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SUPERVISING SCIENTIST

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Supervising Scientist Branch acknowledges the traditional custodians of the lands on which we live and work, and their continuing connection to land, sea and country.

We pay our respects to the cultures of the Mirarr and Larrakia people, and to their elders both past and present.

Photos (clockwise spiral from top left): Fish videography preparation, Gunlom Falls; Gauging stations in Magela Creek; Checking water quality in Baralil Creek; Measuring radiation in bushfoods; Marbled Velvet gecko, *Oedura marmorata*; Wirnmuyurr Billabong; Croc-fenced boat in Gulungul Billabong; LiDAR point cloud of vegetation; Inspecting South Alligator Valley legacy minesites with Traditional Owners and the Northern Land Council.

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SUPERVISING SCIENTIST'S OVERVIEW

2019-20 will be remembered as a uniquely challenging year for us all, and this was certainly the case for the Supervising Scientist Branch (SSB). However, despite the significant disruptions caused by the COVID-19 pandemic in the second half of the year the SSB managed to complete our supervisory, research and monitoring programs with minimal delays. Once again we were able to ensure the people and environment of Kakadu National Park remained protected from the effects of uranium mining.

The Jabiru team ensured our routine monitoring systems continued to function during the biosecurity lock-down, we undertook our first ever virtual inspection of the Ranger uranium mine and conducted a very successful virtual meeting of the Alligator Rivers Region Technical Committee. Once able to resume travel from Darwin to Jabiru we completed one of our largest and most coordinated field campaigns to date and completed our annual recessional flow monitoring program in a greatly reduced time window. It was a great team effort involving the simultaneous collection of airborne and underwater imagery and a range of biological samples.

That we were able to continue to deliver our key functions in the face of such difficult circumstances is a testament to the dedication and adaptability of the SSB team.

Rehabilitation activities at the Ranger uranium mine continue to gather pace as we approach the end of processing operations. Energy Resources of Australia Ltd (ERA), operator of the Ranger uranium mine, published an updated Ranger Mine Closure Plan on 1 October 2019. It was pleasing to note that this version was much improved over the 2018 Plan and addressed a number of the concerns raised by the SSB. We published our assessment of the 2019 Plan on 20 December 2019.

Significant progress has been made by ERA on important ground and surface water modelling work in order to provide reliable predictions of contaminant concentrations in the creeks downstream of the Ranger uranium mine following rehabilitation. This work is critical to ensure the environment will be protected over the long-term.

As we approach the cessation of operations at the Ranger uranium mine the SSB is evolving our monitoring program from one focused on the short-term effects of an operational site to one focused on the seasonal-scale effects likely to result from a rehabilitated site. To achieve this, we are using leading-edge technology to develop monitoring methods which are cost effective and easy to deploy, while exploring options for local indigenous ranger groups to provide assistance in the delivery of our future monitoring programs.

Our fish videography artificial intelligence program will be operational for the 2021 field season removing the need for manual image processing; and our regional macro-invertebrate DNA database is nearing completion which will allow us to move towards a genomics-based macroinvertebrate monitoring program in coming years.

SSB is also applying artificial intelligence technology to the classification of vegetation from airborne imagery. We have acquired two new vertical takeoff and landing UAV platforms with sufficient range to allow us to undertake landscape-scale vegetation surveys. These large-scale surveys will provide the information required to establish the rehabilitation targets for the Ranger uranium mine.

In addition to the development of new monitoring technologies SSB is making good progress in addressing the research Key Knowledge Needs for the rehabilitation of the Ranger uranium mine, closing-out 9 research projects during 2019-20.

In addition to our work on the Ranger uranium mine, the SSB continues to assist Parks Australia with the management of uranium mining legacy sites in the south of Kakadu, provide technical advice to support the EPBC assessment of the National Radioactive Waste Management Facility and undertake a number of international engagements, including with the International Atomic Energy Agency.

It is a privilege to lead the SSB Team and I am very proud of our achievements in 2019-20. I would like to thank each and every team member for their hard work and dedication and look forward to continuing our important work in 2020-21.

Keith Tayler

Supervising Scientist

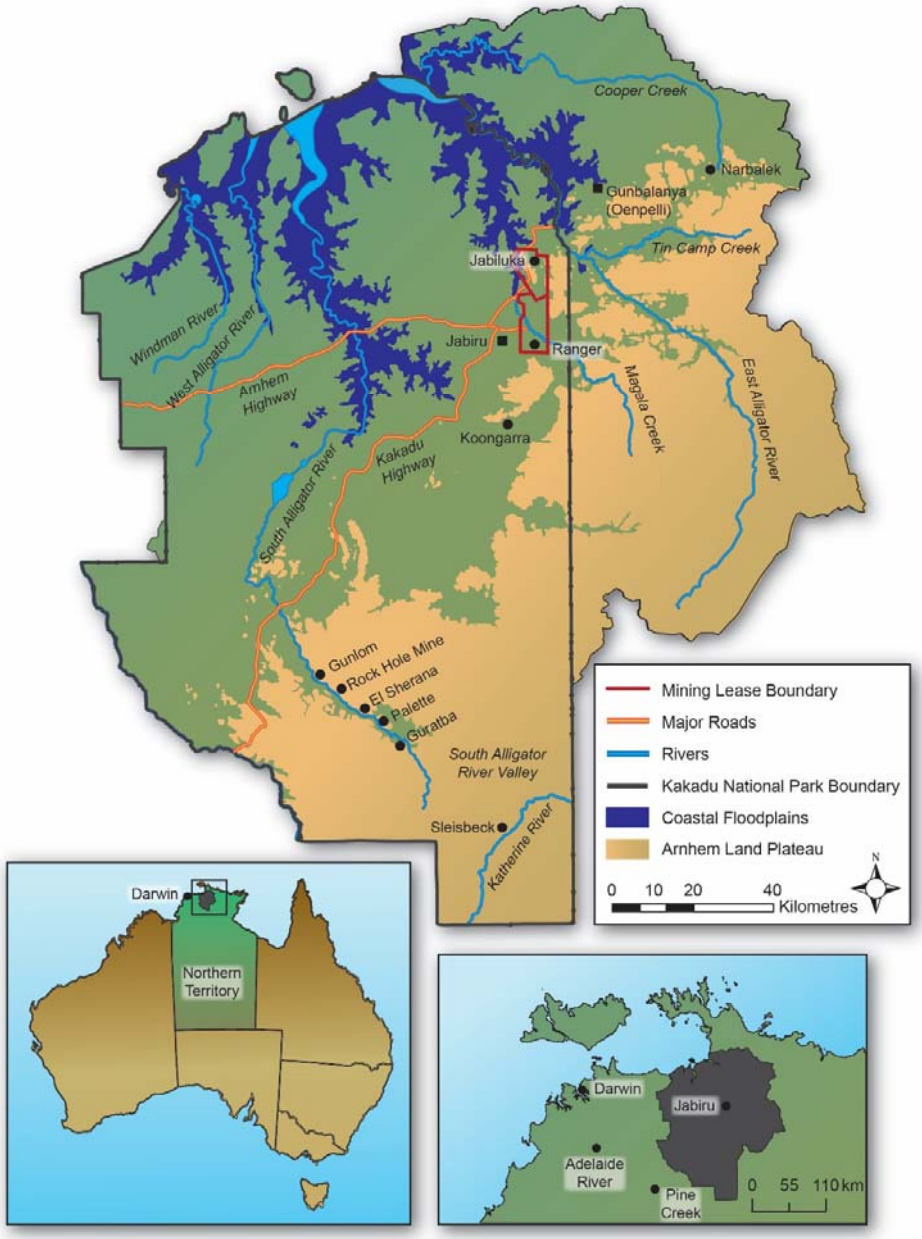


Figure 1 The Alligator Rivers Region

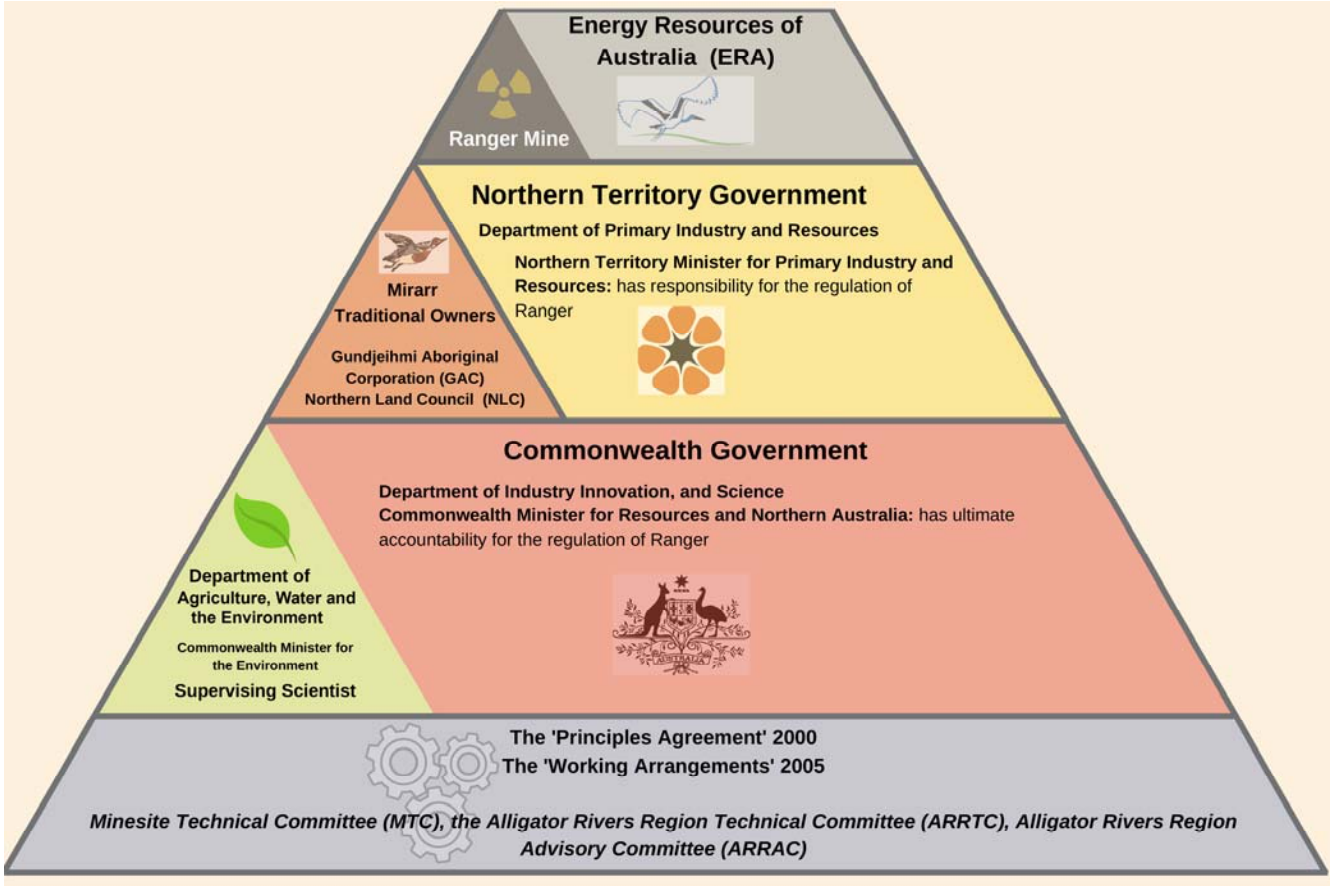
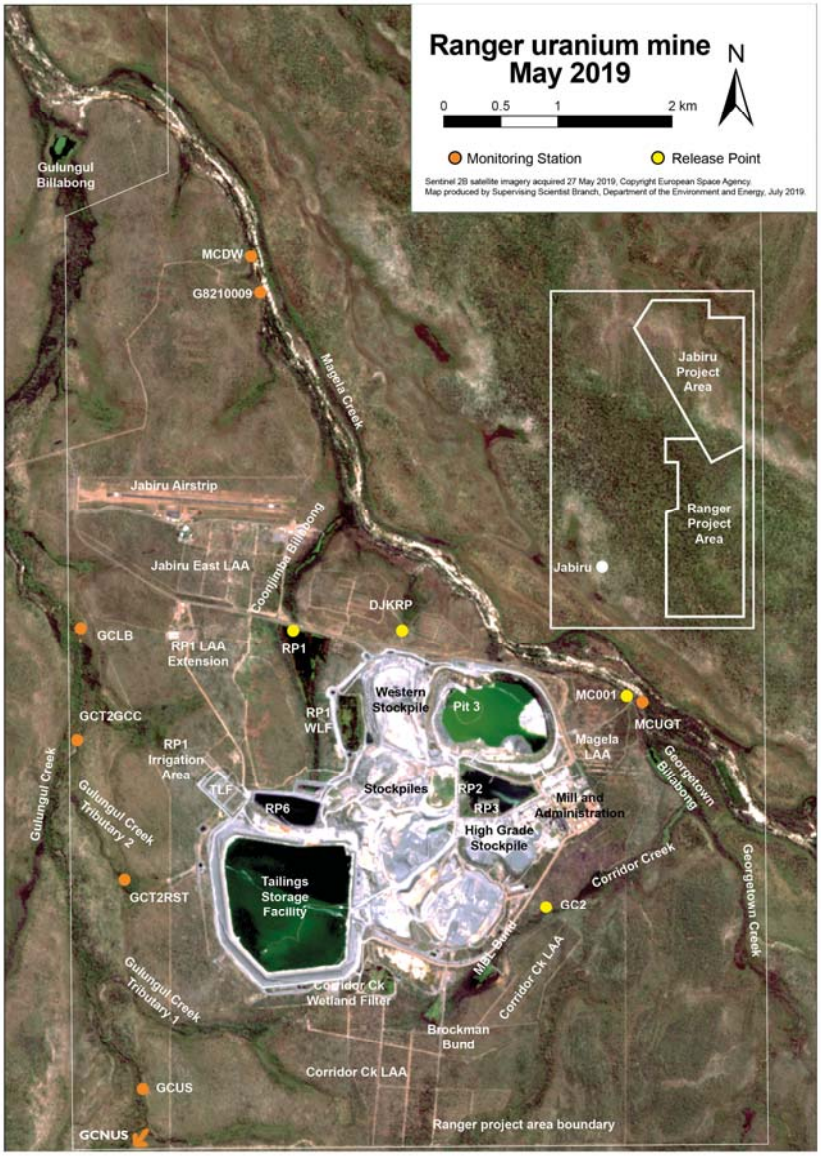


Figure 2 Regulatory framework for Ranger uranium mine



SITE CODE	GULUNGUL SITE DESCRIPTION	SITE CODE	MAGELA SITE DESCRIPTION
GCNUS	Gulungul Creek new upstream	MCUGT	Magela Creek upstream
GCUS	Gulungul Creek upstream	MCDW	Magela Creek downstream
GCLB	Gulungul Creek lease boundary	G8210009	Magela Creek gauging station
GCDS	Gulungul Creek downstream		
GCT2GCC	Gulungul Creek confluence with Tributary 2		
GCT2RST	Gulungul Creek Tributary 2 Radon Springs Track		

Figure 3 Ranger minesite including location of water release points and SSB monitoring sites

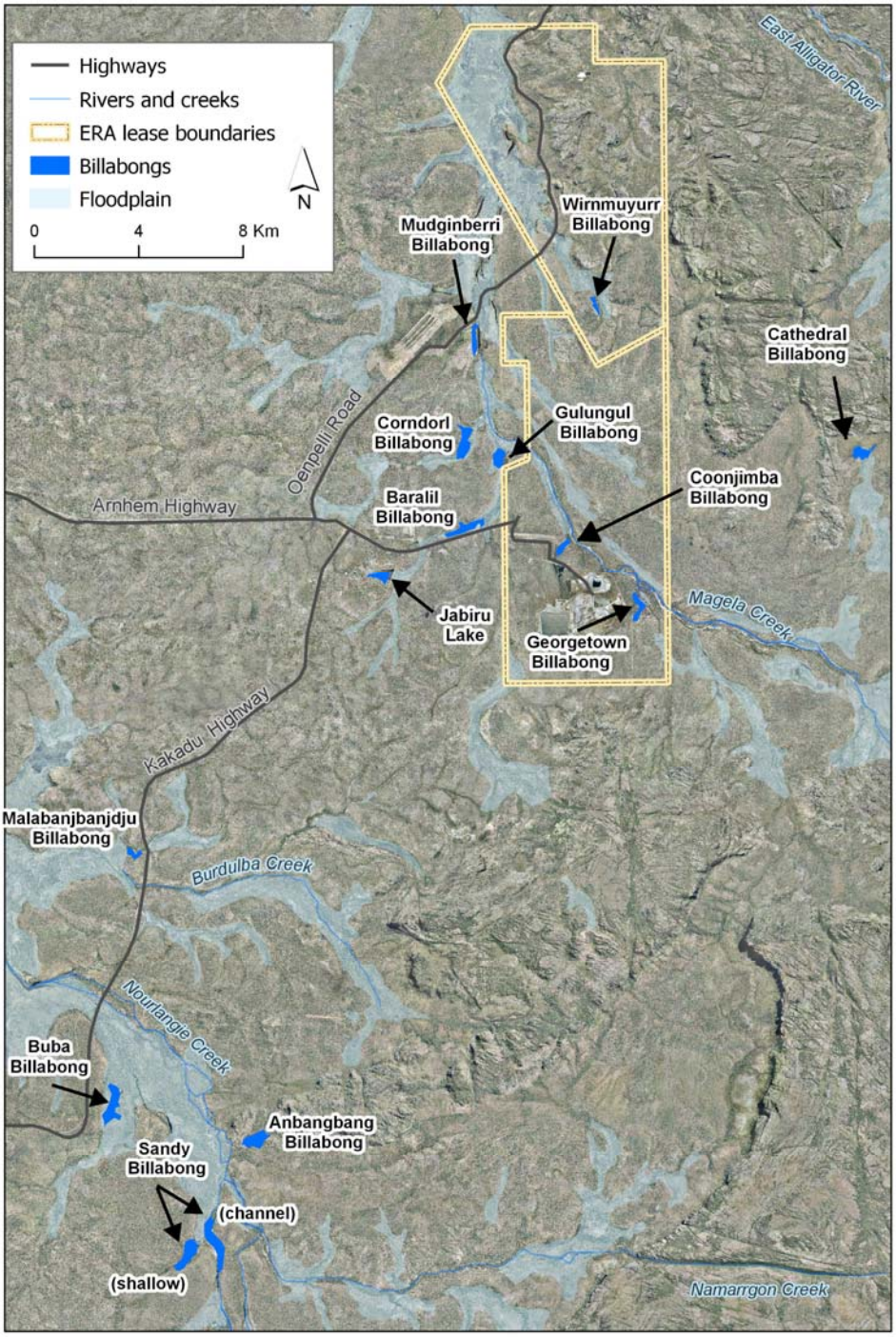


Figure 4 Location of waterbodies in the Supervising Scientist Branch's environmental research and monitoring programs

Plate 2 Wirnmuyurr Billabong, Kakadu National Park

1 INTRODUCTION

1.1 Role and function of the Supervising Scientist

The position of the Supervising Scientist was established under the *Environment Protection (Alligator Rivers Region) Act 1978* in response to a recommendation of the Ranger Uranium Environmental Inquiry Second Report (also known as the Fox Report) in May 1977. The role of the Supervising Scientist is held by the Assistant Secretary of the Supervising Scientist Branch in the Department of Agriculture, Water and the Environment, situated within the Heritage, Reef and Wildlife Trade Division (formerly the Heritage, Reef and Marine Division during the reporting period).

The Supervising Scientist ensures the protection of the Alligator Rivers Region (ARR) from the impacts of uranium mining by undertaking environmental research, monitoring and developing standards and practices for environmental protection. SSB has four key functions with respect to mining activities in the ARR:

- Research
    - Undertake research into the environmental impacts of uranium mining, and to inform uranium mine rehabilitation.
    - Provide a rigorous scientific basis for the development of environmental standards, practices and procedures, including environmental monitoring programs.

- Supervision
    - Supervise uranium mining operations, including oversight of the regulatory process, to ensure regulation is adequate, effective and consistent with Commonwealth requirements.
    - Assess exploration plans, mining activities and rehabilitation planning and implementation to ensure statutory requirements are achieved.
- Monitoring
    - Conduct a comprehensive and independent environmental monitoring program to detect effects of uranium mining on people and the environment.
    - Provide data to inform the Research and Supervision functions.
- Public Assurance and Advice
    - Communicate the science underpinning the rehabilitation of uranium mines to stakeholders and the general public.
    - Advise relevant Ministers, regulators, stakeholders and the general public of environmental monitoring outcomes to provide assurance that people and the environment remain protected from uranium mining activities.
    - Ensure the relevant Ministers, regulators and stakeholders are informed of environmental risks related to uranium mining operations and rehabilitation, and understand how environmental standards ensure protection.

1.2 Uranium in the Alligator Rivers Region

The ARR is located 220 km east of Darwin and encompasses an area of approximately 28,000 km^2 (Figure 1). The ARR extends into western Arnhem Land and includes the catchments of the West Alligator, South Alligator and East Alligator Rivers. The dual World Heritage listed Kakadu National Park lies entirely within the ARR, as do the Ranger, Jabiluka, Nabarlek and Koongarra uranium deposits.

The Ranger and Jabiluka uranium deposits are surrounded by, but remain separate from, Kakadu National Park. The Koongarra project area was incorporated into the Kakadu World Heritage area in 2011, and later incorporated into Kakadu National Park in 2013. Nabarlek is situated to the east of Kakadu National Park within Arnhem Land.

Ranger mine is currently the only operational uranium mine in the ARR. Mining at Ranger ceased in 2012, and processing of stockpiled ore must cease by January 2021. Mining ceased at Jabiluka in 1999 and the site remains under long-term care and maintenance. Operations at Nabarlek ceased in 1988 and the site has been substantially decommissioned and is subject to ongoing rehabilitation. There are also numerous former uranium minesites in the South Alligator River Valley that

operated during the 1950s and 1960s. The Australian Government funded the rehabilitation of these sites, which was completed in 2009.

This report provides an update on the current status of each of these sites and the activities undertaken by SSB for the 2019–20 reporting period.

1.3 The Ranger regulatory framework

The Authority to mine uranium at Ranger is issued under s41 of the *Atomic Energy Act 1953*, which is administered by the Commonwealth Minister for Resources, Water and Northern Australia. The Authority also provides the Commonwealth's environmental protection conditions, which are set out in the *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* (the Environmental Requirements). The Environmental Requirements outline key objectives for mining operations and rehabilitation. Under agreement, regulatory power over uranium mining in the Northern Territory is delegated to the Northern Territory Government and given effect under the *Mining Management Act*, administered by the Northern Territory Department of Primary Industry and Resources (DPIR). The Supervising Scientist provides advice to both the Commonwealth Minister for Resources, Water and Northern Australia, and the Northern Territory Minister for Primary Industry and Resources. See Figure 2 for a visual representation of the regulatory framework for Ranger uranium mine.

Plate 3 Magela Creek, Kakadu National Park

2 PUBLIC ASSURANCE AND ADVICE

The outcomes of the Branch's research and monitoring activities are reported to key stakeholders, interested parties and the general public throughout the year via a range of consultative and communication activities. Regular reporting and engagement activities provide ongoing assurance that the environment of the ARR remains protected from the impacts of uranium mining. It also provides opportunities for the Branch to better understand and address the community's expectations, concerns and sensitivities relating to uranium mining in the Region.

2.1 Alligator Rivers Region Advisory Committee

The Alligator Rivers Region Advisory Committee (ARRAC) provides a forum for community liaison and engagement on uranium mining activities in the ARR. The committee comprises of representatives of government and regulatory bodies, stakeholder organisations, and companies involved in uranium mining activities in the region.

The 52nd ARRAC meeting was held in Jabiru in September 2019. At this meeting the committee was advised of SSB's current activities, including updates on SSB's supervision, assessment and monitoring at Ranger uranium mine and other sites in the ARR. SSB reported on how it has aligned its research and supervision activities to ERA's Ranger rehabilitation schedule to ensure SSB research can inform the rehabilitation process.

Due to COVID-19-related travel restrictions in early 2020 the 53rd ARRAC meeting was conducted as an out of session consultation with update reports submitted by SSB, ERA,

NT Dept of Primary Industry and Resources (DPIR) and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). Following circulation of the reports, questions were invited from Committee members and detailed written responses were prepared and circulated to all members.

The minutes of ARRAC meetings are available on the Department's website at:
http://www.environment.gov.au/science/supervising-scientist/communication/committees/arrac/meetings

2.2 Alligator Rivers Region Technical Committee

The Alligator Rivers Region Technical Committee (ARRTC) reviews the research programs undertaken by the SSB and ERA and provides independent advice on their adequacy to the Assistant Minister for Waste Reduction and Environmental Management.

The 43rd ARRTC meeting was held in Darwin in November 2019. The meeting focussed on ecosystem restoration research for Ranger uranium mine and the integrated program of ERA/SSB research projects proposed to address outstanding Key Knowledge Needs (KKNs). ERA presented an overview on progressive rehabilitation at Ranger and updates on groundwater modelling and the 2019 Ranger Mine Closure Plan and closure applications schedule. A report on the imminent establishment of a small pilot revegetation program was also provided by ERA. SSB gave the Committee an update on SSB's ecosystem restoration standard and the water and sediment quality program.

The 44th ARRTC meeting was held, 'virtually' due to travel restrictions relating to the COVID-19 pandemic, in May 2020. The meeting continued to focus on the research required to inform and underpin ecological restoration of the Ranger uranium mine. The Committee reviewed and endorsed the integrated program of ERA/SSB research projects proposed to address the outstanding KKNs. ERA provided an update on the progress of the water and sediment closure criteria and developments towards an agreed conceptual reference ecosystem. SSB provided the Committee with updates on their monitoring development projects using genomics, videography and hyperspectral drone data.

The minutes of ARRTC meetings are available on the Department's website at:

http://www.environment.gov.au/science/supervising-scientist/communication/committees/arrtc/meetings

2.3 Indigenous engagement

A key focus for the Branch is our communications and two-way knowledge sharing with local Aboriginal stakeholders and communities, including the Mirarr people, Traditional Owners of the land on which the Ranger mine is located. The Branch employs an Indigenous Communications Officer, based at the Jabiru Field Station,

whose role includes keeping the Mirarr and other regional Indigenous stakeholders informed about the Branch's research and monitoring work. This includes consulting with the Kakadu Board of Management as described in protocols for research in Kakadu National Park agreed between the Director of National Parks and SSB.

SSB is exploring opportunities to further engage Gundjeihmi Aboriginal Corporation and the Djurrubu Rangers in our work, with a long-term vision of transferring post-rehabilitation monitoring over to Indigenous ranger groups.

Figure 5 SSB staff work with Djurrubu Rangers to monitor water quality

SSB staff and Djurrubu Rangers collaborated on the Baralil Creek water monitoring project, undertaking numerous sampling campaigns in early 2020 (Figure 5).

SSB also worked closely with Indigenous staff from Kakadu National Park, in the collection of macroinvertebrates from Nourlangie and Burdulba Creeks as part of the Ranger mine four streams macroinvertebrate monitoring program.

Working together helps build scientific capacity in ranger groups, as well as allowing SSB staff to access relevant cultural knowledge. SSB staff also participated in other community activities and events in the reporting period including:

Figure 6 Visitors to SSB's Mahbilil Festival stall viewed macroinvertebrates through a microscope

- the Mahbilil Wind festival in Jabiru in September 2019. Our marquee was again equipped with educative posters, videos and 'hands-on' activities to provide an immersive view of SSB's work. Visitors were able to view live samples of aquatic macroinvertebrates under microscopes (Figure 6) and experience some of SSB's research and monitoring activities through virtual reality.
- SSB scientists and field staff held a community BBQ at Mudginberri Billabong in October 2019, to demonstrate mussel collecting techniques. SSB provided assurance to residents of Mudginberri that 2018 sampling and testing showed that the mussels are still safe to eat.

2.4 Communicating our science

Over the reporting period SSB staff members have participated in meetings, conferences and technical working groups, both within Australia and internationally, as detailed in Table 1. Presentations at these fora allow our staff to share the outcomes of SSB's research and monitoring programs with the broader scientific community and serve to benchmark our programs against national and international leading practice.

Supervising Scientist staff take opportunities to present the Branch's work to school and community groups. In August 2019, the Supervising Scientist visited a local primary school class to talk about SSB's fish videography work, which, importantly, involved students putting on virtual reality headsets and exploring Kakadu's underwater environment and taking a virtual helicopter flight over Kakadu.

The scientific work of SSB is also routinely published in a range of scientific journals and on the Department of Agriculture, Water and the Environment website. All reports and publications are available at: www.environment.gov.au/science/supervising-scientist/publications

The branch engages with the broader community through the Department's Facebook, Twitter and LinkedIn social media platforms. Posting information about the work of the branch has attracted many unique views and shares of our information and has provided significantly greater reach of SSB content over traditional communication channels. Social media has increased the Branch's

engagement with the general public and has become a mainstream element of communication of our work. Using social media, the Branch has been able to strategically target specific audiences with relevant information, by tagging them in posts or sharing posts to other social media pages.

TABLE 1 PRESENTATIONS AT NATIONAL AND INTERNATIONAL CONFERENCES 1 JULY 2019 TO 30 JUNE 2020

Conference	Place/date (no. Papers)
Society of Environmental Toxicology and Chemistry	Darwin, Australia, 7-10 July 2019 (7 Presentations)
13th International Conference on Mine Closure	Perth, Australia, 3-5 September 2019 (4 presentations)
International Atomic Energy Agency (IAEA) Modelling and Data for Radiological Impact Assessments (MODARIA II)	Vienna, Austria, 21–24 October 2019 (1 presentation and working group discussions)
Australian Society of Fish Biology.	Canberra, Australia, October 2019 (1 Presentation – Optimisation of monitoring methods used to characterise tropical freshwater fish community composition)
WisSym 2019	Chemnitz, Germany, 9-11 October 2019 (2 presentations)
International Commission on Radiological Protection (ICRP) 5th International Symposium on the System of Radiological Protection	Adelaide, 17–21 November 2019 (1 presentation)
Ecological Society of Australia	Launceston, Australia, November 24-29th 2019 (1 presentation, 1 poster)
International Youth Nuclear Congress	Sydney, Australia, 8-13 March 2020 (Expert Panel Member – Ethical uranium mining)

Plate 3 Whistling Kite *Haliastur sphenurus,* Kakadu National Park

3 SUPERVISION

SSB provides regulatory oversight of all uranium mining and exploration activities undertaken in the ARR. Throughout 2019-20 this oversight remained focussed on Ranger mine, including assessment of mining and rehabilitation plans, reports and applications made by ERA under the Northern Territory *Mining Management Act*. Through this assessment process SSB and other stakeholders are able to help ensure that the environmental management activities undertaken by ERA will achieve the Environmental Requirements and that the company remains in compliance with its Authorisation.

SSB also carries out a program of routine periodic minesite inspections (RPIs) and annual environmental audits for Ranger mine. These processes allow stakeholders to review ERA's environmental performance and include assessment of all reported environmental incidents and investigations, ensuring the adequacy of systems in place to manage critical on-site risks and to ensure effective maintenance and upkeep of mine infrastructure. Minesite Technical Committees (MTCs) have been established for the Ranger, Jabiluka and Nabarlek sites, each providing a forum for mining operators to discuss environmental management and regulatory issues with regulators and key stakeholders.

3.1 Ranger

ERA operates the Ranger uranium mine, which is located 8 km east of the township of Jabiru. The mine lies within the 78 km² Ranger Project Area (RPA) and is adjacent to Magela Creek, a tributary of the East Alligator River.

Ranger is an open cut mine and has been producing uranium oxide (U_3O_8) via acid leach extraction since 1981. In accordance with current regulatory approvals mining at Ranger ceased in 2012 and stockpiled ore will continue to be processed until 2021. Rehabilitation planning for Ranger has been underway for a number of years, with ERA submitting a Mine Closure Plan at the end of 2016 which has been updated annually since that time. A number of rehabilitation activities have been executed according to the plan, and all rehabilitation works must be complete by 2026.

Orebody No 1 was exhausted in late 1994 and the pit, known as Pit 1, is now used for permanent tailings disposal and has been backfilled with waste rock material. Excavation of Orebody No 3 began in 1997 and mining in the pit, known as Pit 3, ceased in 2012. Pit 3 will also be utilised for permanent tailings disposal. Tailings deposition in Pit 3 commenced in February 2015 and will continue until all tailings have been relocated from the Tailings Storage Facility (TSF) into the pit.

The majority of data presented in this section are reported to SSB by ERA throughout the year.

3.1.1 Operations

3.1.1.1 Water management

All water on the Ranger mine site is managed in accordance with the current approved Ranger Water Management Plan. This plan is updated annually and assessed by the MTC prior to approval. The plan describes the systems for routine and contingency management of the three water classes on-site. These are classified based on water quality using electrical conductivity (EC) as the key indicator, as shown in Table 2.

TABLE 2 WATER CLASSES AT THE RANGER MINE

Water class	Indicative EC range (µS/cm)
Release water	193–476
Pond water	1,220–2,380
Process water	18,800–34,900

Rainfall recorded at Jabiru Airport for the 2019–20 wet season was 1073 mm. This was well below the average annual rainfall of approximately 1554 mm (Figure 7).

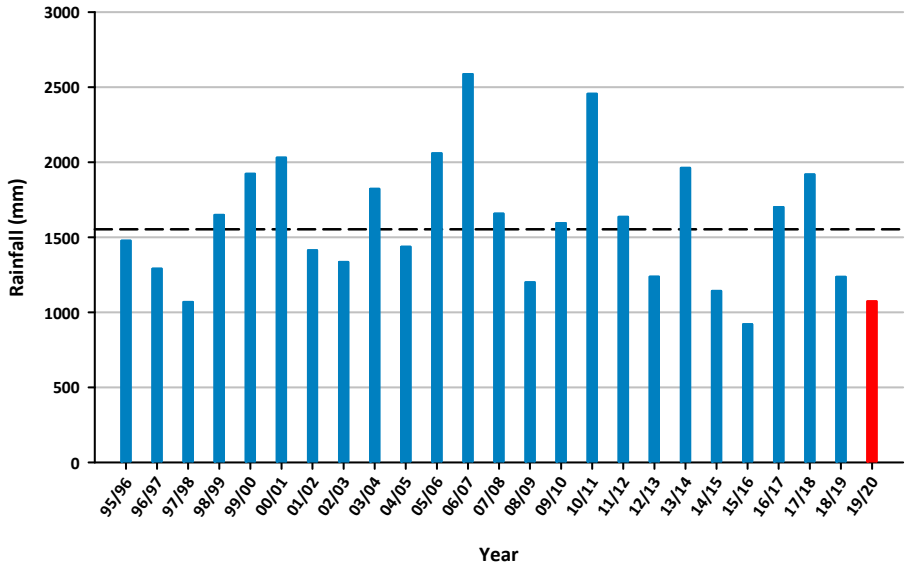


Figure 7 Annual (July - June) rainfall measured at Jabiru Airport from 1995 to June 2020. Black dotted line indicates the average annual rainfall of 1554 mm (1971-2020), blue bars are historical full year rainfall and the red bar is 2019-20 rainfall.

Process water

Process water has been in direct contact with the extraction circuit and must be retained on-site due to its very poor quality. Process water is currently stored in the above-ground TSF and in Pit 3 (Figure 3). As part of the strategy to manage and reduce the process water inventory on-site ERA constructed a brine concentrator water treatment plant in 2013. The plant produces good quality distillate that can be released off-site. Details of water treatment using the brine concentrator are shown in Table 3.

TABLE 3 ANNUAL PROCESS WATER TREATMENT VOLUMES

Date	Annual operating period (days)	Distillate produced (ML)
2013-14	181	470
2014-15	328	1031
2015-16	309	1124
2016-17	321	1474
2017-18	319	1828
2018-19	338	2118
2019-20	310	1956

The brine concentrator distillate is discharged from various locations around the site and ultimately reports to Magela Creek during the wet season or is irrigated on Land Application Areas (LAAs) during the dry season. The brine concentrator has a nominal capacity to treat 1830 ML of process water per year and forms an integral part of ERA's rehabilitation strategy. Modifications and adjustments to the operation of the brine concentrator contributed to distillate production exceeding 115% of nominal capacity in 2018-19. ERA is exploring other options to further optimise the performance of the brine concentrator including fan upgrades to provide additional capacity for process water treatment.

In order to provide additional process water treatment capacity an application was made to recommission a High Density Sludge (HDS) treatment plant located on site. This application was approved in February 2020 following assessment by SSB. The HDS plant will utilise a lime treatment process to remove dissolved salts present in process water to an extent that the water can undergo secondary treatment through the micro-filtration/reverse osmosis water treatment plants (WTPs) prior to release. Brines from the HDS plant are co-disposed with tailings in Pit 3.

Treatment of water through the WTPs generates brine that is added to the process water inventory. To help minimise the process water inventory ERA have completed construction of a brine squeezer, which is designed to further treat brine from the WTPs. Commissioning of the brine squeezer was completed in early 2020 and now ERA is investigating opportunities to utilise the brine squeezer for the direct treatment of process water. Brine Squeezer trials were approved in June 2020 following assessment by SSB.

Other initiatives were implemented during 2019-20 to further reduce the volume of process water on-site, including improved catchment management, the development of interception systems to divert better quality water away from the process water system and the extension of enhanced evaporation irrigation systems around the rim of Pit 3.

Pond water

Pond water is water that has been in contact with stockpiled mineralised material and operational areas at the site, other than those contained within the process water system. Pond water is stored in Retention Ponds 2, 3 and 6 and parts of the Pit 1 catchment area (Figure 3). ERA has previously committed to retaining pond water on-site unless it is treated prior to release. As indicated above, pond water is currently treated via three microfiltration/reverse osmosis WTPs with a combined treatment capacity of 25 ML/day. Table 4 shows the annual total volumes of pond water treated and resulting permeate produced. The volume of pond water treated over the reporting period was similar to 2018 -19 years but less than previous years due to the below average 2019-20 wet season.

TABLE 4 ANNUAL POND WATER TREATMENT VOLUMES

Date	Volume treated (ML)	Permeate produced (ML)
2011-12	7097	4873
2012-13	842	589
2013-14	4782	3311
2014-15	3028	2025
2015-16	634	440
2016-17	3890	2621
2017-18	3392	2306
2018-19	1661	1146
2019-20	1645	1053

Permeate is discharged at various locations around the site, including the Corridor Creek Wetland Filter and RP1, ultimately reporting to Magela Creek during the wet season or irrigated on LAAs during the dry season. In December 2018, ERA submitted an application to vary the permeate release conditions to include direct release of permeate to Magela Creek at MG001 (Figure 3). The SSB assessment concluded that through existing and additional controls proposed in the application, the discharge of permeate presents a low risk to the receiving aquatic environment and to the achievement of the Environmental Requirements. With the commencement of the treatment of HDS product water through the WTPs ERA has decided to discontinue the direct release of permeate to MG001 until further information on the impacts of HDS treatment on permeate are better understood.

In May 2018 ERA commenced operation of two turbomisters on the eastern side of RP1 and installed an additional 12 turbomisters in 2019. These turbomisters will be used as a contingency to dispose of permeate and distillate during the dry season, with approximately 50-60% of the treated water travelling by overland flow through the RP1 land application area to RP1 with the remainder removed through evaporation. To mitigate pond water inputs to the process water system, ERA is currently reviewing options to treat selected water sources through the Corridor Creek Wetland Filter and RP1.

Release water

Rainfall runoff from certain locations of the Ranger site such as Retention Pond 1 (RP1) and the Ranger access road culverts, is referred to as release water. It does not require treatment on-site and is either discharged actively or allowed to discharge passively during the wet season. Major release pathways include the Coonjimba Creek system and the Corridor Creek system (Figure 3).

The volume of water released actively during the wet season generally depends on the amount of rainfall throughout the season, and the water management strategies

in place at the time. Table 5 shows the total volume of water actively released from the site since 2013–14 (noting that water released passively is not quantified). Over the 2019-20 wet season, 296 ML has been actively released. This is significantly less than the 504 ML actively released over the 2018–19 wet season. This is in part attributed to the below average rainfall over the 2019-20 wet season, operational requirements for pond water that would usually be treated and released, and delays in commencements of active releases until mid-January to allow water quality upstream of the mine to stabilise.

TABLE 5 ANNUAL WATER RELEASE VOLUMES

Year	Volume (ML)
2013-14	1674
2014-15	772
2015-16	117
2016-17	1573
2017-18	1521
2018-19	504
2019-20	296

As the mine footprint is gradually rehabilitated the pond and process water catchments will be converted into release water catchments. ERA is currently planning temporary water management and diversion systems that will be installed around the site to facilitate the transition of catchments and ensure that all water released from the site to the surrounding environment is of good quality and will not cause offsite impacts. The SSB will assess the plans to ensure the adequacy of all controls and contingency measures.

3.1.1.2 Tailings and waste management

TABLE 6 MILL TAILINGS HISTORY

Activity	Year
Construction of the TSF approved	1979
Tailings deposition in TSF	1980-96
Tailings deposition in Pit 1	1996-08
Tailings transfer from TSF to Pit 1	1997-99
Tailings deposition in TSF	2008-15
Tailings deposition in Pit 3 from mill	2015-
Tailings transfer from TSF to Pit 3	2016-

Table 6 summarises the management of tailings from the processing mill over time. As part of the site rehabilitation process, ERA is currently focussed on the deposition of tailings into Pit 3 for permanent disposal. Tailings deposition in Pit 1 was completed in 2008 and pit backfill commenced in 2017. Tailings deposition in Pit 3 commenced in 2015, with the pit currently receiving tailings from both the processing mill and from the TSF (via dredging).

The primary mechanisms for disposal of controlled wastes include disposal in Pit 3 and off-site recycling. Non-hazardous wastes are disposed of either through disposal to landfill or off-site recycling.

3.1.2 Rehabilitation

3.1.2.1 Rehabilitation Objectives

The primary rehabilitation objective for Ranger, as set out in the Environmental Requirements, is to rehabilitate the site to a standard that, in the opinion of the Minister for Resources, Water and Northern Australia, with the advice of the Supervising Scientist, may enable it to be incorporated into the surrounding World Heritage-listed Kakadu National Park.

ERA is responsible for the development of closure criteria that can be used to demonstrate the achievement of the Environmental Requirements (refer Section 1.3). In parallel with the development of the closure criteria, SSB has developed a suite of Rehabilitation Standards (www.environment.gov.au/science/supervising-scientist/publications/ss-rehabilitation-standards). These non-binding environmental Standards are in accordance with section 5c of the *Environment Protection (Alligator Rivers Region) Act 1978*, covering key environmental themes: water and sediment, landform, ecosystem restoration and radiation. They draw upon nearly 40 years of research conducted by the Branch to provide quantitative criteria that reflect the Environmental Requirements. The Standards are based upon the highest level of ecosystem protection and will provide benchmarks against which the achievement of the rehabilitation objectives can be assessed. To ensure the relevance of the Standards, routine updates will occur as additional knowledge becomes available.

Throughout the reporting period additional ecotoxicological testing was undertaken to improve the accuracy of the water quality Standards. SSB also continues to refine the ecosystem restoration Standard as more information is gained through monitoring the vegetation surrounding the Ranger mine site. This provides the reference condition upon which site restoration will be based. Further information on the current status of the Standards is provided in Chapter 5.1.

3.1.2.2 Ranger Mine Closure Plan

ERA is required to submit a Mine Closure Plan annually for approval, under both the Commonwealth and Northern Territory legislation. The Plan must detail ERA's approach for the planning and implementation of rehabilitation activities and

demonstrate how these activities will achieve the Environmental Requirements. The plan requires approval by the respective Commonwealth and Northern Territory Ministers, with advice from the Supervising Scientist.

