length of the potential burning season may decrease as a result of a changing climate which may increase the risk of inappropriate burning regimes or wildfires.
- Fire severity may increase over time as a result of increased heat and evapotranspiration. This may lead to increased tree mortality.
- Severe fires and associated tree mortality may impact faunal communities.
- When active mine closure management ceases after close-out, reduced activity on the mine site may result in increased fire potential because of less active onsite management.
- People living, working or visiting Kakadu may be affected by any increased bushfire.
- Bushfires destroying riparian vegetation and leading to increased bank erosion when the wet season commences.

The risk of large-scale fire destroying immature vegetation is recognised and is captured in the risk assessment presented in *Section 7 Risk assessment and management*. Considerations for managing this risk during the post-closure period and longer-term have been incorporated within the Revegetation Adaptive Management Plan, both in terms of species selection and revegetation techniques, as well as monitoring and management actions during the post-closure period.

The Ranger Mine exists within the Australian savanna biome, where frequent fires dominate and lead to a shared dominance of trees and grasses (Cook 2021). Globally savanna vegetation is marked by a co-dominance of grasses and fire tolerant trees. While the ground stratum of savannas is relatively insensitive to variation in fire regimes at least in the short term, the tree stratum is sensitive to intense fires that more commonly occur late in the dry season (Cook 2021).

Developing ecosystems such as rehabilitation/revegetation areas have a different structure and composition to natural ecosystems. Although the same species may have been planted in rehabilitated landscapes as adjoining natural landscapes, they may take a long time to develop resilience to fire (Cook 2021). The resilience of vegetation to single fires depends on a range of vegetation attributes such as (Cook 2021):

- avoiding heat damage through;
  - thick bark,
  - placement in tall canopy above flame height,
  - placement below ground, and
  - placement in moist bark or leaves,
- the ability to recruit following fires through asexual reproduction or protection of seed.

Surviving one fire does not necessarily mean that a plant can survive multiple fires. Different aspects become important when faced with a fire regime including the ability to restore protections damaged in one fire before the next fire (Cook 2021). Fires within the first year of planting can lead to very high mortality of tree seedlings, with plants become more resilient to fire as they increase in size (Cook 2021). Fire resilience is highest in species of *Eucalyptus*, *Corymbia* and *Syzygium* (Gardener et al. 2007). On the RPA, trees greater than 2.5 m tall and 4 cm Diametre at Breast Height (DBH) were more likely to survive a fire than those with less than this threshold. It was therefore concluded that fires should be avoided in revegetation until most trees were greater than these sizes (Cook 2021).

Establishing a good level of ground cover in the revegetated areas is also a key objective of mine rehabilitation. It is noted that increased ground cover provides additional fuel supply during the bushfire season. Bushfire activity during both the closure and rehabilitation period will be monitored and managed accordingly. Management measures include the delayed introduction and active management of high biomass grasses (e.g. cool season burns), the establishment of fire breaks and access tracks and weed management to control exotic grasses. Ground cover in rocky dry areas will have a slower growth rate and consequently lower fuel loads.

The waste rock surface has a low risk for five to seven years post-planting. Species selected for the waste rock areas will be any climate-adaptable, hardy species from the Kakadu NP area that are generally subject to a similar overall fire regime. The chosen taxa will not increase the risk of bush fire, nor be more susceptible than species from agreed reference ecosystems in revegetated areas.

Having a revegetated ecosystem that is resilient to a suitable fire regime is one of the closure criteria that must be met prior to close-out. The knowledge to manage developing ecosystems in a frequently burnt landscape is limited and needs to be supported by adaptive management to achieve the goal of fire-resilient revegetation (Cook 2021). The Fire Management Plan will be developed and implemented in partnership with Traditional Owners based on Traditional Knowledge. Cool burns will be introduced 5-10 years post planting with a focus on wet season burning to help reduce fuel loads without the increased risk of uncontained wildfire.

The use of prescribed burns will assist in controlling exotic grass species. Following close out, climate-driven increased wild-fire risk will be a boarder landscape management issue. A number of the risks of changing weather (increased burning season, increased fire severity) will be similar across the whole Kakadu NP area requiring a coordinated management approach.

5.6.6 Humidity

Climate aspect	Prediction and confidence
Relative humidity	High confidence in little change in relative humidity by 2030 and medium confidence in. a decrease by 2090

5.6.6.1 Predictions

Relative humidity is the amount of moisture in the air as a percentage of the total amount of moisture the air can hold. The projection of future relative humidity indicates an overall tendency for decrease (Moise *et al.* 2015). In the near future there is little change projected, however, by the end of the century under a high emission pathway, a decrease is predicated for Northern Australia (NESP ESCC Hub 2020). Under a high emissions pathway, relative humidity is projected to decrease up to 10% in the dry season with high confidence (NESP ESCC Hub 2020).

The decrease in relative humidity will be apparent in areas away from the coastline due to an increase in the moisture holding capacity of a warming atmosphere and the greater warming of land compared to the ocean (Moise *et al.* 2015). This general tendency to decrease may be counteracted by a strong increase in rainfall. It is noted that changes in rainfall patterns have a higher level of uncertainty.

5.6.6.2 Risks and possible mitigations

A wide range of climate parameter trends were assessed as part of the first pass risk assessment, with risks fitting into four key areas of onsite activities; revegetation, onsite and receiving water quantity, quality and ecology, and erosion and sediment. The first pass risk assessment did not identify any risks within these categories specifically related to changes in relative humidity.

5.6.7 Sea level rise

Climate aspect	Prediction and confidence
Sea level	Very high confidence that sea level will continue to rise, with only minor level differences in emissions scenarios

Sea level rise increases levels of coastal inundation and erosion, with many regions having sensitive environmental features, infrastructure and development (Trewin, Morgan-Bulled & Cooper, 2021). Global sea level has been rising since the beginning of the 20th century at an accelerating rate (Trewin, Morgan-Bulled & Cooper, 2021). Global mean sea level has been rising at a rate of 3.3 mm per year (mm/yr) increasing by around 9 cm from 1993 to 2020 (Trewin, Morgan-Bulled & Cooper, 2021). In northern Australia, the rate of sea live rise after 1993 has increased in some areas up to 5 mm / yr, a major driver is natural climate variability including from the El Nino – Southern Oscillation (Trewin, Morgan-Bulled & Cooper, 2021).

5.6.7.1 Predictions

Climate change can cause sea level to rise via two mechanisms; thermal expansion where water warms and increases in volume as well as melting ice sheets and glaciers adding more water to oceans. Thermal expansion accounts for approximately one-third of sea level rise observed to date, with the remainder occurring from melting ice (NESP ESCC Hub 2020).

There is a very high confidence that sea levels will continue to rise during the 21st century, with only minor differences in levels between emissions pathways (Moise *et al.* 2015). In the near future, the increase is predicated to be 0.06 to 0.17 m above the 1986-2005 levels, with the difference becoming more pronounced as the century progresses (NESP ESCC Hub 2020). At the end of the century, a medium emissions pathway is predicted to increase levels between 0.28 to 0.64 m while a high emissions pathway gives a rise of 0.38 to 0.85 m (NESP ESCC Hub 2020).