The 2019 Ranger Mine Closure Plan (RMCP) was submitted for assessment on 1 October 2019, which included updates on the status of rehabilitation activities and addressed some of the feedback provided on the 2018 version of the plan by SSB and other stakeholders. SSB undertook a detailed technical review of the plan and published an Assessment Report on 20 December 2019 (www.environment.gov.au/science/supervising-scientist/publications/ranger-mine-closure-plan-assessment-report-2019). SSB's assessment of the RMCP found that the broad rehabilitation strategy is acceptable; however, additional evidence is required to demonstrate that all the Environmental Requirements can be achieved. The Supervising Scientist's recommendations included the need for:

- additional detail around decommissioning of the tailings storage facility, tailings consolidation modelling and proposed closure criteria.
- enhanced focus on full ecosystem restoration, including soil formation, faunal recolonisation and the establishment of understorey species and ecological processes.
- greater certainty around predictions of future contaminant concentrations in groundwater and surface waters surrounding the mine site.
- more detail around contingency planning for key rehabilitation activities.

The Minister for Resources, Water and Northern Australia approved the RMCP on 12 May 2020 following consideration of SSB's Assessment Report and advice from other stakeholders. In approving the RMCP, the Minister requested that the 2020 RMCP provide greater detail on tailings management and water treatment works, that closure criteria be finalised and that the 2020 RMCP include risk mitigation strategies should ERA be unable to collect enough seed stock to meet revegetation requirements.

In accordance with regulatory requirements the RMCP will be updated annually during the rehabilitation process as additional information is obtained through planning, research and monitoring, and as rehabilitation activities are completed over time. A number of less complex rehabilitation activities will be approved within the RMCP itself whilst more technically-complex activities will require a stand-alone approval process that occurs externally to the RMCP. This stand-alone approval process will require the submission of specific applications that include all relevant information related to the particular activity. Examples of major activities that will be assessed via a stand-alone approval process include the decommissioning of the TSF; backfill of Pit 3; and construction and revegetation of the final landform.

3.1.2.3 Current status of rehabilitation

Approved progressive rehabilitation works are being undertaken on-site including tailings deposition into the mined-out pits, the final backfill of Pit 1 and subsequent

construction of the final landform. Table 7 shows the performance metrics as at the end of June 2020 for major rehabilitation activities currently occurring on-site. These are discussed in the following sections. Table 8 summarises the approvals related to rehabilitation and Table 9 summarises the rehabilitation works that have been carried out to date.

TABLE 7 KEY REHABILITATION METRICS

Activity	Completed	Remaining
Dredging of TSF tailings	18.8 Mm^3	4.6 Mm^3
Pit 1 Backfill	12.4 Mt	1.0 Mt
Brine injection	82 ML	NA

3.1.2.4 Pit 1

Mining in Pit 1 ceased in 1995 and tailings transfer into the pit commenced in 1996 and was completed in 2008. During 2014 a 2.5 m thick layer of waste rock was placed over the tailings within Pit 1 and a system of vertical 'wick' drains were installed to accelerate consolidation and dewatering of the tailings. To enable conversion of the Pit 1 footprint from a process water catchment to a pond water catchment a low-permeability cap (i.e. compacted laterite) was placed on top of the waste rock in 2016. Incident rainfall and runoff from surrounding areas that report to the capped section of Pit 1 is now managed as pond water, provided the EC remains below 4,000 µS/cm.

On 17 March 2016 ERA submitted an application for a final tailings level in Pit 1. SSB undertook workshops and a comprehensive assessment of the application that included independent review by subject matter experts. On 1 February 2017 SSB publicly released its assessment report (http://www.environment.gov.au/resource/assessment-report-ranger-pit-1-final-tailings-deposition-level-7-mrl) supporting the proposed final tailings level and concluding that the application demonstrated that the risk to Kakadu National Park from tailings stored in Pit 1 was low, compared to the cumulative risk associated with the whole rehabilitated minesite.

TABLE 8 REHABILITATION-RELATED ASSESSMENT ACTIVITIES

Activity	Year of approval
Pit 3	
Deposition of tailings in Pit 3	2007
Notification of intent to deposit tailings in Pit 3	2015
Notification of change to Pit 3 operation	2018
Pit 3 sub-aqueous deposition trial	2018
Application Pit 3 Tailings Deposition	2019
Pit 1	
Relocate 1 Mm^3 from TSF to Pit 1	1997
Interim storage of tailings in Pit 1 to -12 mRL	2007
Interim storage of process water to -15 mRL	2010
Placement of 2.5 m layer of waste rock	2013
Final disposal of tailings to -12 mRL	2017
Pit 1 backfill design	2017
Pit 1 final landform design and monitoring	2019
TSF	
TSF east wall notching and reduction in TSF MOL	2018
TSF north wall notching Stage 1 and TSF MOL adjustment approach	2018
TSF north wall notching Stage 2 and reduction in TSF MOL	2019
TSF north wall notching Stage 3 and TSF MoL adjustment approach	2020
TSF floor access notching and ramps	2020
TSF sub floor contaminated material management	2020
Ranger 3 Deeps	
Ranger 3 Deeps exploration decline decommissioning	2018
Water treatment and release	
Application to change permeate discharge conditions	2019
Brine squeezer pond water treatment	2019
Brine squeezer process water treatment	Trials approved 2020
High Density Sludge process water treatment	Trials approved 2020
Site-wide activities	
Ranger Mine Closure Plan	2018
Surface water modelling	Still under assessment
Groundwater modelling	Still under assessment

TABLE 9 REHABILITATION WORKS

Activity	Year
Pit 1	
Deposition of tailings commenced	1996
Deposition of tailings completed	2008
Preload capping with waste rock	2014
Laterite cover – conversion to pond water catchment	2016
Waste rock backfill – preparation works and commencement of bulk backfill	2017
Stage 13a Revegetation trials	2019
Pit 3	
Waste rock backfill to -100 mRL	2014
Construction of under-bed drainage and brine injection infrastructure	2014
Deposition of mill tailings commenced	2015
Deposition of TSF tailings commenced	2016
Brine injection commenced (currently off-line since September 2016)	2016
Change to multi-point tailings deposition	2017
Commencement of sub-aqueous deposition	2019
TSF	
Tailings dredging commenced	2016
Commissioning of a second tailings dredge	2019

A Pit 1 backfill plan was submitted by ERA for review in early February 2017 and was subsequently assessed and supported by SSB. In March 2018 ERA submitted an application to proceed with placement of the final 6 million tonnes of backfill material. Assessment of this application by SSB identified that further information would be required to demonstrate that the proposed Pit 1 final landform will be able to support a sustainable ecosystem in the future and will effectively isolate tailings from the environment. SSB also recommended that a monitoring program be developed to ensure critical data is collected during and after the construction of the Pit 1 landform to inform tailings consolidation model verification, relevant KKNs and refine future rehabilitation activities as required. An updated application was submitted by ERA in March 2019, which included a proposed monitoring framework consistent with SSBs recommendations. This updated application was supported by SSB, subject to the implementation of the Pit 1 Progress Rehabilitation Monitoring Framework.

The Monitoring Evaluation and Research Review Group (MERRG) was established in 2018 to ensure data collected across the site is fit-for purpose and can incorporated into closure planning, where appropriate. The Pit 1 construction phase monitoring programs have been finalised, with attention turning to development of monitoring plans for the ecosystem re-establishment phase. A timeline of progressive rehabilitation activities has been developed to prioritise the development

of future monitoring plans and to ensure that research and monitoring data collected from the Trial Landform is also included.

3.1.2.5 Pit 3

Mining in Pit 3 was completed in November 2012 and preparation of the pit to receive tailings was completed in December 2014. This included backfilling the lower section of the pit with 31.2 million tonnes of waste rock, establishing brine (waste produced from treatment of process water) injection bores into the waste rock backfill and constructing an under-bed drainage system. Tailings deposition sub-aerially commenced from the mill in February 2015 and via dredging from the TSF in January 2016. The process water levels in Pit 3 and the TSF are currently managed in a closed circuit in order to ensure that the water in the TSF is maintained at an optimal depth for operation of the tailings dredges.

Several projects are underway to transfer all tailings into Pit 3 for permanent disposal. This includes the deposition of mill tailings directly into Pit 3 and the transfer of tailings from the TSF to Pit 3 using two custom-built dredges. Brine injection into the waste rock under fill commenced intermittently 2015 but has been suspended since September 2016 due to the failure of the decant bore used to extract water from the under-bed drainage system in Pit 3. ERA has completed repairs to the decant bore and will be recommissioning it in Q3 2020 in conjunction with reactivation of the under-bed drainage system. In the interim brine produced from process water treatment is being recirculated within the process water system or treated through the processing plant to recover additional uranium product. ERA is monitoring process water quality to ensure that brine recirculation does not impact on its ability to treat the water.

In April 2019 ERA submitted an updated application to deposit tailings into Pit 3 informed by the current deposition trials and to address SSB concerns on tailings management. This application proposed that dredged tailings from the TSF (including those from a second dredge) would be deposited sub-aqueously into the Pit 3 water column. Mill tailings would continue to be deposited sub-aerially with the installation of additional discharge locations along the pit wall. The application proposed that a maximum operating level (MOL) for water in Pit 3 would be established at +3.5 mRL. The bulk of the tailings would have a near horizontal surface of approximately -20.0 mRL by the end of deposition with a small area of tailings near the subaerial discharge locations reaching as high as -15 mRL. The SSB undertook a detailed technical review of the application and concluded that the changes in the deposition strategy did not substantively increase the risk to people or the environment. The SSB also noted in this assessment that:

- further work was required to reduce the uncertainty in potential future impacts from mine contaminants including tailings to the off-site environment.
- ongoing refinement of tailings consolidation modelling and post closure solute egress modelling should be undertaken by ERA.

- that the maximum post consolidation tailings level be better defined to reflect the potential variability in the final tailings surface.

DPIR approved the revised deposition strategy in July 2019 and a final maximum tailings level of -15 mRL in August 2019.

In June 2020 ERA advised stakeholders that the it was likely the average tailings level in Pit 3 may exceed -20 mRL due to the tailings density being lower than predicted. This was attributed to water balance issues impeding the original plan for sub-aerial deposition; an increased rate of deposition of dredged tailings; and issues and delays in verifying tailings characteristics in the Tailings Storage Facility and in Pit 3. SSB considers the consequential risks to the offsite environment to be low during the tailings deposition phase however a revised environmental risk assessment will need to be undertaken by ERA and included in the Pit 3 closure application, which is expected to be submitted at the end of 2020.

3.1.2.6 Tailings Storage Facility

Tailings stored in the TSF are currently being transferred to Pit 3, the final disposal location. A second dredge was commissioned in the TSF in June 2019, which is expected to increase the tailings dredging rate and ensure the transfer of tailings from the TSF to Pit 3 is completed on schedule in Q1 2021.

In February 2018 ERA submitted an application to notch the eastern embankment of the TSF. This notching to reduce the TSF crest height from 60.5 mRL to 51.0 mRL was required to improve process water pumping rates to optimise the water balance between the TSF and Pit 3. This application was assessed and supported by SSB noting that the notching provided an opportunity for ERA to characterise potential contamination in the TSF embankment material to inform future decommissioning. ERA completed the construction of the notch in early June 2018.

In August 2018 ERA submitted an application to construct a second notch and access ramps in the northern embankment of the TSF. The purpose of this notch was to provide ongoing dredge maintenance access and would be constructed in multiple stages as the water level in the TSF reduced through dredging activities. Supporting this application, ERA proposed a method to establish future dam MOLs based on future staged notching of the northern embankment. This method is important to ensure there is sufficient freeboard to contain process water during extreme rainfall events. Stage 1 of this application and the method to establish future MOLs was assessed and supported by SSB. ERA completed construction in December 2018 which reduced the TSF certified crest height from 51.0 mRL to 48.5 mRL. Stage 2 of the northern embankment notch to facilitate the successful launch of the second dredge in the TSF was completed in June 2019 which reduced the certified crest height to 45.1 mRL.

In April 2020 an application for Stage 3 of the northern embankment notch was submitted by ERA. This application to further reduce the certified crest height of

the dam to 37.8 mRL included a process for increasing the certified crest height, if required, through the construction of a temporary bund within the notch. This application was assessed and supported by SSB with construction to be undertaken later in 2020.

3.1.3 Assessment activities

3.1.3.1 Assessments and approvals

As described throughout this report, SSB assesses various documents submitted by ERA in accordance with the Environmental Requirements and the Ranger mine Authorisation, and provides advice to the regulators, the mining operator and key stakeholders through the Ranger MTC. The Ranger MTC met four times during the 2019–20 reporting period. Significant agenda items discussed at the meetings included the following:

- assessment and approval streamlining and potential variations to the Ranger Authorisation
- options for alignment of the Ranger Mine Closure Plan and Mining Management Plan
- Pit 3 brine injection, tailings deposition and tailings consolidation modelling
- site water management processes, pond water treatment initiatives and water inventory forecasting
- Pit 1 water balance, contaminated groundwater management, tailings settlement monitoring and bulk backfill strategy
- environmental incidents and process safety implementation and oversight activities
- progressive tracking of rehabilitation works and performance, including TSF tailings dredging, brine injection and process water treatment.

3.1.3.2 Audits and inspections

The 2019 annual environmental audit on behalf of external stakeholders of Ranger mine was undertaken on site from 23 September to 27 September 2019.

The subject of the 2019 audit was ERA's monitoring of, and management strategies for, major rehabilitation and operational activities occurring on site. These strategies were assessed to ensure ERA has the capacity to identify emerging issues that may impact on their future rehabilitation timeframes and environmental outcomes.

The audit assessed major on-site activities. For each activity a specific focus was adopted based upon recent approvals and/or significant changes to the activity. The areas selected were:

- changes to the tailings dredging management system in relation to the implementation of a second tailings dredge
- the status of Pit 3 tailings deposition monitoring programs described in the approved 2019 *Application Pit 3 Tailings Deposition Rev# 0.19.2*

- the status of construction-phase monitoring described in the approved *Pit 1 Progressive Rehabilitation Monitoring Framework*
- asset integrity assurance in the processing area until the cessation of processing by January 2021.

The audit comprised 24 questions which targeted the known potential risks associated with each of the activities at a high level. The grading for each question was assigned based upon the status of management strategies being developed and in place, in consideration of potential consequences to the environment and/or rehabilitation, and closure timeframes.

The audit found that generally ERA had appropriate strategies in place to manage the activities assessed, including performance monitoring to identify potential deviations from expectations. While robust management systems did not exist for all potential risks, such as the potential risk of dredge interaction with the TSF floor, ERA was able to demonstrate awareness of these risks and have commenced development of processes to effectively manage them.

One Category 2 Non-Compliance was identified relating to compliance with the management system for the replacement of tailings pipelines. Five conditional findings were also identified, where the audit team felt improvement was needed or specific components of the audited activity had yet to be fully implemented. These conditional findings related to:

- updating the TSF process safety hazard package to incorporate the second dredge
- detailing assumptions associated with the latest TSF dredging plan
- updating procedures for tailings pipe inspections to incorporate the second dredge infrastructure
- submission of the updated Pit 3 tailings deposition plan to stakeholders
- reviewing the process safety hazard package for bulk storage of sulphuric acid to ensure changes to the tank maximum fill level are consistently captured

Several observations were provided by the audit team for consideration by ERA aimed at improving the systems or activities relevant to the questions posed.

Through the RPI program stakeholders followed up on the significant findings of this audit and concluded that all matters identified had been satisfactorily addressed

by ERA. The 2020 Annual Environmental Audit, initially scheduled for June 2020, was delayed due to COVID-19 related access restrictions.

Figure 8 RPI stakeholders inspecting the Ranger Tailings Storage Facility

The 2020 Ranger RPI and audit program was agreed by stakeholders in December 2019 with each RPI in the program having a specific theme aligned with relevant activities on-site. RPIs were carried out as scheduled during 2019 and until February 2020 when the program was temporarily suspended due to the outbreak of COVID-19.

The May 2020 inspection was undertaken remotely, and onsite inspections recommenced in June 2020, including the annual tailings dam inspection (Figure 8 RPI stakeholders inspecting the Ranger Tailings Storage Facility. Table 10 shows the focus areas for each of the RPIs completed to date and the planned RPI themes for the remainder of 2020.

TABLE 10 2020 RANGER ROUTINE PERIODIC INSPECTION PROGRAM

Month	Theme	Primary areas inspected
January	Surface water monitoring and release management	Surface water monitoring and release, Pit 3 sub aqueous deposition trials, process water enhanced evaporation and reported incidents for January 2019.
February	Radiation management (completed)	Radiation management, 2018 radiation and atmospheric monitoring results, contamination monitoring and reported incidents for February 2019.
March	TSF 6 monthly inspection	Cancelled
April	Weed, Fire and revegetation management	Postponed
May	Weed, Fire and revegetation management	2019/20 weed management plan implementation, 2019 burn program review, 2020 burn program implementation, revegetation trials and nursery operations.
June	TSF annual inspection	TSF wall integrity and inspection program, piezometer monitoring trends, notching activities, dredging and wall cleaning.
July	Hydrocarbons and waste management. Water treatment	Pending
August	Revegetation trials preparedness, groundwater monitoring and management and contaminated sites	Pending
September	Groundwater monitoring and management	Pending
October	Rehabilitation activities status and planning	Pending
November	Revegetation, ecosystem re-establishment Jabiluka pre wet season inspection	Pending
December	Crushing, milling and processing circuits	Pending

3.1.3.3 Environmental incidents

In 2019–20 29 environmental incidents were reported by ERA to stakeholders. The number of reported incidents increased from 18 reported in 2018–19. This is in part attributed to five incidents related to the activation of fire suppression systems on mobile equipment. Only one of these fire suppression system incidents was associated with a potential vehicle fire, the others where accidental release and the root cause is being investigated by ERA. An annual comparison of incidents reported over the past six years is shown in Figure 9.

The number of process water, tailings and hydrocarbon related incidents notified in 2019–20 are similar to the number reported in 2018–19, although trending higher for process water and hydrocarbon related spills (Figure 10). Most of these hydrocarbon and process water related incidents where minor and are likely due to increased works on site associated with rehabilitation projects and increased ore throughput in the processing circuit.

All incidents were investigated by SSB through the RPI process and were considered to have been resolved satisfactorily and did not result in off-site impacts.

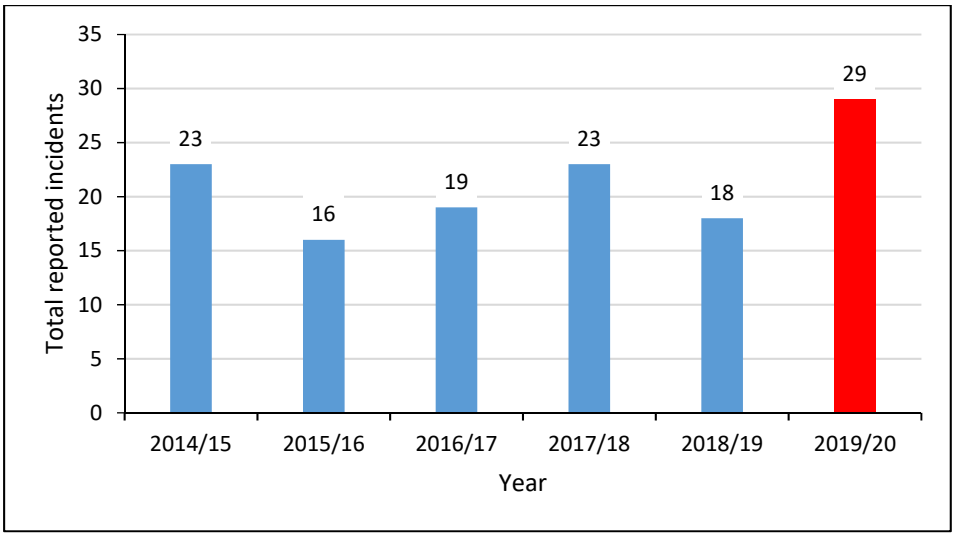


Figure 9 Ranger mine reported environmental incidents by year

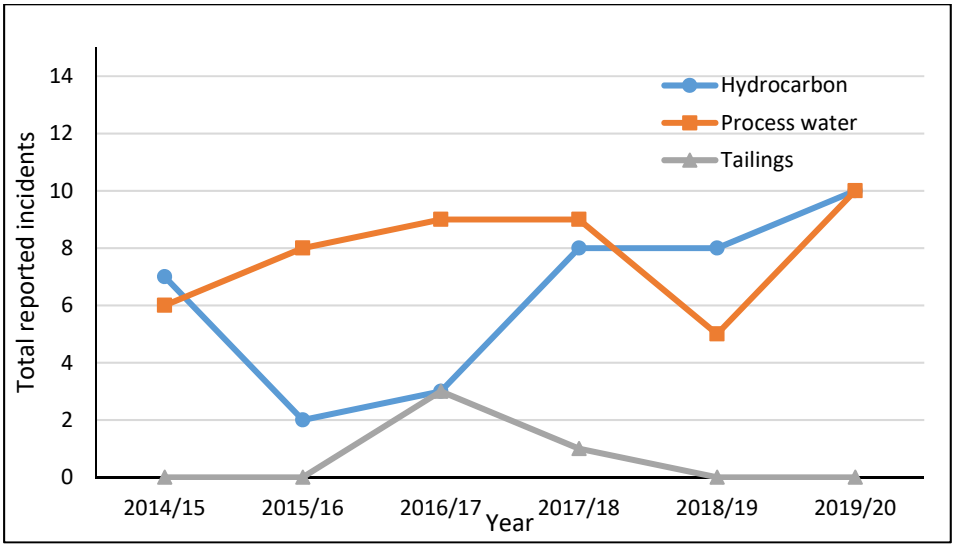


Figure 10 Hydrocarbon, process water and tailings incidents by year

3.1.3.4 Significant incidents

No incidents requiring formal investigation by SSB were reported during 2019–20, however one notable incident was reported:

On 15 January 2020, continuous electrical conductivity (EC) data at the Pit 1 sump reached a maximum of 11,053 μS/cm. Subsequent analysis by ERA indicated this sump water had a process water signature. In accordance with the approved water management controls in the Ranger Water Management Plan (RWMP), the transfer of water from the Pit 1 sump to the pond water circuit should have ceased when EC exceeded 4,000 μS/cm, however, approximately 6.5 ML of high EC water was transferred to the pond water circuit over a 14-hour period before the transfer pumps where turned off. While process water had intruded into the pond water catchment all water remained on site with no off-site impact detected through routine SSB water quality monitoring.

The cause of the process water intrusion was the failure of decant pumps used to extract process water from the consolidating tailings mass in Pit 1. To ensure that this event does not reoccur ERA has implemented initiatives including improved notification of EC exceedances, more regular inspection of decant pump operability and contingency measures to transfer poor quality water to the process water circuit if required. Stakeholders will continue to monitor the effectiveness of these strategies through the RPI process.

Table 11 provides a summary of the significant incidents that have occurred since 2013.

TABLE 11 SUMMARY OF SIGNIFICANT INCIDENTS

Year	Incident	Outcome
2013	**Leach tank failure** In December 2013 Leach Tank No. 1 at the ERA Ranger uranium mine collapsed, spilling approximately 1,400 m^3 of slurry containing ground uranium ore, water and sulphuric acid into the processing area.	In February 2016 DPIR finalised their investigation and concluded they would not be proceeding to prosecution. Noetic Solutions Ltd continued to monitor the implementation of recommendations related to process safety via a series of quarterly inspections. Noetic Solutions were retained by ERA to assist with ongoing process safety management.
2014	**Product packing stack emission** In November 2014 ERA reported that uranium emissions from the product packing stack at Ranger mine exceeded the authorised rate of 1.5 kg of uranium per day.	Subsequent investigations by ERA, SSB and DPIR concluded the limit was not actually exceeded, but the initial notification from ERA was the result of human error in the calculation of uranium emissions. Improvements in how uranium emissions are calculated and verified have been implemented by ERA. As part of the RPI process, a review of these improvements and confirmation that ERA tests relevant alarms and interlocks in accordance with statutory requirements was undertaken in January 2017.
2015	**Uncontrolled fire in Kakadu** On 1 October 2015 a weed management burn by ERA resulted in an uncontrolled fire in Kakadu National Park, which burnt into culturally and environmentally sensitive areas.	The Department of Environment and Energy's Compliance and Enforcement Branch determined the fire was unlikely to have resulted in a significant impact on matters of national environmental significance. As such, the Department does not intend to pursue this matter further under the *Environment Protection Biodiversity and Conservation Act 1999*. SSB and NT Government identified deficiencies in ERA's fire management system, which was subsequently audited in 2016.

3.1.4 Radiation protection

A review of 16 years of atmospheric radiation monitoring data conducted in 2016 clearly indicated that the mine-derived radiation dose from airborne radon progeny and radioactive dust from Ranger uranium mine is negligible and does not currently pose a public health risk (typically contributing less than 5% of the public dose limit). Accordingly, SSB ceased its atmospheric radiation monitoring program at the end of 2015 with the intention to recommence once major rehabilitation activities commence on site in 2021.

The data presented below is summarised from ERA's 2019-20 radiation protection and atmospheric monitoring program.

The radiation dose limits for workers and members of the public from other-than-natural sources recommended by the International Commission on Radiological Protection (ICRP) and adopted in Australia by ARPANSA are:

- Limit to a member of the public (1 mSv in a year)
- Limit to workers (100 mSv over 5 years with a maximum of 50 mSv in any one year).

In addition, ARPANSA has recommended a reference level of 5 mSv in a year to distinguish between designated and non-designated workers at Australian uranium mines. Designated workers are those who could potentially receive an occupational radiation dose above the reference level. These workers are monitored more intensely than the non-designated workers. It is ERA's responsibility to monitor radiation doses and to ensure that radiation exposures to both workers and the general public from operations at Ranger are as low as reasonably achievable, taking into account economic and societal factors.

3.1.4.1 Radiation exposure of ERA workers

The three primary pathways of radiation exposure to workers at Ranger are:

- inhalation of radioactive dust
- exposure to external gamma radiation
- inhalation of radon decay products (RDP)

ERA conducts statutory and operational monitoring of external gamma exposure to employees (through the use of gamma dose badges), radon decay products and long-lived alpha activity (dust) in the air, and surface contamination levels. Dose constraints used as part of optimisation of radiation protection at Ranger mine, are revised annually and detailed in ERA's Annual Radiation and Atmospheric Monitoring Report. The monitoring results for 2019 confirm that doses to designated and non-designated workers were well below the annual dose limits and the current dose constraints as listed in Table 12.

For both designated and non-designated workers the 2019 dose was comparable to the 2018 dose as shown in Table 13 and Table 14 respectively.

TABLE 12 2019 ANNUAL RADIATION DOSE CONSTRAINTS FOR RANGER MINE

Proposed operational area/work group	Existing work group	Annual dose constraint (mSv)
Ranger Operations	Processing Production	6.0
	Processing Maintenance	6.0
Non-Designated Workers	Non-Designated Workers	3.0
Workers under the age of 18	Under 18	3.0
Members of the public	Members of the Public	0.3

TABLE 13 2019 DESIGNATED WORKER DOSE (mSv)

	2019	2018
Occupational dose limit	20	20
Mean annual effective dose (% of dose limit)	1.07 (5.4%)	1.23 (6.1%)
Maximum annual effective dose (% dose limit)	3.58 (17.9%)	3.64 (18.2%)

TABLE 14 2019 NON-DESIGNATED WORKER DOSE (mSv)

	2019	2018
Occupational dose limit	20	20
Mean annual effective dose (% of dose limit)	0.13 (0.65%)	0.15 (0.75%)
Maximum annual effective dose (% dose limit)	1.18 (5.9%)	1.08 (5.4%)

3.1.4.2 Radiation exposure of the public

The two main pathways of potential radiation exposure to the public during the operational phase of Ranger mine and the care and maintenance phase at Jabiluka mine are inhalation and ingestion. The inhalation pathway results from radionuclides released to the air from the minesite, while the ingestion pathway is caused by the uptake of radionuclides into bush foods from the Magela Creek system downstream of the mine.

Inhalation pathway

In accordance with the Ranger mine Authorisation, ERA measures concentrations of radon progeny and dust-bound long-lived alpha activity (LLAA) radionuclides in

air at the Jabiru town and Jabiru East Airport. These locations represent the main areas of permanent habitation in the vicinity of the Ranger mine.

Table 15 provides a summary of annual average radon progeny potential alpha energy concentration (PAEC) in air and estimated doses to the public in 2019. In 2019 the mine-derived annual dose from radon progeny in air was indistinguishable from the background dose from all other natural sources. This dose is dependent on wind direction and has been estimated from the difference in average radon progeny PAEC in air when the wind was from the direction of the mine and when the wind was from directions other than the mine. In 2018 the International Commission on Radiological Protection changed the recommended new radon dose conversion factors for radon however these have yet to be formally adopted in Australia. It is likely that when adopted, these new dose conversion factors will increase the reported annual dose and mine derived dose from radon progeny. For example, when the new dose conversion factor is applied to the 2018 monitoring results, the mine derived dose to the public from radon progeny increases from 0.022 mSv to 0.06 mSv which is still well below the dose limit of 1 mSv.

TABLE 15 RADON PROGENY PAEC IN AIR AND ESTIMATED DOSES TO THE PUBLIC AT JABIRU TOWN

	2019	2018
Annual average PAEC [µJ m^{-3}]	0.054	0.044
Total annual dose [mSv]	0.520	0.423
Mine-derived dose [mSv] [1]	0.000	0.022

[1]The radon progeny PAEC difference used in the mine-derived dose calculation was 0.017 µJ/m^3 for 2018 and - 0.013 µJ/m^3 for 2019. As the 2019 dose calculation was negative, which is not possible it was therefore indistinguishable from the background and has been listed here as 0 mSv.

ERA uses high volume air samplers to monitor airborne concentrations of LLAA in the township of Jabiru and at Jabiru East. Table 16 provides a summary of the annual average LLAA radionuclide concentration reported by ERA and the total and mine-derived doses to the public at Jabiru estimated by SSB. The total annual effective dose from dust-bound LLAA radionuclides, which includes contribution from natural background, has been estimated to be 0.006 mSv at Jabiru town. This total annual dose has been estimated by calculating the annual average LLAA concentration from the individual samples and then multiplying with a dose conversion factor of 0.0061 mSv Bq_{α}^{-1}, breathing rate of 0.75 m^3 h^{-1} and assumed full year occupancy of 8,760 hours.

TABLE 16 LLAA RADIONUCLIDE CONCENTRATIONS IN AIR AND ESTIMATED DOSES TO THE PUBLIC AT JABIRU TOWN

	2019	2018
Annual average concentration ($Bq_{\alpha}^{-1}m^{-3}$)	9.7×10^{-5}	1.5×10^{-4}
Total annual dose (mSv)	0.004	0.006
Mine-derived dose* (mSv)	0.000	3.1×10^{-4}

*Calculated from the assumption that the ratio of mine-derived to total annual dose from dust is the same as that for radon progeny.

In 2019 the total annual dose from LLAA radionuclides to the public at Jabiru town from all sources was 0.004 mSv. The mine-derived contribution to this dose has been estimated by assuming that the ratio of mine-derived to total annual dose from dust is the same as that for radon progeny. The mine derived dose for radon progeny was zero as shown in Table 15, therefore the mine derived dose for LLAA radionuclides has also been calculated as zero.

3.2 Jabiluka

The ERA-owned Jabiluka mineral lease abuts the northern boundary of the Ranger Project Area, with the former Jabiluka minesite situated 20 km north of the Ranger minesite. Jabiluka is in the East Alligator River catchment, adjacent to Ngarradj (Swift Creek), which flows into the Magela floodplains to the north. Development work at Jabiluka took place in the late 1990s but ceased in September 1999, at which time the site was placed in an environmental management and standby phase that lasted until 2003. During 2003 it was agreed that the Jabiluka site would not be mined and the site was placed in long-term care and maintenance. Whilst in long-term care and maintenance revegetation activities have been undertaken by ERA, however final closure of the site is not anticipated in the short-term given that the lease will not expire until August 2024 and may be subject to renewal.

3.2.1 Rehabilitation

3.2.1.1 Revegetation, weed and fire management

Revegetation of the disturbed parts of the Jabiluka mineral lease aimed to recreate a vegetation community of local native plant species of similar density and abundance to that existing in undisturbed adjacent areas.

Between 2006 and 2014 approximately 15,500 seedlings were planted across the Jabiluka mineral lease including the former Jabiluka mine footprint and the former Djarr Djarr exploration camp site. Hot fires originating off the lease have burnt through the revegetated areas at the Djarr Djarr exploration camp site in 2007, 2008 and 2010 resulting in significant vegetation mortality.

In June 2018 ERA carried out vegetation surveys at Jabiluka and Djarr Djarr, assessing species-specific density, recruitment, growth, survival rates and where possible, general ecosystem health. The results were provided to stakeholders in December 2019. The density of original planted individuals at Jabiluka had decreased since 2015 however there has been an overall increase in density of stems. This indicates that recruitment is occurring, however primarily in non-target (i.e. non-Eucalypt) species. The results showed that approximately 71% of woody stems were naturally recruited Acacia and other species. The survey also demonstrated that the native understorey is generally diverse but infrequent with low cover. At Djarr Djarr, stem density had remained relatively stable since a survey in 2012. Monitoring plots at Djarr Djarr contained 39% of species present in reference plots.

ERA uses herbicide to actively manage weeds at the Jabiluka mineral lease. Throughout 2019-20, 326 hours of weed spraying activities were undertaken at the Jabiluka and Djarr Djarr sites, which is a decrease from the 456 hours of weed spraying activity were undertaken during 2018-19. The reduction in weed spraying activity was due, in part, to a decrease in overall weed density and distribution throughout the Jabiluka lease in 2019-20 compared to 2018-19. Due to the reduction in the use of glyphosphate for 'blanket spraying' and the use of more targeted residual herbicides it was noted that native grass abundance has increased, particularly at Djarr Djarr and in the rehabilitated Jabiluka footprint. ERA undertakes annual fuel-reduction burning around the Djarr Djarr and Jabiluka sites to reduce the effects of wildfires on the revegetated areas. Cooler wet season burns were conducted at Jabiluka in January 2020 and Djarr Djarr in February 2020. Follow up burns where conducted in at both Jabiluka and Djarr Djarr in May 2020. Native spear grass that had established within the Jabiluka fenced area that was planned to be burnt during the 2019-20 wet season was treated via weed spraying to minimise the risk of fire on the rehabilitated area.

3.2.1.2 Water management and monitoring

The Jabiluka site lies to the west of Ngarradj Creek and is in the headwaters of three sub-catchments. These sub-catchments are termed the southern, central and northern tributaries of Ngarradj Creek. The Interim Water Management Pond (IWMP) at the Jabiluka site was removed in 2013 and the area was recontoured and revegetated. ERA continues to monitor water quality in groundwater and surface waters upstream and downstream of the Jabiluka site in accordance with the Jabiluka Authorisation. Overall, the monitoring results for the 2019-20 wet season remain within historical ranges reported in previous wet seasons and there has not been any evidence of off-site environmental impacts. ERA continues to assess erosion at the Jabiluka site and has installed a number of sediment traps to reduce the transport of coarse material in surface flows. Given the low environmental risk posed by the site SSB ceased water quality monitoring prior to the 2015–16 wet season.

In July 2018 SSB reviewed the hydrogeological information available on the Mine Valley Bores and provided recommendations for additional groundwater monitoring

to be conducted within the Mine Valley area and the vent shaft from the former underground development works. This monitoring will help to determine if a contamination plume is present and will assist in improving the understanding of the hydraulic gradients in the Mine Valley area. ERA sampled the vent shaft in October 2019. Analytical results of groundwater samples obtained from the vent shaft were comparable to the downgradient bores for most parameters except sulfate, filtered uranium and nitrate results which were higher. ERA is undertaking a review of groundwater contamination risks which will inform updates to groundwater monitoring program for Jabiluka. Mine Valley bore sampling requirements will be evaluated as part of this risk assessment.

3.2.2 Assessment activities

SSB assesses various documents submitted by ERA in accordance with the requirements of the Jabiluka Authorisation and provides advice to key stakeholders through the Jabiluka MTC. Jabiluka MTC meetings are scheduled pre and post-wet season to allow stakeholder discussion of any potential issues identified during the most recent inspection. The latest Jabiluka MTC was held on 3 July 2020 to tie in with the post-wet season RPI.

Due to the low environmental risk posed by the site SSB ceased annual audits of the Jabiluka site in 2017. Pre- and post-wet season inspections will continue to be undertaken to identify and assess emerging issues (e.g. erosion, weeds) and to continue to monitor the progress of revegetation.

The 2019–20 pre-wet season inspection was conducted on 22 November 2019 and focussed on landform stability, general vegetation health and the status of groundwater and surface water monitoring sites. Stakeholders noted the dominance of *Acacia* stems in some revegetated areas. The inspection identified that sand and vegetation had accumulated at JSCTC2 surface water monitoring sites and required removal prior to the wet season. The 2019-20 post-wet season inspection was delayed due to access restrictions associated with COVID-19 and was held on 1 July 2020. The site appeared in a stable condition with minor access track maintenance and repairs to a groundwater bore casing identified as the only significant maintenance issues.

No environmental incidents have been reported for Jabiluka during 2019–20.

3.3 Nabarlek

The former Nabarlek mine is located 280 kilometres east of Darwin and was initially owned by Queensland Mines Ltd. The Nabarlek ore body was mined during the dry season of 1979 and milling continued until 1988 producing around 11,000 tonnes of uranium oxide concentrate (U_3O_8). The mine was decommissioned in 1995 and the site underwent rehabilitation. In early 2008 Uranium Equities Limited (UEL) bought Queensland Mines Ltd thereby acquiring the Nabarlek lease. In early 2018 UEL

changed its name to DevEx Resources (DevEx) and is expanding its exploration focus within the ARR to include targets other than uranium.

Since 2008 DevEx has undertaken extensive exploration on the Nabarlek lease and has assumed responsibility for management of the rehabilitated areas at the site. This includes undertaking a range of programs for weed control, revegetation, fire management and other rehabilitation works as required. The exploration activities and the performance of the ongoing rehabilitation and revegetation program continues to be monitored and assessed by SSB, the regulator and key stakeholders including the NLC.

No site activities have occurred since the outbreak of COVID-19 in early 2020 due to travel restrictions into aboriginal communities.

3.3.1 Rehabilitation

3.3.1.1 Revegetation, weed and fire management

The survival rate of tube stock seedlings planted in 2013 was reviewed by DevEx in August 2016 using photo-monitoring. The results showed variable survival rates ranging from >90% survival on the runoff pond area through to <5% survival on the waste rock dump and former camp areas. A review of tube stock planting techniques and timing, undertaken by DevEx in 2017, identified that planting early in the wet season would improve water availability and assist in decreasing early tube stock mortality. Feral animals and wild cattle are believed to contribute to tube stock mortality. DevEx has repaired the mine perimeter fence and in consultation with local ranger groups, will implement an eradication program within the fenced area as a priority in 2020-21.

Annual fire management activities are undertaken in conjunction with the local DMED Rangers from Oenpelli as recommended during the 2015 stakeholder audit, and usually occur concurrently with weed spraying activities on-site. Controlled burns around the perimeter of the Naberlek mine area were also conducted in January 2019 by DMED Rangers. Weed spraying and water monitoring planned for January 2020 did not go ahead due to the failure of critical equipment. Further weed spraying is planned for December 2020.

Weed mapping was undertaken in conjunction with the 2016 annual weed spraying. This weed mapping measured weed composition and density at 145 sample locations across the lease. General ground observations in 2018-19 indicate a reduction in the overall density of weeds across the site including a reduction in para grass density and the apparent elimination of mission grass from the former evaporation pond region. Further weed mapping was undertaken in January 2019 which is currently being assessed to evaluate the effectiveness of DevEx's weed management program.

During 2019-20 DevEx intended to evaluate the use of residual herbicides to selectively target mission grass which is particularly prevalent in the more open areas

on-site. These trials have been delayed due to the COVID-19 outbreak until 2020-21.

3.3.1.2 Water management and monitoring

Statutory surface and groundwater monitoring are conducted by the Northern Territory Government and DevEx. Monitoring results are reported in the six-monthly Northern Territory Supervising Authorities Environmental Surveillance Monitoring in the ARR reports.

In August 2016 DevEx collected water samples from 11 bores and from surface water sites along Cooper Creek. Results from the groundwater sampling were consistent with previous years monitoring results, with elevated sulfate and uranium concentrations down gradient from the former mine pit and elevated sulfate concentrations and low pH values for bores down gradient of the former irrigation and evaporation pond areas. Sulfate results have remained elevated but stable since 1988, while uranium concentrations downgradient of the mine pit have shown an increasing trend since 2003. While sulfate and uranium concentrations are elevated, they are well below levels that are likely to cause environmental impact.

In October 2017 DevEx undertook further water sampling from monitoring and surface water sites with results reported in the 2018 Mining Management Plan. A groundwater monitoring program review was undertaken in October 2018 to inform remediation of the Radiologically Anomalous Area (RAA) and to assess groundwater conditions to potentially refine the groundwater monitoring program into the future. This review was submitted in conjunction with the 2020 Mining Management Plan (MMP) and is currently being assessed by SSB. Additional groundwater monitoring planned for the 2019-20 wet season did not occur due to equipment failure and the outbreak of COVID-19 prior to replacement equipment being available.

At the beginning of the 2016-17 wet season SSB deployed three continuous EC sensors, one in Kadjirrikamarnda Creek downstream of the former minesite and two in Cooper Creek at sites upstream and downstream of the former minesite. The EC measurements were consistent with DevEx monitoring data and provide a baseline of current seasonal EC trends which can be used to assess changes over time. EC sensors were redeployed for the 2019-20 season and showed similar trends to previous years. SSB will continue to monitor EC in 2020-21.

3.3.1.3 The Radiologically Anomalous Area

The 0.4 ha Radiologically Anomalous Area (RAA) is located immediately south-west of the former pit area. The RAA exhibits elevated levels of radioactivity and contributes about one quarter of the total radon flux from the rehabilitated minesite and historically, the majority of the radionuclide flux from the site via the erosion pathway (more detail is provided in Supervising Scientist Annual Report 2004–05).

In August 2015 DevEx undertook a program of shallow drilling in the RAA to further characterise the radioactivity profile in the area. Analysis of soil composites

suggest that most of the radioactive material is confined to a small section of the RAA and is mostly present in the upper 3 m of the soil profile. SSB conducted a LiDAR survey of the RAA using a remotely Piloted Aircraft System (RPAS) in June 2018 to assist with the remediation activities and material placement.

DevEx has submitted an application for the remediation of the RAA in conjunction with the 2020 MMP which is currently being assessed by SSB. The preferred remediation option being considered by DevEx involves burial of the radiologically contaminated material at the current location and placement of a rock cover with water diversion earthworks to minimise future erosion.

3.3.2 Exploration

The MMP for 2018 dry season works was submitted in July 2018 with a subsequent amendment submitted in October 2018. The proposed work program for 2018 included further geophysical surveying and a small drilling program. Following assessment this work program was supported by SSB in November 2018. Due to operational matters, including the ongoing consultation between DevEx and the NLC regarding ownership and liability of some residual infrastructure on-site, the 2018 work program was deferred until the second half of 2019. DevEx was granted approval to carry over the 2018 MMP work program to the 2019 field season by DPIR in May 2019. An updated MMP detailing the status of rehabilitation activities at Nabarlek was submitted in July 2020 and is currently being assessed by SBB. No significant disturbances are proposed in this MMP with the focus being on the remediation of the RAA as discussed above.

3.3.3 Assessment activities

In June 2019 DPIR and NLC undertook an inspection and MMP compliance assessment of drilling activities occurring on the Devex exploration leases adjacent to the former Nabarlek mine. During this inspection aerial drone surveys of the Nabarlek mine were undertaken and the site status was reviewed. No significant issues were identified and the completion of repair works to damaged fencing was confirmed.

A Nabarlek MTC meeting was held on 31 May 2018 and focussed on the ongoing progress of revegetation and weed management and possible remediation strategies for the RAA and other outstanding disturbed areas on-site. The 2019 Nabarlek MTC has been delayed to the second half of 2020 to allow DevEx to finalise and present their preferred remediation strategy for the RAA to MTC stakeholders.

There were no environmental incidents reported for Nabarlek during 2019-20.