Changes in sea level can occur at many time scales due to a range of factors including tides, storm surges, seasonable changes and the influence of climate divers including El Niño and La Niña (NESP ESCC Hub 2020). Sea levels around the coastline of the Northern Territory have risen at a higher rate compared to much of the rest of Australia due to a combination of natural climate variability and climate change impacts (NESP ESCC Hub 2020). Tides, winds and severe weather systems may cause extreme sea-level events outside of climate induced sea level rise. The Northern Territory is susceptible to extreme storm surges as a result of tropical cyclones (NESP ESCC Hub 2020).

5.6.7.2 Risks and possible mitigations

Rising sea level will exacerbate the impacts of extreme sea-level events, including storm surges, which may cause issues in downstream freshwater sites. The following potential risks were identified in the Ranger Climate Change first pass assessment:

- Sea-level rise may reduce the availability of freshwater refugia downstream of the mine site.
- Wave action from inundated flood plain causing erosion of the mine site.
- Sea-level rise causes floral and faunal species complexes to change, and they may begin to be dominated by saline tolerant (marine) species which may have flow on effects to other important taxa.
- Higher salinity waters may result in the loss of freshwater fauna such as freshwater turtles and amphibians.
- Higher sea-levels and more saline water in receiving waters may affect the ways in which surface water models are interpreted.

Discussions at the 2012 FEPs workshop included large sea level rises, in which the site might progress to a coastal mangrove swamp (INTERA 2017). Such progression may lead to low hydraulic gradients and reducing conditions that may decrease solute releases from the tailings (INTERA 2017). Predicted conditions at the site are considered somewhat speculative under such drastic climate change. The potential for very large sea level rise is considered of low likelihood with uncertain importance. It will be reconsidered at a later time as additional information becomes available (INTERA 2017).

Sea-level rise beyond 2050 is a landscape risk which will affect the entire Kakadu region and is not directly related to Ranger mine closure. Low lying areas of Kakadu NP are likely to be affected, reducing the extent of freshwater billabongs and waterways and the associated floral and faunal communities. Upstream sites will become important refugia and may include freshwater bodies on and adjacent to the mine site not influenced by mine closure. There is potential to consider the opportunity for establishing additional freshwater bodies on the mine site through ecological engineering. Additional management activities for landscape risks are are considered necessary.

5.6.8 Ocean temperature and chemistry

Climate aspect	Prediction and confidence
Sea surface temperature	Very high confidence in a continuation of increases in sea surface temperature
Ocean acidification	Very high confidence that the ocean around Australian will become more acidic High confidence that the rate of ocean acidification will be proportional to carbon dioxide emissions

Sea surface temperatures in the Australian region since 1900 have risen by 1.1 ◦C, slower than increases in land temperatures (Trewin, Morgan-Bulled & Cooper, 2021) (Figure 5-151). The rate of warming is fairly uniform across all seasons but can differ substantially between land and sea temperatures each year (Trewin, Morgan-Bulled & Cooper, 2021). This variation is due to how land and sea temperatures are affected by El Nino-Southern Oscillation and Indian Ocean Dipole, for example La Nina is associated with below average temperatures on land and above average temperatures in Northern Australian Waters (Trewin, Morgan-Bulled & Cooper, 2021).

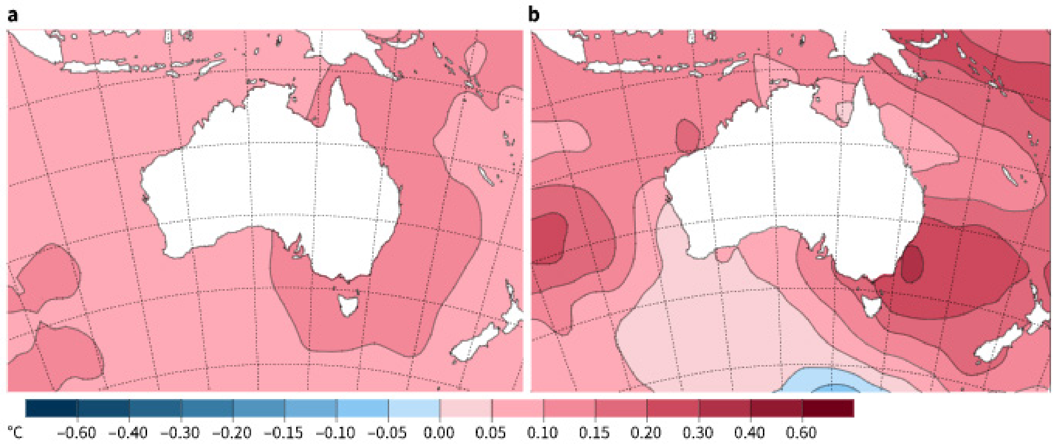


Figure 5-151: Sea surface temperature trends in the Australian region (a) 1910-2020; (b) 1980 - 2020 (State of the environment, 2021 source: BOM, using ERSSTv5 dataset).

High ocean temperatures increase risk of marine heatwaves, resulting in changed marine ecosystems and range of species as well as coral bleaching (Trewin, Morgan-Bulled & Cooper, 2021).

5.6.8.1 Predictions

The general trend for ocean temperature and chemistry is continuing increases in sea surface temperature with the oceans surrounding Australia becoming more acidic (Moise *et al.* 2015). Sea surface temperatures have risen significantly globally over recent decades, with the temperature around the Northern Territory waters increasing by at least 0.5°C since 1950 (NESP ESCC Hub 2020). In the near future sea surface temperature around the Darwin area is predicted to increase between 0.4 to 1.1°C up to 2.2 to 4.1°C under a high emissions pathway by the end of the century (NESP ESCC Hub 2020). Increasing temperature presents a significant risk to the marine environment with associated biological changes in marine species, community structure and increased risk of coral bleaching (Moise *et al.* 2015).

Approximately one-third of the carbon dioxide emitted into the atmosphere over the past 200 years is absorbed by the oceans, decreasing the pH by 0.1 in surface water pH (Moise *et al.* 2015, NESP ESCC Hub 2020). As the carbon dioxide enters the ocean it reacts with seawater causing a decrease in pH and carbonate concentration, a process collectively known as ocean acidification.

In the near future, pH is projected to fall by an additional 0.07 units in the Northern Territory's coastal waters and up to 0.14 under medium emissions, or 0.3 units under a under high emissions pathway projected by the end of the century (NESP ESCC Hub 2020). These values represent a 40 and 100% increase in acidity respectively. The increase in acidity is accompanied by reductions in aragonite saturation state and together with the changes in sea surface temperature will affect all levels of the marine food web and make it harder for calcifying marine organisms to build shells, affecting resilience and viability of marine ecosystems (Moise *et al.* 2015).

5.6.8.2 Risks and possible mitigations

A wide range of climate parameter trends were assessed as part of the first pass risk assessment and did not identify any risks specifically related to changes in ocean temperature and chemistry directly linked to mine site closure.

5.6.9 Future work on climate change risk

The climate change risk assessment undertaken involved a large body of site-specific studies and expert elicitation. A list of recommendations was provided in the report relate to the water and sediment theme and ecosystem rehabilitation theme and have been incorporated into ERA's risk management system and the MCP where relevant.

ERA notes that new information on climate change available in 2022 from the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report has been released. Information from this report is under review for suitability of incorporation into an updated Ranger Uranium Mine Closure Climate Change Risk Assessment. Stakeholder feedback on the 'first-pass' risk assessment will also be considered, as well as recommendations made in the project report.