3.4 Other activities in the Alligator Rivers Region

3.4.1 Uranium rehabilitation projects

3.4.1.1 South Alligator Valley uranium mines and containment facility

During the 1950s and 1960s a number of small uranium mines and milling facilities operated in the South Alligator River Valley located in the southern part of the ARR. The majority of these sites are now the responsibility of the Australian Government Director of National Parks. In May 2006 the Australian Government provided funding over four years for their rehabilitation. A radiological containment facility was constructed in 2009 at the old El Sherana airstrip for the final disposal of historic uranium mining waste recovered from several sites throughout the South Alligator River Valley. Further background on the remediation of historic uranium mining sites in the South Alligator Valley was provided in the 2008–09 Supervising Scientist Annual Report.

An audit of the containment facility was conducted by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) on 30 May 2018 conjointly with an inspection of the facility by SSB staff. The need to monitor and if required repair surface cracks on the containment and ongoing management of annual mission grass were the main findings from this inspection. A RPAS LiDAR survey of the containment facility conducted by SSB on 26 June 2018 will assist in assessing the effectiveness of remediation activities undertaken to restrict the pooling of water on the surface of the facility.

In May 2019 and July 2020 SSB inspected the facility with representatives from Parks Australia. It was noted during both inspections that mission grass continues to be a concern with a noticeable increase in spatial distribution and density compared to previous inspections. A build-up of grass-related fuel load around the perimeter of the facility which posed a risk to the revegetation was also noted during this inspection. An expanded weed spraying program and continuation of a program of late wet season/early dry season low intensity burns to reduce fuel load and protect monitoring equipment was recommended from the SSB inspection.

In November 2019 an inspection of former uranium mines in the South Alligator Valley was conducted by representatives from SSB, Parks Australia, NLC and traditional owners. The purpose of this inspection was to assess the level of risk to people and the environment associated with each of the legacy mine sites. This inspection concluded that none of these sites present a risk to people and the environment, however recommendations where made regarding repairs to fencing, further inspections and additional surface water sample collection and analysis.

3.4.2 Uranium exploration projects

3.4.2.1 Vimy Resources Arnhem Project and Wellington Range – King River Joint Venture Project

In March 2018 Cameco entered into an agreement with Vimy Resources Limited to acquire Cameco's ARR exploration projects with Cameco effectively ceasing its exploration activities in the region.

An environmental audit of the Wellington Range and King River Joint Venture (WRKRJV) project was undertaken from 4 October to 5 October 2018. The audit team was made up of personnel from SSB, NLC and DPIR and the subject of this audit was to assess compliance to selected environmental management commitments contained within the approved WRKRJV Project 2018 MMP. The audit found that generally Vimy had well developed and implemented environmental management systems with no non-compliances determined during the audit. Four conditional findings were identified, where the audit team felt improvement was needed or management practices did not fully align with the relevant commitments within the MMP. These conditional findings related to weed mapping and reporting, ground disturbance sign-off, mapping of historical domestic waste pits and incident reporting.

In May 2019, Vimy Resources submitted an updated MMP for their 2019 work program which included drilling of 61 RC/diamond drill holes and construction of three additional groundwater extraction bores. This was assessed by SSB and approved by DPIR in June 2019. No stakeholder audits or inspections were undertaken in 2019.

The 2020 WRKRJV was submitted in July 2020 and is currently being assessed by SBB.

3.4.2.2 DevEx West Arnhem Joint Venture

As discussed above, UEL changed its name to DevEx in early 2018. No changes to the company's ARR projects occurred as a result of this name change.

The MMP for the 2018 dry season works was submitted by DevEx in June 2018 and SSB supported the acceptance of this updated MMP in August 2018. The exploration program for 2018 involved induced polarisation (IP) surveys. Reverse circulation and diamond drilling proposed within the MMP was not undertaken. Due to the non-invasive nature of the exploration undertaken and limited time on-site, SSB has not undertaken any site inspections or audits of this project during the 2018.

An updated MMP for the 2019 field season was submitted by DevEx in May 2019 and following assessment by SSB, approved by DPIR in June 2019. This work program comprised non-invasive geophysical work and drilling of up to 18 RC and diamond drill holes. An inspection and MMP compliance assessment for these drilling activities was conducted by DPIR and NLC from 27-28 June 2019. This assessment identified no significant incidences of non-compliance with the approved

MMP and concluded that the drilling activities were being undertaken in a manner that did not pose a significant environmental risk. The inspection also identified improvement opportunities relating to drill site housekeeping and additional bunding of hydrocarbon sources.

3.4.2.3 Alligator Energy Tin Camp Creek Project and Beatrice Project

The 2018 audit of Alligator Energy's Tin Camp Creek and Beatrice Projects was undertaken from 11–12 October 2018 to coincide with drilling activities. The objective of this audit was to assess the progressive rehabilitation of the 2018 drilling activities and to assess the environmental management controls described within the approved 2018 MMP. The audit found that Alligator Energy had well developed and implemented environmental management systems with no non-compliances or conditional findings determined during the audit. A number of recommendations were made for consideration in the development of future MMPs pertaining to clearance activities, radiation monitoring and internal sit inspections.

MMPs for the 2019 work programs for the Beatrice Project and Tin Camp Creek Project were submitted in June and July 2019 respectively. No significant disturbances were proposed, with surface sampling and re-logging of historical drill cores the primary focus of the 2019 field season. As no significant disturbances were planned during 2019, no site inspections were undertaken by stakeholders.

3.4.2.4 UXA Resources Nabarlek Group Project

No exploration activities were proposed or carried out at this site during 2019 or are proposed in 2020, therefore SSB has not undertaken any site inspections or audits during the 2019–20 reporting period.

Plate 5 Georgetown Billabong, Ranger Project Area

4 MONITORING

In order to ensure protection of people and the environment of the ARR, ERA is required to achieve specific Water Quality Objectives (WQOs) for both Magela and Gulungul Creeks (Figure 3). Because these WQOs are largely based on site-specific biological effects data their achievement provides a high level of confidence that the environment has been protected. The WQOs for Magela Creek were originally established by the Supervising Scientist in 2004 and were updated in 2016, and again in 2019. The WQOs incorporate a tiered management response framework with a hierarchy of risk-based trigger values for the key contaminants of concern, with each trigger value initiating a different degree of active management and reporting:

Focus Trigger Values – Values that are above the *Focus level* but below the *Action level* will result in a *watching brief*, which involves precautionary ongoing data assessment and possibly further sampling if required.

Action Trigger Values – Values that are above the *Action level* but below the *Guideline/Limit* will result in a *data assessment,* and where the data show the value represents a trend away from background ERA must undertake:

- An *investigation* into the cause of the exceedance; and
- *Correction* of the cause if it is deemed to be mining related.

Investigation, Guideline and Limit Trigger Values – Values that are above the *Limit* will result in a *full investigation*, including:

- Determining the cause of the exceedance;
- Collecting further samples and data; and

- Undertaking immediate *correction* of the cause if it is deemed to be mining related.

Values that are higher than the *Guideline* are treated the same as an exceedance in the *Limit* value, except:

- When there is a corresponding increase at the upstream site; and
- For Mn only, when the flow is less than five cumecs for Magela Creek and one cumec for Gulungul Creek.

Under the above circumstances a *Guideline* exceedance will be treated as for an *Action* exceedance.

In addition to ERA's statutory monitoring program SSB conducts an independent routine environmental monitoring program that uses multiple lines-of-evidence to detect and prevent environmental impacts. Two broad approaches are used by SSB to detect and assess possible environmental impacts from mine water input to receiving surface waters around the minesite, including: (1) monitoring for early detection and impact prevention, and (2) monitoring for assessment of long-term ecosystem-level responses.

Methods used for early detection of water quality deterioration and prevention of impacts include:

(i) Real-time continuous monitoring – through measurement of chemical and physical indicators in surface water;

(ii) In situ toxicity monitoring – through assessment of freshwater snail reproduction rate; and

(iii) Bioaccumulation monitoring – through assessment of metals and radionuclides in freshwater mussels.

Methods used for the long-term assessment of ecosystem-level responses include comparison of benthic macroinvertebrate and fish community data from late wet season sampling in Magela and Gulungul Creek sites with historical data and data from control sites in streams unaffected by mining.

The dates of wet season flow commencement and cessation, since the 2009–10 wet season, are shown in TABLE 17.

TABLE 17 WET SEASON CREEK FLOW SUMMARY

Wet season	Magela Creek			Gulungul Creek		
	Flow commencement	Flow cessation	Flow Duration (days)	Flow commencement	Flow cessation	Flow Duration (days)
2009–10	2 Dec 2009	27 Jul 2010	237	30 Dec 2009	24 Jun 2010	176
2010–11	24 Nov 2010	15 Aug 2011	264	14 Dec 2010	7 Jul 2011	205
2011–12	23 Nov 2011	7 Aug 2012	258	2 Nov 2011	21 Jun 2012	232
2012–13	7 Jan 2013	1 Jul 2013	175	23 Dec 2012	18 Jun 2013	177
2013–14	28 Nov 2013	21 Jul 2014	235	4 Dec 2013	23 Jun 2014	201
2014–15	27 Dec 2014	15 Jun 2015	170	2 Jan 2015	1 May 2015	119
2015–16	25 Dec 2015	6 Jun 2016	163	31 Jan 2016	23 May 2016	99
2016–17	20 Sep 2016	25 Oct 2016	35	22 Sep 2016	3 Oct 2016	11
	16 Nov 2016	17 Jul 2017	244	05 Oct 2016	11 Oct 2016	6
				16 Nov 2016	17 Nov 2016	1
				23 Nov 2016	13 Jun 2017	203
2017-18	15 Nov 2017	12 Jul 2018	240	3 Jan 2018	18 Jun 2018	166
2018-19	14 Dec 2018	28 Jun 2019	196	14 Jan 2019	31 May 2019	137
2019-20	10 Jan 2020	19 Jun 2020	161	10 Jan 2020	15 May 2020	126

In any circumstances where the water quality in Magela or Gulungul Creeks is observed to deteriorate the Supervising Scientist can undertake specific environmental investigations. No such investigations were undertaken during the 2019-20 wet season and no environmental impacts were observed through SSB's monitoring program. Monitoring results are presented in more detail below.

4.1 Early detection monitoring in Magela Creek

4.1.1 Chemical and physical monitoring

Magela Creek flows to the north-west of the Ranger minesite and receives clean runoff and actively and passively treated mine waters via Retention Pond 1, the former Djalkmara Billabong and Georgetown Creek (Figure 3).

The electrical conductivity (EC) measured in Magela Creek at the start of the 2019-20 wet season is slightly higher than that reported in previous wet seasons due to patchy rainfall and low and discontinuous flow along the creek. As the wet season progressed, EC in Magela Creek returned to values comparable to previous wet seasons (Figure 11).

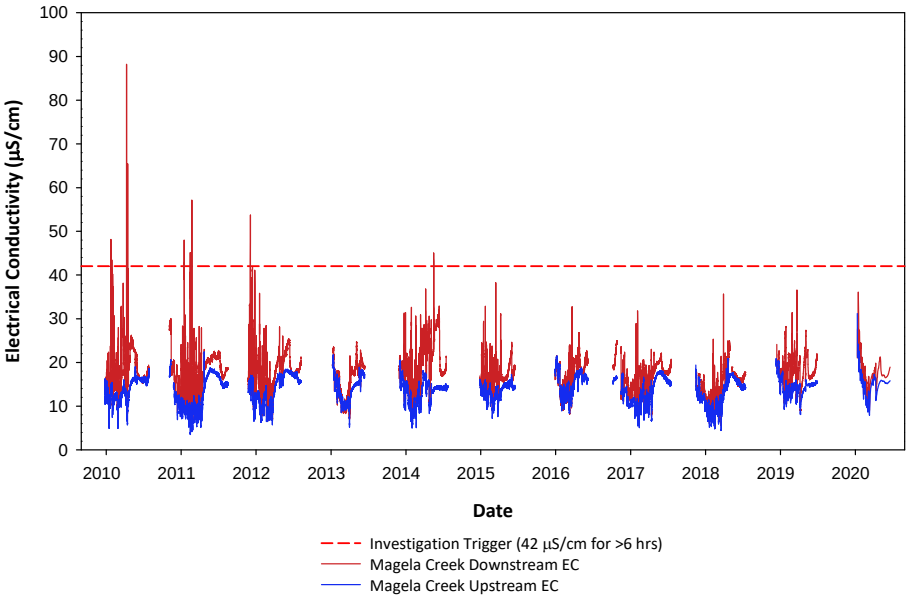


Figure 11 Magela Creek electrical conductivity (EC) data measured during the wet season 2010-2020

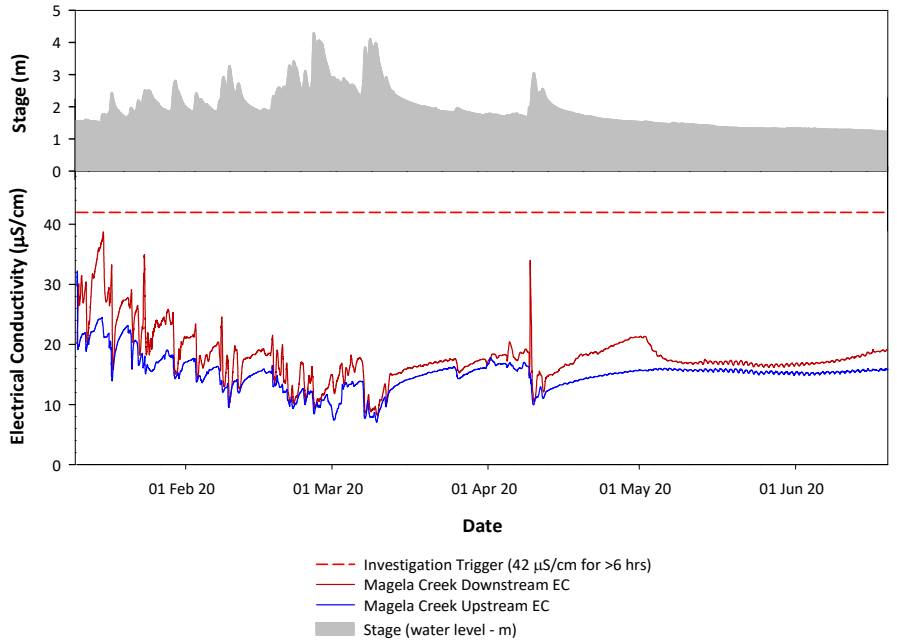


Figure 12 Magela Creek electrical conductivity (EC) and water level (stage) data measured during the 2019-20 wet season

For the duration of the 2019-20 wet season the EC in Magela Creek remained below the Investigation Trigger Value (Figure 12). SSB monitoring showed that all WQOs for Magela Creek were met for the 2019-20 wet season (full results reported at https://www.environment.gov.au/science/supervising-scientist/publications/magela-creek-monitoring-data-2019-20).

Compliance with the ^{226}Ra Limit of 3 mBq/L is assessed by calculating the difference in the geometric mean of ^{226}Ra concentrations measured at the Magela upstream and downstream sites for the entire season. ^{226}Ra samples collected during 2019-20 wet season were within historical ranges and the geometric mean difference for the entire wet season was below the limit trigger value (Figure 13).

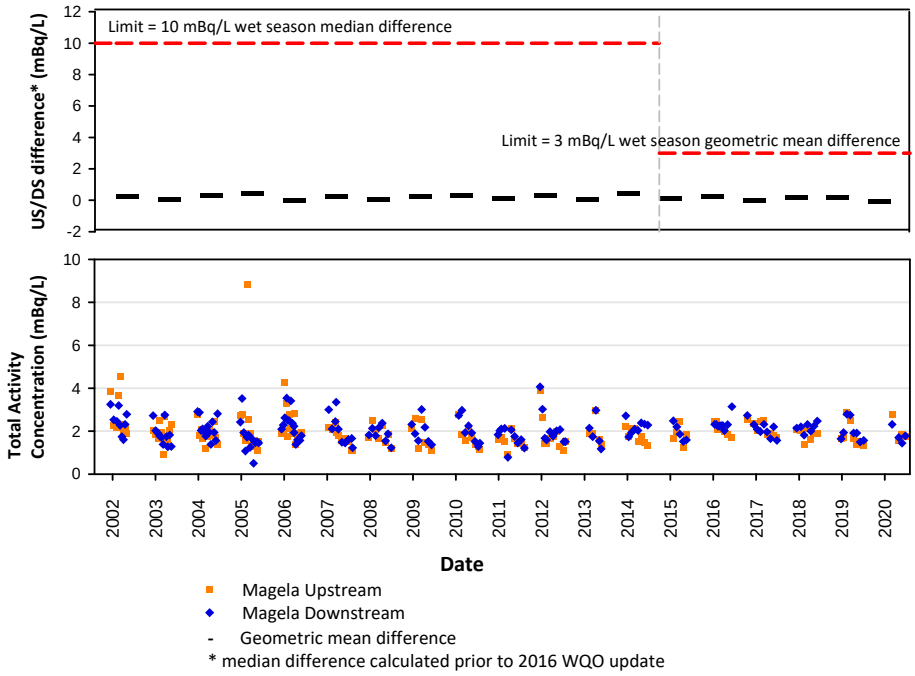


Figure 13 Magela Creek ^{226}Ra measured during 2012-2020 wet seasons

4.1.2 Biological monitoring

4.1.2.1 Toxicity monitoring

Six in situ toxicity monitoring tests using the freshwater snail reproduction response were conducted in Magela Creek over the 2019–20 wet season, spanning the period 20 January 2020 to 6 April 2020. Magela testing alternated on a weekly basis with testing in Gulungul Creek.

The range in mean egg number difference values between upstream and downstream sites was similar to those ranges reported in previous years (Figure 14). For the six tests, analysis of variance testing (ANOVA) showed that egg difference values between the sites were not significantly different for the 2019–20 wet season compared to difference values from all previous wet seasons, indicating that impaired reproduction in this sensitive snail response in Magela Creek was not evident for the periods of 2019–20 wet season testing.

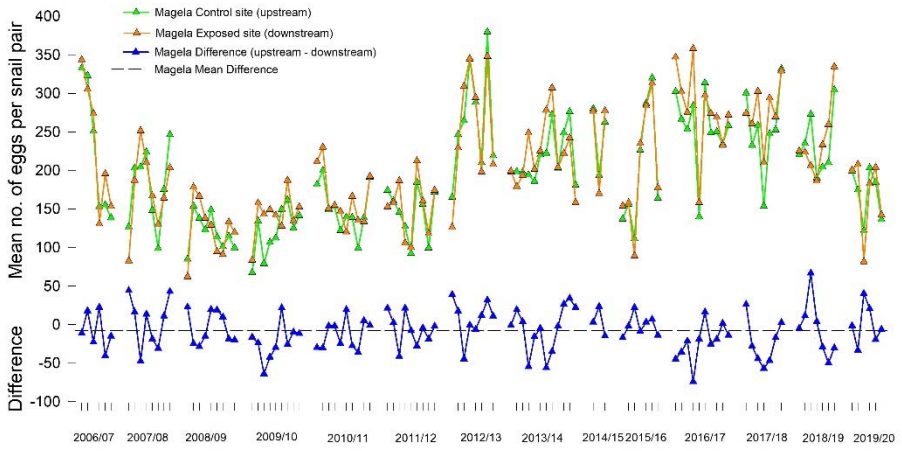


Figure 14 Time series of in situ snail egg production data from toxicity monitoring tests conducted in Magela Creek.

4.1.3 Bioaccumulation in freshwater mussels

Freshwater mussels have previously been identified as the most important food source contributing to radiation dose from a traditional Indigenous diet in Kakadu. This is because they strongly bioaccumulate ^{226}Ra in their flesh. Mussels have been collected annually from Mudginberri Billabong (potentially impacted site) since 2000 and triennially from Sandy Billabong (unimpacted site) since 2002 and analysed for ^{226}Ra as part of a routine bioaccumulation monitoring program.

Freshwater mussels were collected from Mudginberri Billabong in October 2019. Figure 15 shows ^{226}Ra activity concentrations measured in mussel flesh from this collection and compares them with the average and range of values measured in mussels since 2000. Mussel ^{226}Ra activity concentrations in 2019 were within the range of previously measured values.

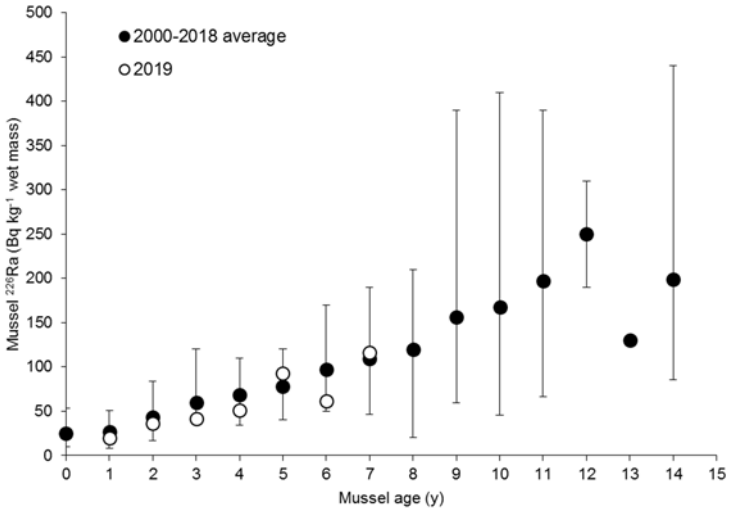


Figure 15 Flesh ^{226}Ra activity concentrations in mussels collected from Mudginberri Billabong. The error bars represent the ^{226}Ra activity concentration range in each age class.

The total annual committed effective dose from ^{226}Ra in mussels has been calculated to be 0.096 mSv for a 10-year-old child who eats 2 kg (wet mass) of mussel flesh based on the 2019 measurement results for Mudginberri Billabong. By comparison, the total annual committed effective dose from ^{226}Ra in mussels based on the average of all Mudginberri Billabong measurement results from 2000 to 2018 has been calculated as 0.148 mSv, with a range from 0.06 mSv to 0.20 mSv during these years.

The radiation dose to traditional owners from freshwater mussels collected from Mudginberri Billabong is almost exclusively from natural background sources of ^{226}Ra in the environment and would be received irrespective of the operation of the Ranger uranium mine. This conclusion is based on: (1) the difference between ^{226}Ra activity concentrations measured in surface waters of Magela Creek upstream and downstream of the Ranger uranium mine is very small; and (2) the findings from previously reported research show that mussel ^{226}Ra activities in Mudginberri Billabong are due to natural catchment sources rather than mining influences.

4.2 Early detection monitoring in Gulungul Creek

4.2.1 Chemical and physical monitoring

Gulungul Creek flows along the western boundary of the Ranger Project Area (Figure 3). ERA does not actively discharge mine waters into Gulungul Creek; however, the creek does receive passive surface runoff and shallow groundwater flows from the mine site. This contribution of mine water has led to variable water quality in Gulungul Creek over the years (Figure 16). EC measured at the upstream control site (GCNUS) and the downstream compliance site (GCLB) was similar to that measured in those

previous wet seasons uninfluenced by contaminated mine water associated with Corridor Creek Land Application Area and Gulungul Creek Tributary 2. (These minewater influences, evident between 2013 and 2016 in Figure 16, are discussed in Sections 4.2.1.1 and 4.2.1.2 below.)

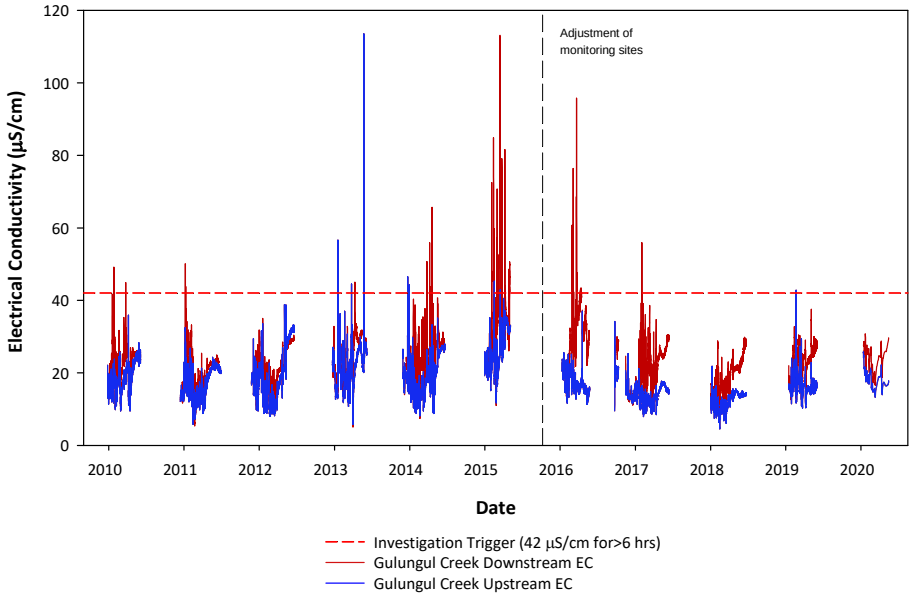


Figure 16 Gulungul Creek electrical conductivity (EC) data measured during the wet season 2010-2020

Throughout the 2019-20 wet season, the EC in Gulungul Creek remained below the Investigation Trigger value (Figure 17 Gulungul Creek electrical conductivity (EC) and water level (stage) data measured during the 2019-20 wet season at Gulungul Upstream (GCNUS) and Gulungul Downstream (GCLB)

This is a result of greater active management by ERA of water inputs to Gulungul Creek over recent years. SSB continues to undertake additional monitoring to better delineate the source and improve understanding of the general behaviour of solutes in the upper Gulungul catchment.

Compliance with the ^{226}Ra Limit of 3 mBq/L is assessed by calculating the difference in the geometric mean of ^{226}Ra concentrations measured at the Gulungul upstream and downstream sites for the entire season. ^{226}Ra samples collected during 2019-20 wet season were within historical ranges and the geometric mean difference for the entire wet season was below the limit trigger value (Figure 18).

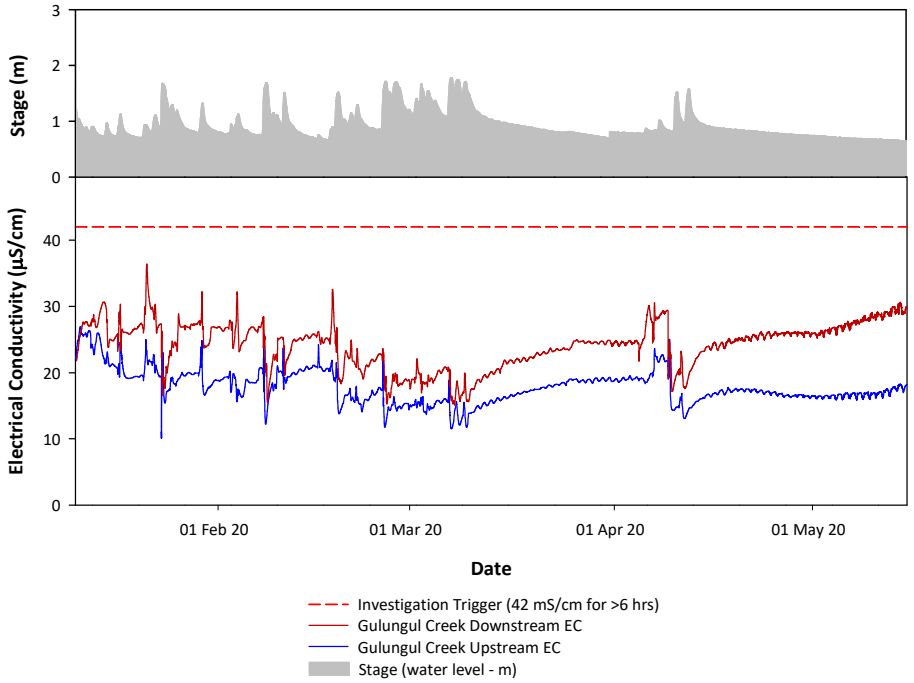


Figure 17 Gulungul Creek electrical conductivity (EC) and water level (stage) data measured during the 2019-20 wet season at Gulungul Upstream (GCNUS) and Gulungul Downstream (GCLB)

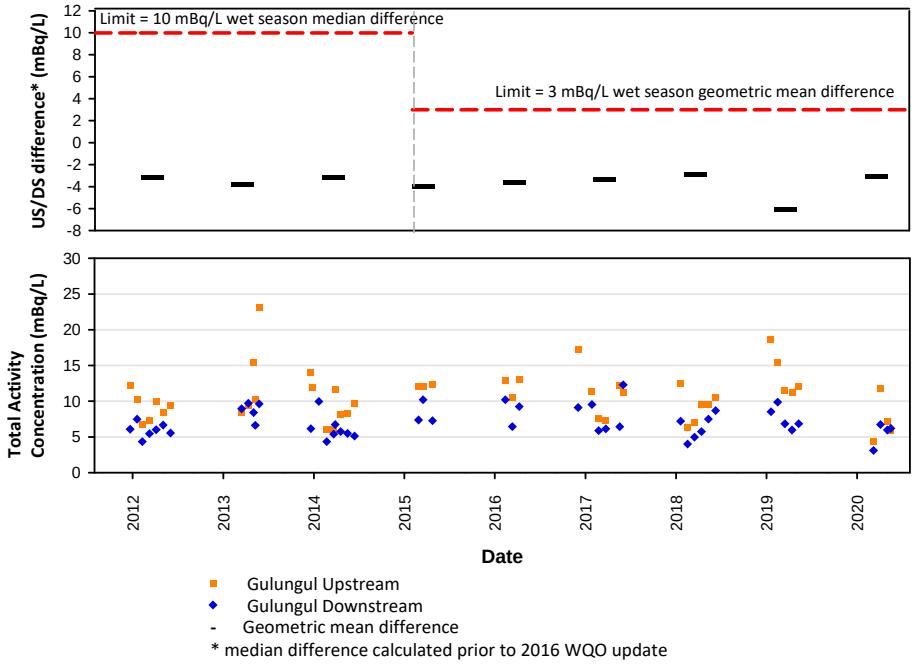


Figure 18 Gulungul Creek ^{226}Ra measured during 2012-2020 wet seasons.

4.2.1.1 Upper Gulungul Catchment Investigation

Since the 2012-13 wet season water quality measured at the original Gulungul Creek upstream control site, GCUS, has deteriorated. A number of high EC events were observed in the 2012-13 wet season (see above, Figure 16), and since that time there was a gradual elevation in the baseline EC measured at the site. Investigations conducted by ERA concluded that the elevated EC was due to irrigation activities in the Corridor Creek Land Application Area (CCLAA).

Figure 19 compares the EC measured at GCUS and at the new upstream control site, GCNUS, for the 2019-20 wet season. The data show that the EC at GCUS continues to be elevated compared to GCNUS, indicating ongoing input of solutes between the two sites. Data from continuous monitoring loggers deployed in the upper Gulungul Creek tributary (GCTS) to detect and track changes in the solute plume originating from the CCLAA show that EC remains elevated at groundwater seepage points to the south of the CCLAA.

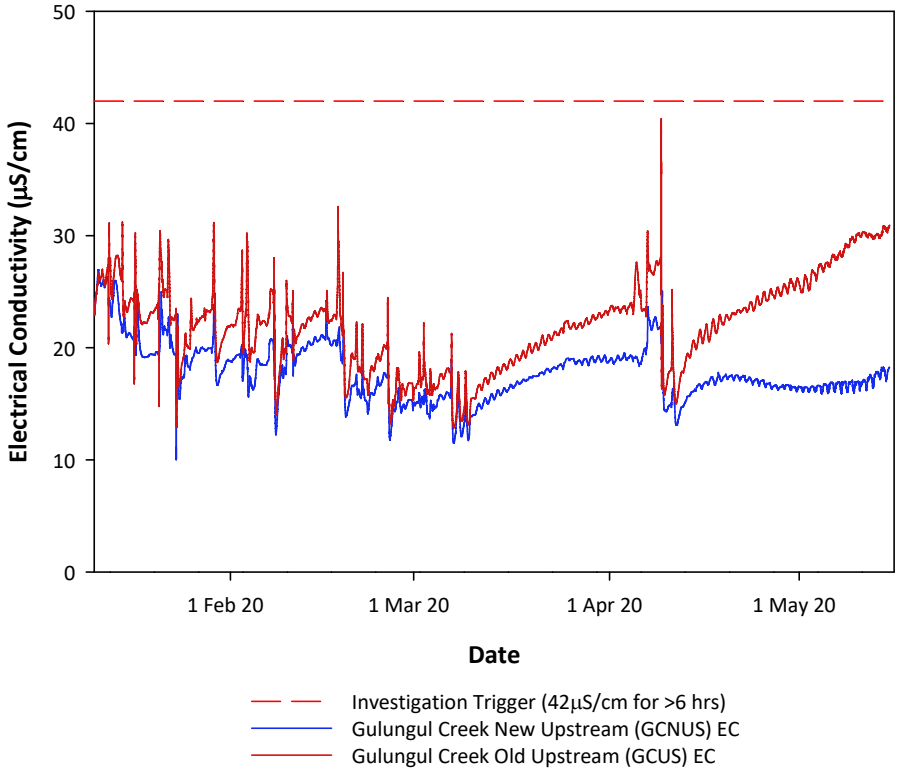


Figure 19 Comparison of EC values measured in Gulungul Creek upstream of the mine, at the original control site (old upstream) and the current control site (new upstream), during the 2019-20 wet season

4.2.1.2 Gulungul Creek Tributary 2 Investigation

A significant amount of work has been undertaken by ERA to manage surface and shallow groundwater to the west of the TSF. This includes the installation of a seepage interception and extraction system comprising an interception trench adjacent to the north-western wall of the TSF and downstream dewatering bores. The system collects shallow groundwater and surface water and transfers it to the pond water system for treatment.

SSB continues to monitor the EC of surface water in the GCT2 tributary at a site called GCT2 Radon Springs Track (GCT2RST), which is located downstream of the interception system and the dewatering bores. The average EC of the base flow in the GCT2 tributary has maintained a downwards trend since mitigation measures were put in place in 2014 (Figure 20). The SSB will continue to measure the EC at GCT2RST which will enable ongoing tracking of the effectiveness of mitigation.

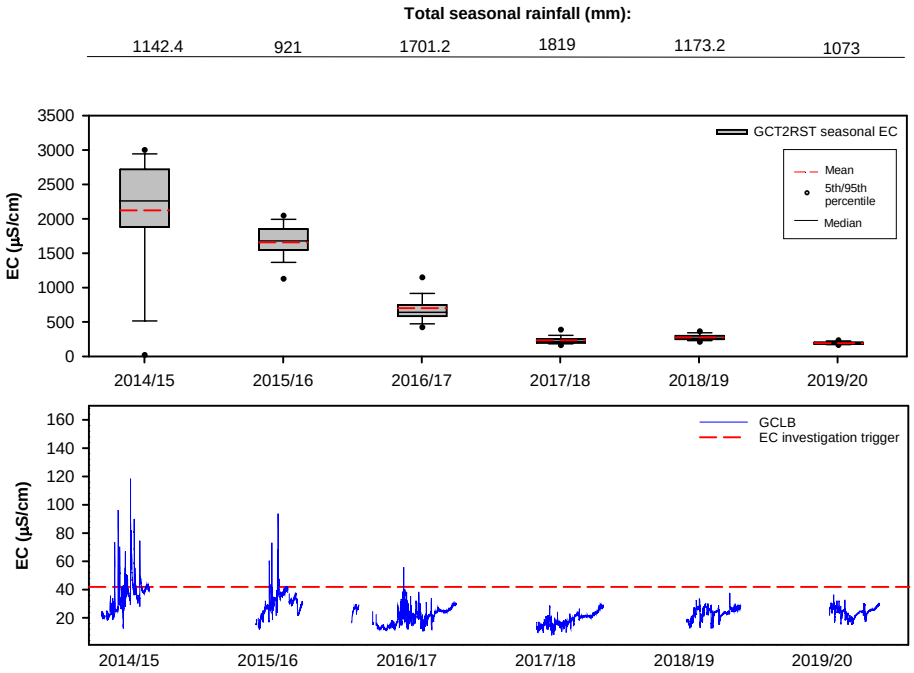


Figure 20. Electrical conductivity measured within Gulungul Creek Tributary 2 (GCT2RST) (top) and Gulungul Creek downstream compliance site (GCLB), and total seasonal rainfall.

(Note for box plot in upper figure: the lower and upper boundaries of the boxes indicate the 25th and 75th percentiles respectively, the black line indicates the median and the dashed red line represents the mean. The lower and upper whiskers represent the minimum and maximum concentration respectively and the dots represent the 5th and 95th percentile).

4.2.2 Biological monitoring

4.2.2.1 Toxicity monitoring

Since 2009–10, toxicity monitoring using the freshwater snail reproduction response has been conducted at the Gulungul Creek upstream (GCUS) and downstream (GCDS) sites. A midstream site (GCLB) was included from 2015 to detect effects arising from contaminated surface water in the GCT2 tributary (see 'Gulungul Creek Tributary 2 Investigation' above). Six in situ toxicity tests were conducted in Gulungul Creek spanning the period 31 January 2020 to 20 April 2020 (Figure 21 and Figure 22). Testing commenced later than usual because of the late onset of rains and subsequent flow in Gulungul Creek.

Results for the 2019–20 wet season are consistent with those reported in previous years where egg production is typically greater at the monitoring sites downstream of Ranger. Confirming this consistent pattern, ANOVA testing showed that snail egg difference values between the routine GCUS and either GCDS or GCLB sites were not significantly different for the 2019–20 wet season compared to all previous wet seasons.

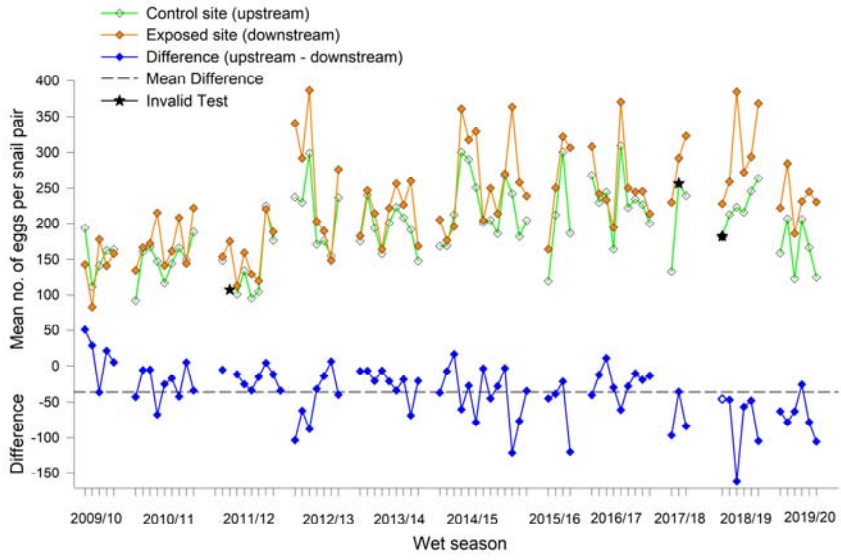


Figure 21 Time series of in situ snail egg production data from toxicity monitoring tests conducted in Gulungul Creek.

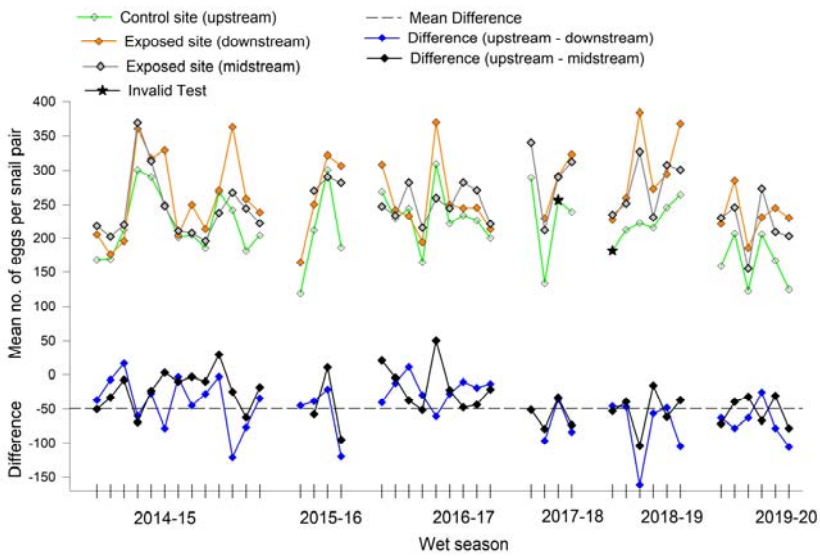


Figure 22 Time series of in situ snail egg production data from toxicity monitoring tests conducted in Gulungul Creek since 2015.

4.3 Ecosystem monitoring

4.3.1 Macroinvertebrate communities

During the recessional flow period of the 2019-20 wet season, macroinvertebrate communities were sampled in 'exposed' streams; Magela and Gulungul Creeks at sites upstream and downstream of the mine, and at the same paired site configuration in control sites, Burdulba and Nourlangie Creeks. In 2015 and thereafter, an additional site located downstream of the GCT2 confluence with Gulungul Creek (GCT2GCC), was included in the annual sampling regime. This additional site was established in response to the discharge of contaminated water from GCT2 tributary to Gulungul Creek, downstream of the confluence, during the 2014–15 wet season.

Details of the statistical methods undertaken on the annual data were last described in the Supervising Scientist Annual Report for 2014-15 (pp. 44–49) and are not repeated here.

In last year's Annual Technical Report the complete 2018-19 recessional flow data set (i.e. including control sites in Nourlangie and Burdulba creeks) was available for reporting, but only as preliminary data that had not been quality assessed. (Usually Nourlangie and Burdulba creek samples are not processed in time for mid-year annual reporting.) The quality assessment process has been completed but as there is no significant change to the data reported on in 2019, there is no need to report the full results from last year (2019).

4.3.1.1 Results for Magela and Gulungul Creeks 2019-20 wet season

At the time of preparation of this report only samples from Magela and Gulungul creeks from the 2019-20 wet season were available for analysis. Without comparable data from the two control streams, it was not possible to run the full ANOVA testing for the 2019-20 wet season. Instead, a modified ANOVA model was used to examine the exposed creeks, Magela and Gulungul, to determine if any change in these streams has occurred over time (Figure 23). The ANOVA showed no significant change from the before (pre 2020) to the after (2020) periods in the magnitude of upstream-downstream dissimilarity across both 'exposed' streams (BA), however, the BA*Stream interaction for the same before-after comparison is significant ($p=0.035$). A distinct lowering of dissimilarity for the Gulungul upstream-downstream pairing shown in Figure 23 for the current wet season is likely to account for this significant BA*Stream result, suggesting that the macroinvertebrate communities for the current wet season are more similar to each other than historically recorded. A slight increase in Magela Creek's dissimilarity for 2020 may have further compound this result (Figure 25).

The same modified ANOVA run with GCT2GCC as the downstream site for the Gulungul Creek upstream-downstream pairing returned the same non-significant result for BA and a significant result for BA*Stream ($p= 0.019$). Although, the current year's dissimilarity value is comparable to those previously observed for the upstream-downstream pairings (Figure 23), further analysis using permutational multivariate analysis of variance testing (PERMANOVA) and MDS ordination were applied to determine possible underlying causes for this significant difference.

PERMANOVA testing on the individual sites (compared to paired-sites dissimilarities for the above ANOVA) has the distinct advantage of detecting whether change is associated with the downstream 'exposed' site and therefore a possible mine related impact. PERMANOVA analysis for the current year's mid-year reporting showed no significant difference between the downstream data (including GCT2GCC) from 2020 with downstream data from previous years, and no significant difference between the upstream data from 2020 with upstream data from previous years. This non-significant PERMANOVA result indicates that the significant BA*Stream interactions detected in ANOVA were a result of changes to both the upstream and downstream macroinvertebrate communities away from those observed in previous years. This outcome indicates that changes in community structure are caused by natural variation through time and are not attributed to a mine related impact.

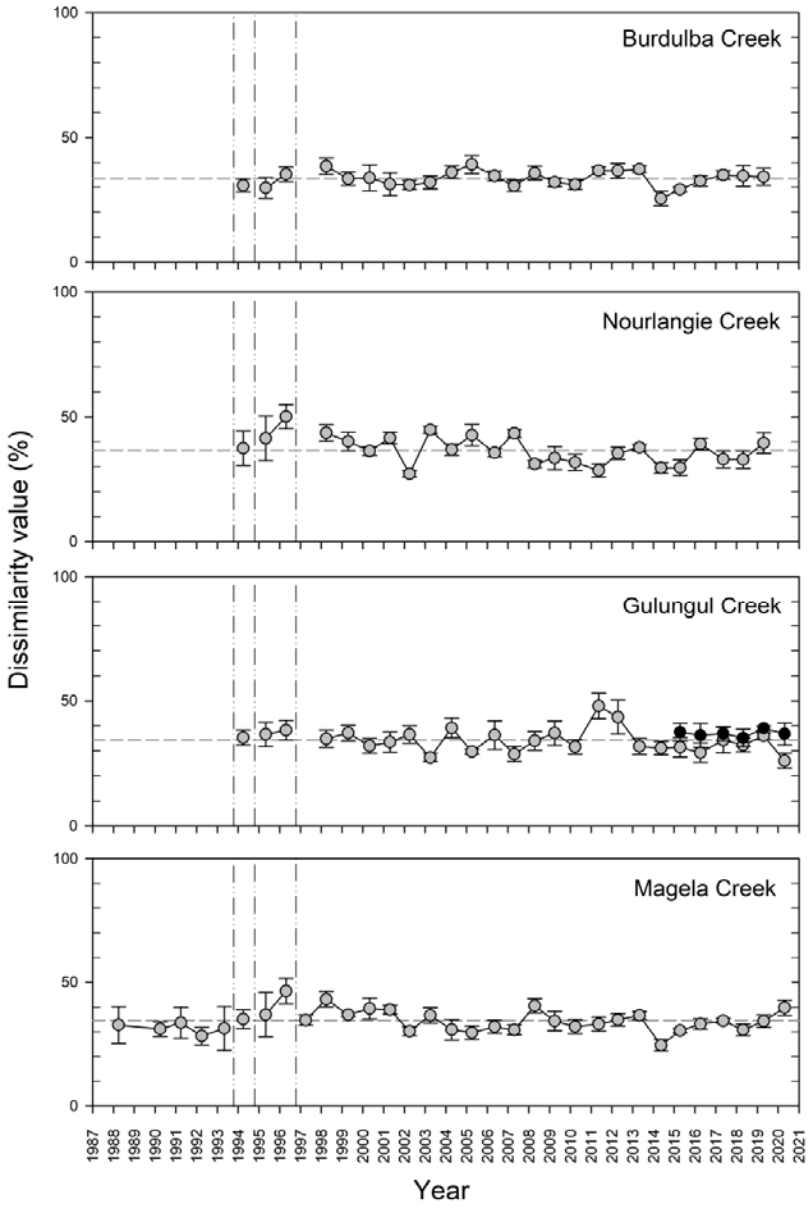


Figure 23 Paired upstream-downstream Bray-Curtis dissimilarity values using family-level (log transformed) data for macroinvertebrate community structure.
Black symbols represent the upstream Gulungul-GCT2GCC stream pairwise comparison. Dashed vertical lines delineate periods for which a different sampling and/or sampling processing method was used. Dashed horizontal lines indicate mean dissimilarity across years. Dissimilarity values represent means (± standard error) of the 5 possible (randomly-selected) pairwise comparisons of upstream-downstream replicate samples within each stream.

Figure 24 shows the multivariate ordination using replicate within-site macroinvertebrate data for Magela and Gulungul creeks sampled downstream (including GCT2GCC) of Ranger mine for each year of study (to 2020), relative to Magela and Gulungul upstream (control) sites for 2020, and all other control sites sampled prior to 2019 (previous years Magela and Gulungul sites, all sites in Burdulba and Nourlangie). Data points associated with the 2020 Gulungul and Magela downstream sites (including GCT2GCC) are generally interspersed among the points representing the control sites, indicating that these 'exposed' sites have macroinvertebrate communities that are similar to those occurring at control sites. An exception to this pattern is seen in the bottom right hand corner of the graph where a single replicate from GCT2GCC has separated slightly from the main cluster (Figure 24). This replicate was collected from a location of lower flow and dense macrophyte cover relative to other replicates, and was previously reported as an outlier in ordination space in 2015 and 2019. In all three-mentioned wet seasons, a macroinvertebrate community dominated by taxa characteristic of low flow (compared to other site replicates) was driving this separation, and based on this the observation cannot be attributed to a mine related influence.

No high-EC events were recorded at GCT2GCC for the 2019-20 wet season, continuing a pattern of improved water quality conditions in Gulungul Creek for recent years (Figure 16). GCT2GCC dissimilarity values for 2020 have remained similar to those seen in previous wet seasons (Figure 23) and are comparable to those recorded for control streams in previous year, reflecting the improved water quality.

Collectively, these graphical and statistical results provide good interim evidence that changes to water quality downstream of Ranger Mine as a consequence of mining during the period 1994 to 2020 have not adversely affected macroinvertebrate communities.

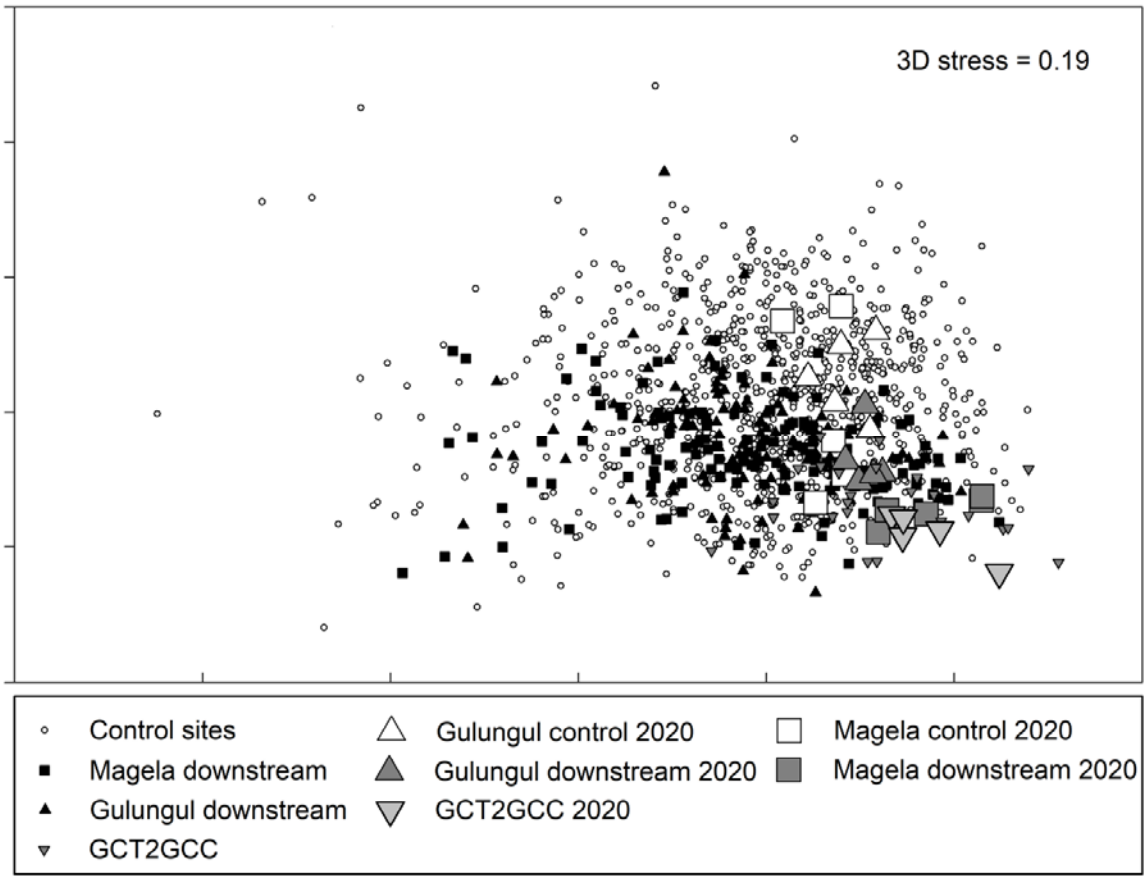


Figure 24 Ordination plot (axis 1 and 2) of macroinvertebrate community structure

4.3.2 Fish communities

Fish communities in shallow lowland billabongs are traditionally assessed for mining-related impacts every two years. The increased risk of crocodile attack led to a reassessment of the risk associated with the 'pop-netting' sampling methodology used for this program. As a result of this review pop-netting has ceased and a research project commenced to develop alternative methods for assessing fish communities in shallow billabongs (see progress in RES-2019-005 Appendix 2).

Fish communities in deep channel billabongs are assessed for impacts annually. Changes in data collection methodology from visual observations to videography commenced in 2016 due to crocodile safety concerns. Historically, SSB has compared (i) multivariate dissimilarity between fish community structures in Mudginberri Billabong (directly exposed site downstream of Ranger in Magela Creek catchment) and Sandy Billabong (control site in Nourlangie Creek catchment, Figure 4), and (ii) rainbowfish abundance in the same two billabongs.

Annual mean paired-site dissimilarity for 2020 (Figure 25) is within the range of dissimilarity reported in all previous years although a research project that has been underway since 2016 is determining the degree of comparability in this metric between the earlier and new monitoring approaches. For now, and until results from this comparative study have been analysed and assessed, all statistical tests for change detection consider just the record of videography data collection between 2016 and 2020.

The fish community structure data for the 2016 and 2020 period have been analysed using a nested three-factor PERMANOVA model, with Before/After (BA), Year (nested within BA) and Exposure (Ex) as factors[1]. In this model, BA tests whether data for the year of interest (2020) are consistent with the range of values reported in previous years (2016 to 2019), the 'Year' factor tests for differences amongst years within the before or after periods, while the exposure factor partitions the control and impact billabongs.

In PERMANOVA, the BA*Ex interaction is the important source of variation to interpret for impact detections. The PERMANOVA results for 2020 show no significant difference between 2020 and previous years (2016 to 2019) using videography method for fish community characterisation. This indicates the relationship between Mudginberri and Sandy Billabong fish communities has remained consistent with relationships observed in these previous years, indicating no mine-related changes.

The 2020 results also indicated there were similar numbers of rainbowfish in Mudginberri Billabong compared to Sandy Billabong, with average maximum number of fish in the imagery frame ("MaxN") of 0.8 and 1.2 for the billabongs respectively (Figure 26). In a year with below average rainfall, greater numbers could have been expected at Mudginberri Billabong due to the natural relationship previously reported (see 2008-09 Supervising Scientist Annual Report for discussion of possible causes), i.e. a negative correlation between rainbowfish abundance in Mudginberri Billabong and the magnitude of antecedent wet season discharge in Magela Creek. This natural relationship was evident in the four previous years for which videography has been adopted for this monitoring program, but not for 2020 (Figure 26). The two consecutive years with below average rainfall, 2019 and 2020, may have reduced recruitment because of the smaller population pool in upper reaches of the catchment as well as the smaller breeding population of these relatively short-lived fishes in the catchment overall.

[1] Full details provided in Appendix 1 of:
Supervising Scientist Division 2011. Environmental monitoring protocols to assess potential impacts from Ranger minesite on aquatic ecosystems: Fish community structure in channel billabongs. Internal Report 590, September, Supervising Scientist, Darwin

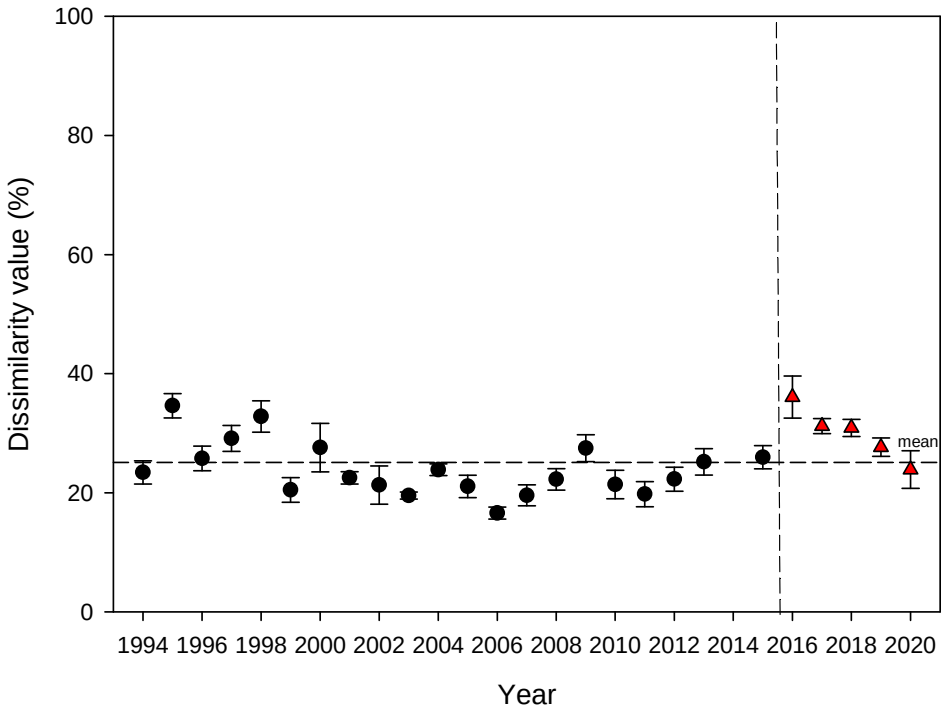


Figure 25 Paired control-exposed dissimilarity values for fish community structure in channel billabongs.

Dissimilarity values calculated using the Bray-Curtis measure, for community structure of fish in Mudginberri ('exposed') and Sandy ('control') Billabongs. Values are means (± standard error) of the 5 possible (randomly-selected) pairwise comparisons of transect data between the two waterbodies. Data prior to and including 2015, were collected using visual observations (left of the vertical dashed line), while data post 2015 were collected using videography (right of the vertical dashed line, denoted by the red triangle).

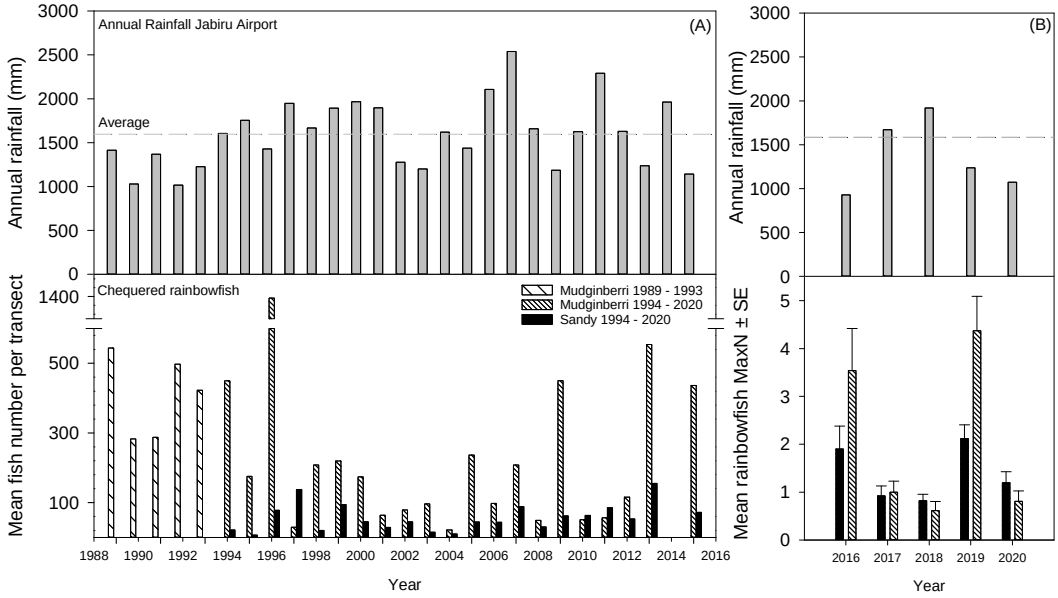


Figure 26 Relative abundance of chequered rainbowfish in Mudginberri and Sandy Billabongs in relation to antecedent annual wet season rainfall recorded at Jabiru Airport: (A) results from 1989 to 2015 using visual observations; (B) results for mean abundance (MaxN) from 2016 to 2020 using videography.

Plate 6 View from Ubirr Rock, Kakadu National Park

5. RESEARCH

Introduction

The Environmental Research Institute of the Supervising Scientist (ERISS) within SSB provides specialist technical advice to the Supervising Scientist on the protection of people and the environment of the ARR from the effects of uranium mining. Its major function is to conduct research into developing standards and leading practice methodologies for monitoring and assessing the environmental impact of uranium mining in the ARR. The research program is now primarily focussed on decommissioning and post-rehabilitation phases of mining at Ranger, with mining operations scheduled to cease by the beginning of 2021.

Identified through an ecological risk assessment, the Ranger Key Knowledge Needs (KKNs) provide the basis upon which SSB and ERA determine their environmental research programs. There is a total of 33 KKNs, divided into five rehabilitation themes (i.e. landform; water and sediment; health impacts of radiation and contaminants; ecosystem restoration; and cross-themes) and each KKN has one or more associated components/questions (total of 119 questions).

The KKNs (www.environment.gov.au/science/supervising-scientist/publications/ssr/key-knowledge-needs) 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 the Ranger Minesite Technical Committee

(MTC) and ARRTC, has been developed to ensure that any changes to the KKNs are undertaken in consultation with all relevant stakeholders.

Responsibility for undertaking research projects to address each of the KKNs has been allocated to ERA and/or SSB, according to available expertise/resources and relevant accountability within the respective organisations. Each KKN (and associated projects) has also been prioritised according to when the information is needed during the Ranger rehabilitation process, as outlined in ERA's current annual Mine Closure Plan (www.energyres.com.au/sustainability/closureplan/). Key milestones in ERA's rehabilitation schedule include submission of applications for regulatory approval of a) Pit 3 Backfill (October 2020) and b) Final Landform (May 2022).

A joint list of over 200 projects has been developed by SSB and ERA, and endorsed by ARRTC. This provides assurance to stakeholders that all projects have been adequately identified and planned, so that the information to address each KKN will be generated when it is needed to inform the rehabilitation process. The information outputs of each SSB research project are provided to ERA in the first instance, in the format of a technical report/memo (refer Section 5.2.5 below). Many of the research findings are also published as peer-reviewed scientific papers to provide assurance that the work is undertaken to the highest standard.

5.1 Current SSB 2019-20 research program

5.1.1 Project progress

A total of 126 SSB research projects have been developed to address the KKNs. To date, 55 have been completed (9 during the 2019-20 reporting period), 37 are currently active and 33 are planned to commence in future. The majority of the remaining planned projects are scheduled for completion by the end of 2021-22 in order to meet the Ranger rehabilitation schedule (Figure 27). Projects still active after this period address either specific knowledge informing revegetation establishment and sustainability, or the development of improved methods for monitoring the success of rehabilitation generally.

To ensure that the KKNs for which SSB has responsibility are delivered when they are needed, the progress of each project is closely tracked according to a 'health' scale. Projects are classified as either 'green', 'amber' or 'red', according to whether any project milestones are behind schedule and how soon the project is due to be completed. The health status of current projects is illustrated in Figure 28, which indicates that 81% of research projects are on schedule.

Assessing priorities and ways of achieving efficiencies are ongoing activities. As part of this, emphasis continues to be placed on working with external consultants and collaborators to achieve research outcomes. Over one quarter (33) of the currently active or proposed projects involve external contracts and/or significant external

collaboration with other research organisations. We will continue to look for such collaborative opportunities where they align with our strategic research priorities.

Figure 27 Number of SSB research projects planned to be active each financial year until 2025-26

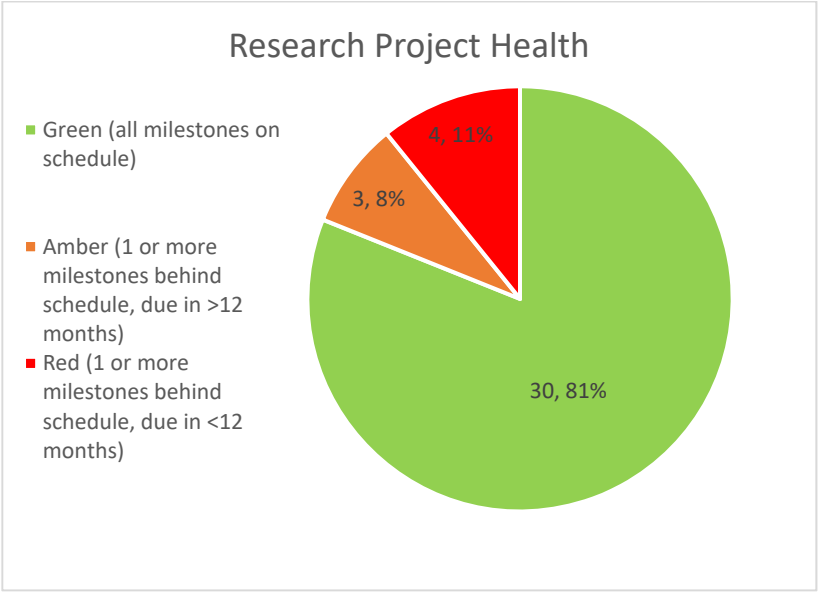


Figure 28 SSB research project health (data labels: number of projects, % of total projects), June 2020

5.1.2 KKN completions

As research projects are completed and the required knowledge is obtained the relevant KKNs and their associated component questions are being progressively closed out. During the 2019-20 reporting period, 13 KKN component questions were closed-out/removed and there are currently 17 being finalised by SSB and ERA for close-out/removal during the remainder of 2020. There is a strong emphasis on completing projects and associated KKNs needed to finalise closure criteria. In particular, and as a priority, KKNs need to be completed for the Water and Sediment Quality rehabilitation theme since these inform the design and assessment of ERA's application for the closure of Pit 3, which is scheduled for submission in late 2020.

5.1.3 Rehabilitation standards

The rehabilitation standards that are being developed represent the Supervising Scientist's view of what is required to achieve the environmental objectives detailed in the Ranger Environmental Requirements. They enable clear visibility of the science underpinning each Standard and provide a scientifically robust basis for decisions. The majority of the Standards were published on SSB's website in September 2018 – see Table 18.

TABLE 18 REHABILITATION STANDARDS

Closure theme	Rehabilitation standard
Water and sediment	Magnesium (surface water)
	Uranium and Manganese (surface water)
	Ammonia (surface water)
	Sulfate – acid sulphate soils (surface water)
	Other metals (surface water)
Landform	Landform – stability and erosion
Ecosystem restoration	Ecosystem restoration (flora, fauna, ecological processes)
Radiation	Environmental Radiation Protection
	Public Radiation Protection

Since 2018, revisions and drafting have been underway for a number of the Standards. The most significant amongst these include:

- Other metals (surface water): These metals occur in tailings and brine and while they have been managed onsite throughout mining operations (through the strict containment of pond and process water), they may present risks to receiving waters in the long-term (post-closure). From a suite of candidate

metals elevated in concentration in process waters, i.e. Al, Cr, Cd, Cu, Fe, Pb, V and Zn, further screening was undertaken to:

  - Determine which of these metals would have relatively high concentrations (i.e. close to their national default GV or reference-site (background) concentrations) if magnesium was at its guideline value. This was calculated using the ratio of Mg to metals in process water;
  - Of the metals remaining after the previous step, which metals were bioavailable (using speciation modelling) for Magela Creek water quality conditions.
  - This left Cu and Zn as metals requiring guideline values. National Default Guideline Values will be used in the interim, while site specific values are determined.

- A Turbidity and sedimentation Standard for aquatic ecosystem protection is being developed. It will apply the following guidance: (i) sedimentation rates in both on-site and off-site billabongs not to exceed natural background deposition rates; and (ii) (and in agreement with ERA) no mine-related, statistically significant increase in turbidity in Magela and Gulungul creeks.
- The current Ecosystem restoration Standard identified a number of attributes for the achievement of long-term sustainability of the restored ecosystem on the rehabilitated Ranger site and its degree of similarity to the surrounding areas. Metrics applicable to closure criteria for vegetation similarity have recently been drafted (March 2020). Metrics applicable to vegetation sustainability and all aspects of fauna have yet to be considered.

5.1.4 NESP projects

Three projects related to Ranger rehabilitation have been included in the National Environmental Science Program (NESP) Northern Australia Environmental Resources (NAER) Hub's version 4 research plan that commenced in 2018. The projects and current status are:

1. *Ecohydrology and sensitivity of riparian vegetation* (Water and Sediment closure theme) – The project is designed to fill knowledge gaps relating to the potential groundwater dependence of riparian ecosystems within the Ranger Mine site area, and to quantify risks posed to those ecosystems from surface and groundwater egress of mine-related contaminants. Field work commenced in late 2018 and pot trials to determine possible toxicity of magnesium to riparian tree species commenced in shade-house facilities at CDU in April 2019, while early pot trials had been undertaken at the University of Western Australia (UWA) in 2018 and 2019. Some results for exposure of the seedlings of local riparian tree species to magnesium sulfate have shown species-specific responses. UWA trials showed *Melaleuca viridiflora* was tolerant to high concentrations of $MgSO_4$ (~15,300 mg/L), with foliar concentrations of ions suggesting plants regulate uptake, while in contrast, *Alphitonia excelsa* was sensitive to elevated concentrations of

$MgSO_4$ (~960 mg/L), exhibiting reduced plant vigour and growth. CDU pot trials with seedlings of *Syzygium armstrongii* and *S. forte* and the local endemic *Lophopetalum arnhemicum*, have demonstrated tolerance of these species so far to $MgSO_4$ concentrations up to 7,100 mg/L. This information improves the understanding of the toxicity of $MgSO_4$ as a contaminant of concern and, when combined with contaminant exposure modelling, will enable an estimate of risk to tree species of this region, which needs to be considered for rehabilitation planning.

2. *Rehabilitation of faunal assemblages at Ranger uranium mine* (Ecosystem Restoration closure theme) – This completed project was designed to inform development of criteria that signify the successful recolonisation of fauna at the rehabilitated Ranger uranium mine, and provide information on the performance of different revegetation practices in terms of broader ecosystem restoration. The project focused on sampling of soil fauna (and respective functional groups) from non-mine disturbed and Ranger trial landform survey sites (undertaken in 2018), together with the provision of recommendations on suitable monitoring methods for terrestrial vertebrates. SSB is considering the recommendations from the report arising from this study for development of its ecosystem restoration Standard.
3. *Effects of surface and ground water egress of mining-related solutes on aquatic ecological connectivity, Magela Creek* (Water and Sediment closure theme) – The project is designed to assist SSB in assessing the extent to which water quality criteria relevant to off-site impacts, set for Ranger rehabilitation, are sufficiently protective of organism movements in the creek channels. In particular, the project is investigating the extent to which plumes of magnesium sulfate in Magela Creek arising from Ranger could interfere with the migrations of native fish populations, which need to be able to move between the river, floodplain and escarpment country upstream and downstream of the minesite. The project commenced in November 2018 and to date, fish tracking and imaging technologies have been deployed for two wet seasons (2018/19 and 2019/20) to enumerate and characterise fish migration and residence in Magela Creek both upstream and downstream of the Ranger mine. Where possible, the results will be linked to surface and groundwater solute modelling and additional risk assessments to assess the likely effects of surface and ground water egress on fish migration and to develop future monitoring strategies. Data downloaded from acoustic receivers placed along Magela Creek for the 2018/19 wet season revealed that, despite the poor wet season and intermittent peak flows through Magela Creek, some fish migrated past the mine site from Bowerbird (20 km upstream of Ranger) and into Mudjinberri Billabong (12 km downstream of Ranger) and beyond, with several returning to Bowerbird during recessional flows. Unfortunately, the two poor wet seasons to date

have not allowed an assessment of any possible avoidance of fish past Ranger during times of (permitted) mine water releases.

These projects represent a significant resource investment by NESP that will provide valuable information for SSB and ERA on the Ranger rehabilitation.

5.1.5 SSB Technical advice series

The SSB Technical Advice series was introduced in 2019 to enhance communication of the outcomes of SSB's research and monitoring activities. The intent of the series is to provide ERA and other Ranger mine stakeholders with transparent and succinct advice arising from project work undertaken by SSB. The key information contained in these documents is provided to ERA as soon as it becomes available to meet closure planning schedules.

Technical advice memoranda provided to ERA during the reporting period include:

1. Technical Advice #010: Updated assessment of FLV6.2 landform
2. Technical Advice #011: Water chemistry and biological communities of shallow groundwater in Magela Creek
3. Technical Advice #012: Rn226 monitoring on the trial landform
4. Technical Advice #013: DATA SHARE - Investigation into CCLAA influence on Gulungul Creek

A full list of all Technical Advices that are have been issued (or in draft) to date is provided in Appendix 4.

5.2 Planned SSB 2020-21 research program

SSB conducted an annual Branch-wide project planning day in February 2020 to review available resourcing against projects scheduled to continue or commence in the 2020-21 financial year. A total of 44 research projects scheduled to be active during 2020-21 were reviewed, including the commencement of 13 new projects. Resource constraints have resulted in 5 planned projects being cancelled, in order to focus on projects for which information is higher priority and/or required in a shorter time frame. These were mostly projects allocated to 'method optimisation/development' KKNs, which are of lower priority than projects allocated to KKNs needed to inform closure criteria development and specific rehabilitation activities.

5.3 SSB 2019-20 research highlights

5.3.1 Water and Sediment Quality

The Water and Sediment Quality team is developing, or has developed, Rehabilitation Standards for the key contaminants of potential concern for receiving

waters, including standards for magnesium, uranium, manganese, sulfate, ammonia and other metals. A Rehabilitation Standard for turbidity and sedimentation is also currently being developed. The results of other program work will be used to assess modelled water quality in receiving waters post-mine closure (GCT2 study, mixture toxicity, seasonal sensitivities of creek macroinvertebrates, Magela saturated sands water quality and fauna, fish migration), and cumulative risks to aquatic ecosystems after rehabilitation, and to optimise biological monitoring techniques (genomics, fish videography, snail egg counts).

Active project work undertaken and key research outcomes delivered in the reporting period included:

1. The advancement of Deep Learning techniques has made it possible to automate the identification of fish species from videography. In partnership with Microsoft, a project has been developing an end-to-end cloud-based Artificial Intelligence solution for automating the analysis of videos collected for SSB monitoring activities. To date, an architecture for a Deep Learning model in Microsoft Azure has been developed and is achieving ~80% accuracy for fish identification. Once finalised, the Deep Learning model will be launched publicly on BUVNet and made available for researchers and regulators to train the model to identify species for their region of interest.
2. The assessment of the toxicity of mixtures of COPCs to local freshwater species is close to completion. The project investigated mixtures of COPCs both at their operational limits and also as they occur in representative minesite surface and ground waters. The analysis of the toxicity datasets has been completed for the different water types and results are currently being drafted into a paper and technical memo. The results have shown that single COPC guideline values are adequate predictors of the toxicity of mine-water mixtures and are suitable closure criteria.
3. Data collection for the 'seasonal sensitivity' project is complete. The purpose of this study is to provide assessment of the relative risks of mine waters discharged from Ranger to resident macroinvertebrate assemblages during different phases of stream flow in Magela Creek. Nineteen successful acute toxicity tests with magnesium were conducted on a range of macroinvertebrate taxa throughout the 2018/19 wet season. The targeted macroinvertebrates groups were reported to be sensitive to salts but are difficult to culture in laboratory. Notably, this project will be the first to provide acute toxicity estimates for these potentially at-risk species and determine their relative sensitivity to magnesium. The macroinvertebrate taxa tested varied in their sensitivities, ranging between EC10 of 22 (caenid) to 4,400 (coleopteran) mg/L Mg. Species level identification of the macroinvertebrate assemblage present throughout the hydrograph is close to completion. Once the data compilation is finalized, a full assessment of the results will be undertaken and published in a peer-reviewed journal.

4. A PhD project that was investigating the sensitivity of local freshwater mussels to contaminants of potential concern (COPCs) from the Ranger mine has been completed and the thesis has passed examination. The project developed standardised acute and chronic toxicity test protocols for larval (24-h mortality) and juvenile (14-d growth rate) life stages. Three papers on the response of juvenile mussels to ammonia and magnesium have been published. The toxicity estimates derived from these studies have improved the modelling used to predict the impacts of these contaminants. The information has been used to update the rehabilitation standards for these COPCs and ensures that these culturally important species are protected. A fourth paper about the acute toxicity of uranium to larval life-stages is in draft.

5. A paper that describes a 7-day fish sub-lethal toxicity test has been submitted for publication. This chronic toxicity test protocol measures the growth-rate of larval fish over 7-d and has been demonstrated to be many times more sensitivity than the 96-h acute protocol, which had a mortality endpoint. Importantly, we compared the 7-d test to a 28-d fish growth-rate protocol, and the 7-d test produced comparable toxicity estimates for uranium. Hence, the new protocol will be a cost-effective tool for providing ecologically relevant toxicity estimates for fish. A reference data set for chronic uranium toxicity to the fry larvae has now been established. This new test protocol has also been used to conduct chronic exposures to Mg and Mn. These data will also be included in a relevant publication associated with the protocol.

6. Development of a method for the digitisation of snail egg counting has continued and machine-learning Artificial Intelligence platforms are now being used to automate the counting of snail egg masses. This technique is being used successfully for in situ snail toxicity monitoring and the technique will be adopted in the laboratory whenever snail testing recommences for a particular toxicity project. This will significantly improve efficiencies of laboratory and in situ snail toxicity testing.

7. A DNA library for freshwater macroinvertebrates in the Alligator Rivers Region has commenced. This library will eventually be used as a biomonitoring tool to detect potential mine-related changes to macroinvertebrate communities. The high resolution taxonomy available in DNA technologies provide, potentially, more accurate, efficient and cost-effective approaches over traditional biomonitoring. So far, the DNA of approximately 400 priority mayfly, caddisfly and chironomid samples have been extracted and prepared for shotgun sequencing of their entire mitochondrial genes or single gene sequencing where extracted DNA content is low. Sequencing will commence soon and the database for species examined so far should be completed by July.

8. A paper that contains the re-analysis of data from a mesocosm study conducted in 2002 was recently published. This study has provided additional candidate magnesium guideline values for phytoplankton and zooplankton communities. The results were used in the derivation of the current magnesium rehabilitation standard for surface waters.
9. A PhD project to characterise the chemistry and biota of the shallow saturated subsurface sands of Magela Creek in the dry season is nearing completion. All field work has been completed. Analysis of the data and results are currently being drafted as a thesis (including a number of journal papers), scheduled to be submitted in October 2020. Initial findings indicate the contaminant plume of elevated $MgSO_4$ in an area in the western channel of Magela Creek adjacent to Coonjimba Billabong is associated with changes in microbial community structure. Technical advice (Tech #011) with initial analysis of chemistry and biological data has been provided to ERA.

5.3.2 Ecosystem Restoration and Landform

The Ecosystem Restoration and Landform team has developed Rehabilitation Standards for erosion and containment of tailings in relation to the final landform. Results of landform studies continue to inform construction and performance of the reconstructed landforms at Ranger (viz erosion and modelling refinement). A Standard for ecosystem restoration (vegetation and fauna) has also been developed based on the Society for Ecological Restoration Australasia's '*National standards for the practice of ecological restoration in Australia*'. Our project work has focused on providing the information required in the Ecosystem Restoration Standard including: deriving the conceptual reference ecosystem; narrative statements for similarity and sustainability closure criteria and quantitative metrics supporting these; the approach used to assess achievement of closure criteria; and development of a restoration trajectory. Additional project work has been aimed at determining whether there are environmental correlates (i.e. substrate parameters) that may constrain revegetation efforts using local native species. Cost effective techniques to derive and measure indicators for similarity and sustainability (e.g. species identification and densities, canopy cover, reproductive fruiting and flowering) are being developed at scale using drones.

Active project work undertaken and key research outcomes delivered in the reporting period included:

1. Publication of a journal manuscript on the impact of different surface particle sizes as a parameter in landform evolution modelling. This work informed the effect of particle size as a parameter on model outputs and therefore improves confidence in model outcomes for assessing the design of the final landform.

2. Preparation of a journal paper describing the methods used to calibrate outputs of the CAESAR-Lisflood landform evolution model (LEM) against field measurements and observation from the Ranger trial landform. The paper assesses the degree to which model results for sediment load compare with field measurements over a multi-year period. Final results confirming the degree to which the model can successfully predict the evolution of the final rehabilitated landform will be reported by end of Oct 2020.
3. Submission of a journal manuscript on large historical floods on the East Alligator River over an 8000-year period. As a result of this work, the rainfall associated with the 2007 flood event has been used as data input in the extreme wet rainfall scenario for modelling of the final landform.
4. Collaborative work continues with Professor Bob Wasson (James Cook University) on natural rates of erosion in the Alligator Rivers Region. This work has included: 1) a review of natural sedimentation rates; and 2) natural denudation rates. The denudation rate to be used in the Landform stability Standard has been revised to 0.113±0.033 mm $year^{-1}$, which is about 2.8 times the previously referenced denudation rate. To date this revised denudation rate has not changed landform modelling assessments.
5. Provision of technical advice to ERA on the latest version of the final landform for Corridor Creek under a dry rainfall scenario for 10,000 years. While gullies up to eight metres deep were predicted to form, these were not expected to expose buried tailings. Furthermore, after 10,000 years the denudation rate was predicted to be less than the revised background natural rate. The design of the Corridor Creek catchment landform meets the requirements for landform stability under a dry rainfall scenario.
6. Project work on characterising and quantifying species composition and community structure attributes of the conceptual reference ecosystem is near completion. This work informs the closure criteria related to those attributes that address elements of similarity under the Environmental Requirements. One notable finding is the low occurrence of the Georgetown low open forest in the savanna adjacent to Ranger. Several journal manuscripts have been prepared on the following topics: 1) documentation of, and, the approach taken to quantify, the conceptual reference ecosystem; 2) the reference site selection protocol; and 3) assessment of understorey vegetation diversity in the reference ecosystem to inform restoration. Additionally, Technical Advices have been drafted. The outcomes of this project work are being discussed amongst the stakeholder group.
7. A journal manuscript and Technical Advice are being drafted on SSB's approach to assessing closure criteria related to attributes of similarity for ecosystem restoration. Simulations of what constitutes a pass or fail based

on the SSB assessment approach for attributes has been undertaken as part of this project work and will be shared with stakeholders. This work informs assessment of ecosystem restoration and potentially revegetation planning.

8. Two journal manuscripts have been published that quantify canopy cover in the savanna adjacent to Ranger mine and examine the influence of environmental factors over long-time scales on canopy cover. This project work was undertaken to inform community structure closure criteria and demonstrated that over a 66-year period canopy cover has remained stable and is resilient to short term variations in rainfall and fire activity. A third publication has been submitted that provides a robust distribution of canopy cover values and associated at-scale spatial heterogeneity that can be used to set closure criteria and inform restoration trajectories and monitoring activities for the restored mine site.

9. A project has commenced to operationalise the use of hyperspectral drone data for identification of dominant vegetation species. The key outcomes of this project will be: 1) cost effective, robust and repeatable methods for collecting data on species composition (stem densities); and 2) the ability to scale data to produce more robust metrics for measuring the ecosystem against adjacent natural reference ecosystems. Two journal manuscripts have been prepared based on historical data that aim to characterise spectral signatures of select native and non-native grasses. The hyperspectral sensor has been tested and calibrated to show that it is suited for our purposes.

10. A PhD focussed on drone derived indicators of ecosystem health to guide ecological restoration has commenced. Preliminary drone data (hyperspectral and LiDAR) have been collected and data processing analysis methods are currently being developed. A journal manuscript is being drafted to link drone-derived crown measurements to diameter at breast height (DBH). The outcomes of the PhD will provide a monitoring tool to assess plant health at various stages of ecosystem restoration.

11. Collaborative work has continued with Associate Professor Peter Erskine and his team from the Centre for Mined Land Rehabilitation (CMLR) on projects that inform the Ecosystem Restoration Rehabilitation Standard. Chemical and physical analyses have been conducted on soil samples from SSB reference sites to determine if vegetation in the reference ecosystem is dependent on environmental factors such as water-holding capacity of soils. This work informs whether there are substrate conditions that will constrain revegetation using species from the reference ecosystem.

12. Collaborative work with CSIRO (Dr Anna Richards) and ERA to develop a restoration trajectory for Ranger minesite is nearing completion. This project will deliver a number of outcomes: 1) inform ongoing revegetation monitoring and subsequent adaptive management interventions to ensure

the restored ecosystem remains on an acceptable trajectory; 2) articulate both desirable and undesirable rehabilitation trajectories for Ranger mine based on stakeholder and expert opinion; 3) provide a risk based framework in not meeting ecosystem restoration trajectories; and 4) provide an assessment tool for minesite closure in relation to long term viability of the restored ecosystem.

13. Collaborative work has commenced with John Fulton and Joe Adams from the United States Geological Survey (USGS) to measure river discharge from drones. We have received a Q-CAM radar doppler sensor from the USGS and are currently integrating the sensor and components on a DJI M600 drone. The use of drones will enable more efficient data collection, allowing us to obtain data at spatial extents not previously possible in a time effective manner. Additionally, the method will improve safety during high flow events and allow staff to keep a greater distance from the water, thereby reducing risks associated with flooded waters and crocodiles.
14. Collaborative work has commenced with Microsoft to automate drone data processing and analytics through deep learning and Microsoft Azure. The first work flows are near completion, using drone derived LiDAR to obtain vegetation community structure measures from reference plots. The work flows being developed are important for processing large and complex data obtained from drones at increasing larger spatial scales. Additionally, the use of deep learning algorithms enables transfer of the technology to non-experts. The workflows will be made publicly available.

5.3.4 Radiation

The Radiation team has developed Rehabilitation Standards for radiation protection of the public and the environment based on world's best practice standards for radiation protection. Project work is aimed at assessing the achievement of the Rehabilitation Standards, including modelling and analyses of public radiation exposure pathways and the derivation of parameter values for estimating radiation exposure to wildlife.

Active project work undertaken and key research outcomes delivered in the reporting period included:

1. Publication of a journal article on gamma radiation dose rates from surface waste rock on the Ranger final landform and resultant doses to traditional owners for hypothetical land use. This work informs the public radiation dose assessment for the final landform against the rehabilitation standard and suggests that gamma radiation will be the most important radiation exposure pathway to a person on the landform.
2. Publication of a journal article on radon-222 diffusion length in waste rock on the Ranger final landform. This work enables the radon-222 source

strength and capping capability of waste rock to be determined. For a waste rock thickness of 10 m or more on the surface of the landform, over 99% of the radon-222 originating from buried tailings will be attenuated and the waste rock layer itself will be the primary source of radon-222 exhalation.

3. Publication of a journal article on whole organism concentration ratios of radionuclides in terrestrial vertebrates. Radionuclide uptake in different species of the same general taxonomic group (e.g. mammals, reptiles) was similar. This finding could enable streamlining of future sampling. Overall, the work provided site-specific data to inform the environmental radiation dose assessment for the Ranger final landform against the rehabilitation standard.
4. Re-commencement of radon-222 exhalation flux density measurements on the Ranger trial landform. This work is being undertaken to investigate whether there has been any increase in exhalation flux density since 2014 when measurements were last conducted, and informs the modelling of the radon-222 dose pathway. Results to date indicate no increase in radon-222 exhalation flux density since 2014.
5. Derivation of concentration factors for non-radioactive metals in bush foods. This work informs the derivation of site-specific health-based investigation levels for bush food ingestion pathways for the Ranger final landform following the approach set out in the National Environment Protection Measure for assessment of contaminated sites.
6. Continued collaboration with the Australian National University on a PhD project aimed at developing new radiochemistry methods for measuring actinium-227 and protactinium-231 in environmental samples. The project will provide the first-ever results on the uptake of these radionuclides by fauna and flora and will inform both the public and environmental radiation dose assessments for the Ranger final landform. The results will enhance the accuracy of radiation dose estimates and enable the dose significance of these radionuclides to be determined.
7. Continued participation in the International Atomic Energy Agency (IAEA) technical program on Modelling and Data for Radiological Impact Assessments (MODARIA II) to ensure the research of the Radiation team, which provides the scientific basis for demonstrating achievement of the Rehabilitation Standards, aligns with world's best practice standards for radiation protection of people and the environment.