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APPENDIX 5.1: KEY KNOWLEDGE NEEDS

APPENDIX 5.1 KEY KNOWLEDGE NEEDS (KKNs)

KKN	KNN Title	Question	Responsibility	Status
Landform Theme				
LAN1	Determining baseline erosion and sediment transport characteristics in areas surrounding the RPA	LAN1A. What are the baseline rates of gully formation for areas surrounding the RPA?	SSB	Active
		LAN1B. What are the baseline rates of sediment transport and deposition in creeks and billabongs?	SSB	Active
LAN2	Understanding the landscape-scale processes and extreme events affecting landform stability	LAN2A. What major landscape-scale processes could impact the stability of the rehabilitated landform (e.g. fire, extreme events, climate)?	SSB	Active
		LAN2B. How will these landscape-scale processes impact the stability of the rehabilitated landform (e.g. mass failure, subsidence)?	Both	Active
LAN3	Predicting erosion of the rehabilitated landform	LAN3A. What is the optimal landform shape and surface (e.g. rip lines, substrate characteristics) that will minimise erosion?	Both	Active
		LAN3B. Where, when and how much consolidation will occur on the landform?	ERA	Active
		LAN3C. How can we optimise the landform evolution model to predict the erosion characteristics of the final landform (e.g. refining parameters, validation using bedload, suspended sediment and erosion measurements, quantification of uncertainty and modelling scenarios)?	SSB	Active
		LAN3D. What are the erosion characteristics of the final landform under a range of modelling scenarios (e.g. location, extent, timeframe, groundwater expression and effectiveness of	SSB	Active

		mitigations)?		
		LAN3E. How much suspended sediment will be transported from the rehabilitated site (including land application areas) by surface water?	Both	Active
LAN4	Development of remote sensing methods for monitoring erosion	LAN4A. How do we optimise methods to measure gully formation on the rehabilitated landform?	SSB	Active
LAN5	Development of water quality monitoring methods for assessing landform erosion	LAN5A. How can we use suspended sediment in surface water (or turbidity as a surrogate) as an indicator for erosion on the final landform?	SSB	Active
Water and Sediment Theme				
WS1	Characterising contaminant sources on the RPA	WS1A. What contaminants (including nutrients) are present on the rehabilitated site (e.g. contaminated soils, sediments and groundwater; tailings and waste rock)?	ERA	Active
		WS1B. What factors are likely to be present that influence the mobilisation of contaminants from their source(s)?	ERA	Active
WS2	Predicting transport of contaminants in groundwater	WS2A. What is the nature and extent of groundwater movement, now and over the long-term?	ERA	Completed
		WS2B. What factors are likely to be present that influence contaminant (including nutrients) transport in the groundwater pathway?	ERA	Active
		WS2C. What are predicted contaminant (including nutrients) concentrations in groundwater over time?	ERA	Completed
WS3	Predicting transport of contaminants in surface	WS3A. What is the nature and extent of surface water movement, now and over the long-term?	ERA	Completed

	water	WS3B. What concentrations of contaminants from the rehabilitated site will aquatic (surface and ground-water dependent) ecosystems be exposed to?	ERA	Completed
		WS3C. What factors are likely to be present that influence contaminant (including nutrients) transport in the surface water pathway?	ERA	Completed
		WS3D. Where and when does groundwater discharge to surface water?	Both	Completed
		WS3E. What factors are likely to be present that influence contaminant transport (including nutrients) between groundwater and surface water?	ERA	Completed
		WS3F. What are the predicted concentrations of suspended sediment and contaminants (including nutrients) bound to suspended sediments in surface waters over time?	Both	Active
		WS3H. Where and when will suspended sediments and associated contaminants accumulate downstream?	ERA	Active
WS4	Characterising baseline aquatic biodiversity and ecosystem health	WS4A. What are the nature and extent of baseline surface water, hyporheic and stygofauna communities, as well as other groundwater dependent ecosystems, and their associated environmental conditions?	SSB	Completed
WS5	Determining the impact of contaminated sediments on aquatic biodiversity and ecosystem health	WS5A. Will contaminants in sediments result in biological impacts, including the effects of acid sulfate sediments?	Both	Active
WS6	Determining the impact of nutrients in surface water on aquatic biodiversity and	WS6C. Will the total loads of nutrients (N and P) to surface waters cause eutrophication?	ERA	Active

	ecosystem health			
WS7	Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health	WS7B. What is the risk associated with emerging contaminants?	Both	Active
WS9	Optimisation of water quality monitoring programs and assessment methods	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?	ERA	Active
Health Impacts of Radiation Theme				
RAD1	Radionuclides in the rehabilitated site	RAD1A. What are the activity concentrations of uranium and actinium series radionuclides in the rehabilitated site, including waste rock, tailings and land application areas?	ERA	Active
RAD2	Radionuclides in aquatic ecosystems	RAD2A. What are the above-background activity concentrations of uranium and actinium series radionuclides in surface water and sediment?	ERA	Completed
RAD3	Radon progeny in air	RAD3A. What is the above-background concentration of radon and radon progeny in air from the rehabilitated site?	Both	Completed
RAD4	Radionuclides in dust	RAD4. What is the above-background activity concentration in air of long-lived alpha-emitting radionuclides in dust emitted from the final landform?	SSB	Completed
RAD5	Radionuclides in bushfoods	RAD5A. What are the concentration ratios of actinium-227 and protactinium-231 in bush foods?	SSB	Active
RAD6	Radiation dose to wildlife	RAD6A. What are the representative organism groups that should be used in wildlife dose assessments for the rehabilitated site?	ERA	Completed

		RAD6B. What are the whole-organism concentration ratios of uranium and actinium series radionuclides in wildlife represented by the representative organism groups?	SSB	Active
		RAD6C. What are the tissue to whole organism conversion factors for uranium and actinium series radionuclides for wildlife represented by the representative organism groups?	SSB	Completed
		RAD6E. What is the sensitivity of model parameters on the assessed radiation doses to wildlife?	ERA	Active
RAD7	Radiation dose to the public	RAD7A. What is the above-background radiation dose to the public from all exposure pathways traceable to the rehabilitated site?	ERA	Active
		RAD7B. What is the sensitivity of model parameters on the assessed doses to the public?	ERA	Active
RAD8	Impacts of contaminants on wildlife	RAD8A. Will contaminant concentrations in surface water (including creeks, billabongs and seeps) pose a risk of chronic or acute impacts to terrestrial wildlife?	ERA	Active
RAD9	Impacts of contaminants on human health	RAD9A. What are the contaminants of potential concern to human health from the rehabilitated site?	ERA	Completed
		RAD9B. What are the concentration factors for contaminants in bush foods?	SSB	Completed
		RAD9C. What are the concentrations of contaminants in drinking water sources?	ERA	Completed
		RAD9D. What is the dietary exposure of, and toxicity risk to, a member of the public associated with all contaminant sources, and is this within relevant Australian and/or international guidelines?	ERA	Active

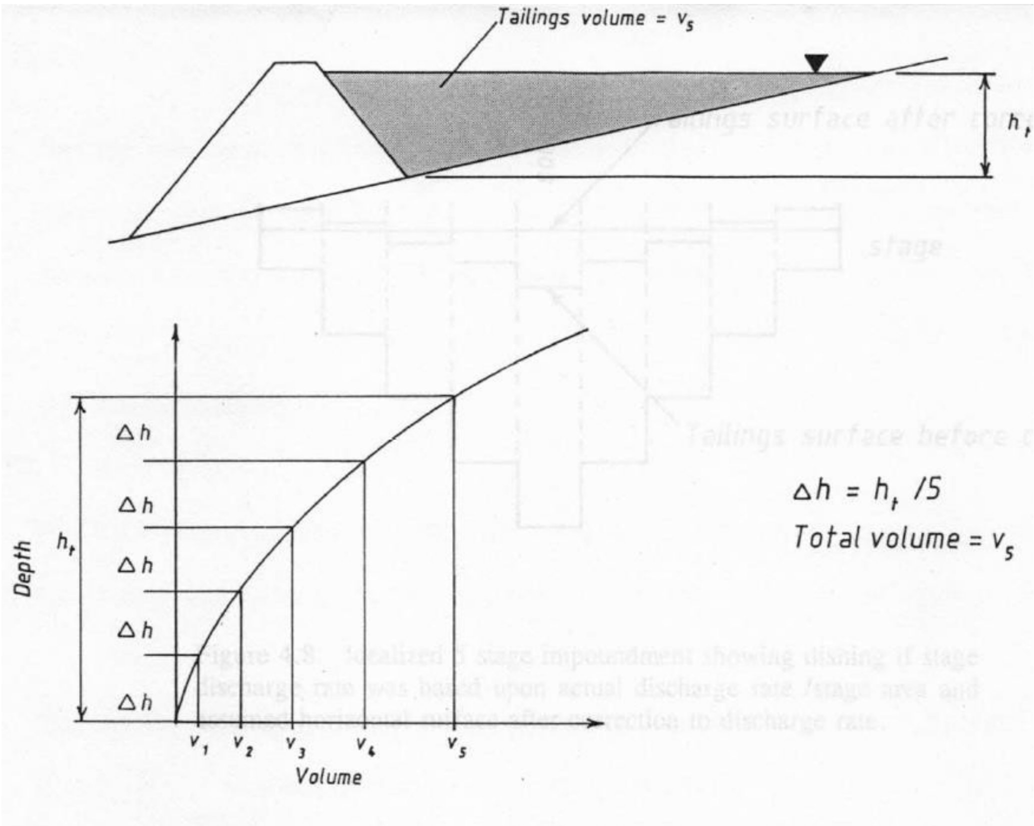
RAD10	Optimisation of radionuclide monitoring and assessment methods	RAD10A. How do we optimise methods to monitor and assess radionuclides?	SSB	Completed
Ecosystem Restoration Theme				
ESR1	Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the mine site, including Kakadu National Park.	ESR1A. What are the compositional and structural characteristics of the terrestrial vegetation (including seasonally inundated savanna) in natural ecosystems adjacent to the mine site, how do they vary spatially and temporally, and what are the factors that contribute to this variation?	ERA	Active
		ESR1B. What values should be prescribed to each indicator of similarity to demonstrate revegetation success?	SSB	Completed
ESR2	Determining the requirements and characteristics of a terrestrial faunal community similar to natural ecosystems adjacent to the mine site, including Kakadu National Park	ESR2A. What faunal community structure (composition, relative abundance, functional groups) is present in natural ecosystems adjacent to the mine site, and what factors influence variation in these community parameters?	Both	Active
		ESR2B. What habitat, including enhancements, should be provided on the rehabilitated site to ensure or expedite the colonisation of fauna, including threatened species?	ERA	Active
		ESR2C. What is the risk of introduced animals (e.g. cats and dogs) to faunal colonisation and long-term sustainability?	ERA	Active
ESR3	Understanding how to establish native terrestrial vegetation, including understory species.	ESR3A. How do we successfully establish terrestrial vegetation, including understory (e.g. seed supply, seed treatment and timing of planting)?	ERA	Active
ESR4	Determine the incidence and abundance of introduced species in natural ecosystems	ESR4A. What is the incidence and abundance of introduced animals and weeds in areas adjacent to the mine site, and what are the factors that will inform effective management of introduced species on	SSB	Proposed

	adjacent to the mine site, including Kakadu National Park, and their potential to impact on the successful rehabilitation of Ranger mine	the rehabilitated mine site?		
ESR5	Develop a restoration trajectory for Ranger mine	ESR5A. What are the key sustainability indicators that should be used to measure restoration success?	Both	Active
		ESR5B. What are possible/agreed restoration trajectories (flora and fauna) across the Ranger mine site; and which would ensure they will move to a sustainable ecosystem similar to those adjacent to the mine site, including Kakadu National Park?	Both	Active
ESR6	Understanding the impact of contaminants on vegetation establishment and sustainability	ESR6A. What concentrations of contaminants from the rehabilitated site may be available for uptake by terrestrial plants?	Both	Active
		ESR6B. Based on the structure and health of vegetation on the Land Application Areas, what species appear tolerant to the cumulative impacts of contaminants and other stressors over time?	ERA	Active
ESR7	Understanding the effect of waste rock properties on ecosystem establishment and sustainability	ESR7A. What is the potential for plant available nutrients (e.g. nitrogen and phosphorus) to be a limiting factor for sustainable nutrient cycling in waste rock?	ERA	Completed
		ESR7B. Will sufficient plant available water be available in the final landform to support a mature vegetation community?	Both	Active
		ESR7C. Will ecological processes required for vegetation sustainability (e.g. soil formation) occur on the rehabilitated landform and if not, what are the mitigation responses?	ERA	Completed

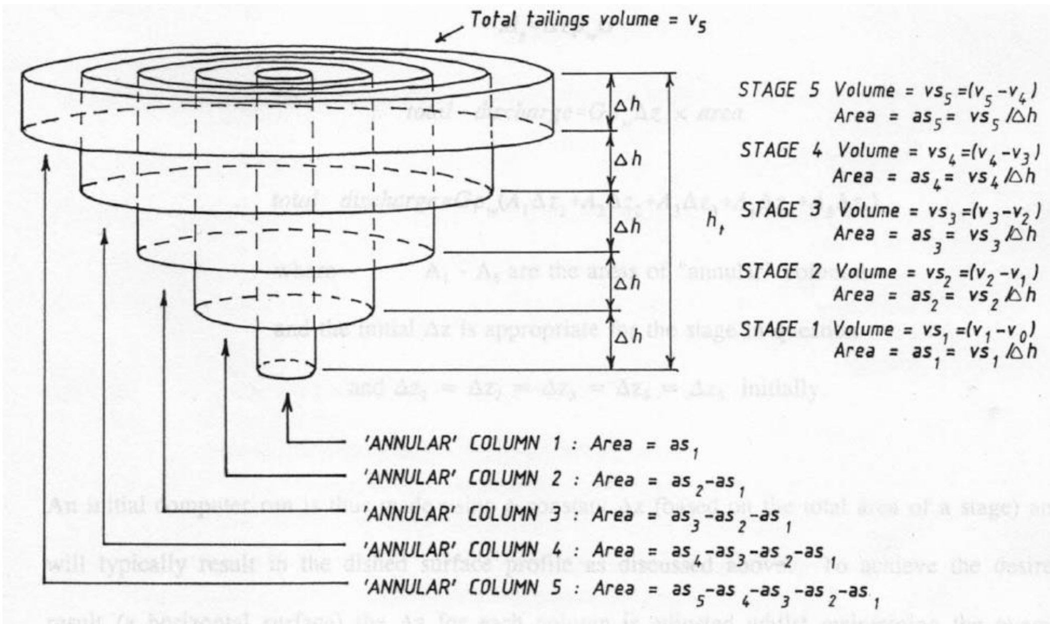
ESR8	Understanding fire resilience and management in ecosystem restoration	ESR8A. What is the most appropriate fire management regime to ensure a fire resilient ecosystem on the rehabilitated site?	Both	Active
ESR9	Developing best-practice monitoring methods for ecosystem restoration	ESR9A. How do we optimise methods to measure revegetation and faunal community structure and sustainability on the rehabilitated site, at a range of spatial/temporal scales and relative to the areas surrounding the RPA?	SSB	Active
Cross-Theme				
CT1	Assessing the cumulative risks to the success of rehabilitation on-site and to the protection of the off-site environment.	CT1A. What are the cumulative risks to the success of rehabilitation on-site and to the off-site environment?	Both	Completed
CT2	Characterising World Heritage values of the Ranger Project Area	CT2A. What World Heritage Values are found on the Ranger Project Area, and how might these influence the incorporation of the site into Kakadu National Park and World Heritage Area?	Both	Completed