5.4 Other Activities

Research for other sites within the Supervising Scientist's remit has continued to be scaled back to focus on the research needs for the rehabilitation of Ranger. The

project developing Remotely Piloted Aircraft-based monitoring methods for the Ranger rehabilitation is using the Jabiluka rehabilitated area and, to a lesser extent, the El Sherana radiological containment site in the South Alligator River Valley, as study sites. Surface water loggers are currently deployed at Nabarlek (see section 3.3.1.2).

Appendix 1 Supervising Scientist publications for the period July 2019 to June 2020

Supervising Scientist Research publications

Aughterson RD, Lumpkin, GR, Smith KL & Cairney, JM 2020. Novel complex ceramic oxides, Ln2TiO5 (Ln = La, Sm, Gd, Tb, Dy, Ho, Er, and Yb), for polyphase nuclear waste-forms. *Journal of the American Ceramic Society*, DOI: 10.1111/jace.17318 ISBN: 0002-7820.

Doering C 2019. Public exposure to external gamma radiation on a mine landform covered by low uranium grade waste rock. *Radiation Protection Dosimetry*, DOI: 10.1093/rpd/ncz267.

Doering C 2019. Whole organism concentration ratios of radionuclides and metals in terrestrial vertebrates of an Australian tropical savanna environment. *Journal of Environmental Radioactivity* 207, 7–14, DOI: 10.1016/j.jenvrad.2019.05.016.

Doering C, Akber R, Bollhöfer A & Lu P 2020. Radon-222 diffusion length and exhalation characteristics of uraniferous waste rock and application to mine site remediation in the Australian wet-dry tropics. *Journal of Environmental Radioactivity*, 106186, DOI: 10.1016/j.jenvrad.2020.106186.

Gaw S, Harford A, PettigroveV, Sevicke-Jones G, Manning T, Ataria J, Dafforn K, Leusch F, Moggridge B, Cameron M, Chapman J, Coates G, Colville A, Death C, Hageman K, Hassell K, Hoak M, Gadd J, Jolley D, Karami A, Kotzakoulakis K, Lim R, McRae N, Metzeling L, Mooney T, Myers J, Pearson A, Saaristo M, Sharley D, Stuthe J, Sutherland O, Thomas O, Tremblay L, Wood W, Boxall A, Rudd M & Brooks B 2019. Towards sustainable environmental quality: Priority research questions for the Australasian region of Oceania. *Integrated Environmental Assessment and Management*. 15(6): 917-935. DOI:10.1002/ieam.4180.

Hancock GR, Saynor M.J, Lowry JBC & Erskine WD 2020. How to account for particle size effects in a landscape evolution model when there is a wide range of particle sizes. *Environmental Modelling & Software* Volume 124, 104582.

Kleinhenz LS, Humphrey CL, Mooney TM, Trenfield MA, van Dam RA, Nugegoda D & Harford AJ 2019. Chronic ammonia toxicity to juveniles of two tropical Australian freshwater mussels (*Velesunio* spp.): toxicity test optimization and implications for water quality guideline values. *Environmental Toxicology and Chemistry* 38, 841-851. (DOI: 10.1002/etc.4370).

Kleinhenz LS, Nugegoda D, Trenfield MA, van Dam RA, Humphrey CL, Mooney TJ & Harford AJ 2019. Acute and chronic toxicity of magnesium to the early life stages of two tropical freshwater mussel species. *Ecotoxicology and Environmental Safety* 184: 109638.

Leung KMY, Yeung KWY, You J, Choi K, Zhang X, Smith R, Zhou GJ, Yung MMN, Arias-Barreiro C, An YJ, Burket SR, Dwyer R, Goodkin N, Hii YS, Hoang T, Humphrey C, Iwai CB, Jeong SW, Juhel G, Karami A, Kyriazi-Huber K, Lee KC, Lin BL, Lu B, Martin P, Nillos MG, Oginawati K, Rathnayake IVN, Risjani Y, Shoeb M, Tan CH, Tsuchiya MC, Ankley GT, Boxall ABA, Rudd MA & Brooks BW 2020. Toward Sustainable Environmental Quality: Priority Research Questions for Asia. *Environmental Toxicology & Chemistry* 39, 1485–1505.

Mooney, T.J., McCullough, C.D., Jansen, A., Chandler, L., Douglas, M., Harford, A.J., van Dam, R. and Humphrey, C. 2020. Elevated Magnesium Concentrations Altered Freshwater Assemblage Structures in a Mesocosm Experiment. *Environmental Toxicology and Chemistry*. DOI: 10.1002/etc.4817

Prior LD, Whiteside TG, Williamson, GJ, Bartolo RE & Bowman DMJS 2020. Multi-decadal stability of woody cover in a mesic eucalypt savanna in the Australian monsoon tropics. *Austral Ecology*, 45(5), 621-635. doi: 10.1111/aec.12877

Short J, Page T & Humphrey C 2019. *Caridina biyiga* sp. nov., a new freshwater shrimp (Crustacea: Decapoda: Atyidae) from Leichhardt Springs, Kakadu National Park, Australia, based on morphological and molecular data, with a preliminary illustrated key to Northern Territory Caridina. *Zootaxa* 4694, 1-25. 10.11646/zootaxa.4695.1.1.

van Dam RA, Hogan AC, Harford AJ & Humphrey CL 2019. How specific is site specific? A review and guidance for selecting and evaluating approaches for deriving local water quality benchmarks. *Integrated environmental assessment and management* 15(5): 683-702. DOI:10.1002/ieam.4181.

Whiteside TG, Esparon AJ & Bartolo RE 2020. A semi-automated approach for quantitative mapping of woody cover from historical time series aerial photography and satellite imagery. *Ecological Informatics* 55, 101012.

Supervising Scientist Corporate publications

Supervising Scientist 2018. Annual Technical Report 2018–19, Commonwealth of Australia, Darwin.

Supervising Scientist 2019. Assessment Report of 2019 Ranger Mine Closure Plan Rev #: 1.19.0. Internal Report 659, December 2019, Supervising Scientist, Darwin.

Turner K, Tayler K, Tyrrell J & Leggett A 2019. Revised Ranger Mine Water Quality Objectives for Magela Creek and Gulungul Creek. Internal Report 670, Supervising Scientist, Darwin.

Supervising Scientist publications in train

Chandler L, Harford AJ, Hose GC, Humphrey CL, Chariton A, Greenfield P, Sutcliffe B & Davis J. Saline mine-water alters the structure and function of microbial communities in shallow groundwater below a tropical stream. *Environmental Microbiology.* (in prep)

Harford AJ, Bartolo RE, Dambancher J, Rissik D, Richardson D, Iles M and Humphrey CL. Qualitative Mathematical Models to Support Ecological Risk Assessment for Rehabilitation and Closure of Ranger Uranium Mine, Australia. *Integrated Environmental Assessment and Management.* (in prep)

Hernandez-Santin L, Rudge ML., Bartolo RE, Whiteside TG, Erskine PD. Protocols for reference site selection for mine site ecosystem restoration. *Restoration Ecology.* (in review)

Lowry J, Saynor M, Hancock G & Coulthard T. Calibrating landform evolution model predictions with multi-year observations from a rehabilitated landform. (in prep)

McMaster SA, Humphrey CL, Harford AJ & Noller B. 2020. Uranium Partitioning in Waterbodies Near the Ranger Project Area. *Environmental Chemistry.* (in review)

Nicholson J.D, Hernandez-Santin L, Rudge ML,. Ufer NG, Erskine PD & Bartolo RE. Assessing understorey vegetation diversity of tropical savanna to inform mine site restoration in northern Australia. *Australian Journal of Botany* (in review)

Pease CJ, Trenfield MA, Mooney TJ, van Dam RA, Walker S Tanneberger C & Harford AJ. 2020, Development of a sub-lethal chronic toxicity test for the Northern Trout Gudgeon, *Mogurnda mogurnda*, and application to uranium, magnesium and manganese. *Environmental Toxicology and Chemistry.* (in review)

Smith REW, Boulton AJ, Baldwin DS, Humphrey CL, Butler B & Halse S 2020. *Assessing and managing water quality in temporary waters*. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. CC BY 4.0. Australian and New Zealand Governments and Australian state and territory governments, Canberra, ACT, Australia. (in review)

Richards A, Bartolo R, Loewensteiner D & Warnick A. Rehabilitation trajectories for Ranger mine, Final report. CSIRO, Australia. (in review)

Saynor MJ, Wasson RJ, Erskine WD & Lam D. Holocene Palaeohydrology of the East Alligator River, Northern Australia, for Application to Mine Site Rehabilitation. *Quaternary Science Reviews*. (in review)

Trenfield MA, Pease CJ, Walker SL, Mooney TJ, Tybell L, Humphrey C, van Dam RA & Harford AJ 2020 Standardised chronic toxicity test protocols and culturing methods for a suite of tropical freshwater species. *Australasian Bulletin of Ecotoxicology and Environmental Chemistry*. (in review)

Loewensteiner DA, Bartolo RE, Whiteside TG, Esparon AJ & Humphrey CL 2020 Measuring savanna woody cover at scale to inform ecosystem restoration. *Ecosphere* (in review)

Wilson GDF & Humphrey CL 2020. The species flock *Eophreatoicus* Nicholls, 1926 from Kakadu and Arnhem Land, with a description of a new genus of Amphisopidae (Crustacea : Isopoda : Phreatoicidea). *Zootaxa* (in review)

Appendix 2 Supervising Scientist Branch Research Project Descriptions 2019-20

CONTENTS

WATER AND SEDIMENT QUALITY

Project Title	Predicting uranium accumulation in sediments		
KKN Theme	Water and sediment		
KKN Title	WS3. Predicting transport of contaminants in surface water		
KKN Question	WS3G. To what extent will the interaction of contaminants between sediment and surface water affect their respective qualities?		
Project Status	Active		
Project number	RES-2016-013	**Project commencement date**	01/06/2018
Project duration (months)	11	**Estimated completion date**	01/08/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	Collaboration	**Supporting team(s)**	Barry Noller (University of Queensland)
Resources 2020-21 (person weeks)	0 (scheduled for completion in 2019-20)		

Aims

- To estimate the accumulation of uranium (U) in sediments for various water column concentrations, e.g.in particular, the proposed surface water U rehabilitation standard of 2.8 μg/L (guideline value for surface waters).

Background

Uranium Guideline Uranium Guideline Values (GVs) for water and sediment have been derived separately and have been based on biological responses that were measured in laboratory and field experiments, respectively. The water quality GV of 2.8 μg/L U was based on a Species Sensitivity Distribution of toxicity estimates from 7 local species (van Dam et al. 2017). The interim sediment quality GV was derived from a No Effect Concentration of 94 mg/kg AEM U in a field experiment, where laboratory-spiked sediments were assessed for re-colonisation after being deployed in the field for the duration of a wet-season (Harford et al.

2013). Following rehabilitation, U will enter the aquatic environment from various sources in both particulate bound and dissolved forms. It will partition from the water column to the sediment and vice-versa, depending on environmental conditions. An understanding of the movement of U between the water column and sediments is needed in order to predict if water and sediment GVs will be achieved. This project will involve a desktop review using local and international data to determine the partitioning coefficient of U, which can be used to make predictions regarding the effect of water column U concentrations on sediment concentrations.

Progress against plan

- Water and sediment quality data provided to consultant, Dr Barry Noller, Centre for Mined Land Rehabilitation.
- Consultant has provided a report with indicative results.
- Internal and external reviews have been completed and the model tested with additional water and sediment quality data from Ranger and surrounds.
- A paper has been accepted for publication in *Environmental Chemistry* pending minor changes.

Key findings

- Uranium in sediment modelled as mostly weak acid extractable uranyl-organic complexes (i.e. bioavailable).
- Strong Freundlich isotherm correlation for U water/sediment partitioning was found in the waterbodies sampled.
- Using the sorption isotherm, the weak extractable U in sediment when the water column [U] = 2.8 μg/L was predicted to be 48 ± 20 mg/kg.

Workplan for 2020-21

- N/A – scheduled for completion in 2019-20

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Estimation of the accumulation of uranium (U) in sediments for various water column concentrations.
- Internal Report describing the derivation of sediment U partition fractions from empirical and experimental data

The outcome that this project will achieve is:

- This project provides assurance that the site-specific uranium water quality guideline will not result in an accumulation of U in sediments to a level of concern.

Planned communication activities

The primary communication activities for the project are:

- Report to ARRTC at end of year (Nov 2020) meeting.
- Technical Adivce to ERA and other stakeholders.
- Report to SSB Supervision and Monitoring on any findings that significantly change the rehabilitation standard.

Project publications to date (if applicable)

Harford AJ, Simpson SL, Chariton AA, van Dam RA & Humphrey CL 2013. The toxicity of uranium (U) to sediment biota of Magela Creek backflow billabong environments. In *eriss research summary 2012–2013*. Supervising Scientist Report 205, Supervising Scientist, Darwin NT, 2–7.

Noller B 2018. Review of Water - Sediment partitioning. Consultancy report from Centre For Mine Land Rehabilitation for the Environmental Research Institute of the Supervising Scientist (ERISS),

McMaster SA, Humphrey CL, Harford AJ & Noller B. (in press) Uranium Partitioning in Waterbodies Near the Ranger Project Area. *Environmental Chemistry*

van Dam, R.A, Hogan AC and Harford AJ 2017. Development and implementation of a site-specific water quality limit for uranium in a high conservation value ecosystem. *Integrated environmental assessment and management* 13(4), 765-777.

Project Title	Identification and mapping of Groundwater Dependent Ecosystems (GDEs)		
KKN Theme	Water and Sediment		
KKN Title	WS4. Characterising baseline aquatic biodiversity and ecosystem health		
KKN Question	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?		
Project Status	Complete		
Project number	RES-2018-003	**Project commencement date**	13/12/2019
Project duration (months)	12	**Estimated completion date**	27/04/2020
Lead team	ERL	**Date required**	1/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	WASQ
Resources 2020-21 (person weeks)	N/A – project is complete		

Aims

- To identify and map Groundwater Dependent Ecosystems (GDEs) on the Ranger Project Area to inform studies relating to riparian communities and their potential exposure to contaminants through shallow groundwater;
- To undertake a historical hyper-temporal analysis of remote sensing data to identify potential GDEs; and
- To collect ultra-high resolution and multi-temporal and ground-truth data to validate the GDEs identified through the historical analysis.

Background

The screening level ecological risk assessment for Ranger rehabilitation and closure highlighted the potential risks associated with stressors impacting the receiving environment (aquatic habitats) via the groundwater pathway. Elevated solutes is one such stressor. Groundwater dependent ecosystems (GDEs) were not identified as a specific receptor in the ecological risk assessment, but these habitats are useful

indicators for environmental change as they may show the expression of contaminants from shallow groundwater. It is important to know what GDEs are present on the RPA and where they located so that the risk of their exposure to mine-derived contaminants (such as $MgSO_4$) can be assessed and subsequent advice can be provided on mitigation measures and the success of rehabilitation. The GDEs for the RPA have not been previously identified and mapped at an appropriate scale. Given interactions between surface water and groundwater this is critical information. The National Atlas of Groundwater Dependent Ecosystems presents the current knowledge of GDEs across Australia. The data from this atlas were used in a preliminary mapping exercise along with some satellite data analysis of potential GDEs using late dry season greenness as an indicator. This preliminary exercise demonstrated that a robust method of identifying and mapping GDEs is required. This project is linked to RES-2017-022 (Ecohydrology and sensitivity of riparian flora) with UAV surveys being conducted in conjunction with field surveys undertaken for the ecohydrology project. In addition, Amie Leggett (SSB) completed a Masters project that mapped GDEs within the Magela catchment (as a whole and therefore includes the RPA) using multi-temporal Landsat data.

Progress against plan

- N/A – project is complete

Key findings

- Currently available mapping products can act as a road map to refine our ability to identify and monitor groundwater dependent ecosystems. Combining these mapping products with the results of in-situ field measurements, drone derived health metrics, and magnesium sulfate mapping may provide an effective monitoring toolset.

Workplan for 2020-21

- N/A – project is complete

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Map and spatial coverage of groundwater dependent ecosystems GDEs on the RPA to inform risk assessments of exposure of riparian communities to mine-derived contaminants.
- A tool to assess the need for mitigation measures for GDEs on the RPA
- A greater level of confidence in the assessment of the achievement of closure criteria for ecosystem sustainability.

Planned communication activities

- Key findings published in the Annual Technical Report and reported to ARRTC and ARRAC
- Presentations to key stakeholders on request

Project publications to date (if applicable)

Leggett A 2018. Detecting terrestrial groundwater dependent ecosystems in the wet-dry tropics using time series Landsat data and vegetation dynamics. Master's Thesis. Murdoch University. 42pp.

Project Title	Assess the ecological risks of mine water contaminants in the dry season, subsurface waters of Magela sand channel		
KKN Theme	Water and sediment		
KKN Title	WS4. Characterising baseline aquatic biodiversity and ecosystem health		
KKN Question	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?		
Project Status	Active		
Project number	RES-2016-012	**Project commencement date**	31/03/2017
Project duration (months)	36	**Estimated completion date**	01/10/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	Collaboration	**Supporting team(s)**	Jenny Davis (Charles Darwin University - primary supervisor) Grant Hose (Macquarie University)
Resources 2020-21 (person weeks)	5		

Aims

- To characterise the groundwater communities and associated habitat and water quality in Magela Creek, by:
  - describing the community structure and function of groundwater fauna and environmental conditions (water quality, habitat) in Magela Creek sand channel, and
  - assessing the uniqueness or otherwise of Magela Creek sand channel communities in relation to another creek (Nourlangie) in Kakadu National Park.

- To assess the sensitivity of these communities to contaminants of potential concern arising from Ranger minesite.
- To investigate the implications for ecological functions provided in Magela subsurface sands of elevated contaminants of potential concern arising from Ranger mine site.

Background

Following closure of the Ranger uranium mine in 2026, the rehabilitated site is predicted to become a source of both contaminated surface water runoff and exfiltrating groundwater with elevated electrical conductivity (EC). The major component of the elevated EC will be magnesium sulfate ($MgSO_4$) derived from the waste rock landform and pit capping. Solute egress modelling predicts that within 10 years of closure, groundwater with $MgSO_4$ concentrations greater than the current chronic exposure limit (3 mg/L) will reach Magela Creek and that concentrations above this limit will remain for 10,000 years.

The effects of magnesium on surface water organisms have been well documented by the Supervising Scientist Branch. However, to date, little is known of the groundwater ecology of Magela Creek, nor of the potential impacts of elevated magnesium concentrations and other COPCs on these communities.

During the dry season, and when there are no longer surface waters, there is a reported resident fauna in the dry and moist surface sands of Magela Creek. Through re-wetting experiments, Paltridge et al (1997)[2] observed invertebrates in the top 20 cm of the sands that were a mix of (i) dormant taxa commonly observed in the surface waters and associated benthos, as well as (ii) groundwater (presumably obligate) specialists (i.e. stygofauna). A pilot study was undertaken in 2016 to characterise fauna and water quality in subsurface sands of Magela Creek during the dry season. The results are reported in Chandler et al (2017) These authors also observed stygofauna (i.e. Parabathynellidae and harpacticoid copepods) in samples collected from the top 1.5 m of the saturated sand channel.

Stygofauna are particularly sensitive to groundwater environment disturbance because they are adapted to near steady-state environment conditions and have very narrow spatial distributions (Hose et al 2015). Changes to environmental conditions, such as those predicted to occur in the Magela Creek sand channel after closure could be considered a potential threat to stygofauna.

[2] Paltridge RM, Dostine PL, Humphrey CL & Boulton AJ 1997. Macroinvertebrate recolonization after re-wetting of a tropical seasonally-flowing stream (Magela Creek, Northern Territory, Australia). *Marine and Freshwater Research* 48 (7), 633-645.

Progress against plan

- All field and laboratory work completed.
- Technical memo provided to ERA detailing chemistry data and preliminary biotic findings.
- Publication of results in progress.

Key findings

- Examination of water chemistry data indicates contamination gradient around Coonjimba Billabong reported in 2016 pilot still present between 2017 and 2019.
- Elevated EC, magnesium and sulfate concentrations were recorded at sites adjacent to Coonjimba Billabong, with maximum values recorded in October 2017 (416 μS/cm, 24 mg/L and 160 mg/L, respectively).
- Site near ERA MG001 monitoring and release point showed elevated concentrations of manganese and strontium but uncertain as to whether this is natural variation or due to mine derived contamination.
- Continuous data recorded maximum EC values of 605 μS/cm from a site near Coonjimba Billabong.
- Investigations of fauna samples indicate groundwater taxa (stygofauna) more prevalent during later months of the dry season. Specimens of Syncarida (Parabathynellidae and Bathynellidae), collected in the 2016 pilot study, were recorded from 2018 samples, but were not found in 2017 samples. These are likely to be new species, and specimens have been sent for sequencing to assist in identifications.
- Investigations of the 2017 and 2018 eDNA data indicate microbial (prokaryotic) communities at exposed sites are significantly different to the unexposed sites, and this variation is strongly correlated with the elevated levels of $MgSO_4$ at the exposed sites near Coonjimba Billabong.
- Multi-celled (eukaryotic) communites are also significantly different between the exposed and unexposed sites. However, although variation is correlated to elevated levels of $MgSO_4$ at the exposed sites, other physical variables such as depth to water table (standing water level) may also be influencing the variation seen in the community data. Further analysis is being undertaken to characterise the changes observed in the eukaryotic communities.

Workplan for 2020-21

- Analysis of 2017 and 2018 Eukaryotic sequencing data
- Production of 4 papers/chapters for publication and PhD thesis

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Characterisation of the dry season subsurface faunal communities in Magela Creek sandbed.
- Characterisation of the dry season surface and subsurface water quality in Magela Creek.
- Relationships between environmental variables (including mine-derived COPCs) and biological communities, including fuctional attributes

The outcomes that this project will achieve are:

- An understanding of spatial and temporal patterns in water quality characteristics and biological communities of the shallow groundwater (to 2 m) in Magela Creek
- An improved ability to assess the risk to environmental values in Magela Creek from solute contamination in groundwater discharge from Ranger uranium mine.

Planned communication activities

The primary communication activities for the project are:

- Four journal papers covering different aspects of the project
- Conference presentations at Australian Society Freshwater Sciences, Adelaide 2018 and SETAC, Darwin 2019
- Reports/presentations as necessary to ARRTC and other key stakeholders and research updates to the university involved (CDU)
- A PhD thesis

Project publications to date (if applicable)

Confirmation of Candidature seminar successfully presented in November 2017 as part of PhD assessment requirements.

Chandler L, Tomlinson M & Humphrey C 2017. Water quality and biota in the subsurface sands of Magela Creek – report of a pilot project. Internal Report 626, Supervising Scientist, Darwin NT (this report produced for RES-2016-004, the pilot project which feeds into the current project)

Project Title	The toxicity of U to sediment biota of Gulungul Billabong		
KKN Theme	Water and sediment		
KKN Title	WS5. Determining the impact of contaminated sediments on aquatic biodiversity and ecosystem health		
KKN Question	WS5A. Will contaminants in sediments result in biological impacts, including the effects of acid sulfate sediments?		
Project Status	Active		
Project number	RES-2009-002	**Project commencement date**	01/07/2008
Project duration (months)	131	**Estimated completion date**	30/08/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	Jenny Stauber and Stewart Simpson Centre for Environmental Contaminants Research (CSIRO) Anthony Chariton (Macquarie University)
Resources 2020-21 (person weeks)	2		

Aims

- To derive a site-specific sediment quality guideline value for uranium (U).

Background

This project aims to derive a sediment Guideline Value (GV) for uranium (U) and has been ongoing since 2009. Following an initial site characterisation during the 2008–09 wet season, two pilot studies were conducted during the 2009-10 and 2010-11 wet seasons, respectively. The methods and results of the pilot studies

have been previously reported in Annual Research Summaries (van Dam et al 2010, Harford et al 2011, Harford et al 2012). Briefly, sediments spiked with U were deployed in an un-impacted billabong (Gulungul) for the duration of the wet season. They were retrieved and sub-sampled for the analysis of bacteria (prokaryotes), and micro- and macro-invertebrates (eukaryotes) using a combination of ecogenomic and traditional taxonomic methods.

The analyses showed that benthic macroinvertebrate taxa typically colonising fine silt-clay sediments of backflow billabongs are only likely to be directly impacted by high U contamination. However, all multivariate analyses indicated a compositional change of microinvertebrates (as measured by ecogenomics) across the U concentration range, as well as effects at lower concentrations. Numerous analyses found statistically significant changes across the concentration gradient, with thresholds of change determined between 40–420 mg/kg U.

It was identified in 2017 that the original method of molecular sequencing of the 18S gene was too limiting to be making strong inferences about threshold change detection and to that end, the original sequencing data were bolstered by sequencing a different region of the 18S gene plus the COI gene. Analyses of new data acquired since 2018 have been underway to corroborate or refine the original conclusions. The results will be published in peer-reviewed journals. The results will be used to derive a sediment quality Guideline Value (GV) for U for current operations and closure of the mine. The GV will inform SSB's rehabilitation standard and, potentially, ERA's final closure criterion.

Progress against plan

- All field experiments have been completed.
- Results have been communicated to ERA.
- Write-up of the results was delayed due to competing priorities and the recognition that the original DNA sequencing was too limited.
- Additional sequencing of the 18S and COI gene has been undertaken with data analysis underway and journal publication to be finalised.

Key findings

- A sediment quality guideline for U of 94 mg/kg (AEM) or 115 mg/kg (TRM) was derived and this interim GV has been communicated to ERA. This interim value will be compared that arising from additional sequencing, together with information from other locally-derived lines of evidence.

Workplan for 2020-21

- Completion of genomic dataset analysis and publications.

Planned project outputs and associated outcomes

The primary output for the project is:

- A sediment quality GV for U which can be used as closure criteria for the rehabilitation of on-site billabongs.

The outcome that this project will achieve is:

- The project indicates that U in billabong sediments has a low bioavailability and that the risk of adverse effects is low under natural water quality conditions prevailaing over the seasons.

Planned communication activities

The primary communication activities for the project are:

- Four papers published in peer-reviewed journals.
- Reports in annual research summaries and presentations to key stakeholders such as ERA and ARRTC.

Project publications to date (if applicable)

Sutcliffe B, Chariton AA, Harford AJ, Hose GC, Greenfield P, Stephenson S, Midgley DJ & Paulsen IT 2017. Insights from the genomes of microbes thriving in uranium-enriched sediments. *Microbial Ecology* 75, 970-984.

Sutcliffe B, Chariton AA, Harford AJ, Hose GC, Paul G, Elbourne LD, Oytam Y, Stephenson S, Midgley DJ & Paulsen IT 2017. Effects of uranium concentration on microbial community structure and functional potential. *Environmental Microbiology*. 19(11), 4799.

Harford AJ, van Dam RA, Humphrey CL, Jones DR, Simpson SL, Stauber JL, Gibb KS & Streten-Joyce C 2011. The toxicity of uranium to sediment biota of Magela Creek backflow billabong environments. In eriss research summary 2009–2010. Jones DR & Webb A (eds) Supervising Scientist Report 202, Supervising Scientist, Darwin NT.

Harford AJ, van Dam RA, Humphrey CL, Jones, DR, Simpson SL, Chariton AA, Gibb KS & Stauber, JL 2012. The toxicity of uranium to sediment biota of Magela Creek backflow billabong environments. In eriss research summary 2010–2011 Jones DR & Webb A (eds). Supervising Scientist Report 203, Supervising Scientist, Darwin NT.

Harford AJ, Simpson SL, Chariton AA, van Dam RA & Humphrey CL 2013. The toxicity of uranium (U) to sediment biota of Magela Creek backflow billabong environments. In eriss research summary 2012–2013. Supervising Scientist Report 205, Supervising Scientist, Darwin NT, 2–7.

Project Title	Review of acid sulfate soil knowledge and development of a rehabilitation standard for sulfate		
KKN Theme	Water and sediment		
KKN Title	WS5. Determining the impact of contaminated sediments on aquatic biodiversity and ecosystem health		
KKN Question	WS5A. Will contaminants in sediments result in biological impacts, including the effects of acid sulfate sediments?		
Project Status	Complete		
Project number	RES-2016-010	**Project commencement date**	30/03/2017
Project duration (months)	36	**Estimated completion date**	30/03/2020
Lead team	WASQ	**Date required**	
In-house or outsourced	Collaboration	**Supporting team(s)**	Dr Darren Baldwin, Rivers and Wetlands
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To review and assist with development of SSB's Rehabilitation Standard for sulfate.
- To review ERA's Ranger Acid Sulfate Soils (ASS) investigation reports, SSB's draft dry season Magela Creek (sub-surface) water quality report and long-term water quality datasets for Coonjimba Billabong and Retention Pond 1 (RP1).

Background

There is a need to develop a Rehabilitation Standard for sulfate in the context of ongoing issues associated with 'mine-generated' acid sulfate soils (ASS). A Standard has been developed but requires the review of a specialist ASS expert for completion. Further, there is a need to review ERA's recent studies on ASS in Coonjimba Billabong, where significant acid events have been occurring in the early wet season since 2002, and a recently-completed *Site Wide Acid Sulfate Soil*

Conceptual Model. SSB contracted Dr Darren Baldwin to advice on these ASS matters.

Progress against plan

- N/A – project is complete

Key findings

- The antecedent conditions in Coonjimba Billabong and RP1 leading to acid sulfate events were consistent with the need to maintain the long term sulfate concentrations in surface waters below 10 mg/L. This threshold is consistent with national guidelines.

Workplan for 2020-21

- N/A – project is complete

Planned project outputs and associated outcomes

The primary output for the project is:

- Review of relevant ERA/SSB reports and long-term water quality datasets to develop a Rehabilitation Standard for sulfate.

The outcome that this project will achieve is:

- The knowledge will be used to assess the risk of Acid Sulfate Sediment generation off-site and on-site.

Planned communication activities

The primary communication activities for the project are:

- Rehabilitation standard for sulfate.
- Communicate outcomes and recommendations of consultants' reports to key stakeholders, including ERA.

Project publications to date (if applicable)

Baldwin DS 2017. Understanding acid sulfate soils in Coonjimba Billabong. Prepared for the Supervising Scientist Branch, the Department of Environment and Energy by Rivers and Wetlands, May 2017, 24 pp.

Baldwin DS 2017. Review of Supervising Scientist Branch Rehabilitation Standard for Sulfate. Prepared for the Supervising Scientist Branch, the Department of Environment and Energy by Rivers and Wetlands, June 2017, 8 pp.

Project Title	Toxicity of ammonia and other key contaminants of potential concern to freshwater mussels		
KKN Theme	Water and sediment		
KKN Title	WS6. Determining the impact of nutrients in surface water on aquatic biodiversity and ecosystem health		
KKN Question	WS6A. What is the toxicity of ammonia to local aquatic species, considering varying local conditions (e.g. pH and temperature)?		
Project Status	Complete		
Project number	RES-2015-025	**Project commencement date**	01/09/2015
Project duration (months)	46	**Estimated completion date**	18/12/2019
Lead team	WASQ	**Date required**	01/03/2020
In-house or outsourced	In-house	**Supporting team(s)**	Dayanthi Nugegoda (RMIT)
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To complete the collation and review of available information on freshwater mussel culturing and toxicity testing
- To collect mussels (Velesunio spp.) and develop a culturing method for the species (larvae and juvenile stages).
- To develop standardised acute and chronic test methods for the species.
- To conduct ammonia toxicity testing using the species and publish results.
- To conduct toxicity testing with other COPCs.

Background

An assessment of ammonia toxicity has recently been undertaken in order to develop a site-specific water quality Guideline Value (GV) for the Ranger uranium mine. This GV replaces an interim ammonia GV that was developed using toxicity estimates from international species with adjustments made for site-specific pH and temperature conditions. In a preliminary review of all the Genus Mean

Chronic Values collected by the USEPA (USEPA 2013), *Lampsilis* and *Vilosa* (both genera of freshwater mussel) were the most sensitive to the effects of ammonia. Unionid mussel feeding includes filtration of surface and pore water, suspended sediment, and sediment-associated fine particles, which may increase their exposure to ammonia in their surrounding media (Augspurger et al. 2003). Two species of hyriid freshwater mussels (*Velesunio*) are present downstream of the Ranger uranium mine, and are important bushtucker of the Mudginberri Aboriginal community. Thus, it was identified that ammonia toxicity should be assessed using these species. Toxicity estimates from local mussel species will be incorporated into the the site-specific Species Sensitivity Distribution, allowing for the derivation of a GV and thereby ensuring the protection of freshwater mussels as well as other species. This project is being carried out by PhD student, Linda Kleinhenz (RMIT University), using mainly external funding. The toxicity test protocol will also be used for an assessment of the effects of uranium (U), copper (Cu) and magnesium (Mg) on freshwater mussels.

Progress against plan

- N/A – project complete.

Key findings

- DNA analyses showed that what was thought to be a single mussel species in Magela Creek was actually two different species. Preliminary studies showed (small) differences in sensitivity of the two species to COPCs.
- Local *Velesunio* mussel species were relatively sensitive to acute copper and ammonia exposure. Exposure of larvae to 6 – 7 µg/L copper for 24 h resulted in a 50% reduction in survival (referred to as a Lethal concentration: LC50). Copper was used as a reference toxicant with which to compare to international toxicity data. Larvae were also acutely sensitive to ammonia with a 24-h LC50 of 7 mg/L TAN.
- Larvae were moderately sensitive to magnesium with a 24-h LC50 of 278 mg/L $MgSO_4$. This places this species as the third most sensitive species of SSB's suite of local species to magnesium at a 9:1 Mg:Ca ratio
- The chronic juvenile growth-rate test was less sensitive to ammonia than the acute larvae survival test. It showed a 50% reduction in growth-rate when exposed to ammonia at 7-12 mg/L TAN. Juvenile mussel growth-rates were more sensitive to magnesium than the larvae survival with a 50% reduction in growth-rates observed at 204-227 mg/L $MgSO_4$.

Workplan for 2020-21

- N/A – project complete.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Chronic toxicity estimates for mine-related contaminants: TAN and Mg.
- Acute toxicity estimates: TAN, Mg, Cu and U.
- Standard Operating Protocols for acute and chronic toxicity tests using larvae and juveniles of freshwater mussels, *Velesunio* spp.

The outcomes that this project will achieve are:

- The addition of another local aquatic species that can be used in routine monitoring if necessary, providing better representation across trophic levels.
- Greater reliability of site-specific guidelines generated for key contaminants of concern, through the addition of the mussel species to the suite of test organisms.

Planned communication activities

The primary communication activities for the project are:

- Three journal papers covering different aspects of the project
- Oral presentations at SETAC conferences (2016, 2017 & 2019)
- Contributions to Supervising Scientist Annual Technical Report
- Reports/presentations as necessary to ARRTC and other key stakeholders
- Research updates to the collaborating university (RMIT).

Project publications to date (if applicable)

Kleinhenz LS, Humphrey CL, Mooney TM, Trenfield MA, van Dam RA, Nugegoda D & Harford AJ 2019. Chronic ammonia toxicity to juveniles of two tropical Australian freshwater mussels (Velesunio spp.): toxicity test optimization and implications for water quality guideline values. *Environ Toxicol Chem* 38, 841-851. (DOI: 10.1002/etc.4370).

Kleinhenz LS, Trenfield MA, Mooney TJ, Nugegoda D, Humphrey CL, van Dam RA & Harford AJ 2019. Acute and chronic toxicity of magnesium to the early life stages of two tropical freshwater mussel species. *Ecotox. Environ. Safety*. 184, 109638.

Kleinhenz LS, Trenfield MA, Mooney TJ, Humphrey CL, van Dam RA, Nugegoda D & Harford AJ 2018. Acute ammonia toxicity to the larvae (glochidia) of the tropical Australian freshwater mussel *Velesunio* spp. using a modified toxicity test protocol. *Environmental Toxicology and Chemistry* 37, 2175-2187.

Oral presentations

Kleinhenz L, Nugegoda D, Trenfield MA, Harford AJ & van Dam RA 2019. The freshwater mussel Velesunio spp is a valuable test species for assessing the

acute and chronic toxicity of contaminants in tropical environments. Proceedings of the SETAC Australasia Conference, 7-10 July 2019, Darwin, Australia.

Kleinhenz L, Nugegoda D, Trenfield MA, van Dam RA, Humphrey C & Harford A 2017. Chronic toxicity of ammonia to the tropical freshwater mussel *Velesunio* spp. Proceedings of the SETAC – Australasia Conference, 4-6 September 2017, Gold Coast, Australia.

Kleinhenz L, Nugegoda D, Trenfield MA, Harford AJ & van Dam RA 2016. Development of an acute and chronic toxicity test for the freshwater mussel *Velesunio angasi* and an assessment of ammonia toxicity. Proceedings of the 4th SETAC – Australasia Conference, 4-7 October 2016, Hobart, Australia.

Project Title	Assessing the toxicity of mine water mixtures for operational and closure scenarios		
KKN Theme	Water and sediment		
KKN Title	WS7. Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health		
KKN Question	WS7A. Are current guideline values appropriate given the potential for variability in toxicity due to mixtures, modifying factors and different exposure scenarios?		
Project Status	Active		
Project number	RES-2017-001	**Project commencement date**	01/05/2017
Project duration (months)	24	**Estimated completion date**	30/07/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	1		

Aims

- To assess whether the Guideline Values (GVs) derived from single COPC toxicity testing are still protective for all species when combined together as a mixture in a synthetic water.
- To test whole mine waters to establish the protectiveness of the derived GVs when in natural waters as mixtures.
- If testing indicates that the derived GVs are not protective, to develop the capacity to predict the toxicity of a given mine site water with particular physicochemical conditions using statistical modelling.
- To assess the toxicity of the mixture predicted to emanate to surface waters from the Ranger site post closure.

Background

Much effort has been invested in deriving site-specific water quality guideline values for individual COPCs (such as uranium, manganese, magnesium and ammonia). However, this approach does not consider potential interactive (e.g.

additive, synergistic, antagonistic) effects of toxicant mixtures in mine site waters or other modifying effects that may occur in the field. It is important to ensure that the GVs for the individual COPCs are protective of the aquatic environment when found in a mixture. It is also important, if toxicity is observed in mine-site waters, to be able to predict the toxicity of future waters with particular physiochemical conditions to ensure the protection of the aquatic environment within and surrounding the Ranger Project Area following rehabilitation.

Progress against plan

- Aim 1 of this project is complete. The GVs were protective for all species at the Ca:Mg ratios observed in the creek (5:1 and 9:1). When there is less Ca in the system (28:1) effects were observed at GV concentrations.
- For Aim 2, three site waters were initially selected for testing, TDWW, PJ and RP2. Toxicity testing is complete and an additional shallow seepage water SIS2 was also tested. TDWW was also tested at an adjusted pH (6).
- For Aim 3, advice was obtained from modelling experts (Peter Bayliss, Angus Webb and Joe Myers) on the best approach to analysing the complex data set. It was determined that the body of toxicity data was not large enough to use to build a predictive model. Metal speciation modelling has also been used to ensure we are considering only the predicted bioavailable fractions of each contaminant.
  Aim 4 was not achievable

  given that a predictive model could not be developed with the current dataset. Additive models applied to the data (Concentration Addition and Independent Action) showed that for >90% of the data, the COPCs were antagonistic, i.e. the overall toxicity of the mixture was less than that expected based on the sum of toxicity of individual components. Thus for the majority of the data, application of the individual site-specific GVs would provide adequate protection for local aquatic biota. However, Direct Toxicity Assessments could also be performed if necessary on a simulated water once the predicted composition of the final waters is known from the surface-ground water modelling.

Key findings

- Testing of a COPC mixture at each of the COPCs' guideline value concentrations and at background calcium concentrations (Mg:Ca ratio ~ 28:1) resulted in toxicity to 5 of the 6 freshwater species of the routine laboratory-based monitoring suite. However, the same testing at Mg:Ca ratios of 5:1 and 9:1 resulted in no toxicity of the COPCs at their GV concentrations. Hence, the addition of calcium appears to greatly influence the toxicity of the COPCs, acting most likely and predominantly on Mg, and to varying degrees depending on the species.

- Process water from TDWW with a Mg:Ca ratio of 14:1 was very toxic to all species, with the snail most affected (EC10 = 0.002% strength water) and the duckweed least affected (EC10 = 0.4% strength water).
- Process water from PJ was less toxic than TDWW but with the snail again the most sensitive species (EC10 = 0.01%) and duckweed growth stimulated at up to 1% strength.
- Pond water from RP2 (Mg:Ca = 4:1) was less toxic than the process water (as anticipated) with the most sensitive species being the snail (EC10 = 2%) and the cladoceran (EC10 = 6%).
- Shallow seepage water from SIS2 with a Mg:Ca ratio of 4:1 was most toxic to the snail (EC10 = 1% strength) and the alga (EC10 = 5%).
- Speciation modelling of the waters and the use of Hazard Indices tools show that for the process water, the contaminant that is most bioavailable and of most concern is manganese. For the shallow seepage water this is magnesium.
- Modelling the bioavailability of the metals in these waters shows that a large proportion of Mg (84-95%) and Mn (76-92%) remains bioavailable (is not bound by organic matter in the water). However, for other metals such as U, Cu and Al, the majority of the metal (70-95%) is bound to organic carbon and is not considered to be bioavailable.
- Modelling of the process and shallow seepage water mixture toxicity showed that in most cases, toxicity can be predicted using an additive model such as Concentration Addition, but single metal site-specific guideline values were also good predictors of toxicity. There were only several instances (for the alga and the snail) where those species would be underprotected using such a prediction, where toxicity is greater than that predicted summing the toxicity of individual contaminants. Copper and zinc were also incorporated into these models due to the Hazard Quotients calculated for these metals.
- Further site-specific Cu and Zn toxicity data are being generated as part of a separate project to develop site-specific guidelines for these two additional contaminants.

Workplan for 2020-21

- Draft journal paper has been completed, reviewed by co-authors and submitted. Some time will need to be set aside to implement changes suggested by reviewers.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Additional knowledge regarding the toxicity of Ranger COPCs to local freshwater species when those contaminants occur as mixtures – either in mine waters or simulated mine waters.

- Information to assess the appropriateness of the guideline values for the individual contaminants.
- Verification of data using Direct Toxicity Assessments of various site waters.

The outcome that this project will achieve is:

- Increased confidence in, and justification for, the proposed rehabilitation standards.

Planned communication activities

The primary communication activities for the project are:

- Journal manuscript.
- Conference presentation at SETAC US meeting 2017, SETAC AU 2019 and SETAC North America 2020.
- Internal presentation to Chemicals & Assessment Branch 2018.
- Discussions with key stakeholders as appropriate.
- Progress report presented to ARRTC members (Jenny Stauber and Fran Sheldon) prior to 2019 ARRTC meeting. Subsequent advice incorporated into the project design.

Project publications to date (if applicable)

Trenfield MA, Pease CJ, Walker SL, Humphrey CL, van Dam RA, Markich SJ & Harford AJ 2020. Assessing the chronic toxicity of aquatic contaminant mixtures and validation the protectiveness of individual water quality guideline values. Submitted to *Ecotoxicology and Environmental Safety*.

Project Title	Deriving a candidate Mg guideline value based on a mesocosm study (re-analysis of 2002 PhD data)		
KKN Theme	Water and sediment		
KKN Title	WS7. Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health		
KKN Question	WS7A. Are current guideline values appropriate given the potential for variability in toxicity due to mixtures, modifying factors and different exposure scenarios?		
Project Status	Complete		
Project number	RES-2017-031	**Project commencement date**	01/04/2016
Project duration (months)	39	**Estimated completion date**	01/05/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To assess the toxicity of magnesium (Mg) to aquatic communities (phytoplankton, zooplankton and macroinvertebrates) in Magela Creek by re-analysing data collected from a mesocosm study conducted in 2002.
- To derive candidate GVs from Mg community effects data to incorporate as a line of evidence in the magnesium rehabilitation standard.

Background

Magnesium is a contaminant of concern for the operation and closure of Ranger Mine. A laboratory-based, site-specific guideline value (GV) has been derived. However, to ensure the adequacy of the GV for closure, a weight-of-evidence

approach is being implemented. This evaluation is using additional lines of evidence from field studies of the toxicity of Mg to biota in Magela Creek. Previously, McCullough (2006) reported the results of a mesocosm experiment conducted during the 2002 dry season in the Magela Creek channel upstream of Ranger. Mesocosms were spiked with a range of Mg sulfate concentrations (0-68 mg/L) and left for 2 months. Periodically, the mesocosms were sampled for a range of community biota, including: macroinvertebrates, microinvertebrates, diatoms and phytoplankton communities. Changes to these assemblages were assessed across the range of Mg concentrations.