APPENDIX 5.2: CONSOLIDATION MODEL A

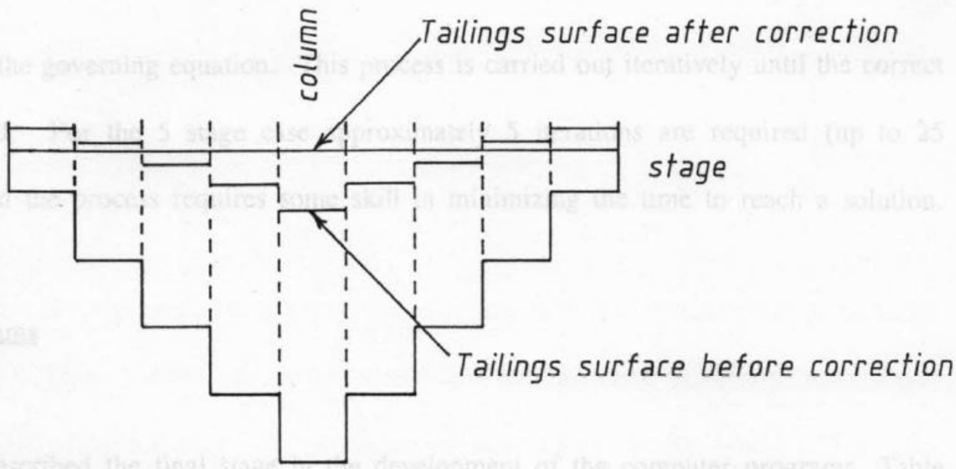
CONSOLIDATION MODEL A



ACTUAL IMPOUNDMENT



MODEL IMPOUNDMENT



Idealized 5 stage impoundment showing dishing if stage discnarge rate was based upon actual discharge rate /stage area and assumed horizontal surface after correction to discharge rate.

APPENDIX 5.3: CONSOLIDATION MODEL B

CONSOLIDATION MODEL B

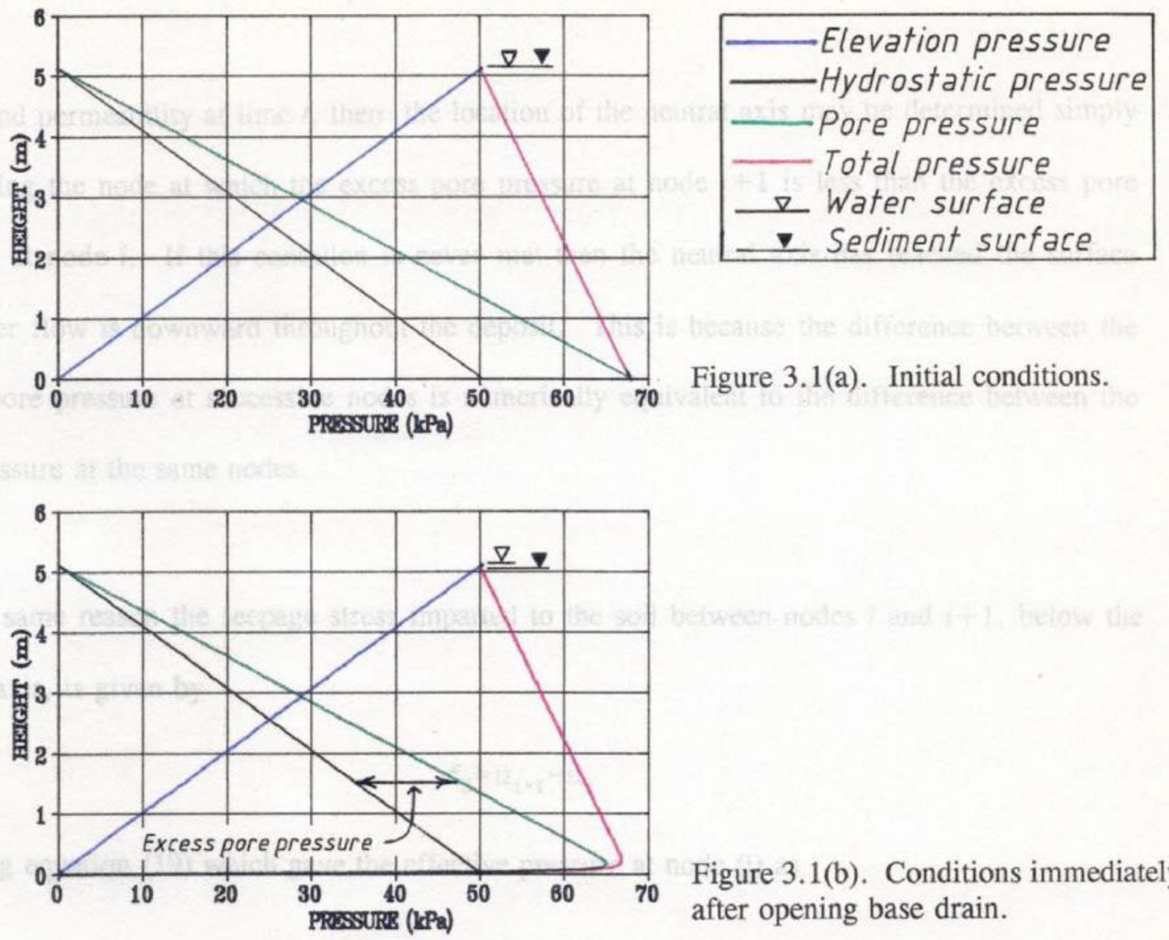


Figure 3.1(a). Initial conditions.

Figure 3.1(b). Conditions immediately after opening base drain.

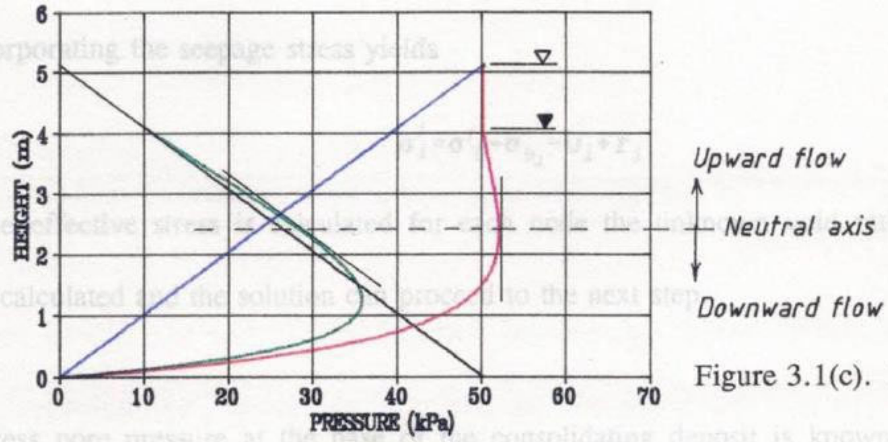


Figure 3.1(c). Intermediate case.