Given advances in statistical analysis methods and software since 2006, the results require re-analysis, together with publication in a peer reviewed scientific journal.

Progress against plan

- The results of this study have been accepted for publication in Environmental Toxicology and Chemistry.

Key findings

- Results of this work, including recent re-analyses, demonstrated sensitivity after four-week exposure of phytoplankton (algal biomass viz chlorophyll a and green algal abundance) and zooplankton. The 1% effect concentrations (EC1) for algal biomass and community structure response measures for zooplankton were 1.5 and 2.6 mg/L Mg respectively.
- These results have been incoporated with other laboratory and field evidence in a weight of evidence evaluation to derive a Mg standard for Ranger mine-site closure. In 2019, phytoplankton community data gathered from mine and reference waterbodies in 2009 and 2011 were analysed. Some major algal groups were shown to respond strongly (and negatively) to magnesium, supporting the chlorophyll result reported in the mesocosm study.

Workplan for 2020-21

- N/A – project complete

Planned project outputs and associated outcomes

The primary output for the project is:

- Field community-based toxicity estimate(s) for Mg arising from an earlier (2002) mesocosm study

The outcome that this project will achieve is:

- An additional line of evidence for the weight of evidence assessment deriving a magnesium standard for Ranger receiving waters

Planned communication activities

The primary communication activities for the project are:

- Journal manuscript
- Presentations to relevant fora (e.g. ARRTC, SETAC).

Project publications to date (if applicable)

McCullough C 2006. A multi-scale assessment of the ecological risk of magnesium sulphate to aquatic biota of Magela Creek, Northern Territory, Australia. Charles Darwin University, PhD Thesis

Mooney TJ, McCullough C, Jansen A, Chandler L, Harford AJ, Douglas M, van Dam R & Humphrey C. 2020. Elevated magnesium concentrations altered freshwater community structures in a mesocosm. *Environmental Toxicology and Chemistry*. doi.org/10.1002/etc.4817

Project Title	Hazard and risk assessments for potential / emerging water quality contaminants and toxicity modifying factors		
KKN Theme	Water and sediment		
KKN Title	WS7. Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health		
KKN Question	WS7B. What is the risk associated with emerging contaminants?		
Project Status	Active		
Project number	RES-2018-005	**Project commencement date**	01/03/2019
Project duration (months)	34	**Estimated completion date**	30/09/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	2		

Aims

- To conduct a hazard assessment on existing water quality monitoring data and if relevant, modelled water quality data for post-closure scenarios, to:

  i) determine if concentrations of contaminants which have not been assessed and tested for toxicity are increasing/will increase in concentration e.g. K, HCO3 and herbicides.
  ii) determine if toxicity modifying stressors such as temperature and pH have potential to contribute direct or indirect (modifying) toxic effects.

- To identify contaminants or stressors that are high risk and require quantitative assessment.

Background

The project will be phased by way of initial desktop assessment, followed by toxicity assessment should emerging contaminants of potential concern (COPCs) or stressors be deemed sufficiently important to warrant further assessment. The hazard assessment will include ions and toxicity modifying factors currently

measured in surface waters, but also contaminants identified from modelling of future water quality post closure, together with those that may play a role in ecosystem establishment, including herbicides.

Emerging COPCs may be identified through ongoing field investigations. For example, changes in lentic macroinvertebrate communities in Ranger mine site waterbodies (Georgetown Billabong, Coonjimba Billabong and RP1) over time (1979-2013) can predominately be attributed to Mg increase. However, changes in macroinvertebrate responses over this time span were also strongly correlated with potassium, calcium and carbonate. Little is known about the toxicity of potassium and carbonate, and their interaction with other COPCs, to tropical species resident in soft-waters. Thus further investigation may be required to determine how the toxicity of these ions, and other stressors such a pH and temperature, are contributing to the direct and indirect effects on macroinvertebrates observed.

Progress against plan

- Desktop reviews have been completed for all of the issues below:
  - Metals toxicity under conditions of acidification
  - Herbicides
  - Nutrients (nitrate and phosphate)
  - Hydrocarbons
  - Potassium and bicarbonate
  - Increasing temperature as a stressor
  - Sodium as a contaminant in HDS water
  - PFAS
- A draft discussion paper has been produced which compares the risk of the eight issues using a risk matrix with scoring based on the source, pathway, toxicity and persistence of each issue.
- Risk estimates will be agreed within SSB and ERA will be asked to assist with the risk scoring and provide additional details to the hazard assessments.

Key findings

- Nil to report

Workplan for 2020-21

- 2020: Workshop with ERA to discuss the hazard assessments
- 2021: If any laboratory assessment work is deemed necessary based on discussions with ERA a separate project will be initiated to incorporate this.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- An understanding of the potential hazards from emerging contaminants or physical stressors of potential concern in order to prioritise these for further risk assessment.
- Where necessary, provide quantitative assessments and aquatic effects data for any hazards deemed to be of a high enough risk.

The outcome that this project will achieve is:

- Identification of emerging hazards considered to be of most risk to the local aquatic ecosystem.

Planned communication activities

The primary communication activities for the project are:

- Reports to ARRTC and ARRAC
- A journal article if quantitative laboratory assessments of any of the emerging hazards need to be carried out.
- If quantitative effects data are generated, these will be presented either as a poster or an oral presentation at the SETAC Asia Pacific in 2021.

Project publications to date (if applicable)

Nil

Project Title	'Seasonal sensitivity' (to Mg) profile for organisms in the Magela creek channel		
KKN Theme	Water and sediment		
KKN Title	WS7. Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health		
KKN Question	WS7C. Are current guideline values appropriate to protect the key groups of aquatic organisms that have not been represented in laboratory and field toxicity assessments (e.g. flow-dependent insects, hyporheic biota and stygofauna)?		
Project Status	Active		
Project number	RES-2018-006	**Project commencement date**	01/07/2018
Project duration (months)	27	**Estimated completion date**	31/12/2020
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	5		

Aims

- To characterise the macroinvertebrate fauna in Magela creek channel receiving waters across different key phases of the hydrological cycle.
- To determine the sensitivity of macroinvertebrate fauna of Magela creek channel receiving waters to magnesium by conducting acute laboratory toxicity tests on field-collected macroinvertebrates from different phases of the hydrological cycle.

Background

The magnesium rehabilitation standard has been derived from laboratory and field (mesocosm phytoplankton and zooplankon, and lentic macroinvertebrates) lines of evidence that do not include stream macroinvertebrates, especially forms that depend on flowing water. Inclusion of additional information on sensitivities of flow-dependent communities, which include some species known to be sensitive to salts, would further increase our level of confidence in the magnesium (Mg) Rehabilitation Standard. Such knowledge will also enable an impact assessment of

solutes transported via groundwater to these communities. This study will identify phases of the hydrological cycle in Magela and Gulungul creek channels when, after mine site closure, receiving surface water ecosystems will be exposed to surface water runoff and exfiltrating groundwater with significant elevated electrical conductivity (EC). This information in turn would guide further work needed to characterise the associated macroinvertebrate fauna in the creek channel receiving waters. Using this information, selected macroinvertebrate taxa, including those known to be salt-sensitive, from different phases of the hydrological cycle would be used in rapid (acute) toxicity tests to rank their sensitivities to salts ($MgSO_4$). Such rapid testing protocols have been developed and applied elsewhere in Australia and enable identification of sensitive taxa quickly and effectively. Additionally, incorporating selected taxa routinely assessed in the laboratory in the rapid toxicity testing program will allow for a qualitative comparative assessment of macroinvertebrate taxa tested. The ranked sensitivities, coupled with the information on the phases of the hydrological cycle most at risk from elevated EC, will be used to assess the risk of Mg throughout the key phases of the hydrological cycle, as well as the adequacy of the existing rehabilitation standard.

Progress against plan

- Macroinvertebrate communities were sampled at four periods of the hydrograph (from early wet season flow to dry season pool formation) using sweep nets and artificial substrates.
- Single species acute toxicity tests were conducted using macroinvertebrates commonly found during each sampling round.
- All macroinvertebrate samples have been sorted to family level. Species level identifications for a select group of samples have been completed.

Key findings

- Single species Mg toxicity testing derived acute LC50 values between 36 and 4000 mg/L Mg.
- Communitiy assemblage dataset is currently being finalised.

Workplan for 2020-21

- Write and publish journal manuscript

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Assess the relative sensitivities of resident aquatic insects to Mg across different phases of stream flow in Magela Creek.
- From ERA's surface water modelling, identify phases of the hydrological cycle in Magela and Gulungul creek channels which will be exposed to

surface water runoff and expressed groundwater with significant elevated electrical conductivity (EC).
- Using the information from dot-points 1 and 2, undertake a risk assessment identifying phases of the hydrological cycle most at risk from Mg.

The outcomes that this project will achieve are:

- The macroinvertebrate assemblages of Magela Creek channel resident during different hydrological phases.
- The relative risks of mine waters discharged from Ranger uranium mine to resident macroinvertebrate communities during different hydrological phases

Planned communication activities

The primary communication activities for the project are:

- Standard corporate reporting requirements;
- Reporting and presentations to key stakeholders as necessary;
- Journal publication; and
- Conference and workshop presentations.

Project publications to date (if applicable)

Mooney T 2020. Supporting Lines of Evidence for SSB's Mg Rehabilitation Standard. ERA Technical Advice 014, Supervising Scientist, Darwin NT.

Project Title	Effects of surface and ground water egress of mining-related solutes on stream ecological connectivity (NESP fish migration)		
KKN Theme	Water and sediment		
KKN Title	WS7. Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health		
KKN Question	WS7F. Can a contaminant plume in creek channels form a barrier that inhibits organism migration and connectivity (e.g. fish migration, invertebrate drift, gene flow)?		
Project Status	Active		
Project number	RES-2018-002	**Project commencement date**	01/07/2018
Project duration (months)	25	**Estimated completion date**	30/07/2021
Lead team	WASQ	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	David Crook (Charles Darwin University)
Resources 2020-21 (person weeks)	1		

Aims

- To identify sources of colonization by different fish species of the Magela sand channels during the wet season.
- To characterise the seasonal movements of different fish species through the sand channels and thereby determine key periods when different species may be at risk from mine-derived solute egress to the creeks after Ranger mine rehabilitation.
- To determine where possible, the risks to migrating fish species associated with mine-derived solute egress to Magela Creek through exposure observations or experiments.

Background

The importance of ecological connectivity in maintaining critical ecosystem processes has been increasingly recognised over recent years. Egress of contaminants into Magela Creek associated with the waste rock cover of the

Ranger uranium mine (RUM) final landform via surface and ground water has been identified as a potentially important threat to ecological connectivity and the processes it supports (Bishop et al. 1995[3]; Humphrey et al 2018[4]; Supervising Scientist 2017[5]). Following closure of RUM, the rehabilitated landform is predicted to become a source of surface water runoff and exfiltrating groundwater with elevated electrical conductivity (EC) derived from waste rock. Detailed studies of the movements of fish in Magela Creek based on visual observations and trapping were conducted by SSB in the 1980s and 1990s. Based on this research, Bishop et al. (1995) identified that fish in Magela Creek took dry season refuge in billabongs in the escarpment country upstream of Ranger mine, and in channel and floodplain billabongs downstream of the mine. During the wet season fish migrate from these refugia to spawn and feed: downstream migration from below-escarpment billabongs to the sand channels and inundated floodplains, and lateral or upstream migrations from channel and floodplain billabongs to the sand channels and adjacent inundated floodplains. At the end of the wet season, large numbers of fish migrate back upstream from or through the sand channels. This conceptual model of fish migration suggests that future egress of saline surface and ground waters from Ranger has the potential to both affect fish resident in the sand channels during the wet season and reduce connectivity between upstream refugia and the floodplain and, thus, interrupt important ecological processes.

Building upon the early work of Bishop et al. (1995), this research will use the most up-to-date methods available (sonar, videography, electronic tagging) to develop a comprehensive understanding of fish migration dynamics in the Magela Creek region. Where possible, these results will be directly linked to surface and ground water solute modelling for the Ranger mine rehabilitation site, as well as to additional possible risk assessments, to assess the likely effects of saline mine waters on ecological connectivity and the processes it supports. This will include exposure information available from operational mine water releases to Magela Creek. Such risk assessment will include observations of fish migrating adjacent to sites of mine waste water releases in Magela Creek.

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[3] Bishop K, Pidgeon R & Walden D 1995. Studies of fish movement dynamics in a tropical floodplain river: prerequisites for a procedure to monitor the impacts of mining. *Australian Journal of Ecology* 20, 81-107

[4] Humphrey CL, Bishop KA & Dostine PL 2018. Vulnerability of fish and macroinvertebrates to key threats in streams of the Kakadu region, northern Australia: assemblage dynamics, existing assessments and knowledge needs. Marine and Freshwater Research 69, 1092-1109.

[5] Supervising Scientist 2017. Review of the potential effects of increased solute egress from mine tailings and waste rock on ecological connectivity in Magela Creek. Project number – RES-2016-005 unpubl. Report.

Additionally, the project will use Magela Creek as a model system to build upon previous work on food web dynamics conducted under the NERP and NESP programs by providing quantitative estimates of the biomass transported via fish migration.

Progress against plan

- Late 2018 and 2018/2019 wet season field work were successfully completed. Approximately 55 fish were tagged in Bowerbird Billabong in late 2018 before Magela Creek started flowing and approximately 35 fish were tagged at Magela crossing and Mudginberri Billabong during recessional flow (2019). These fish were tracked with in-situ loggers over the 2018/2019 and 2019/2020 wet seasons
- Fish communities were monitored in Bowerbird and Mudginberri Billabongs throughout the 2018/2019 and 2019/2020 wet seasons using sonar imaging.
- A preliminary download of two receivers at Bowerbird Billabong showed that the transmitters implanted in fish were being successfully detected and that tagged fish were moving between receivers. Final testing of the ARIS 1800 sonar unit was conducted in November 2018 and sonar surveys of fish assemblages were conducted in Bowerbird and Mudjinberri billabongs in December 2018.
- Analysis of the sonar data commenced in January 2019. Early indications are that the sonar will have utility for obtaining data on fish assemblage composition, length frequency distributions and fish behaviour as expected.

Key findings

- Data downloaded from acoustic receivers placed along Magela Creek for the 2018/19 wet season revealed that, despite the poor wet season and intermittent peak flows through Magela Creek, some fish migrated past the mine site from Bowerbird (20 km upstream of Ranger) and into Mudjinberri Billabong (12 km downstream of Ranger) and beyond, with several returning to Bowerbird during recessional flows. Unfortunately, the two poor wet seasons to date have not allowed an assessment of any possible avoidance or disruption to migration of fish past Ranger during times of (permitted) mine water releases.

Workplan for 2020-21

- Journal manuscripts to be prepared by NESP.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Understanding of dry and wet season fish residency in Magela Creek, and use of Magela Creek channel as a migration conduit by various fish species during the period of creek flow
- Where possible, quantification of the inhibition/avoidance of migrating fish species to current mine water releases from Ranger.
- From above dot-points, identification of key periods when different species may be at risk from mine-derived solutes associated with solute egress to Magela Creek after Ranger mine rehabilitation.

The outcomes that this project will achieve are:

- An improved understanding of the use of Magela Creek channel by resident and migrating fish species.
- An assessment of the risks of saline mine discharged from Ranger uranium mine waters on ecological connectivity (including fish migration) and the processes it supports.

Planned communication activities

The primary communication activities for the project are:

- Standard corporate reporting requirements.
- Reporting and presentations to key stakeholders as necessary.
- All NESP Northern Australia Environmental Research (NAER) hub generated publications arising from the project will be made freely available on the NAER website.
- Journal publication.
- Conference and workshop presentations.

Project publications to date (if applicable)

Nil

Project Title	Developing videography-based methods for monitoring fish communities (CDU and SSB)		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2013-016	**Project commencement date**	01/03/2013
Project duration (months)	89	**Estimated completion date**	30/12/2020
Lead team	WASQ	**Date required**	01/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	5		

Aims

- To develop a quantitative and easily-repeatable fish monitoring method, using remote cameras, that will replace the previously-adopted visual census method used in channel billabongs (MON-1989-001), the latter approach having significant (crocodile) safety concerns.
- To compare the fish community structure data from the former visual and new video methods for fish observations in suitable clear-water, crocodile-free, locations in Kakadu National Park and elsewhere.

Background

For monitoring and assessment of potential mine-related changes to biodiversity downstream of Ranger, an annual visual fish monitoring technique was conducted in two channel billabongs by SSB between 1994 and 2015 (MON-1989-001). This method employed a small custom-made boat with a clear Perspex dome, in which an observer lay to identify and count fish. While this method has produced a valuable long-term dataset of fish community structure along the littoral margins of the channel billabongs, the risk of crocodile attack associated with this technique

has increased in recent years. Since a larger (unwieldy) replacement boat is not a suitable option for the habitats sampled, underwater videography has been identified as a potential alternative technology. Initial research and development were conducted in channel and shallow lowland billabongs of the ARR in 2015 to assess different cameras and relative locations of the cameras (near-surface, benthic, littoral and central channel). These findings have guided decisions for work conducted since 2016. In July 2016, videography was undertaken in the same two channel billabongs surveyed since 1994, placing near-surface and benthic cameras along six transects in each billabong. The full imagery was analysed in order to derive the necessary subset of data required for the same paired-billabong comparisons as used for the previous method. On the basis of this analysis, the protocol was refined and implemented for 2017 imagery. Comparative (side-by-side) observer-based and videographic imagery was acquired in 2017, 2018 and 2019 to assess the implications of the change in methodology.

Progress against plan

- Fish videography has replaced the previous visual census method, following trials and validation of methodology. The design imitated that of the previous method, using five existing 50 metre transects in both Mudginberri (exposed) and Sandy (control) billabongs, an additional 50 metre central transect, and deploying ten GoPro cameras at five-metre intervals for each transect. The cameras were orientated for surface and benthic deployment (five of each) and set to record for 1 hour and 30 minutes each.
- SSB staff are competent in the identification of fish from the videos. Additional staff will be trained in fish identification and counting metrics for videography.
- Data have been collected for the videography method comparison study, with an additional year of data required to fully calibrate the new technique. This has involved conducting side-by-side fish surveys using both the visual census and the videography methods in crocodile-free environments (Gunlom and Edith falls).
- Channel billabong fish videography surveys for routine monitoring have been undertaken in the early dry seasons for the past 5 years (2016 to 2020).

Key findings

- Methods and design for the new videography sampling method were reported in the 2016-17 Annual Technical Report. The videography method uses stationary, unbaited cameras, in both surface and benthic orientation, capturing relative species abundance data of the type acquired using the previous method.
- Results arising from the new methodology are a suitable replacement for those reported for fish community structure in the channel billabongs monitoring project (MON-1989-001). Results from the 2020 channel

billabong monitoring are reported in the Environmental Monitoring section of the current (2019-2020) Annual Technical Report.

Workplan for 2020-21

- The results of this study will quantify any differences between methods for three annual measurement events.
- Comparative data collected over the three years will be analysed and published in a scientific journal.
- Further research refining the fish videography method is reported separately under RES-2019-025, "Automation of Fish Identification".

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A SOP for continued videographic-based fish monitoring in channel billabongs,
- Reporting of results of the observer-based and videographic technique comparisons.

Planned communication activities

The primary communication activities for the project are:

- Annual update of monitoring results on the Supervising Scientist website.
- Annual reporting of results in the Supervising Scientist Annual Technical Report.
- Reports and presentations for ARRTC and ARRAC meetings.
- A peer-reviewed journal paper.

Project publications to date (if applicable)

King AJ, George A, Buckle D & Novak P 2016. Developing remote underwater video camera techniques for monitoring fish communities in wetlands of the wet/dry tropics. Unpublished technical report. Charles Darwin University and the Department of the Environment's Environmental Research Institute of the Supervising Scientist (ERISS)

King AJ, George A, Buckle DJ, Novak PA & Fulton CJ 2018. Efficacy of remote underwater video cameras for monitoring tropical wetland fishes. *Hydrobiologia*, 807(1), 145-164.

Project Title	Genomics - building the database for northern macroinvertebrate species		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2015-019	**Project commencement date**	01/04/2015
Project duration (months)	58	**Estimated completion date**	01/01/2026
Lead team	WASQ	**Date required**	01/01/2026
In-house or outsourced	Collaboration	**Supporting team(s)**	Anthony Chariton
Resources 2020-21 (person weeks)	19		

Aims

- To build a baseline DNA barcode library for freshwater macroinvertebrate species from ARR streams, commencing with (Phase 1) caddisflies (Trichoptera), mayflies (Ephemeroptera) and non-biting midges (Diptera: Chironomidae). Other macroinvertebrate groups will be processed and analysed after these three initial groups have been well described locally (Phase 2).

Background

Macroinvertebrate communities are the most commonly employed biological monitoring group for freshwater ecosystems, including monitoring and assessment of potential mining impacts in the ARR. An ongoing impediment to their use is the labour-intensive processing of samples and accurate identification of the constituent fauna. Emerging genetic techniques in monitoring (ecogenomics) offer vastly improved and cost effective approaches to deriving accurate, species-level information for macroinvertebrate samples, and there are moves worldwide to undertake the necessary R&D to build regional baseline DNA barcode libraries.

This library provides the basis for determining the composition of fauna in collected samples, using suitable new generation genomic technologies. Preliminary discussions have been undertaken amongst SSB, NT Government and Macquarie University researchers to pilot a proof of concept using three freshwater insect orders, caddisflies (Trichoptera), mayflies (Ephemeroptera), and Dipteran family, Chironomidae. Material for this study is being drawn from NT Top End streams, including the ARR.

Progress against plan

- SSB, Macquarie University and NT Government researchers have held meetings to coordinate and integrate information needs.
- Approximately 350 macroinvertebrate samples have been collected and sent to Macquarie University for DNA extraction and sequencing
- DNA extractions have yielded both low-quality and high-quality DNA; however, sequencing trials have demonstrated that most samples yield sufficient DNA for sequencing

Key findings

- There are no key findings to date.

Workplan for 2020-21

- The final batch of samples associated with phase 1 has been collected and sent to Macquarie University for DNA extraction and sequencing.
- Results from sequencing will be provided to SSB
- A journal manuscript of the key findings and methodologies will be prepared.
- Commence project phase 2: Additional taxa will be collected and sequenced to expand the DNA library.
- Capacity for extraction, amplication and bioinfomatics process will be increased in-house

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Initial proof of concept, viz development of a regional, baseline DNA barcode library for caddisflies (Trichoptera), mayflies (Ephemeroptera) and non-biting midges (Diptera: Chironomidae).
- Once a DNA library for these three groups has been established, additional groups (Odonata, Coleoptera, Hemiptera, etc.) will be included to expand this library.

The outcome that this project will achieve is:

- Accurate and cost effective species-level identifications of freshwater macroinvertebrates used as indicators of water quality in the ARR.

Planned communication activities

The primary communication activities for the project are:

- Standard corporate and grant reporting requirements
- Contributions to Supervising Scientist Annual Technical Report
- Reports/ presentations as necessary to ARRTC, ARRAC and other key stakeholders.
- Journal publication.
- Conference and workshop presentations.

Project publications to date (if applicable)

Nil

Project Title	Develop a technique for automating snail egg counts for toxicity testing and monitoring		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2012-006	**Project commencement date**	31/10/2017
Project duration (months)	24	**Estimated completion date**	30/10/2020
Lead team	WASQ	**Date required**	01/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	Microsoft - Steve van Bodegraven - Computer engineer
Resources 2020-21 (person weeks)	2		

Aims

- To develop an automated method for counting freshwater snail eggs within an egg mass. This will improve the efficiency and accuracy of this sub-lethal, reproductive endpoint used in field toxicity monitoring and laboratory testing.

Background

The snail, *Amerianna cumingi*, is currently used by the Supervising Scientist Branch for in-situ monitoring in Magela and Gulungul Creeks. *A. cumingi* is also one of six species native to Kakadu National Park that is used in laboratory toxicity testing to derive water quality guidelines for Magela and Gulungul Creeks adjacent to Ranger uranium mine. The endpoint used for both tests is reproduction, with the number of eggs laid by the snails after 96-hours counted and recorded manually under a dissecting microscope. This is a time consuming process, particularly considering that each replicate pair of snails can produce more than 200 eggs in the exposure period. The development of a new, automated method for counting snail eggs will

improve the speed and accuracy of counting, ensuring the toxicity estimates derived from these tests are more efficient and reliable.

Progress against plan

- An egg-laying surface lying within the cylindrical egg chambers and which can be removed for digital image analysis has successfully been developed. Laboratory testing has determined that the egg-laying surface, a thin and flexible clear polycarbonate plastic, has no significant impact on *A. cumingi* egg production.
- A photographic platform has been engineered to capture high resolution images of egg masses on the egg-laying surfaces. This uses a macro lens attached to a tripod-mounted SLR camera, pointed towards egg masses which are suspended in a glass tank filled with water. A light box is positioned an appropriate distance behind the glass tank to illuminate the snail eggs.
- This new method was used for the first time during the 2018-19 wet season. Progress has been made using the computer image software 'Matlab' to automate counting. The software can successfully recognise and count number of egg masses and embryos using combinations of light thresholding, size and shape criteria.
- However, implementation of this statistical approach to automate counting had only marginal improvements on time efficiencies over manually counting on the screen. Due to recent development of skills and capacity within the SSB team, Deep Learning approaches to automate counting are being explored which will resolve issues around mis-counts and the necessity to adjust analysis parameters for each individual image.

Key findings

- A suitable egg-laying substrate has been identified which does not impact on *A. cumingi* egg laying rates and numbers.
- It is possible to capture high resolution images of all egg masses on the egg-laying surface.
- A computer code capable of identifying the egg mass and embryo number for each replicate has been derived. Further optimization of the automation process is being explored to improve on total efficiency gains for this project.

Workplan for 2020-21

- The computer code developed for automating egg mass and embryo counting will be tested and refined by processing approximately 550 images collected from the 2018-19 and 2019-20 season. After each image is processed by the software, an analyst will confirm the count and quantify any difference between automatic and manual counting.

- The overall error rate associated with the code will be determined, and must fall below 5% to meet current quality control criteria. Possible improvements to the code, based on visual inspection of counts, will be undertaken to ensure achievement of the greatest possible accuracy.
- In partnership with Microsoft, the use of Convolutional Neural Networks to automate the counting is being explored to improve the accuracy and reduce statistical manipulation required per image to automate the counting.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- An internal report describing the new methodology
- A peer-reviewed journal paper
- Annual reporting to ARRTC

The outcome that this project will achieve is:

- Increased efficiency and accuracy of snail egg counts arising from in-situ monitoring and toxicity testing.

Planned communication activities

The primary communication activities for the project are:

- Presentation at the biannual SETAC Australasia conference (July 2019)
- Reports/presentations tailored to key stakeholders as required.

Project publications to date (if applicable)

Nil

Project Title	Automation of Fish Identification		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2019-025	**Project commencement date**	25/11/2019
Project duration (months)	24	**Estimated completion date**	30/06/2021
Lead team	WASQ	**Date required**	01/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	Microsoft - Steve van Bodegraven - Computer engineer
Resources 2020-21 (person weeks)	4		

Aims

- To develop an Artificial Intelligence model that can count and identify freshwater fish from videography.

Background

- Monitoring fish communities in Channel and Shallow Lowland Billabongs has recently undergone methodology changes in response to WHS concerns with increased crocodile activity in the region. This has resulted in a transition from traditional visual observation or manual catch techniques to the use of underwater videography to characterise fish community structure. Videography methods result in acquisition of significant hours of video that a technician is required to observe and extract identifications and counts from on a computer. Rapid advancement of Deep Learning techniques in the computer vision space has made it possible to automate the identification of fish species from videography. In partnership with Microsoft, this project aims to develop an end-to-end cloud based solution for automating videography collected for SSB monitoring activites.

Progress against plan

- An architecture for deploying a Deep Learning model in Microsoft Azure has been developed and is currently in use.
- A repository on GitHub has been created for writing and building computer code. Collaboration amongst all users involved is enabled through this platform and will be used to publish the final product.
- Annotation of fish imagery is currently being assisted by an external consultant. As of July 2020, ~50,000 images had been labelled.
- Model training has commenced to assess the performance of current labelling and inform the direction of future labelling requirements for a balanced model.

Key findings

- Model training on ~10,000 labelled images resulted in 79.9% accuracy in identification. Performance for the most common and most labelled species indicates adequate labelling.
- Several species have low number of labelled images which has resulted in low accuracy when scored. For a successful model to be developed, efforts to increase and balance image labels across species are required.

Workplan for 2020-21

- Transition from a development architecture in Microsoft Azure to a production workspace designed for end-to-end automation fish videography.
- Review of model performance from labelled dataset acquired through external consultants. Identify the need and scope for improving model through transfer learning from published datasets.
- Testing model against 2019-20 fish videography identifed by human operator and determining associated machine-learning error.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A Deep Neural Network with weights that can be used to identify freshwater fish community composition from the Alligators Rivers Region.
- An annotated library of fish images that can be shared in a national database.

Planned communication activities

- Presentation at the Australian Society of Fish Biology Conference (2019) Canberra.
- Article in the Australian Society of Fish Biology 2019 December Newsletter.
- Article in the Department of Agriculture, Water and Environment Data Management Group (January 2020)

Project publications to date (if applicable)

Nil

Project Title	Developing methods for monitoring fish communities in shallow lowland billabongs		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2019-005	**Project commencement date**	4/06/2019
Project duration (months)	30	**Estimated completion date**	24/12/2020
Lead team	WASQ	**Date required**	1/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	Duncan Buckle (Freshwater Ecologist) consultant
Resources 2020-21 (person weeks)	4		

Aims

- To design a method for characterising fish and vegetation community composition in shallow lowland billabongs.

Background

Assessment of fish communities in billabongs has been conducted between late April and July each sampling year using non-destructive sampling methods applied in 'exposed' and 'control' locations. Two billabong types have been sampled: deep channel billabongs studied every year, and shallow lowland billabongs, dominated by aquatic plants, which are studied every two years. Fish community monitoring in shallow lowland billabongs is conducted at six sites, comprising three 'control' versus 'exposed' billabong pairs. The similarity of fish communities in the exposed billabong sites downstream of Ranger on Magela Creek (Georgetown, Coonjimba and Gulungul billabongs) to those of communities of the control sites (Sandy Shallow and Buba billabongs on Nourlangie Creek and Wirnmuyurr Billabong – located on a Magela floodplain tributary) is determined using multivariate

dissimilarity indices calculated for each sampling occasion. These indices are a measure of the extent to which fish communities of the paired sites (control versus exposed) differ from one another. A value of zero percent indicates fish communities are identical in structure while a value of 100 percent indicates totally dissimilar communities, sharing no common species. This project assesses any significant change or trend in the dissimilarity values over time, which could imply mining impact.

Monitoring of fish communities in shallow billabongs has historically been conducted biennially using 'pop-net' fish traps deployed overnight. Proposed sampling in 2018 was cancelled due to an assessment of increased crocodile activity and risk of attack. This project aims to develop a new method for sampling fish and vegetation community structure in shallow lowland billabongs using videography and drone imagery.

Progress against plan

- The experimental design for the new proposed monitoring method was developed using underwater videography for fish community characterisation and multi-spectral imagery for aquatic vegetation (fish habitat) classification.
- An observation platform capable of deployment amongst thick aquatic vegetation was built and tested.
- Aerial imagery was collected and analysed to separate vegetation communities using remote sensing techniques.
- Monitoring was performed in Georgetown and Gulungul Billabongs, July 2019. Working practices which address the safety concerns around increase crocodile interaction were successful.
- In June 2020, the monitoring method was expanded to the six sites used under monitoring project MON-1992-001. Lessons from fieldwork conducted in July 2019 were applied.

Key findings

- Camera deployment was performed in the morning, midday and afternoon to observe any temporal variation in the monitoring method. Preliminary analysis indicated no significant temporal differences in fish community composition when compared through Analysis of Similarity (ANOSIM).
- Comparisons of taxa richness indicate a significant difference between the morning and afternoon for transects in thick emergent vegetation dominated by *Hymenachne* spp. at Gulungul Billabong. No temporal differences in taxa richness were found at Georgetown Billabong.
- Using multi-spectral imagery, it was possible to discriminate between cover/vegetation types when merged into categories: emergent (dead &

alive), floating, submerged and open water. Near-infrared and red-edge bands were best at separating aquatic vegetation groups.

Workplan for 2020-21

- A monitoring method and associated protocol will be completed.
- Analysis and publication of the results.
- This project will resume under MON-1992-001 as a monitoring program.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Manuscript/report outlining background to project, methodology, results, analysis and summary of method success.

Planned communication activities

- Presentation at the Australian Society of Fish Biology Conference (October 2019)
- Presentation at the biannual SETAC Australasia conference (July 2019)

Project publications to date (if applicable)

Nil

Project Title	Measuring river discharge from drones		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Active		
Project number	RES-2019-026	**Project commencement date**	20/01/2020
Project duration (months)	22	**Estimated completion date**	30/11/2021
Lead team	ERL	**Date required**	01/01/2026
In-house or outsourced	Collaboration	**Supporting team(s)**	John Fulton and Joe Adams (United States Geological Survey)
Resources 2020-21 (person weeks)	6		

Aims

- To determine whether drone derived surface velocity and bathymetry data can be used to calculate mean channel discharge in Magela and Gulungul Creeks
- To develop
- a collaborative relationship with USGS researchers to continue developing monitoring approaches which leverage leading edge remote sensing methods

Background

The US Geological Survey (USGS) hydrologists and National Unmanned Aircraft System Project Office (NUPO) are developing new technology (Q-Cam) using drones to facilitate collection of discharge in areas where traditional methods could be unsafe or difficult to access. The USGS team has expressed interest in a

collaboration to determine if drone derived surface velocity measurements can be used to quantify stream discharge in seasonally-flowing streams of the wet-dry tropics.

Flow data are needed for surface water modelling, and for suspended sediment monitoring for load calculations, for Ranger rehabilitation. The method will improve safety during high flow events and allow staff to keep a greater distance from the water, thereby reducing risks associated with flooded waters and crocodiles. If successful, the use of drones will enable more efficient data collection, allowing us to obtain data at spatial extents not previously possible in a time effective manner.

The project will require targeted data collection and data analysis prior to routine drone based deployment. This will consist of targeted flow measurements at trial sites to determine the optimum location for the radar-based measurements, and analysis of the flow data to calculate algorithm constants for future drone derived surface velocity measurements.

Test sites will be located in several creeks and rivers to optimise data outputs for the trial. Local sites (Magela and Gulungul) will be selected to be consistent with historical data and future monitoring needs. One or two larger river sites (e.g. Adelaide River), currently monitored as part of the NT government's hydrography program, will also be included as these will have established and regularly-reviewed rating curves.

The project will provide a unique opportunity to build on international relationships when developing leading monitoring technology.

Progress against plan

- The Q-Cam sensor integration onto a DJI M600 drone is 90% complete.

Key findings

- NIL to date

Workplan for 2020-21

- Complete integration of Q-Cam on DJI M600 drone
- Complete stationary bed test
- Undertake test Q-Cam flights to collect data

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Drone-based solution to measure discharge

- Technical advice to ERA
- Journal publication on the application in northern Australia in collaboration with the USGS

The outcome that this project will achieve is:

- A safer method for collecting discharge data during high flow events in unsafe or difficult areas to access.
- Building a collaborative relationship with the US Geological Survey in developing safer and cost-effective monitoring methods.

Planned communication activities

The primary communication activities for the project are:

- Research paper published in an international peer-reviewed journal.
- Key findings published in Annual Technical Report.
- Presentations to key stakeholders as required.
- Presentations to the broader scientific community at conference and/or workshop.
- Technical Advice to ERA

Project publications to date (if applicable)

Nil

Project Title	Developing a short-term chronic toxicity test for the fish, *Mogurnda mogurnda*		
KKN Theme	Water and sediment		
KKN Title	WS9. Optimisation of water quality monitoring programs and assessment methods		
KKN Question	WS9A. How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?		
Project Status	Complete		
Project number	RES-2015-028	**Project commencement date**	30/07/2015
Project duration (months)		**Estimated completion date**	30/04/2020
Lead team	WASQ	**Date required**	01/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	N/A – project complete		

Aims

- To develop a short term (7-d) chronic toxicity test for *Mogurnda mogurnda* incorporating sub-lethal (growth) endpoints.
- To compare the sensitivity of this test to the 4-d acute survival test and the 28-d growth test, using key Contaminants of Potential Concern (COPCs).

Background

In the ERISS ecotoxicology laboratory, a suite of local species has been routinely used to derive water quality Guideline Values (GV) for Magela and Gulungul creeks adjacent to Ranger uranium mine. The current routine toxicity test protocol for the Northern Trout Gudgeon, *Mogurnda mogurnda*, is an acute 96-h exposure (using a survival endpoint). This test is typically a less sensitive indicator of toxicity than the chronic tests used for the other species in the suite. The acute data generated from this test are not ideal for water quality GV derivation as they do not represent the long term effects of contaminant exposure in the environment. Thus, there was a need to update the current method to a cost-effective, chronic test based on sub-lethal endpoints.

A 28-d chronic toxicity test for *M. mogurnda* was previously developed using length and weight as sub-lethal endpoints (Cheng et al., 2010)[6]. This test detected responses to uranium (U) at lower concentrations than the acute test and found that dry weight was the most sensitive sub-lethal endpoint. The present project aimed to develop a shorter, more cost-effective chronic toxicity test, specifically, a 7-d larval growth toxicity test, as this is the minimum test duration required for a test to be considered chronic in Australia and New Zealand (Batley et al. 2014[7], Warne et al. 2015[8]).

Progress against plan

- A paper has been accepted for publication in *Environmental Toxicology and Chemistry* pending minor revisions.

Key findings

- A chronic sub-lethal 7-d toxicity test has been successfully developed for *Mogurnda mogurnda*.
- The 7-d EC50 of 1416 μg/L U with lower and upper confidence limits (LCL: 1050, UCL: 1919 μg/L) is comparable with the EC50 derived by Cheng et al's (2010) 28-d test of 1130 μg/L (LCL:1020, UCL: 1240 μg/L).
- The 7-d EC50s for Mg and Mn are more sensitive than the previous acute data (chronic data - Mg: 409 mg/L, Mn: 986 μg/L, acute data - Mg: 4 g/L, Mn: 240 mg/L). This would be expected as sub-lethal growth-rate endpoints are usually more sensitive than lethal acute endpoints.
- The result demonstrates that the 7-d test is a cost-effective alternative to the 28-d test method for toxicity testing, will require less resources, while producing equivalent toxicity estimates for toxicants.

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[6] Cheng KL, Hogan AC, Parry DL, Markich SJ, Harford AJ, van Dam RA. 2010. Uranium toxicity and speciation during chronic exposure to the tropical freshwater fish, *Mogurnda mogurnda. Chemosphere, 79*(5), 547-554. doi:10.1016/j.chemosphere.2010.02.017

[7] Batley GE, van Dam RA, Warne MSJ, Chapman JC, Fox DR, Hickey CW, Stauber JL. 2014. *Technical Rationale for Changes to the Method for Deriving Australian and New Zealand Water Quality Guideline Values for Toxicants*. Canberra: Prepared for the Council of Australian Government's Standing Council on Environment and Water (SCEW).

[8] Warne MSJ, Batley GE, van Dam RA, Chapman J, Fox DR, Hickey, CW, Stauber JL. 2018. *Revised method for deriving Australian and New Zealand water quality guideline values for toxicants*. Prepared for the revision of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra, 48 pp.

Workplan for 2020-21

- N/A – project complete

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A routine chronic sub-lethal toxicity test for the fish, *M. mogurnda*.
- A SOP and subsequent peer-reviewed journal paper describing the new methodology.

Planned communication activities

The primary communication activities for the project are:

- Presentation at the SETAC Australasia conference 2019.
- Peer reviewed journal article.
- Annual reporting of results on the Supervising Scientist website.
- Reports and presentations for ARRTC and ARRAC meetings

Project publications to date (if applicable)

Pease CJ, Costello CE, Trenfield MA, Mooney TJ & Harford AJ 2016 Development of a 7 day chronic toxicity test for larval Northern Trout Gudgeon, *Mogurnda mogurnda*, using sub-lethal growth endpoints. SETAC Australasia: Industry, science and environment – Towards a sustainable future (4-7th of October, Hobart, Australia).

Pease CJ, Trenfield MA, Mooney TJ, van Dam RA, Walker S Tanneberger C & Harford AJ (in review) Development of a sub-lethal chronic toxicity test for the Northern Trout Gudgeon, *Mogurnda mogurnda*, and application to uranium, magnesium and manganese. *Environmental Toxicology and Chemistry*.

Trenfield MA, Pease CJ, Walker SL, Mooney TJ, Tybell L, Humphrey C, van Dam RA & Harford AJ 2020 Standardised chronic toxicity test protocols and culturing methods for a suite of tropical freshwater species. *Australasian Bulletin of Ecotoxicology and Environmental Chemistry*. In press.

HEALTH IMPACTS OF RADIATION AND CONTAMINANTS

Project Title	Radon exhalation from waste rock on the Ranger trial landform		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD3. Radon progeny in air		
KKN Question	RAD3A. What is the above-background concentration of radon and radon progeny in air from the rehabilitated site?		
Project Status	Active		
Project number	RES-2019-021	**Project commencement date**	01/05/2019
Project duration (months)	30	**Estimated completion date**	31/12/2021
Lead team	ENRAD	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	16.8		

Aims

- To measure the exhalation flux of radon-222 from waste rock on the trial landform.
- To measure radium-226 in waste rock samples collected from the trial landform.
- To measure gamma dose rates on the trial landform.
- To determine the radon-222 exhalation flux density normalised to waste rock radium-226 activity concentration (i.e. $R_{E\text{-}R}$).
- To determine whether the $R_{E\text{-}R}$ has increased since 2014, when radon exhalation flux from waste rock on the trial landform was last measured.

Background

Radon exhaled from waste rock and transported in the atmosphere by wind represents a radiation exposure pathway to the public from the Ranger final landform. Estimates of public radiation dose from radon require its exhalation flux

from waste rock to be quantified. The Ranger trial landform provides a unique opportunity to acquire site-specific data on radon exhalation flux from waste rock, including its seasonal and long-term variability. Measurements of radon exhalation flux on the trial landform from 2009 to 2014 showed an increase in dry season values over time, which may have implications for estimating dose rates to the public from the final landform. This project will provide data to confirm whether any further increase in the radon exhalation flux from waste rock has been occurring during the five years since measurements were last made.

Progress against plan

- Radon exhalation measurements were conducted in May 2019, August 2019, December 2019 and March 2020.
- Gamma dose rate measurements were conducted on the trial landform in August 2019.
- Waste rock samples were collected from the trial landform in August 2019 and have been analysed for radium-226 activity concentration.

Key findings

- The measurements to date indicate that there has been no increase in radon exhalation flux densities or $R_{E\text{-}R}$ since 2014.

Workplan for 2020-21

- Additional measurements of radon exhalation rates on the trial landform are planned to occur at approximately 6 month intervals during 2020-21.

Planned project outputs and associated outcomes

The primary output for the project is:

- Data on radon exhalation flux from waste rock to confirm whether any changes have occurred since 2014 when the last measurements were made.

The outcome that this project will achieve is:

- Enhanced knowledge of radon exhalation from waste rock that can be used in radiation dose modelling of radon exposure to the public from the Ranger final landform.

Planned communication activities

The primary communication activities for the project are:

- Research paper.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Nil

Project Title	Environmental fate and transport of Ac-227 and Pa-231		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD5. Radionuclides in bushfoods		
KKN Question	RAD5A. What are the concentration ratios of actinium-227 and protactinium-231 in bush foods?		
Project Status	Active		
Project number	RES-2015-014	**Project commencement date**	01/02/2015
Project duration (months)	72	**Estimated completion date**	31/08/2021
Lead team	ENRAD	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	ANU
Resources 2020-21 (person weeks)	4		

Aims

- To develop new methods for measuring actinium-227 and protactinium-231 in environmental samples.
- To measure actinium-227 and protactinium-231 in environmental samples and determine concentration ratios between the measured activity concentration in bush foods and wildlife and that in soil or water.
- To estimate radiation dose contributions to the public and wildlife from actinium-227 and protactinium-231.