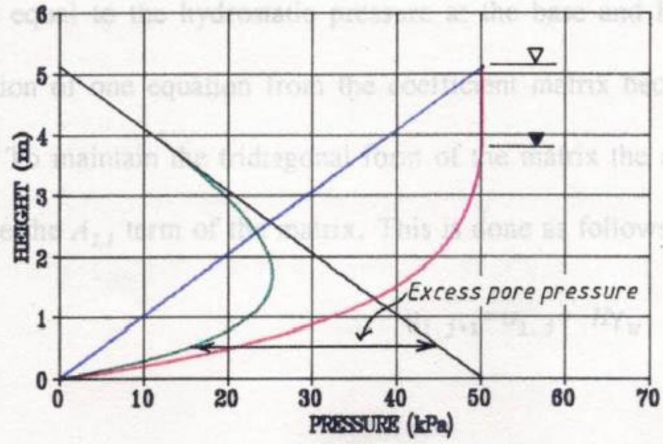


Figure 3.1(d). Approaching equilibrium conditions.

Figure 3.1. Pore pressure conditions in an underconsolidated slurry.

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APPENDIX 5.4: THE RANGER REVEGETATION STRATEGY (REDDELL & MEEK 2004

Appendix 5.4: Ranger Revegetation Strategy (Reddell & Meek 2004)

The Ranger Revegetation Strategy was developed based on decades of learnings from extensive revegetation research and trials; it was first endorsed by stakeholders and an independent scientific advisory panel (the Alligator Rivers Region Technical Committee) in 2004. Recently it has been updated, refined and published in the Ranger Mine Closure Plan. ERA are in the process of developing an Ecosystem Establishment Strategy, building on the 2004 strategy, for the Final Landform Application submission at the end of 2023.

Table A-1: The fourteen key strategy elements from Reddell and Meek (2004) and their relevance to ERA's Ecosystem Establishment Strategy

Element	Revegetation Strategy Elements from 2004	Relevance in 2022	Related MCP Section(s)
1	*Determine the likely physical and chemical characteristics of the final landform that will influence both the initial establishment and the long-term growth, development and functioning of revegetated plant communities*	Still relevant	Section 5 ESR7 & ESR3
2	*Identify and describe vegetation types that are ecologically, culturally and technically realistic target endpoints, for different facets of the final landform, based on the likely physical and chemical environments that will be created*	Still relevant	Section 5 ESR1 & ESR7
3	*Avoid disturbing, transporting and spreading the very limited topsoil available by establishing vegetation directly into in-situ materials* [waste rock]	Still relevant as waste rock is our only available growth media	Section 5 ESR1, ESR7 & ESR3
4	*Maximise surface roughness and 'patchiness' during site preparation*	Still relevant, however further development and refinement since 2004	Section 9.3.5
5	*Use seed and propagation material collected within 30 km of Ranger for all species*	Still relevant, however further development and refinement since 2004	Section 5 ESR3
6	*Focus on initially establishing a floristic composition that is dominated by a diverse range of the long-lived 'framework' species*	Still relevant, however further development and refinement since 2004	Section 5 ESR1 Appendix 5.5
7	*Introduce a range of mycorrhizal fungi from local environments to aid in the establishment of the framework species*	Still relevant	Section 5 ESR3

Element	Revegetation Strategy Elements from 2004	Relevance in 2022	Related MCP Section(s)
8	*Avoid the use of high densities of [aggressive] Acacia species*	Still relevant, however further development and refinement since 2004	Section 5 ESR3 & ESR4 Appendix 5.5
9	*Avoid actively re-introducing grasses and vigorous herbaceous species in the first year*	Currently being challenged considering the ecosystem services provided by understorey species such as stabilisation, erosion control, and habitat creation, and the difficulties experienced with establishing desirable understorey cover on TLF	Section 5 ESR3
10	*Use nursery-grown planting stock to establish the framework species*	Still relevant	Section 5 ESR3 Section 9.3.6
11	*Apply fertilisers in a strategic manner using formulations and delivery methods that maximise their effectiveness*	Still relevant	Section 9.3.6
12	*Rigorously control potential threatening weed species*	Still relevant	Section 5 ESR4 Section 9.3.6 Section 10.4
13	*Exclude fire from revegetation areas during the first three years after establishment*	Currently being challenged (ie. exclusion period extended beyond three years) considering species survivability height thresholds and potential impact on waste rock soil development and nutrient cycling	Section 5 ESR8 & ESR7 Section 10.4
14	*Design and implement a rigorous and scientifically-based strategy for on-going evaluation of the performance of the revegetation*	Still relevant	Section 5 ESR3 Section 10.4

APPENDIX 5.5: SERP SPECIES ERA ARE POTENTIALLY CONSIDERING FOR REVEGETATION

APPENDIX 5.5: SERP species ERA are potentially considering for revegetation

The majority of stems (approximately 70%) used for revegetating Ranger FLF will consist of a handful of species, including dominate *Eucalyptus* and *Corymbia* trees, *Acacias*, and common fruiting shrubs. The remaining stems will be a range of tree, shrub and groundcover plants that, although in smaller densities, contribute significantly to the ecosystem's species richness, provide food and shelter for fauna, and/or are important species for Traditional Owners.

Species below include all those being considered for revegetation of the *Eucalyptus tetrodonta / miniata* savanna woodland sections of FLF. Some SERP species are not included on this list because they are not currently being considered for active revegetation due to the potential risks they pose to the establishing ecosystem, their proven ability to readily colonise waste rock, or because they typically occur in a different type of ecosystem (eg. riparian).

Species	Family	Lifeform
Overstorey Species		
Alstonia actinophylla	Apocynaceae	Tree
Corymbia bleeseri *	Myrtaceae	Tree
Corymbia chartacea	Myrtaceae	Tree
Corymbia disjuncta *	Myrtaceae	Tree
Corymbia dunlopiana	Myrtaceae	Tree
Corymbia foelscheana *	Myrtaceae	Tree
Corymbia latifolia *	Myrtaceae	Tree
Corymbia polycarpa *	Myrtaceae	Tree
Corymbia polysciada *	Myrtaceae	Tree
Corymbia porrecta	Myrtaceae	Tree
Elaeocarpus arnhemicus *	Elaeocarpaceae	Tree
Erythrophleum chlorostachys *	Fabaceae	Tree
Eucalyptus miniata *	Myrtaceae	Tree
Eucalyptus phoenicea *	Myrtaceae	Tree
Eucalyptus tectifica	Myrtaceae	Tree
Eucalyptus tetrodonta *	Myrtaceae	Tree
Eucalyptus tintinnans	Myrtaceae	Tree
Ficus racemosa *	Moraceae	Tree
Midstorey Species		
Acacia difficilis *	Fabaceae	Shrub
Acacia dimidiata *	Fabaceae	Small shrub
Acacia hemignosta	Fabaceae	Shrub
Acacia lamprocarpa *	Fabaceae	Tree
Acacia latescens	Fabaceae	Shrub
Acacia mimula	Fabaceae	Shrub
Acacia oncinocarpa	Fabaceae	Small shrub
Allosyncarpia ternata *	Myrtaceae	Tree
Brachychiton megaphyllus *	Malvaceae	Tree
Buchanania obovata *	Anacardiaceae	Tree
Calytrix exstipulata *	Myrtaceae	Small shrub
Clerodendrum floribundum *	Lamiaceae	Shrub/Small tree
Cochlospermum fraseri *	Bixaceae	Shrub/Small tree
Coelospermum reticulatum *	Rubiaceae	Shrub/Small tree
Ficus brachypoda *	Moraceae	Shrub
Gardenia fucata *	Rubiaceae	Small shrub

Species	Family	Lifeform
Gardenia megasperma	Rubiaceae	Shrub
Grevillea decurrens *	Proteaceae	Small shrub
Livistona humilis *	Arecaceae	Palm
Owenia vernicosa *	Meliaceae	Tree
Pandanus spiralis *	Pandanaceae	Palm
Persoonia falcata *	Proteaceae	Shrub/Small tree
Petalostigma pubescens *	Picrodendraceae	Shrub/Small tree
Planchonella arnhemica	Sapotaceae	Tree
Planchonia careya *	Lecythidaceae	Tree
Syzygium eucalyptoides ssp. bleeseri *	Myrtaceae	Tree
Syzygium eucalyptoides ssp. eucalyptoides *	Myrtaceae	Small tree
Syzygium suborbiculare *	Myrtaceae	Tree
Terminalia carpentariae *	Combretaceae	Tree
Terminalia ferdinandiana *	Combretaceae	Shrub/Small tree
Terminalia pterocarya	Combretaceae	Shrub/Small tree
Xanthostemon eucalyptoides *	Myrtaceae	Tree
Xanthostemon paradoxus	Myrtaceae	Tree
Understorey species		
Acacia gonocarpa	Fabaceae	Small shrub
Alloteropsis semialata	Poaceae	Grass
Ampelocissus acetosa *	Vitaceae	Vine (climber)
Aristida holathera	Poaceae	Grass
Aristida inaequiglumis	Poaceae	Grass
Aristida spp.	Poaceae	Grass
Cartonema spicatum	Commelinaceae	Herb
Cayratia trifolia *	Vitaceae	Vine (climber)
Chrysopogon fallax	Poaceae	Grass
Corynotheca lateriflora *	Hemerocallidaeae	Herb
Crotalaria spp.	Fabaceae	Herb
Cymbopogon spp.	Poaceae	Grass
Cyperus spp.	Cyperaceae	Sedge
Dioscorea transversa	Dioscoreaceae	Vine (climbing)
Eragrostis spp.	Poaceae	Grass
Eriachne armittii	Poaceae	Grass
Eriachne obtusa	Poaceae	Grass
Eriachne schultziana	Poaceae	Grass
Eriachne spp.	Poaceae	Grass
Eriachne triseta	Poaceae	Grass
Fimbristylis spp.	Cyperaceae	Herb
Flemingia parviflora	Fabaceae	Subshrub
Galactia megalophylla	Fabaceae	Shrub
Galactia tenuiflora	Fabaceae	Vine (prostrate)
Gonocarpus leptothecus	Haloragaceae	Subshrub
Grevillea dryandri ssp. dryandri *	Proteaceae	Small shrub
Grevillea goodii ssp. gooddii *	Proteaceae	Shrub (prostrate)
Grewia retusifolia	Malvaceae	Shrub
Haemodorum coccineum	Haemodoraceae	Herb
Heteropogon triticeus	Poaceae	Grass
Hibbertia spp.	Dilleniaceae	Shrub
Indigofera spp.	Fabaceae	Herb / Shrub
Larsenaikia suffruticosa	Rubiaceae	Subshrub
Marsdenia spp.	Apocynaceae	Vine
Microstachys chamaelea	Euphorbiaceae	Shrub

Species	Family	Lifeform
Petalostigma quadriloculare	Picrodendraceae	Shrub
Tephrosia oblongata	Fabaceae	Shrub
Tephrosia remotiflora	Fabaceae	Herb / Subshrub
Tephrosia spp.	Fabaceae	Herb / Shrub
Tephrosia subpectinata	Fabaceae	Shrub
Themeda triandra	Poaceae	Grass
Uraria lagopodioides	Fabaceae	Herb (Prostrate)
Vigna spp.	Fabaceae	Vine (Twining)

APPENDIX 5.6: FAUNA SPECIES LIST (SLR 2021)

Energy Resources Of Australia

APPENDIX 5.6 FAUNA SPECIES LIST (from SLR 2021)

Species list

Common name	Scientific name
Amphibians	
Bilingual Frog	*Crinia bilingua*
Copland's Rock Frog	*Litoria coplandi*
Giant Frog	*Cyclorana australis*
Giant Frog	*Litoria australis*
Green Tree-Frog	*Litoria caerulea*
Marbled Frog	*Limnodynastes convexiusculus*
Northern Dwarf Tree Frog	*Litoria bicolor*
Northern Spadefoot Toad	*Notaden melanoscaphus*
Northern Territory Frog	*Austrochaperina adelphe*
Ornate Burrowing Frog	*Platyplectrum ornatus*
Pale Frog	*Litoria pallida*
Rocket Frog	*Litoria nasuta*
Roth's Tree Frog	*Litoria rothii*
Stonemason Toadlet	*Uperoleia lithomoda*
Tornier's Frog	*Litoria tornieri*
Birds	
Apostlebird	*Struthidea cinerea*
Australasian Darter	*Anhinga novaehollandiae*
Australasian Figbird	*Sphecotheres vieilloti*
Australian Hobby	*Falco longipennis*
Australian Owlet-Nightjar	*Aegotheles cristatus*
Banded Honeyeater	*Cissomela pectoralis*
Barking Owl	*Ninox connivens*
Bar-Shouldered Dove	*Geopelia humeralis*
Black Kite	*Milvus migrans*
Black-Breasted Buzzard	*Hamirostra melanosternon*
Black-Faced Cuckoo-Shrike	*Coracina novaehollandiae*
Black-Faced Woodswallow	*Artamus cinereus*
Black-Necked Stork	*Ephippiorhynchus asiaticus*
Black-Tailed Treecreeper	*Climacteris melanura*
Blue-Faced Honeyeater	*Entomyzon cyanotis*
Blue-Winged Kookaburra	*Dacelo leachii*
Boobook Owl	*Ninox novaeseelandiae*
Broad-Billed Flycatcher	*Myiagra ruficollis*
Brown Falcon	*Falco berigora*
Brown Goshawk	*Accipiter fasciatus*
Brown Honeyeater	*Lichmera indistincta*