Background

Although a significant body of research has been undertaken on the behaviour of radionuclides of the uranium decay series in the environment, there is very little information for actinium decay series radionuclides, partly because techniques for measurement of two key isotopes in the actinium decay series – protactinium-231 and actinium-227 – are limited and prone to technical difficulties (particularly in the chemical separation steps). It is also argued that the activity concentration of uranium-235, at the head of the actinium decay series, is ~20 times below that of uranium-238 for natural uranium and therefore presents fewer radiological risks. However, actinium-227 dose coefficients are typically higher than those for the

uranium decay series radionuclides, with ingestion dose coefficients similar to those of polonium-210, 1.6 times higher than lead-210 and 4 times higher than radium-226. Inhalation dose coefficients for both actinium-227 and protactinium-231 are higher than those for polonium-210, lead-210 and radium-226 even after taking into account the relative abundances of the parents of the different decay series. Uranium mining and milling may significantly increase the mobility of radionuclides in both the uranium and actinium decay series compared to the natural state, creating the potential for these isotopes to be released into the environment and potentially leading to increased exposure to ionising radiation for humans and wildlife. Environmental assessment of the Ranger uranium mine, both before and after mine closure, requires that all potential pathways of exposure to ionising radiation be considered. This PhD project involves research into techniques for measurement of environmental concentrations of protactinium-231 and actinium-227, and the potential mobility of these isotopes in aquatic and terrestrial environments in the vicinity of the Ranger mine.

Progress against plan

- A working method to separate and measure protactinium-231 in environmental samples has been developed using accelerator mass spectrometry. The method was successfully piloted on freshwater mussel samples, with the method and results published in Nuclear Instruments and Methods in Physics Research B.
- A method to separate and measure actinium-227 has been developed, but not yet applied to environmental samples. The separation method uses micro-precipitation and does not require hydrofluoric acid, thereby enhancing the safety aspects of its use. The measurement method uses alpha spectrometry to indirectly measure actinium-227 through the radioactivity of its decay products thorium-227 and radium-223.
- Progress on sample analysis for actinium-227 and protactinium-231 was delayed during 2019–20 due to the COVID-19 pandemic and other factors affecting access to ANU laboratories. Sample analysis is now expected to occur during 2020–21.

Key findings

- Protactinium-233 can be effectively separated from neptunium-237 for use as a tracer isotope for protactinium-231 measurement in environmental samples via accelerator mass spectrometry.
- Using the injection species of PaO_2 is the most efficient in the 14UD accelerator mass spectrometer for measurement of protactinium-231 and reduces interference from uranium-233 to non-significant levels.
- Sufficient activity of protactinium-231 is present in freshwater mussels of the Alligator Rivers Region to enable the use of current sample preparation methods for analysis of protactinium-231.

- Source preparation of actinium-227 as a lanthanide hydroxide for alpha spectrometry resulted in chemical recoveries of more than 90% with a resolution of less than 40 keV at full width half maximum in the alpha-particle spectrum.
- Autoradiography of alpha sources prepared for actinium-227 analysis showed a reproducible distribution of actinium-227 on the sources.

Workplan for 2020-21

- SSB is a collaborator on this work, which is being undertaken as a PhD project through the Australian National University. SSB is providing materials, data and advice on an as-needs basis to support the work.
- Sample analysis delayed in 2019–20 is now planned to occur in 2020–21.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- New radiochemistry and measurement techniques for actinium-227 and protactinium-231 in environmental samples.
- Data on actinium-227 and protactinium-231 activity concentrations in animals, plants, soil and water.
- Concentration ratios for actinium-227 and protactinium-231 in selected bush foods and wildlife.
- Tissue to whole organism activity concentration conversion factors for actinium-227 and protactinium-231 for selected wildlife.
- Estimates of radiation doses to people and wildlife from actinium-227 and protactinium-231.

The outcomes that this project will achieve are:

- Knowledge of the radiological importance of actinium-227 and protactinium-231.
- Enhanced knowledge of public and environmental radiation exposure that could be used to inform decision-making on the achievement of closure criteria for the Ranger mine.

Planned communication activities

The primary communication activities for the project are:

- PhD thesis.
- Research papers.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Medley P, Tims SG, Froehlich MB, Fifield LK, Bollhöfer A, Wallner A & Pavetich S 2019. Development of ^{231}Pa AMS measurements to improve radiological dose assessment from uranium mining and milling. *Nuclear Instrumentation and Methods in Physics Research B* 438, 66–69.

Project Title	Radionuclide uptake in understorey vegetation		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD6. Radiation dose to wildlife		
KKN Question	RAD6B. What are the whole-organism concentration ratios of uranium and actinium series radionuclides in wildlife represented by the representative organism groups?		
Project Status	Active		
Project number	RES-2020-009	**Project commencement date**	14/01/2020
Project duration (months)	14	**Estimated completion date**	31/03/2022
Lead team	RAD	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	ERL
Resources 2020-21 (person weeks)	26		

Aims

- To measure uranium decay series radionuclides in understorey vegetation (e.g. shrubs and grasses).
- To derive whole organism concentration ratios of uranium decay series radionuclides in understorey vegetation.
- To update the current wildlife dose assessment for the Ranger final landform using new site-specific data for understorey vegetation.

Background

Standard wildlife dose assessment tools (e.g. ERICA) use whole organism concentration ratios to predict radionuclide activity concentrations in wildlife from those in soil or water. Site-specific data for the Alligator Rivers Region on whole organism concentration ratios of uranium decay series radionuclides are currently limited to a few organism groups and do not include understorey vegetation (e.g. shrubs and grasses). The current radiation assessment for terrestrial wildlife, upon which the soil radiological guideline value for radiation protection of the terrestrial ecosystem is based, uses international default values of whole organism concentration ratio to fill gaps in site-specific data. The assessment suggests that

understorey vegetation is the next most highly exposed wildlife group in the terrestrial environment after reptiles (site-specific reptile data were available and used in the current assessment). The acquisition and use of site-specific data for understorey vegetation would strengthen the current assessment by providing a more accurate indication of radiation exposure to this wildlife group after rehabilitation of the Ranger mine.

Progress against plan

- Target species for sampling have been identified.
- A sampling plan (including sampling sites and methods) has been developed.
- Permit 8A approval has been granted for collection of target species from Kakadu National Park.
- Sample collection originally planned for March 2020 was delayed due to the COVID-19 pandemic and associated biosecurity restrictions for accessing Kakadu National Park. This sampling has been rescheduled to March 2021.

Key findings

Nil to report

Workplan for 2020-21

- Field work to collect understorey vegetation and soils from selected sites in Kakadu National Park.
- Commencement of sample processing and analysis for radionuclides and metals.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Site-specific data on whole organism concentration ratios of uranium decay series radionuclides and metals in understorey vegetation (e.g. grasses and shrubs).
- Updated radiation dose assessment for terrestrial wildlife for the Ranger final landform.

Planned communication activities

- Research paper.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Nil

Project Title	Radionuclide uptake in small proliferators		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD6. Radiation dose to wildlife		
KKN Question	RAD6B. What are the whole-organism concentration ratios of uranium and actinium series radionuclides in wildlife represented by the representative organism groups?		
Project Status	Active		
Project number	RES-2019-002	**Project commencement date**	01/06/2020
Project duration (months)	13	**Estimated completion date**	30/06/2021
Lead team	RAD	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	WASQ
Resources 2020-21 (person weeks)	26		

Aims

- To measure uranium decay series radionuclides in small proliferators (e.g. algae).
- To derive whole organism concentration ratios of uranium decay series radionuclides in small proliferators.
- To update the current wildlife radiation dose assessment for the Ranger final landform using new site-specific data for small proliferators.

Background

Standard wildlife dose assessment tools (e.g. ERICA) use whole organism concentration ratios to predict radionuclide activity concentrations in wildlife from those in soil or water. Site-specific data on whole organism concentration ratios of uranium decay series radionuclides is currently limited to a small number of organisms and do not include small proliferators such as algae, which form the base of the ecosystem food chain. The small proliferator whole organism concentration ratios used in the current wildlife dose assessment for the Ranger final landform are international default values derived largely from data

representing non-tropical ecosystems. The acquisition and use of site-specific data for algae would strengthen the current assessment.

Progress against plan

- Algae (viz epiphytes)
- and water samples were collected from six billabongs in June 2020.

Key findings

- Nil to report

Workplan for 2020-21

- Process and analyse samples for radionuclides and metals
- Analyse data and update wildlife radiation dose assessment for the Ranger final landform
- Write-up results as a research paper for publication in a peer-reviewed scientific journal.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Site-specific data on whole organism concentration ratios of uranium decay series radionuclides in small proliferators (e.g. algae).
- Updated radiation dose assessment for freshwater wildlife.

The outcomes that this project will achieve are:

- Enhanced knowledge of whole organism concentration ratios of radionuclides in wildlife.
- Enhanced wildlife radiation dose assessment for the Ranger final landform.
- Public and regulator assurance that the Ranger final landform meets the rehabilitation standard for radiation protection of the environment.

Planned communication activities

The primary communication activities for the project are:

- Research paper.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Nil

Project Title	Gamma radiation dose rates to the public from the Ranger final landform		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD7. Radiation dose to the public		
KKN Question	RAD7A. What is the above-background radiation dose to the public from all exposure pathways traceable to the rehabilitated site?		
Project Status	Complete		
Project number	RES-2019-018	**Project commencement date**	01/04/2019
Project duration (months)	3	**Estimated completion date**	30/09/2019
Lead team	ENRAD	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To estimate gamma radiation dose rates to the public based on the uranium radioactivity of surface waste rock.
- To assess whether annual doses from gamma radiation could potentially restrict future land use scenarios for the final landform.

Background

Low uranium grade waste rock is planned to be used as the surface substrate on the Ranger final landform. The activity concentration of uranium-238 and uranium-235 decay series radionuclides in this waste rock is elevated compared to the surrounding environment and pre-mining radiological conditions of the site. Gamma radiation emitted from uranium-238 and uranium-235 decay series radionuclides in surface waste rock represents one of the potential radiation exposure pathways to the public from the Ranger final landform. Analysis of this pathway forms part of the overall radiation dose assessment for the Ranger final landform to determine whether doses above natural background to the public are

likely to exceed the dose limit and whether restrictions on future land use may be necessary.

Progress against plan

- N/A – project is complete.

Key findings

- Dose rates from gamma radiation on the final landform are predicted to be one and two orders of magnitude higher than those from radon progeny and radionuclides in dust, respectively.
- The predicted gamma radiation dose rates on the final landfrom would result in an above-background dose equal to the statutory dose limit of 1 mSv per year after a continuous exposure time of about 6 months. However, when the currently envisioned land use is averaged over the entire Ranger project area, the annual above-background dose from gamma radiation is a small fraction (~4%) of the statutory dose limit.

Workplan for 2020-21

- N/A – project is complete.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Data on radiation dose rates to the public from gamma radiation emitted from uranium-238 and uranium-235 decay series radionuclides in waste rock on the Ranger final landform.

The outcome that this project will achieve is:

- Enhanced knowledge of public radiation exposure that could be used to inform decision-making on the achievement of closure criteria for the Ranger mine.

Planned communication activities

The primary communication activities for the project are:

- Research paper.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Doering C 2020. Public exposure to external gamma radiation on a mine landform covered by low uranium grade waste rock. *Radiation Protection Dosimetry* 188(1), 123–128.

Project Title	Deriving site-specific concentration factors for metals in bush foods to inform human health risk assessments for the Ranger final landform		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD9. Impacts of contaminants on human health		
KKN Question	RAD9B. What are the concentration factors for contaminants in bush foods?		
Project Status	Active		
Project number	RES-2017-024	**Project commencement date**	01/03/2018
Project duration (months)	16	**Estimated completion date**	30/09/2020
Lead team	ENRAD	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	

Aims

- To derive concentration factors for metals in bush foods consumed by the indigenous population within the ARR.
- If possible, derive maximum allowable concentrations of metals in soil and water that would give rise to site-specific, food safety guidelines for metals.

Background

Ingestion of elevated concentrations of some metals can be harmful to humans. The Environmental Requirements for the Ranger mine stipulate that its rehabilitation must not result in "an adverse effect on the health of Aboriginals and other members of the regional community by ensuring that exposure to … chemical pollutants is as low as reasonably achievable and conforms with relevant Australian law". This project will derive concentration factors between the concentrations of metals in bush foods and those in soil and water. If possible, the concentration factors will be used to derive health investigation levels for metals in soil and water from ingestion toxicity reference values given in the National Environment Protection Measure (NEPM) guidelines for assessment of site contamination.

Progress against plan

- Concentration factors for metals in bush foods have been derived from existing data.
- A draft report presenting the concentration factors and discussing their potential use in site assessment has been prepared.

Key findings

- Currently available data support the derivation of metal concentration factors for buffalo, fish, fruit, goanna magpie goose, mussel, pig, wallaby and yam.
- There are currently no data available to derive metal concentration factors for crocodile, filesnake, turtle and waterlily.
- Variability in metal concentration factors is typically 1–3 orders of magnitude.
- Concentration factors show trends based on metal essentiality (macronutrients > micronutrients and nonessential metals) and tissue physiological function (kidney and liver > flesh).
- The concentration factors may help in the derivation of pathway-specific health-based investigation levels for bush food ingestion in the context of the rehabilitation of the Ranger mine. However, additional information on background intakes and the fraction of contaminated bush foods in the diet is needed to further support the derivation of health investigation levels for metals.

Workplan for 2020-21

- Finalise and publish the draft report.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Site-specific concentration factors of metals in bush foods that could be used in site assessment for the rehabilitated Ranger mine.

The outcomes that this project will achieve are:

- Enhanced knowledge of metal uptake in Aboriginal bush foods.
- Enhanced knowledge of data gaps for possible future research.

Planned communication activities

The primary communication activities for the project are:

- Internal report.
- Presentations to stakeholders on request.

Project publications to date (if applicable)

McMaster S & Doering C (in draft). Metal concentration factors in Aboriginal bush foods. Internal Report, Supervising Scientist, Darwin.

Project Title	Quantifying radon retention characteristics of ERISS acrylic gamma spectroscopy containers		
KKN Theme	Health Impacts of Radiation and Contaminants		
KKN Title	RAD10. Optimisation of radionuclide monitoring and assessment methods		
KKN Question	RAD10A. How do we optimise methods to monitor and assess radionuclides?		
Project Status	Active		
Project number	RES-2019-023	**Project commencement date**	9/09/2019
Project duration (months)		**Estimated completion date**	30/07/2020
Lead team	RAD	**Date required**	
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	N/A – project to be completed in 2019-20		

Aims

- To measure radon (^{222}Rn) retention in the acrylic gamma spectroscopy containers.
- To assess the impact of variations in radon retention on the accuracy of the radium (226Ra) analysis.
- To investigate methods for improving the radon retention of the acrylic containers.

Background

226Ra and 222Rn are difficult to measure because of their low gamma emission intensities, so the preferred 226Ra analysis method is to measure the gamma emissions of the 222Rn progeny (214Pb & 214Bi) which are of higher intensity. This method requires that samples be sealed in 222Rn tight containers so that the 222Rn progeny can reach equilibrium with the parent radium isotope. This equilibrium is reached (> 97%) after 23 days of sealed storage.

The containers currently in use by ERISS are manufactured from acrylic plastic and sealed with a rubber o-ring and petroleum grease. It is known that these containers can allow radon to leak if the o-ring seal is not complete. There is also anecdotal

evidence that 222Rn may leak out of the acrylic plastic. This project aims to establish if these leaks occur and if so, to quantify both the rate and measured variations of the leakage.

ERISS measurement of 226Ra does not appear to be compromised by leakage of 222Rn, as standards and IAEA reference materials are routinely analysed to ascertain the robustness of the analytical techniques. This project will provide added confidence in the gamma spectroscopy results published by ERISS.

Progress against plan

- Calibration standards and environmental samples pressed and sealed in acrylic plastic containers have been tested for 222Rn leakage.
- Data from these measurements have been analysed to estimate 222Rn leakage rates.
- An internal report describing the measurement method and result has been drafted.

Key findings

- Leakage of 222Rn from acrylic plastic containers is very low and has negligible effect on the determination of 226Ra based on gamma spectrometry counting of 222Rn progeny radionuclides.

Workplan for 2020-21

- Finalise and publish internal report.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Data on 222Rn leakage rates from acrylic plastic containers used in gamma spectrometry analysis.

The outcome that this project will achieve is:

- Assurance that determination of 226Ra based on gamma spectrometry counting of 222Rn progeny radionuclides produces accurate results.

Planned communication activities

The primary communication activities for the project are:

- Internal report.
- Presentations to stakeholders on request.
- Presentations to the broader scientific community at conferences.

Project publications to date (if applicable)

Nil

LANDFORM

Project Title	What are the baseline rates of sediment transport and deposition in creeks and billabongs?		
KKN Theme	Landform		
KKN Title	LAN1. Determining baseline erosion and sediment transport characteristics in areas surrounding the RPA		
KKN Question	LAN1A. What are the baseline rates of gully formation for areas surrounding the RPA?		
Project Status	Active		
Project number	RES-2019-022	**Project commencement date**	11/12/2019
Project duration (months)	25	**Estimated completion date**	01/04/2021
Lead team	ERL	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	RAD
Resources 2020-21 (person weeks)	28		

Aims

- To determine the background/natural sedimentation rates in the backflow billabongs and backswamps, and their variation through time.
- To determine the sources of the largest sedimentation events as these are likely to be a result of large rainfall events that, when they reoccur, will move sediment from the constructed landform and the two fluvial sources, Coonjimba and Corridor creeks.

Background

Three backflow billabongs (Georgetown, Coonjimba and Gulungul Billbongs) downstream of the Ranger mine site are of interest in this study. They are formed at tributary junctions where creek channels are dammed by sand from Magela Creek. These billabongs have a natural/ baseline sedimentation rate with deposition of very fine sediment and organic matter. It is important to know what

the natural rates of sedimentation are to ensure that these rates are not increased/accelerated by sediment from the rehabilitated Ranger landform. Dating of sediment cores will provide information on the rates of pre-mine sedimentation. Bathymetric surveys and DEM developed from Lidar coverage will provide additional information on rates of change over nearly 40 years. However, if sedimentation is highly variable in time because it is mainly a result of large flood events, and this will only be known by fine-scale dating informed by stratigraphic boundaries, then sedimentation rate derived from seiment core dating alone will not be sufficient to determine if the constructed landform is a major source of sediment. Hence pre- and post-rehabilitation bathymetry will be required for such future assessments of mine-derived sedimentation.

Progress against plan

- Pilot study field work was completed in December 2019.
- Samples prepared and are being counted on the detectors at the SSB laboratories:
- Gamma spectrometry to determine 210Pb excess and 137Cs (recent sedimentation, within last 100 yrs)
- Radiochemistry/alpha spectrometry to determine 226Ra/230Th ratios (chronology out to ~2000 yrs)

Key findings

Nil to date

Workplan for 2020-21

- Bathymetric survey the three billabongs
- Field campaign to collect additional cores if required
- Continue to process and count samples collected from 2019

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Interim Report with results and preliminary work from the late 2019 pilot study available - December 2020
- Final report on baseline sedimentation of backflow billabongs - July 2021

The outcomes that this project will achieve are:

- Knowledge of the natural sedimentation rates in backflow billabongs downstream of the Ranger mine site.
- This knowledge will be used in the future to assist in determining whether erosion of the rehabilitated Ranger site is resulting in any increase in sedimentation rates in the billabongs by: (i) re-examining cores from the billabongs for both sedimentation rates and those geochemical properties

that distinguish the various sediment sources; and/or (ii) comparing billabong bathymetry pre- and post-rehabilitation.

Planned communication activities

To be determined

Project publications to date (if applicable)

Report - Magela Creek Backflow Billabongs: A Review of Sedimentation Rates and Sediment Sources - R.J. Wasson. 11/12/19

Project Title	Mapping and characterisation of geomorphology of on-site creeks in and adjacent to the mine site, including historical change		
KKN Theme	Landform		
KKN Title	LAN1. Determining baseline erosion and sediment transport characteristics in areas surrounding the RPA		
KKN Question	LAN1B. What are the baseline rates of sediment transport and deposition in creeks and billabongs?		
Project Status	Active		
Project number	RES-2020-007	**Project commencement date**	1/11/2019
Project duration (months)	8	**Estimated completion date**	30/07/2020
Lead team	ERL	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	3		

Aims

- To map
- and characterise geomorphology of creeks, including historical change, and thereby provide a baseline that can be used to detect increased sedimentation rates from the rehabilitated landform in the future.

Background

This project will involve mapping and characterisation of geomorphology of on-site creeks and waterbodies, including historical change, to provide baseline rates of sediment transport and deposition in creeks and billabongs in and adjacent to Ranger Mine. This will be done using aerial photography and satellite imagery in ArcGIS Pro with some ground truthing as required if there is access during the wet season.

Mine site tributaries and their associated floodplains and backflow billabongs are the most significant sediment storage sites downstream of the mine site (Erskine &

Saynor, 2000[9]). Mine site tributaries and billabongs will be mapped to investigate any historical change and to provide a baseline map of the creeks and tributaries surrounding Ranger Mine.

Coonjimba, Georgetown and Gulungul Billabongs and Corridor Creek will be mapped (dependant on available imagery), as well as the extent of tributaries of either Gulungul or Magela Creeks. This will generate a base map that can be compared to future UAV data and aerial imagery to assess future geomorphological changes to these receiving waters associated with the rehabilitated mine. Specifically, it will allow for detection of future change in tributaries, including visualisation of increased sediment and can potentially provide indication of gully formation.

The project has been undertaken by a Departmental graduate and has used historical aerial photography acquired through the savanna change project.

Progress against plan

- Historical aerial photographs have been mapped.
- Report is being written.

Key findings

Nil to date

Workplan for 2020-21

- Completion of final report and geomorphic base map

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Mapping of the sediments in the creeks on and adjacent to the minesite to determine (i) whether any sediment from the mine has been transported into them over the life of the mine, and (ii) as a pre-rehabilitation baselines against which to assess geomorphological change after rehabilitation.

Planned communication activities

To be determined

Project publications to date (if applicable)

Nil

[9] Erskine WD & MJ Saynor 2000. Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia. Supervising Scientist Report. Darwin, Supervising Scientist.

Project Title	Ranger trial landform erosion research		
KKN Theme	Landform		
KKN Title	LAN3. Predicting erosion of the rehabilitated landform		
KKN Question	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)?		
Project Status	Active		
Project number	RES-2009-011	**Project commencement date**	01/03/2018
Project duration (months)	29	**Estimated completion date**	30/10/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	5		

Aims

- To assess whether different surface treatments and vegetation establishment strategies on the Ranger trial landform result in different erosion rates through measurements of hydrology and infiltration.
- To assist in knowledge needs for plant available water and terms for groundwater modelling through measurements of infiltration rates and particle size of surface material on the trial landform.

Background

Construction of the trial landform was completed in early March 2009, with instrumentation of erosion plots and planting of tube stock and direct seeding completed by November 2009. Four plots were established: two on waste rock and two on laterite mix surfaces. Each surface was initially divided into areas of direct seeding and tubestock, thus each plot initially collected information for a unique surface cover and revegetation strategy. Quantitative data on rainfall, runoff, water quality, bed load, suspended sediment load and solute load have been collected

from the trial landform since the 2009-2010 wet season. This directly informs erosion rates and solute loads leaving the erosion plots and informs infiltration rates indirectly using runoff coefficients.

In addition to the variables described above, additional data are also being gathered on particle size of surface material. (Particle size is also being measured ex situ, on Ranger waste rocks originally collected in 1998, placed in metal and plastic containers and exposed outdoors to weathering elements.) The collective data are being used for a number of purposes including validation of surface water discharge from the CAESAR-Lisflood model, discharge predictions from groundwater modelling, infiltration and input for plant available water calculations.

Progress against plan

- Rainfall, runoff and bedload data have been collected for ten wet seasons 2009–2010 to 2018–19 with data from the 2018-19 wet season currently being analysed. The project was scaled back during the 2014–2015 wet season with only rainfall runoff and bedload collected during the subsequent wet seasons.
- Rainfall and runoff data have been cleaned, quality assessed and checked, and archived in Hydstra for all plots for the 2009–2010 to 2017–2018 wet seasons.
- Bedload yields have been calculated for all four plots for nine wet seasons (2009–2010 through to 2017–2018).
- Continuous monitoring of EC, turbidity and stage height in calibrated flumes has been undertaken at each of the four plots over the five wet seasons (2009–2010 to 2013–2014), and associated data will be used to derive total loads of suspended sediment and solutes.
- Chemical analysis was completed for selected runoff samples collected by turbidity and/or EC activated auto samplers during the first five wet seasons (2009–2010 to 2013–2014).
- Particle size distribution has also been completed for the surface samples collected in 2009, 2012, 2014 and 2018 and the 2009 data has been reported in an internal report.

Key findings

- Suspended sediment appears to comprise less than 20% of the total sediment load for erosion plot1 (5 wet seasons 2009-2010 to 2013-2014). CAESAR-Lisflood model predictions for the trial landform of high initial sediment loads with a subsequent rapid decline bear some resemblance to the field measurements, though the degree of this correspondence requires further investigation.

- As reported in the 2016-17 Annual Technical Report, bedload has been found to be declining in the eight years since the trial landform was constructed.
- Rainfall and runoff data have been used to inform infiltration rates. Runoff coefficients show that most of the rainfall infiltrates the trial landform. Infiltration has also been measured directly by disk permeameter and this method confirms the high rates of infiltration. Rates from direct measurement need to be further analysed and compared with those reported in previous infiltration studies at the Ranger site.
- Results from particle size measurement of surface material measured in 2009, 2012, 2014 and 2018 indicate that there has been little change in particle size distribution on the erosion plots (Plots 1 & 2 waste rock).

Workplan for 2020-21

- Write up suspended sediment results as an internal report.
- Weigh and measure particle sizes of the ex-situ rocks (see background above, located on the roof at the Jabiru Field Station).
- Undertake particle size measurements on erosion plots 1 & 2 on the trial landform.
- Completion of Internal Report (changed from SSR) on the background and broad results for the trial landform.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Rainfall and runoff data sets for the four erosion plots on the trial landform. This part of the project has been incorporated into RES-2010-024.
- Quantify
- parameters that will assist with the validation of the CAESAR-Lisflood LEM modelling. The data and modelling validation will assist with the development and construction of the rehabilitated landform.
- Annual bedload eroded and transported from the four erosion plots.
- Journal publications and technical advice to ERA.

The outcomes that this project will achieve are:

- The physical and chemical parameters on the Ranger Trial landform that will assist with:
  - The assessment of whether different surface treatments and vegetation establishment strategies on the Ranger trial landform result in different erosion rates through measurements of hydrology and infiltration.
  - Knowledge needs for plant available water and terms for groundwater modelling through measurements of infiltration rates and particle size of surface material on the trial landform.

Planned communication activities

The primary communication activities for the project are:

- Presentations and discussions with the relevant technical working group for mine rehabilitation and ARRTC.
- Journal publications.
- Supervising Scientist Report.
- Internal reports and annual research summaries.

Project publications to date (if applicable)

Boyden J, Saynor M & Erskine W 2016. Ranger Trial Landform: Hydrology – Rainfall & runoff data for Erosion Plot 1: 2009 - 2015. Internal Report 646 Supervising Scientist, Darwin.

Hancock GR, Lowry JBC & Saynor MJ 2016. Early landscape evolution - a field and modelling assessment for a post-mining landform. *Catena*, 147, pp. 699-708.

Hancock GR, Lowry JBC & Saynor MJ 2017. Surface armour and erosion – impacts on long-term landscape evolution. *Land Degradation & Development* DOI: 10.1002/ldr.2738.

Hancock GR, Saynor, MJ, Lowry JBC & Erskine WD 2020. How to account for particle size effects in a landscape evolution model when there is a wide range of particle sizes, *Environmental Modelling and Software 124*.

Lowry J, Saynor M, Erskine W, Coulthard T & Hancock G, 2014. A multi-year assessment of landform evolution model predictions for a trial rehabilitated landform, in Proceedings: Life-of-Mine 2014, The Australasian Institute of Mining and Metallurgy, Melbourne.

Saynor M, Boyden J & Erskine W 2016. Ranger Trial Landform: Hydrology – Rainfall & runoff data for Erosion Plot 2: 2009 - 2014. Internal Report 632 Supervising Scientist, Darwin. Unpublished paper.

Saynor MJ & Erskine WD 2016. Bed load losses from experimental plots on a rehabilitated uranium mine in northern Australia. In Proceedings of the Life-of-Mine 2016 Conference, 28-30 September, Brisbane Australia, The Australasian Institute of Mining and Metallurgy,pp. 168-171.

Saynor MJ & Houghton R 2011. Ranger trial landform: Particle size of surface material samples in 2009 with additional observations in 2010. Internal Report 596, August, Supervising Scientist, Darwin.

Saynor MJ, Lowry J, Erskine WD, Coulthard T, Hancock G, Jones D & Lu P 2012. Assessing erosion and run-off performance of a trial rehabilitated mining landform. In Proceedings: Life-of-Mine 2012. Maximising Rehabilitation

Outcomes, 10–12 July 2012, Brisbane, Qld, The Australasian Institute of Mining and Metallurgy, Carlton Victoria, 123–134.

Saynor MJ & Lowry JBC 2018. The impact of rip lines on erosion at the Ranger mine site, in Proceedings: Life-of-Mine 2018, The Australasian Institute of Mining and Metallurgy, Melbourne.

Saynor MJ, Lowry J & Boyden JM 2019. Assessment of rip lines using CAESAR-Lisflood on a trial landform at the Ranger Uranium Mine. *Land Degradation & Development*, 5, pp504-514.

Supervising Scientist 2019. Technical Advice 005 -Particle size on the trial landform, Supervising Scientist Branch.

Project Title	Assessing the geomorphic stability of the Ranger trial landform: calibrating model outputs		
KKN Theme	Landform		
KKN Title	LAN3. Predicting erosion of the rehabilitated landform		
KKN Question	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)?		
Project Status	Active		
Project number	RES-2010-007	**Project commencement date**	01/07/2017
Project duration (months)	27	**Estimated completion date**	30/07/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	Tom Coulthard, University of Hull
Resources 2020-21 (person weeks)	1		

Aims

- To assess the accuracy and reliability of CAESAR-Lisflood model simulations by comparing model outputs - specifically predictions of suspended sediment load and bedload - with field measurements from the Ranger trial landform for the same variables over comparable time periods.

Background

Modelling the geomorphic stability of the rehabilitated Ranger landform is undertaken using the CAESAR-Lisflood Landscape Evolution Model (LEM). The ability of the CAESAR-Lisflood model to predict erosion and sediment movement has been tested by comparing modelled predictions with measured observations from the erosion plots on the Ranger trial landform (TLF). Model predictions of bedload movement have demonstrated a good correspondence with measured observations since 2009. However, it has not been possible to compare modelled

and observed suspended sediment outputs for the same period. While field data on suspended sediment were collected between 2009 and 2014, only recently has it been possible to compile the data in a form suitable to be used to calibrate model outputs. The focus of this project is now directed at calibrating the model to achieve the necessary correspondence between model predictions and observed measurements of suspended sediment from the trial landform for the years where recorded data are available.

Progress against plan

- Calibration of the CAESAR-Lisflood LEM for suspended sediment from the trial landform was completed in May 2019, with testing showing a good correspondence between model prediction and field observations / measured outputs.
- Suspended sediment samples have been collected and analysed in the laboratory. The turbidity data have been cleaned and, where possible, a suspended sediment-turbidity relationship developed. In other cases, regression and averages have been used to estimate suspended sediment data for occasions when water was flowing over the flumes. Suspended sediment has been determined only for erosion plot 1, which is the most representative plot for Ranger rehabilitation (ie waste rock, tube-stock vegetation establishment treatment).
- A draft report documenting the methodology and initial results of the calibration of the model outputs of suspended sediment has been submitted for review.
- A sensitivity analysis of parameters affecting modelled sediment outputs has been completed and published in a peer-reviewed publication.
- A draft of a journal paper describing the calibration of the CAESAR-Lisflood model against suspended sediment and bedload data collected from the trial landform has been completed and is currently being revised following internal review.

Key findings

- The revised parameters identified in this project within the past year have resulted in good agreement between field and modelled outputs for both bedload and suspended sediment from the trial landform for periods of up to five years.This complements work in previous years which found similar results for bedload only.
- The results of the sensitivity analysis show that the selection of the appropriate sediment transport equation is the most important parameter in model simulations.

Workplan for 2020-21

- Complete revision of draft journal paper and re-submit for review.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Report from Professor Coutlthard (University of Hull) showing outcomes of sensitivity analysis of different model parameters and identifying optimal parameters to be used for model simulations.
- Peer-reviewed publication on results of uncertainty analysis on model undertaken by the University of Hull.
- Peer-reviewed journal publication comparing model predictions of sediment loads from erosion plots on trial landform with observed measurements.

The outcome that this project will achieve is:

- Increased confidence in model predictions of sediment load (both suspended sediment and bedload) through ability to successfully calibrate landform evolution model at the erosion plot scale.

Planned communication activities

The primary communication activities for the project are:

- A research paper published in an international and peer reviewed scientific journal comparing model predictions of sediment loads from erosion plots on trial landform with observed measurements.
- Key findings published in Annual Technical Report.
- Presentations to key stakeholders on request.
- Presentations to the broader scientific community at conferences and/or workshops.

Project publications to date (if applicable)

Lowry J, Saynor M & Erskine W 2015. A multi-year assessment of landform evolution model predictions for the Ranger trial landform. Internal Report 633, February, Supervising Scientist, Darwin.

Lowry J, Saynor M, Erskine W, Coulthard T and Hancock G 2014. A multi-year assessment of landform evolution predictions for a trial rehabilitated landform, in Proceedings of the Life-of-Mine 2014 Conference, 16–18 July 2014, Brisbane Australia. Australasian Institute of Mining and Metallurgy, pp. 67–80.

Lowry J, Coulthard T, Saynor M & Hancock G (in prep). A multi-year comparison of landform evolution model predictions with field observations.

Saynor MJ, Lowry J, Erskine WD, Coulthard T, Hancock G, Jones D & Lu P 2012. Assessing erosion and run-off performance of a trial rehabilitated mining landform. In Proceedings: Life-of-Mine 2012.

Saynor MJ & Erskine WD 2016. Bed Load losses from Experimental Plots on a Rehabilitated Uranium Mine in Northern Australia. Life-of-Mine 2016, Brisbane, Australasian Institute of Mining and Metallurgy.

Skinner CJ, Coulthard TJ, Schwanghart W, van de Wiel MJ & Hancock G 2018. Global sensitivity analysis of parameter uncertainty in landscape evolution models. *Geoscientific Model Development Discussions*,vol. 11, pp.4873-4888.

Project Title	Determining and testing representativeness of long-term rainfall patterns for use in final landform modelling		
KKN Theme	Landform		
KKN Title	LAN3. Predicting erosion of the rehabilitated landform		
KKN Question	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)?		
Project Status	Active		
Project number	RES-2014-006	**Project commencement date**	20/05/2015
Project duration (months)	50	**Estimated completion date**	31/08/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	
Resources 2020-21 (person weeks)	1		

Aims

- To use slackwater deposits in the East Alligator River, representing historic extreme floods, to determine the number, magnitude and frequency of palaeofloods that occurred before the start of hydrographic measurements on the river in 1971.
- To ensure the derived long term rainfall data set used in erosion modelling captures extreme flood events occurring in the recent (Holocene) past.

Background

SSB must assess the stability of the rehabilitated Ranger Mine for 10,000 years after construction and convince the stakeholders that there will be no major on- and off-site environmental effects associated with erosion. There is evidence of the occurrence of large historic floods on the East Alligator River in the past and floods of this magnitude have the potential to impact on the rehabilitated landform at Ranger. Therefore, to undertake landform evolution modelling at the 10,000

year scale, it is essential that the synthetic rainfall datasets used, which include large rainfall events, sufficiently represent extreme events as have occurred historically. This study seeks information on the number, magnitude and frequency of palaeofloods that have occurred during the last 7000 years since sea level has been stable, and which are larger than the largest (modern) recorded event.

Locating and dating of the slackwater deposits, either by optically stimulated luminescence (suitable for quartz sand) (OSL) and/or accelerator mass spectroscopy radiocarbon dating (suitable for coherent charcoal, wood or leaves), are essential in describing these extreme events.

Progress against plan

- Sites on the East Alligator River and Magela Creek were visited in 2015. A site on the upper East Alligator River in the gorge section was identified as the most likely to contain slackwater deposits andsediment samples were collected and dated.
- The site in the gorge section of the East Alligator River was visited again in August 2017. Several holes were excavated and the stratigraphy profile was described. Sediment samples from these holes were collected for particle size analysis and five samples from the profile were dispatched for dating by Optically stimulated luminescence (OSL).
- A journal paper has been accepted for publication pending authors' revision

Key findings

- Slackwater deposits have been identified in gorge areas in the East Alligator River. The height above the river bed indicates that the sediments were deposited by large floods. Nine very large floods, each about the same magnitude, occurred during the past 8,400 years in the East Alligator River (determined by dating). The latest, in 2007, had about the same specific discharge as the calculated Probable Maximum Flood in Magela Creek and hence the East Alligator R and Magela Ck floods can be considered as a single set. These floods have magnitudes larger than the Australian flood envelope curve and an Annual Exceedance Probability of 0.3% which can be assumed to be the probability of the Maximum Probable Rainfall at Ranger. The 2007 flood was, therefore, an extreme, and perhaps the most extreme, flood (and associated rainfall) likely to occur in the vicinity of Ranger.
- The recorded rainfall during the large rainfall event in 2007 has been incorporated into the synthetic rainfall data to be used in the CAESAR-Lisflood model. Rainfall from the largest three day rainfall recorded in Australia at Bellenden Ker has also been included in the wet scenario of the synthetic rainfall record.

Workplan for 2020-21

- Completion of Technical Advice to ERA - Large flood events

Planned project outputs and associated outcomes

The primary output for the project is:

- Knowledge of the number and magnitude of large floods that have occured in the East Alligator River during the Holocene (10000 years).
- Two journal publications from this investigation

The outcomes that this project will achieve are a better understanding of:

- The derived long term rainfall data set used in erosion modelling captures extreme flood events occurring in the recent (Holocene) past.

Planned communication activities

The primary communication activities for the project are:

- Journal publication.
- Presentations and discussions with relevant working groups, committees and ARRTC.
- Internal reports (data) and annual research summaries.

Project publications to date (if applicable)

Saynor MJ, Wasson RJ, Erskine WD & Lam D Accepted. Holocene Palaeohydrology of The East Alligator River, for Application to Mine Site Rehabilitation, Northern Australia. *Quaternary Science Reviews*

Saynor MJ & Erskine WD 2016. Sand slugs formed by large-scale channel erosion during extreme floods on the East Alligator River, Northern Australia. Geografiska Annaler: Series A, *Physical Geography* 98 (2), 169-181.

Saynor MJ & Erskine WD 2015. Use of slackwater deposits and other forms of geologic evidence to determine the number, magnitude and frequency of palaeofloods in the Alligator Rivers Region In eriss research summary 2013-2014, ed Supervising Scientist, Darwin NT, 150-156.

Project Title	Development of a method for monitoring gully formation on the rehabilitated landform using stereopsis and LiDAR		
KKN Theme	Landform		
KKN Title	LAN4. Development of remote sensing methods for monitoring erosion		
KKN Question	LAN4A. How do we optimise methods to measure gully formation on the rehabilitated landform?		
Project Status	Active		
Project number	RES-2017-005	**Project commencement date**	01/12/2017
Project duration (months)	36	**Estimated completion date**	01/11/2020
Lead team	ERL	**Date required**	01/01/2026
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	9		

Aims

- To develop a RPAS (remotely piloted aircraft system)-based method to identify and monitor gully formation on the final landform;
- To test and compare methods for assessing gully formation through the capture of Digital Elevation Models (DEMs) from both LiDAR and optical sensors; and
- To determine the accuracy of the RPAS derived DEMs in assessing gully formation.

Background

There will be a requirement to monitor and assess erosion and gully formation for landform closure criteria. It is critical that gully formation does not occur over tailings in mine pits such as to expose the tailings. Given the large size of the final rehabilitated landform, RPAS (remotely piloted aircraft systems), commonly referred to as drones, are a potentially useful tool to monitor and assess gully formation at such a scale.

SSB has various RPAS that produce digital elevation data at spatial accuracies suitable for measuring gully formation. Recently, SSB has acquired a LiDAR sensor, which has the capacity to generate very high -resolution DEMs. The LiDAR data and sensor will supplement and complement DEMs derived from SfM (structure from motion) techniques which utilise optical sensors. Together, these technologies will be used to identify and monitor gullies located in the area adjacent to the South Alligator River Valley (SAV) containment facility. The increasing accuracies of these technologies and the ease of obtaining data, make LiDAR a valuable monitoring tool. Focussing on this site will enable SSB to develop methodologies that can be applied to monitoring the final landform at Ranger and elsewhere in the region.

Progress against plan

- LiDAR flights were completed in December 2017 and June and November 2018 over the area of the SAV Containment. Data have been processed from both flights.
- Comparisons between flights have identified the need to incorporate geoidal corrections into dataset processing, to reduce offset between base elevations recorded for the datasets flown on different dates.
- Field activities were completed in September 2019.
- Workflows are being developed and data are being processed.

Key findings

- Due to delays in field work in 2019, there are no key findings to report.

Workplan for 2020-21

- Fly RPAS over SAV in September 2020
- Process RPAS data to detect and measure gullies and determine changes to the gully dimensions as a result of the 2018-19 and 2019-20 wet seasons.
- Compare accuracy of gully digital elevation models determined from ground based (Digital SLR & LiDAR backpack) and different RPAS platforms and sensors.
- Write up results in a journal paper.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Peer-reviewed publication documenting and describing the development of an RPAS-based method for monitoring gully formation on the rehabilitated landform.

The outcome that this project will achieve is:

- Development of a robust and cost effective method for use in detecting and assessing gully development on the Ranger rehabilitated landform.

Planned communication activities

- A research paper published in an international and peer reviewed scientific journal on gully determination using RPAS LiDAR.
- Key findings published in Annual Technical Report.
- Presentations to key stakeholders on request.
- Presentations to the broader scientific community at conferences and/or workshops.

Project publications to date (if applicable)

No project publications have been produced to date.

Project Title	Turbidity and suspended sediment relationships for Gulungul and Magela Creeks		
KKN Theme	Landform		
KKN Title	LAN5. Development of water quality monitoring methods for assessing landform erosion		
KKN Question	LAN5A. How can we use suspended sediment in surface water (or turbidity as a surrogate) as an indicator for erosion on the final landform?		
Project Status	Active		
Project number	RES-2016-007	**Project commencement date**	1/07/2016
Project duration (months)	48	**Estimated completion date**	1/05/2022
Lead team	ERL	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	3		

Aims

- To determine site specific relationships for suspended sediment and turbidity in Gulungul and Magela Creeks.
- To use these relationships to synthesise/develop a continuous suspended sediment trace from in-situ turbidity traces.
- To apply suspended sediment predictions arising from the turbidity-suspended sediment relationships to agreed statistical methods for future determination of mine-derived suspended sediment loads

Background

Fine suspended sediment (FSS) concentrations in streams have been measured indirectly using turbidimeters in numerous studies in the ARR. As part of several studies in the ARR, in situ turbidimeters were installed at gauging stations within the Magela Creek catchment to measure turbidity values on an almost continuous basis during the period of creek flows. The measurement of suspended sediment is a time and resource dependant activity. Water samples collected at gauging stations

by an automatic pump sampler during larger rainfall-runoff events have the FSS concentration determined by sieving, filtering and oven drying techniques. These FSS data along with concurrent in situ turbidity can be used to derive statistically significant relationships between FSS concentration and turbidity for gauging stations. These relationships allow the continuous turbidity data to be used to derive surrogate continuous FSS. In Moliere and Evans (2010), suspended sediment and turbidity relationships were developed up until 2008 for stations on Magela and Gulungul creeks. This project will check FSS versus turbidity relationships for Gulungul Creek and Magela Creek (MCDS & MCUS) using samples collected since 2008, and update the relationships as necessary.