Common name	Scientific name
Brown Quail	*Coturnix ypsilophora*
Brush Cuckoo	*Cacomantis variolosus*
Bush Stone-Curlew	*Burhinus grallarius*
Channel-Billed Cuckoo	*Scythrops novaehollandiae*
Chestnut-Backed Button-Quail	*Turnix castanota*
Cicadabird	*Coracina tenuirostris*
Crimson Finch	*Neochmia phaeton*
Diamond Dove	*Geopelia cuneata*
Dollarbird	*Eurystomus orientalis*
Double-Barred Finch	*Taeniopygia bichenovii*
Dusky Honeyeater	*Gallinula tenebrosa*
Dusky Honey-Eater	*Myzomela obscura*
Eastern Koel	*Eudynamys orientalis*
Forest Kingfisher	*Todiramphus macleayii*
Galah	*Eolophus roseicapilla*
Galah	*Eulophus roseicapilla*
Golden-Headed Cisticola	*Cisticola exilis*
Great Bowerbird	*Phalacrocorax carbo*
Green-Backed Gerygone	*Gerygone chloronota*
Grey Shrike-Thrush	*Colluricincla harmonica*
Grey-Crowned Babbler	*Pomatostomus temporalis*
Helmeted Friarbird	*Philemon buceroides*
Large-Tailed Nightjar	*Caprimulgus macrurus*
Leaden Flycatcher	*Myiagra rubecula*
Lemon-Bellied Flycatcher	*Microeca flavigaster*
Little Bronze-Cuckoo	*Chrysococcyx minutillus*
Little Corella	*Cacatua sanguinea*
Little Friarbird	*Philemon citreogularis*
Little Woodswallow	*Artamus minor*
Long-Tailed Finch	*Poephila acuticauda*
Magpie Lark	*Grallina cyanoleuca*
Masked Finch	*Poephila personata*
Masked Owl	*Tyto novaehollandiae*
Mistletoebird	*Dicaeum hirundinaceum*
Nankeen Kestrel	*Falco cenchroides*
Northern Fantail	*Rhipidura rufiventris*
Northern Rosella	*Platycercus venustus*
Olive-Backed Oriole	*Oriolus sagittatus*
Orange-Footed Scrubfowl	*Megapodius reinwardt*
Owlet Nightjar	*Aegotheles chrisoptus*
Partridge Pigeon	*Geophaps smithii*
Peaceful Dove	*Geopelia striata*
Pheasant Coucal	*Centropus phasianinus*
Pied Butcherbird	*Cracticus nigrogularis*

Common name	Scientific name
Pied Imperial-Pigeon	*Ducula bicolor*
Rainbow Bee-Eater	*Merops ornatus*
Rainbow Lorikeet	*Trichoglossus haematodus*
Rainbow Pitta	*Pitta iris*
Red-Backed Fairywren	*Malurus melanocephalus*
Red-Tailed Black Cockatoo	*Calyptorhynchus banksii*
Red-Winged Parrot	*Aprosmictus erythropterus*
Rose-Crowned Fruit-Dove	*Ptilinopus regina*
Royal Spoonbill	*Platalea regia*
Rufous Fantail	*Rhipidura dryas*
Rufous Whistler	*Pachycephala rufiventris*
Rufous-Banded Honeyeater	*Conopophila albogularis*
Rufous-Throated Honeyeater	*Conopophila rufogularis*
Sacred Kingfisher	*Todiramphus sanctus*
Shining Flycatcher	*Myiagra alecto*
Silver-Crowned Friarbird	*Philemon argenticeps*
Southern Boobook	*Ninox boobook*
Spangled Drongo	*Dicrurus bracteatus*
Spotted Harrier	*Circus assimilis*
Spotted Nightjar	*Eurostopodus argus*
Straw-Necked Ibis	*Threskiornis spinicollis*
Striated Pardalote	*Pardalotus striatus*
Sulphur-Crested Cockatoo	*Cacatua galerita*
Tawny Frogmouth	*Podargus strigoides*
Torresian Crow	*Corvus orru*
Varied Lorikeet	*Psitteuteles versicolor*
Varied Triller	*Lalage leucomela*
Weebill	*Smicrornis brevirostris*
Whistling Kite	*Haliastur sphenurus*
White-Bellied Cuckoo-Shrike	*Coracina papuensis*
White-Bellied Sea-Eagle	*Haliaeetus leucogaster*
White-Gaped Honeyeater	*Lichenostomus unicolor*
White-Throated Gerygone	*Gerygone albogularis*
White-Throated Honeyeater	*Melithreptus albogularis*
White-Winged Triller	*Lalage sueurii*
Willie Wagtail	*Rhipidura leucophrys*
Yellow Oriole	*Oriolus flavocinctus*
Yellow-Throated Miner	*Manorina flavigula*
Zebra Finch	*Taeniopygia guttata*
Mammals	
Agile Wallaby	*Macropus agilis*
Antilopine Wallaroo	*Macropus antilopinus*
Black Flying-Fox	*Pteropus alecto*
Black-Footed Tree-Rat	*Mesembriomys gouldii*

Common name	Scientific name
Claw-Snouted Blind Snake	*Ramphotyphlops unguirostris*
Common Brushtail Possum	*Trichosurus vulpecula*
Common Wallaroo	*Macropus robustus*
Dingo	*Canis dingo*
Fawn Antechinus	*Antechinus bellus*
Grassland Melomys	*Melomys burtoni*
Northern Brown Bandicoot	*Isoodon macrourus*
Northern Quoll	*Dasyurus hallucatus*
Short-Beaked Echidna	*Tachyglossus aculeatus*
Sugar Glider	*Petaurus breviceps*
Black-Necked Snake-Lizard	*Delma tincta*
Black-Tailed Monitor	*Varanus tristis*
Reptiles	
Blind Snake	*Anilios*
Burton's Legless Lizard	*Lialis burtonis*
Bynoe's Gecko	*Heteronotia binoei*
Children's Python	*Antaresia childreni*
Frilled Lizard	*Chlamydosaurus kingii*
Gilbert`S Dragon	*Lophognathus gilberti*
Green Tree Snake	*Dendrelaphis punctulata*
Grey's Menetia	*Menetia greyii*
Karl Schmidt's Lerista	*Lerista karlschmidti*
Lively Ctenotus	*Ctenotus alacer*
Long-Nosed Water Dragon	*Lophognathus longirostris*
Marbled Velvet Gecko	*Oedura marmorata*
Metallic Snake-Eyed Skink	*Cryptoblepharus metallicus*
Northern Dtella	*Gehyra australis*
Northern Dwarf Skink	*Menetia maini*
Northern Mulch-Skink	*Glaphyromorphus darwinensis*
Northern Shovel-Nosed Snake	*Brachyurophis roperi*
Northern Small-Eyed Snake	*Cryptophis pallidiceps*
Northern Snake-Lizard	*Delma borea*
Orange-Naped Snake	*Furina ornata*
Ornate Snake-Eyed Skink	*Notoscincus ornatus*
Port Essington Ctenotus	*Ctenotus essingtonii*
Robust Ctenotus	*Ctenotus robustus*
Scant-Striped Ctenotus	*Ctenotus vertebralis*
Slender Rainbow Skink	*Carlia gracilis*
Slender Snake-Eyed Skink	*Proablepharus tenuis*
Smooth-Tailed Skink	*Glaphyromorphus isolepis*
Spotted Tree Monitor	*Varanus scalaris*
Storr's Ctenotus	*Ctenotus storri*
Storr's Snake-Eyed Skink	*Morethia storri*
Striped Rainbow Skink	*Carlia munda*

Common name	Scientific name
Swanson's Snake-Eyed Skink	*Cryptoblepharus cygnatus*
Three-Spined Rainbow Skink	*Carlia triacantha*
Two-Lined Dragon	*Diporiphora bilineata*
Two-Spined Rainbow Skink	*Carlia amax*
Water Python	*Liasis fuscus*
Zig-Zag Gecko	*Oedura rhombifer*