Progress against plan

- Consultant Professor Ken Evans has provided a report on the analysis of fine suspended sediment transport in Gulungul Creek. This report analysed data from 2005-2006 to 2014-2015 for for Gulungul Creek.

Key findings

- The suspended sediment turbidity relationships were compared for Gulungul Creek upstream (GCUS) and Gulungul Creek downstream (GCDS).
- The relationship at GCUS had changed slightly from previous analysis (Moliere and Evans 2010) and there were insufficient additional samples at GCDS to determine if the relationship had changed.
- Similar data analysis should be undertaken for Magela Creek with any additional data collected since the analysis of Moliere and Evans (2010). It is also recommended that additional fine suspended sediment samples should be collected to further check these relationships.

Workplan for 2020-21

- Initial determination of suspended sediment-turbidity relationship for Magela and Gululgul Creek using data collected in 2019-2020.
- For the four locations, Magela Creek (upstream and downstream) and Gulungul Creek (GCUS & GCDS): apply suspended sediment predictions arising from the turbidity-suspended sediment relationships to agreed statistical methods for future determination of mine-derived suspended sediment loads.
- Continue data collection in Magela and Gululgul Creeks for the 2020-21 wet season

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Determination of site specific suspended sediment and turbidity relationships that will enable continuous suspended sediment loads to be determined.
- Application of suspended sediment predictions arising from the turbidity-suspended sediment relationships to agreed statistical methods for future determination of mine-derived suspended sediment loads.

Planned communication activities

- Journal publication
- Presentations and discussions with relevant stakeholders.

Project publications to date (if applicable)

Evans KG, Naravan M & Saynor MJ 2017 Analysis of fine suspended sediment transport in Gulungul Creek adjacent to Ranger Mine, Jabiru NT, Unpublished Confidential Report.

Moliere DR & Evans KG 2010. Development of trigger levels to assess catchment disturbance on stream suspended sediment loads in the Magela Creek, Northern Territory, Australia. Geographical Research 48, 370–385.

Moliere DR, Evans KG, Saynor MJ & Smith BL 2005. Hydrology and suspended sediment of the Ngarradj catchment, Northern Territory: 2003–2004 wet season monitoring. Internal Report 497, February, Supervising Scientist, Darwin. Unpublished paper.

ECOSYSTEM RESTORATION

Project Title	Assessing the effect spatial scale has on species composition and community structure for revegetation planning		
KKN Theme	Ecosystem restoration		
KKN Title	ESR1. Determining the characteristics of ecosystems in the areas surrounding the RPA.		
KKN Question	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?		
Project Status	Active		
Project number	RES-2019-013	**Project commencement date**	04/03/2019
Project duration (months)	4	**Estimated completion date**	11/09/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	Peter Erskine, Lorna Hernandez-Santin
Resources 2020-21 (person weeks)	1		

Aims

- To select and establish two 1 ha reference site plots in the Georgetown area of the Ranger Project Area for quantifying vegetation
- To compare existing ecosystem similarity measures with new data acquired from larger reference plots to determine whether proposed revegetation measures (i.e. stem densities) are appropriate
- To develop closure measures for species composition and community structure for both the overstorey and understorey

Background

A range of vegetation survey methods have been used to assess reference ecosystems to serve as targets for revegetation surrounding Ranger mine. One significant body of work was conducted in the Georgetown analogue site and surrounding area where 20 x 20 m plots were used to derive similarity and stem density metrics. However, due to recent advancements in paradigms of savanna ecology, the importance of spatial scales in savanna ecosystems has been elucidated, particularly for canopy structure metrics (see Staver 2018[10]). Importantly, this may have implications for the derivation of revegetation closure metrics at appropriate scales for restoration, and the assessment of restoration outcomes. In order to determine the effect that plot size has on revegetation metrics, two 1 ha plots have been established within the Georgetown analogue site and surveyed using the AusPlots survey method. These andadditional 1-ha scale data, together with small-scale (20 x 20 m) plot data gathered in earlier years, will be used to quantify the extent that scale has on revegetation metrics (i.e. stem densities and Bray-Curtis similarity). Additionally, data will be cross-checked to any proposed species composition and community structure metrics based on small-scale plot data to determine whether the proposed metrics are appropriate.

Progress against plan

- Two 1 ha plots were established within the Georgetown analogue site and the under- and overstorey surveyed using the AusPlots survey method
- Understorey and Overstorey datasets combined for analyses and manuscript.
- Data analysis completed
- Manuscript is receiving internal review prior to submission.

Key findings

- Plot sizes of at least 60 m x 60 m are suitable for monitoring species composition and functional attributes.
- Measuring structural attributes with a high level of confidence may require considerably increased sampling effort or incorporation of remote sensing techniques.
- Tree size distribution and stem density are also particularly affected by scale/plot size, indicating that remote sensing techniques may be a better option for effectively estimating these attributes.

Workplan for 2020-21

- Submission of journal paper and Technical Advice to ERA.

[10] Staver AC 2018. Prediction and scale in savanna ecosystems. *New Phytologist* 219, 52–57.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Information on the effect spatial scale has on determining revegetation components such as stem densities for species.
- Cross-checking of any proposed stem densities and species composition metrics with appropriate scale stem densities and species composition.

The outcome that this project will achieve is:

- Implications of metrics used to quantify restoration standards derived at different spatial scales

Planned communication activities

The primary communication activities for the project are:

- Report to the Ecosystem Restoration Working Group with key recommendations for setting vegetation closure criteria.
- Journal paper.

Project publications to date (if applicable)

Hernandez-Santin L, Nicholson J, Loewensteiner D A, Bartolo RE & Erskine PD (draft) Plot size does matter in vegetation assessments of savanna ecosystems, *Ecological Engineering*, in preparation.

Project Title	Using hyperspectral drone data for deriving species composition		
KKN Theme	Ecosystem Restoration		
KKN Title	ESR1. Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the mine site, including Kakadu National Park.		
KKN Question	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?		
Project Status	Active		
Project number	RES-2017-008	**Project commencement date**	17/06/2019
Project duration (months)	18	**Estimated completion date**	26/03/2021
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	16		

Aims

- To provide robust and cost-effective methods of calibrating and validating hyperspectral data collected using drones used for species identification.

Background

SSB is using analogue sites in the natural areas surrounding Ranger mine as the basis for reference ecosystems in line with Environmental Requirement 2.2a which in part states that revegetation of the disturbed sites of the Ranger Project Area is undertaken using local native plant species and is similar in density and abundance to those communities in adjacent areas of Kakadu National Park. The intent is to use RPAS (remotely piloted aircraft systems)-based remote sensing to scale the knowledge gathered from analogue sites to areas equivalent to the Ranger disturbed area. Using the areas of larger spatial scale will enable us to produce

more robust metrics for assessing achievement of closure criteria. Imagery collected by RPAS has a much finer spatial resolution when compared to other remote sensing data (e. g. satellite imagery). In addition, many of the sensors used on RPAS are early technology and standardised calibration and validation procedures for these sensors either do not exist or are still in development. This project will aim to develop robust methods for collecting, calibrating and validating the RPAS spectral data that we collect to surface reflectance. In particular, hyperspectral data will be used for a number of metrics associated with closure criteria, namely community structure elements such as species composition and abundance. Calibrated spectral imagery will provide a sound basis for accurate measurements of biophysical parameters used in the metrics across various spatial and temporal scales. These measurements will be used to assess progress towards mine close out.

Progress against plan

- Manuscripts
- describing the spectral characteristics of grass and understorey species and the implications for detection have been prepared for journal publication.
- Initial laboratory characterisation of the hyperspectral sensor has commenced.
- Testing of suitable media for calibration panels has also commenced.
- End of wet season flights over reference sites completed June 2020.

Key findings

- Morphologically and taxonomically similar grasses can be differentiated using spectra collected from multiple dates using phenological differences. This knowledge will inform the timing of flights to collect hyperspectral data for species discrimination.

Workplan for 2020-21

- Collection of hyperspectral and multispectral data over reference sites (from RES-2017-007) at various phenological stages (most likely late August-early September, mid-October and mid- November 2020).
- Collection of hyperspectral and multispectral data over Ranger trial landform at various phenological stages (same dates as above).
- Collection and processing of site irradiance data coinciding with drone flights (same dates as per above).
- Processing and analysis of data (ongoing throughout the time period).
- Submission of journal paper describing procedures for hyperspectral data acquisition and processing including calibration and validation (October 2020)
- Submission of journal paper describing method for, and accuracy of, detecting framework species using hyperspectral RPAS data (March 2021).

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A procedure for collecting, calibrating and validating hyperspectral data using drones suitable for deriving species composition.
- An operational field irradiance sensor and model for robust reflectance conversion.

The outcomes that this project will achieve are:

- Cost effective, robust and repeatable methods for collecting data that will describe community structure, particularly species composition.
- The ability to scale data to derive more robust metrics for comparing the revegetated mine site to adjacent reference ecosystems.

Planned communication activities

- Research papers published in an international and peer reviewed scientific journal detailing the methods, data collected and accuracies of validation.
- Key findings published in Annual Technical Reports.
- Presentations to key stakeholders on request.
- Presentations to the broader scientific community at conferences and/or workshops.

Project publications to date (if applicable)

Pfitzner KS, Bartolo RE, Loewensteiner DA, Esparon AJ, & Whiteside TG (in prep) Hyperspectral monitoring of non-native grass over phenological seasons. *Remote Sensing*, in preparation.

Pfitzner KS, Bartolo RE, Whiteside TG & Loewensteiner DA (in prep) The spectral reflectance of tropical savanna understorey species and recommendations for drone-based hyperspectral remote sensing for mine site closure planning. *Remote Sensing*, in preparation

Project Title	Quantifying spatial and temporal change in savanna		
KKN Theme	Ecosystem restoration		
KKN Title	ESR1. Determining the characteristics of ecosystems in the areas surrounding the RPA.		
KKN Question	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?		
Project Status	Complete		
Project number	RES-2013-002	**Project commencement date**	01/09/2013
Project duration (months)	68	**Estimated completion date**	16/04/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To develop a timeline of landscape disturbances and change for Kakadu National Park, and in particular, the Ranger lease area (1950-2016).
- To characterise vegetation change for a 'stable' temporal envelope (1996-2016) using the aerial photography record.
- To characterise vegetation recovery using the aerial photography record, (a) immediately post the Brucellosis and Tuberculosis Eradication Campaign (BTEC) (from 1996), and (b) post Cyclone Monica (from 2006).
- To characterise vegetation trajectories under a disturbance regime (1950–1981) using the aerial photography record.

Background

It is important that closure criteria, and our understanding of reference sites informing closure criteria for Ranger mine site, are developed in the context of temporal change in the landscape and disturbance of the site. The Environmental

Requirements refer specifically to revegetation under the primary environmental objectives for rehabilitation:

> *"revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, to form an ecosystem the long term viability of which would not require a maintenance regime significantly different from that appropriate to adjacent areas of the park".*

There are both spatial and temporal components in this objective that need to be addressed in order to derive closure criteria and assess their achievement. A landscape ecology approach is an appropriate framework to do this by. The aerial photography record of the region provides a suitable dataset to analyse vegetation change and trajectories for the Ranger minesite and surrounds over a number of temporal phases spanning 1950-2016.

The previous vegetation analogue research provides some of the information required for informing terrestrial vegetation criteria (such as species lists), but it is limited in both spatial and temporal extent, providing snapshots across the landscape but not more complete ecosystem dynamics. A landscape approach, such as deriving measures from time series remote sensing, provides a full dataset to compare an area of interest with the surrounding landscape through time. This approach will capture the natural variability, change and disturbance which have not been analysed in the previous research.

This project will provide an envelope of variability, or trajectory, in setting closure criteria and will provide a continuous representation of the landscape rather than discrete sampling points both spatially and temporally.

Progress against plan

- N/A – project complete.

Key findings

Results indicate that overall canopy cover in the area has been stable over long time scales with no temporal trends evident. Over the entire study area for the period 1950-2016, the average percentage woody cover per ha was 35.1% ± 15.1% standard deviation.

At finer temporal and spatial resolution, woody cover can be more variable. Amongst years there were fluctuations between 43% in 2010 and 28% in 1978. Spatially, there is a slight increase in cover moving in the north to south and west to east directions.

The long-term stability and resilience of woody cover in the savanna adjacent to the Ranger mine provide a robust basis to inform ecosystem restoration targets. For example, the at-scale analyses of attributes such as canopy cover are well

placed to describe the inherent heterogeneity within the reference ecosystem, which would be a restoration goal.

Workplan for 2020-21

- N/A – project complete

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Decadal time series analysis of woody cover change over the region surrounding the Ranger mine between 1950 and 2016.
- Revegetation trajectories informed by change in woody cover
- Interim closure measures for canopy cover.

The outcome that this project will achieve is:

- Change in woody cover can be used to inform revegetation trajectories and will provide a closure measure for canopy cover for Ranger mine rehabilitation.

Planned communication activities

The primary communication activities for the project are:

- Timeline of landscape change.
- Report to the relevant Ecosystem Restoration Working Groups with key recommendations for setting vegetation closure criteria.
- Plain language summary of the key findings and advice on when (timeframe) the revegetation may be on an agreed trajectory to meeting the ERs.
- Conference presentation.
- Journal papers.

Project publications to date (if applicable)

Whiteside TG, Esparon AJ & Bartolo RE 2020. A semi-automated approach for quantitative mapping of woody cover from historical time series aerial photography and satellite imagery. *Ecological Informatics* 55, 10112.

Loewensteiner DA, Bartolo RE, Whiteside TG, Esparon AJ & Humphrey CL In review Measuring savanna woody cover at scale to inform ecosystem restoration. *Ecosphere*

Project Title	Factors affecting spatial and temporal change in savanna		
KKN Theme	Ecosystem restoration		
KKN Title	ESR1. Determining the characteristics of ecosystems in the areas surrounding the RPA.		
KKN Question	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?		
Project Status	Complete		
Project number	RES-2017-026	**Project commencement date**	30/03/2018
Project duration (months)	12	**Estimated completion date**	24/12/2019
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	Lynda Prior, David Bowman, Grant Williamson - University of Tasmania
Resources 2020-21 (person weeks)	0 (Project is complete)		

Aims

- To link landscape disturbances (fire, feral animals, cyclones and rainfall) to measured landscape changes in the surrounding environment through statistical inference techniques.
- To identify the key drivers of temporal vegetation cover change.
- To provide data to inform the envelope of trajectories for Ranger rehabilitation.

Background

It is important that vegetation closure criteria for the Ranger mine site are developed in the context of temporal change in the area surrounding the Ranger mine lease. The Environmental Requirements refer specifically to revegetation and ecosystem restoration endpoints as similar to the surrounding environment under the primary environmental objectives for rehabilitation.

The current state of vegetation surrounding Ranger mine has been influenced by disturbances such as fire, rainfall variability, cyclones, buffalo and previous land tenures. This project provides a statistical analysis of the relative importance of these disturbances on vegetation trajectories. For this, the analysis uses landscape metrics derived from a time series of remote sensing imagery (RES-2013-002). The data set compiled under this linked project (the descriptive component) is time-series woody cover, extracted from historical aerial photo archive and satellite imagery. The woody cover is restricted to particular land units described as upland savanna. Years for the dry season imagery are: 1950, 1964, 1976, 1978, 1981, 1984, 2004, 2010 and 2016. The woody cover is available at three scales: the woody cover itself (e.g. canopy level), percentage per 1 ha cells within the land unit polygons, and percentage per land unit polygon.

The University of Tasmania will undertake inferential analysis to determine the drivers (natural and anthropogenic) of woody cover change for the savanna landscape surrounding Ranger uranium mine over the 1950-2016 time series of woody cover data sets. The findings will inform an envelope of outcomes/trajectories for the Ranger uranium mine revegetation.

Progress against plan

- N/A – project complete

Key findings

- No overall trend in woody cover was detected through time (see also Project RES-2013-002). Some variation in woody cover was related to rainfall in the previous 12 months, and there were weak effects associated with fire history in the year of image acquisition and the antecedent four years. The results suggest that at the local (or regional) scale, mesic eucalypt savannas are resilient to short term variations in rainfall and fire activity.

Workplan for 2020-21

- N/A – project complete.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Identification of the drivers of change based on the correlative analysis. This will include contextualising the changes (i.e. predominant drivers compared with secondary drivers) observed over the past and present with the landscape change timeline for Kakadu, and discussion on projected future changes (if possible).
- Refinement of the State and Transition Model for Ranger revegetation.
- Confirmation of the major natural drivers of landscape change in the surrounding environment.

The outcome that this project will achieve is:

- The statistical inference of the key drivers of historical change in woody cover which can be used to indicate potential future change and recovery after natural disturbance in savanna surrounding the rehabilitated mine site

Planned communication activities

The primary communication activities for the project are:

- Research paper published in an international peer-reviewed journal.
- Key findings published in Annual Technical Report.
- Presentations to key stakeholders as required.
- Presentations to the broader scientific community at conference and/or workshop.

Project publications to date (if applicable)

Prior LD, Whiteside TG,Williamson G, Bartolo RE & Bowman DMJS 2020. Multi-decadal stability of woody cover in a mesic eucalypt savanna in the Australian monsoon tropics. *Austral Ecology*, 45(5), 621-635. doi: 10.1111/aec.12877

Project Title	Deriving species composition measures and their environmental correlates to assess ecosystem restoration similarity		
KKN Theme	Ecosystem restoration		
KKN Title	ESR1. Determining the characteristics of ecosystems in the areas surrounding the RPA.		
KKN Question	ESR1C. What values should be prescribed to each indicator of similarity to demonstrate revegetation success?		
Project Status	Active		
Project number	RES-2017-007	**Project commencement date**	01/10/2017
Project duration (months)	33	**Estimated completion date**	30/09/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	Centre for Mined Land Rehabilitation, The University of Queensland
Resources 2020-21 (person weeks)	15		

Aims

- To select and establish ecologically appropriate 1-ha reference site plots in areas of Kakadu National Park adjacent to Ranger mine site and undisturbed areas of the Ranger Project Area.
- To conduct floristic surveys of the 1-ha reference site plots.
- To derive environmental correlates of vegetation species composition using existing plot data from Kakadu National Park and Georgetown studies, and from physical and chemical properties of additional soil samples.
- To assess 1-ha plot variability using the above-listed data.

Background

Over the last few decades, a considerable amount of work has been conducted throughout the Alligator Rivers Region to explore and assess reference

communities to serve as targets for the Ranger mine site rehabilitation (see RES-2014-002 'Assessment of available vegetation reference site information for use in ecological restoration at Ranger mine site'). Surveys have generally focused on areas close, or adjacent, to the mine lease areas, and have been conducted by a number of different groups. Not surprisingly, there has also been a range of approaches to the design, replication, plot size and strata selected for the survey of vegetation. Common elements amongst studies have generally included: a stratified random design; a plot size of 20 x 20 m; and, assessments of trees/shrubs above 2 m. However, one study had a stratified systematic design and collected triplicate plot data (1200 m^2 total), another used 30 x 30 m sampling plots, whilst one conducted seasonal sampling, counted trees/shrubs >1.5 m and collected data up to 100 km from the Ranger mine. Understorey components were collected in two studies. These inherent differences make these datasets difficult to combine for use in deriving and setting clear closure criteria.

Some of the most applicable datasets are more than 20 years old, and, representing point surveys in time, do not capture the necessary inherent seasonal and inter-annual changes and variability required for specifying a number of the relevant closure criteria for ecosystem restoration. The availability of understorey data from earlier surveys is also very limited. Further, for the development of some closure criteria, the spatial scale of measurement used in the earlier surveys may not be appropriate. For these reasons and for key ecosystem attributes, it is timely to collect new data at appropriate sampling scales that can be used to derive and assess revegetation closure criteria for Ranger mine site. Using information and sites investigated in the vegetation trajectory project (RES-2013-002), one-hectare sites will be selected for measurement and assessment using the AusPlots method of field sampling. These field data will be used to provide interim species composition measures that can be used in revegetation planning for rehabilitation. Importantly, this project will include measures of understorey and seasonal changes in vegetation (phenology). These data will also be used in the development of methods for monitoring revegetation at-scale with drones.

In addition to the results of Humphrey et al (2012)[11] and Erskine et al (2019)[12], ecologically-relevant relationships between environmental data (soil chemistry, landscape position) and vegetation communities derived from the current study will be derived and reported.

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11 Humphrey CL, Lowry J & Fox G 2012. Use of vegetation analogues to guide planning for rehabilitation of the Ranger mine site. In ***eriss*** research summary 2010–2011. eds Jones DR & Webb A, Supervising Scientist Report 203, Supervising Scientist, Darwin NT, 135–145

12 Erskine PD, Bartolo R, McKenna P & Humphrey C. 2019. Using reference sites to guide ecological engineering and restoration of an internationally significant uranium mine in the Northern Territory, Australia. *Ecological Engineering* 129, 61-70.

Progress against plan

- Twelve one-hectare plots from savanna forest have been established and surveyed using the Ausplots method on suitable land units surrounding the mine, including two in the Georgetown analogue area.
- All data have been collected to populate the ecosystem restoration standard 'similarity' attributes with interim metrics
- Two intermittent flooding savanna plots have been established with surveys completed in May 2019
- Soil samples for chemical analyses and metagenomics have been collected from all plots; chemical analyses were completed in April 2020.
- Final draft of a journal article on understorey diversity has been submitted for publication.
- Draft of journal paper on practical method of developing reference ecosystem in progress.
- Journal paper on reference site selection in preparation for submission to Restoration Ecology.
- Technical Advice reports on species richness and composition submitted with two more Technical Advices a in final draft phase, i.e. on the proportion of Georgetown low open forest surrounding Ranger and functional types of vegetation.
- Presentation of the findings to the Ecosystem Restoration Working Group (and meetings with ERA)

Key findings

- Savanna woodland communities are diverse and variable across the landscape in both the understorey and overstorey. For overstorey, two open forest community types were identified, consistent with previous vegetation classifications undertaken using smaller spatial scale (20 x 20 m) data. One of these overstorey community types (low open forest) is prominent only in the Georgetown area. Greater variability was observed in understorey composition compared to overstorey with three broad understorey groups identified. Functional types across the landscape vary less than species composition, indicating convergence of functional types and possible functional redundancy in the surrounding understorey.
- Vegetation cover in both strata are dominated by a small number of species, with 10 species accounting for 80% of understorey cover and 10 species accounting for 95% of overstorey cover.

Workplan for 2020-21

- Finalise submission of journal article on understorey reference ecosystems in savanna woodlands
- Submission of journal article on method of generating reference ecosystem

- Finalise remaining Technical Advices (Functional characteristics of vegetation, physical and chemical soil data, seasonally inundated reference sites, proportions of forest types surrounding Ranger) Planned project outputs and associated outcomes

The primary outputs for the project are:

- Interim species composition data for both overstorey and understorey at 1-ha scale that can be used in nursery planning for the rehabilitation being undertaken at Ranger. Measures include stem densities.
- Interim measures for SSB's Ecosystem Restoration Standard for sub-attributes of species composition
- Journal publication on savanna understorey diversity
- Journal publication on the method undertaken for reference site selection.
- Journal publication on a practical method for generating a reference ecosystem.
- Technical Advice reports on species composition, plant functional types, and proportions of forest, edaphic conditions and environmental correlates in the savanna surrounding Ranger.
- Conference presentations on savanna woodland diversity and alignment with the SSB Ecosystem Restoration Standard

The outcomes that this project will achieve are:

- Information informing revegetation planning, closure criteria and assessment of whether the rehabilitated site will be similar to surrounds.
- Conceptualisation of reference ecosystems for communication with stakeholders

Planned communication activities

The primary communication activities for the project are:

- Key findings published in the Annual Technical Report and reported to ARRTC and ARRAC
- Presentations to key stakeholders on request.
- Research papers published in peer reviewed scientific journals
- Presentations to the broader scientific community at conferences and/or workshops.
- Series of Technical Advice reports submitted to ERA.

Project publications to date (if applicable)

Supervising Scientist 2019. Species richness and composition indicator values for assessing ecosystem similarity for savanna woodland. Technical Advice 006. Supervising Scientist, Darwin.

Supervising Scientist 2019. Vegetation strata, woody plant species size class distribution and total basal area data for use as indicator values. Technical Advice 007. Supervising Scientist, Darwin.

Hernandez-Santin L, Rudge ML., Bartolo RE, Whiteside TG, Erskine PD (in review) Protocols for reference site selection for mine site ecosystem restoration. *Restoration Ecology*.

Nicholson JD, Hernandez-Santin L, Rudge ML,. Ufer NG, Erskine PD & Bartolo RE (submitted) Assessing understorey vegetation diversity of tropical savanna to inform mine site restoration in northern Australia. *Australian Journal of Botany*.

Project Title	Deriving vegetation community structural attributes that inform the conceptual reference ecosystem		
KKN Theme	Ecosystem restoration		
KKN Title	ESR1. Determining the characteristics of terrestrial vegetation in the areas surrounding the RPA.		
KKN Question	ESR1C. What values should be prescribed to each indicator of similarity to demonstrate revegetation success?		
Project Status	Active		
Project number	RES-2019-012	**Project commencement date**	04/02/2019
Project duration (months)	29	**Estimated completion date**	30/09/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	CMLR: Peter Erskine; Lorna Hernandez-Santin CSIRO: Shaun Levick
Resources 2020-21 (person weeks)	2		

Aims

- To select and establish ecologically appropriate 1-ha reference site plots in areas of Kakadu National Park adjacent to Ranger mine site and undisturbed areas of the Ranger Project Area.
- To conduct floristic surveys of the 1-ha reference site plots.
- To develop interim closure measures for community structure (canopy, understorey and ground cover, size class distribution, stem diameter at breast height) of both the overstorey and understorey.
- To develop vegetation monitoring methods for measuring community structure attributes using drones.

Background

Over the last few decades, a considerable amount of work has been conducted throughout the Alligator Rivers Region to explore and assess reference communities to serve as targets for the Ranger mine site rehabilitation (see RES-2014-002 'Assessment of available vegetation reference site information for use in ecological restoration at Ranger mine site'). Surveys have generally focused on areas close, or adjacent, to the mine lease areas, and have been conducted by a number of different groups. Not surprisingly, there has also been a range of approaches to the design, replication, plot size and strata selected for the survey of vegetation. Common elements amongst studies have generally included: a stratified random design; a plot size of 20 x 20 m; and, assessments of trees/shrubs above 2 m. However, one study had a stratified systematic design and collected triplicate plot data (1200 m^2 total), another used 30 x 30 m sampling plots, whilst one conducted seasonal sampling, counted trees/shrubs >1.5 m and collected data up to 100 km from the Ranger mine. Understorey components were collected in two studies. These inherent differences make these datasets difficult to use together for the goal of setting clear closure criteria.

Some of the most applicable datasets are more than 20 years old, and, representing point surveys in time, do not capture the necessary inherent seasonal and inter-annual changes and variability required for specifying a number of the relevant closure criteria for ecosystem restoration.The availability of understorey data from earlier surveys is also very limited. Further, for the development of some closure criteria, the spatial scale of measurement used in the earlier surveys may not be appropriate. For these reasons and for key ecosystem attributes, it is timely to collect new data at appropriate sampling scales that can be used to derive and assess revegetation closure criteria for Ranger mine site. Using information and sites investigated in the vegetation trajectory project (RES-2013-002), one-hectare sites will be selected for measurement and assessment using the AusPlots method of field sampling. These field data will be used to provide interim community structure measures (canopy, understorey and ground cover, size class distribution, stem diameter at breast height) for both the overstorey and understorey that can be used in revegetation planning for rehabilitation. These data will also be used in the development of methods for monitoring revegetation at-scale with drones.

Progress against plan

- Twelve one hectare plots from savanna forest have been established and surveyed using the Ausplots method on suitable land units surrounding the mine, including two in the Georgetown analogue area.
- All data have been collected to populate the ecosystem restoration standard for 'similarity' attributes with interim metrics

- Two intermittent flooding savanna plots have been established with surveys completed in May 2019 (DBH surveys have not yet been conducted due to logistical constraints).
- Submitted Technical Advice report on community structure.
- Presentations to Ecosystem Restoration Working Group and ARRTC undertaken with updates of recent data collected.
- A study comparing the utility of terrestrial (TLS), mobile (MLS) and drone-based (DLS) LiDAR for measuring structural attributes has been completed.

Key findings

- Basal area varied amongst plots with an average of 7.5 m^2 ha^{-1}. However, the two most abundant eucalypt species (*E. miniata* and *E. tetrodonta*) made up over 50% of this area, indicating their significant dominance across the landscape.
- 80% of stems were less than 10 cm diameter at breast height (DBH). A large proportion of these smaller trees were *Acacia mimula* and *Eucalyptus tetrodonta*. There were few trees greater than 30 cm DBH in all plots.
- LiDAR data can be used to accurately measure community structural attributes in savanna:
  - Attributes such as height and canopy volume can be readily calculated for each tree from data collected by all three LiDAR platforms.
  - MLS and TLS data can provide DBH and basal area measuresin reference plots.
  - DLS data have the advantage of providing attribute measures at scale.
  - The use of allometric equations based on data collected from TLS and MLS will enable us to develop estimates of DBH and basal area at scale from the DLS data.

Workplan for 2020-21

- Review and submit publication from Shaun Levick (CSIRO) on LiDAR data comparisons

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Interim vegetation community structure measures for both overstorey and understorey at 1-ha scale that can be used in establishment planning for the rehabilitation being undertaken at Ranger. Measures include canopy cover and size class distribution.
- Development of methods and metrics for monitoring and assessing revegetation closure criteria at-scale for community structure through the linking of plot data to drone data.

- Conceptualisation of reference ecosystems for communication with stakeholders

The outcomes that this project will achieve are:

- Conceptualisation of reference ecosystems for communication with stakeholders
- Understanding of differences between ground-based and airborne LiDAR data collection in savanna woodland

Planned communication activities

The primary communication activities for the project are:

- Key findings published in the Annual Technical Report and reported to ARRTC and ARRAC.
- Presentations to key stakeholders on request.
- Research papers published in peer reviewed scientific journals.
- Presentations to the broader scientific community at conferences and/or workshops.
- Series of Technical Advice reports submitted to ERA.

Project publications to date (if applicable)

Nil.

Project Title	Long-term viability of the ecosystem established on the trial landform		
KKN Theme	Ecosystem restoration		
KKN Title	ESR5. Develop a restoration trajectory for Ranger mine		
KKN Question	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?		
Project Status	Active		
Project number	RES-2017-009	**Project commencement date**	26/02/2019
Project duration (months)	12	**Estimated completion date**	30/4/2021
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	9		

Aims

- To use remote sensing and field-based methods to undertake a quantitative assessment over a number of years of the long-term sustainability of the ecosystem established on the trial landform, including the monitoring of vegetation health, survival and recruitment, and soil development and evolution of nutrient cycling.
- Use the data from above to help inform the rehabilitation trajectory for the entire landform.
- Develop routine monitoring techniques that can be applied across the entire rehabilitated landform.

Background

Revegetation of the trial landform (TLF) commenced 10 years ago with the planting of overstorey species (trees and large shrubs). Most other research on ecosystem establishment in waste rock at Ranger has been undertaken on much

shorter time frames and many of these areas have since either been cleared or covered in stockpiles. Therefore, the TLF provides a valuable 'baseline' for the assessment of revegetation efforts on waste rock over a long term period (10-15 years). This project will use quantitative methods to assess the long term sustainability of the ecosystem that has been established on waste rock. Analysis of the trajectory of the waste rock system as it further matures (including dynamics in plant phenology, recruitment, mortality, species preferencing, understory establishment, soil development and litter decomposition etc.) will contribute to informing whether closure criteria for the rehabilitated landform are likely to be met.

Progress against plan

- The GPS location of all plants above 0.5 m on all sections of the TLF has been completed and data provided to ERA.
- Multispectral flights pre- and post-burns on the TLF have been conducted and image mosiacs provided to ERA.

Key findings

- Nil to report

Workplan for 2020-21

- Analysis of the data collected to define the state of the vegetation established on the TLF (December 2020).
- Routine end of dry and wet season UAV data collections (October 2020 and April 2021).
- Data analysis (November 2020)
- Reporting (December 2020)

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A quantitative assessment of key indicators of similarity and sustainability of the plant community on the trial landform post 10 years establishment.
- Refinement of the State and Transition Models being developed for revegetation.

The outcome that this project will achieve is:

- Information that can be used to assess the long term sustainability of the ecosystem that has been established on Ranger waste rock.

Planned communication activities

The primary communication activities for the project are:

- Research papers published in international and peer-reviewed scientific journals describing methods and validation, and findings, including comparisons to analogue sites.
- Key findings published in Annual Technical Report.
- Presentations to key stakeholders on request.
- Presentations to the broader scientific community at conferences and/or workshops

Project publications to date (if applicable)

Whiteside T, Bartolo, R & Boyden J 2017. Application of multi-source UAV data to assess revegetation efforts on waste rock, In: UAS4RS 2017 Conference, 24-25 May 2017, Hobart.

Project Title	Developing restoration trajectories to predict when the restored site will move to a sustainable ecosystem		
KKN Theme	Ecosystem restoration		
KKN Title	ESR5. Develop a restoration trajectory for Ranger mine		
KKN Question	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?		
Project Status	Active		
Project number	RES-2019-017	**Project commencement date**	21/01/2019
Project duration (months)	6	**Estimated completion date**	30/08/2020
Lead team	ERL	**Date required**	01/03/2022
In-house or outsourced	External	**Supporting team(s)**	CSIRO- Anna Richards and Amy Warnick
Resources 2020-21 (person weeks)	1		

Aims

- To develop ecosystem restoration trajectories for Ranger mine site using a state and transition modeling approach by:
  - Interpreting and synthesizing the considerable body of scientific research on savanna ecosystems that has been undertaken for the site and region;
  - Documenting competing or alternative viewpoints on rehabilitation trajectories and end states; and
  - Undertaking uncertainty analysis.
- To identify knowledge gaps and inform future experimental design.

Background

Ranger uranium mine is scheduled to close in 2026. Close-out of the site will be achieved once environmental requirements set out in the Australian Government's environmental protection conditions (Environmental Requirements) have been

met (or are on a trajectory to being met). The key environmental requirements for ecosystem restoration of the mine site are "to establish an environment with habitats and erosion characteristics similar to adjacent areas of Kakadu National Park and stable radiological conditions that comply with national requirements and are as low as reasonably achievable".

The Supervising Scientist's Ecosystem Restoration Standard specifies a trajectory-based approach to closure assessment. Full ecosystem restoration of the Ranger mine site will take many decades. To account for this long time scale, restoration success can be assessed against modelled restoration trajectories. The trajectories represent multiple possible restoration outcomes based on factors that may influence the progress of restoration over time, such as fire and weeds. Ongoing monitoring will be required to: assess where the ecosystem has developed relative to the possible trajectories over time; inform management activities; and validate and assess confidence in the model. The trajectory model can then be used to determine the point at which the ecosystem is likely to progress to successful restoration without further management input. Previous research (see project RES-2016-015 "Review of revegetation outcomes arising from historic mine sites in the Alligator Rivers Region") has resulted in a preliminary state and transition model for Ranger mine site based on existing research and trajectories for flora and fauna at mine sites in the Alligator Rivers Region and near surrounds.

This project will build further on the preliminary state and and transition model and aims to address Key Knowledge Need ERS5B: "What are possible/agreed restoration trajectories (flora and fauna) that would ensure the rehabilitated site will move to a sustainable ecosystem without further management intervention which is significantly different from that of the surrounding natural ecosystems?".

Progress against plan

- An expert elicitation workshop (30 attendees) was held in April 2019. A number of end states were presented and described by workshop participants, along with deviated states and management actions.
- A survey was provided to workshop attendees post-workshop to quantify likelihood, consequence and uncertainty for the components of the state and transition model.
- A report has been drafted by lead researchers from CSIRO, SSB and ERA.

Key findings

- A state and transition model describing desirable and undesirable transitions (and associated states) along a trajectory to closure was developed by workshop participants.
- Three potential end-states were described: 1) Similar to surrounds (assuming a plausible climate change scenario 100 years from present day; 2) Extreme climate drying (assuming an extreme climate change scenario

from present day); and 3) Functional understorey (assuming a dry-adapted overstorey and midstroey species mix).
- A further 9 establishment states and 12 intermediate states were identified and described.
- Threats that drive undesirable transitions, together with management interventions applied to reverse the transitions resulting from these threats, were identified.
- A list of undesirable transitions, their drivers, timeframe for the transitions to occur, and any pre-conditions necessary for transition, was developed.
- The results of risk analyses identified one critical transition risk moving from an ideal dry-adapted overstorey and midstorey species mix state to a weedy understorey as the result of excessive fire and grassy-transformer weed invasion.

Workplan for 2020-21

- Finalisation of report through formal review of the project and outputs in collaboration with ERA to ensure the resulting state and transition model is useful for informing operational management of ecosystem restoration at Ranger mine site.
- Finalisation of Technical Advice to ERA

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Project report documenting: (i) the restoration trajectories against which to assess the achievement of closure criteria expected to be reached after a period of time from initial establishment, and (ii) defined end state(s) for up to 50-100 years after initial establishment.
- Conference presentation at the Ecological Society of Australia Conference in November 2019.

The outcomes that this project will achieve are:

- Agreed ecosystem restoration trajectories that ensure the rehabilitated site will move to a sustainable ecosystem without further management intervention significantly different from that of the surrounding natural ecosystems.
- Address the requirements for an ecosystem restoration trajectory approach as outlined in the Supervising Scientist Ecosystem Restoration Standard.

Planned communication activities

The primary communication activities for the project are:

- Presentations to ARRTC.

- Presentations to stakeholders including the Ecosystem Restoration Working Group.
- Conference presentation at the Ecological Society of Australia Conference 2019.
- Technical Advice.

Project publications to date (if applicable)

Richards A, Bartolo, R, Loewensteiner, D & Warnick, A (In review).
Rehabilitation trajectories for Ranger mine, Final report. CSIRO, Australia.

Project Title	Ecohydrology and sensitivity of riparian flora (NESP project)		
KKN Theme	Ecosystem restoration		
KKN Title	ESR6. Understanding the impact of contaminants on vegetation establishment and sustainability		
KKN Question	ESR6A. What concentrations of contaminants from the rehabilitated site may be available for uptake by terrestrial plants?		
Project Status	Active		
Project number	RES-2017-022	**Project commencement date**	01/03/2018
Project duration (months)	31	**Estimated completion date**	15/01/2021
Lead team	WASQ	**Date required**	01/03/2022
In-house or outsourced	Collaboration	**Supporting team(s)**	Charles Darwin University: Lindsay Hutley; Clement Duvert; Michael Brand; Sam Setterfield
Resources 2020-21 (person weeks)	2		

Aims

- To use stable isotopes and tritium to age and quantify water sources (soil water, creek water and/or surface and deep groundwaters) used by riparian vegetation within the Magela Creek catchment in the vicinity of Ranger uranium mine.
- To undertake pot trials to examine the sensitivity of dominant riparian woody species to $MgSO_4$.
- To assess the implications to riparian vegetation of groundwater solute expressing to Magela and Gulungul Creeks, and determine the salt toleerances of key riparian species.

Background

Current understanding of ecohydrological properties of Northern Australian vegetation suggests spring-fed monsoon vine forests and riparian vegetation have a high groundwater dependence. Contamination of surface and/or groundwater post-rehabilitation of Ranger mine site could have a potential impact on riparian vegetation and thus stream health.

Pit closure at Ranger mine site is predicted to result in exfiltrating groundwater with high levels of $MgSO_4$ derived from waste rock. Solute modelling predicts that within 10 years of closure, groundwater may have a $MgSO_4$ concentration >3 mg L^{-1}, i.e., in excess of desired exposure limits for surface waters. This presents a potential threat to the ecology of Magela Creek for any organisms utilising groundwater sources. This project will focus on risks posed to groundwater dependant ecosystems (GDEs), in particular, riparian vegetation of Magela and Gulungul Creeks.

Environmental isotopes and tritium analysis will be used to quantify groundwater dependence of riparian vegetation in the Ranger Project Area. This knowledge will be coupled with testing of common riparian woody species for sensitivity to $MgSO_4$ thereby informing a risk assessment of impact from surface and/or groundwater egress of mine-related contaminants.

This project is linked to RES-2018-002 'Effects of groundwater egress to ecological connectivity'.

Progress against plan

- NESP collaborators have held consultation and planning meetings with SSB.
- Identification of species to conduct pot trials (seedling exposures to $MgSO_4$)
- Preliminary pot trials have been completed at the University of Western Australia and the results have been published in a peer-reviewed journal It was found that the growth of *Alphitonia excelsa* was not affected until $MgSO_4$ concentrations in soil water exceeded 960 mg/L. There were no measurable effects of elevated $MgSO_4$ on *Melalueca viridiflora* at the concentrations that were tested.
- Definitive experiments are nearly complete at Charles Darwin University with 4 additional riparian species propagated and tested over a period of 10 months. There have been little to no observed effects on the growth of these species after seven months of exposure to elevated $MgSO_4$. Plants were planned to be harvested in April 2020 to quantify biomass and assess ion concentration in plant tissues across all treatments.
- In October 2019 the second major sampling at Magela Creek was conducted. Twigs from each tree species, soil from different depths (to 3.2 m), and shallow groundwater were collected. Groundwater samples and

water extracted from the twigs and soil will be analysed for the stable isotopes deuterium and ^{18}O, which can determine the source of the water.
- The West Australian Biogeochemistry Centre has analysed around 230 samples collected over three field trips.
- Samples of deeper groundwater are being analysed for stable isotopes and tritium. Tritium analysis is being undertaken by the Australian Nuclear Science and Technology Organisation (ANSTO). SSB staff at Jabiru also collected daily rainwater samples throughout the 2019–20 wet-season for isotope analysis.

Key findings

- The preliminary pot trials conducted at UWA were used as range finders to optimise test conditions under which the experiments at CDU were to be conducted.
- The preliminary pot trials showed that *Melaleuca* sp. was very tolerant to magnesium sulfate exposure but *Alphitonia* sp. was of intermediate sensitivity.
- The additional 4 riparian species were tolerant of high $MgSO_4$ concentrations.

Workplan for 2020-21

- Final field campaign – mid-dry season sampling (soil, twigs, groundwater, tritium sampling), processing (July-August 2020)
- Final field campaign - late dry season sampling (soil, twigs, groundwater), sample processing (September 2020)
- Isotope data collation, manuscript preparation.
- Pot trial – Operation, application of treatments, ongoing measures of growth and plant stress. Examining two culturally important species, i.e. *Barringtonia acutangula* (freshwater mangrove) and *Pandanus aquaticus* (river pandanus). Further trials with *A. excelsa* will be conducted to determine a more accurate $MgSO_4$ toxicity threshold.
- Pot trial – Data analysis, manuscript preparation and publication submission, synthesis and collation of data and reports, and communication activities (December 2020)
- Modelling to determine the proportion of water being used by riparian trees from each source, i.e. soil water at different depths, shallow groundwater, deeper groundwater.
- Modelling of the tritium data to determine the rate of groundwater flow towards Magela Creek.
- Characterisation of vegetation abundance and health from sites on Magela Creek that have a history of elevated $MgSO_4$ concentrations. This will be undertaken in collaboration with SSB staff.

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Assessment of the risks to riparian vegetation of groundwater solute expressing to Magela and Gulungul Creeks, and determine the ($MgSO_4$) tolerances of key riparian species.

The outcome that this project will achieve is:

- The $MgSO_4$ concentrations that will be "safe" for riparian vegetation, which will inform the risk to off-site environment and ALARA process for the on-site rehabilitation.

Planned communication activities

The primary communication activities for the project are:

- Key findings published in the Annual Technical Report and reported to ARRTC and ARRAC.
- Presentations to key stakeholders on request.
- All NESP Northern Australia Environmental Research (NAER) hub generated publications arising from the project will be made freely available on the NAER website.
- Research papers published in peer reviewed scientific journals.
- Presentations to the broader scientific community at conferences and/or workshops.

Project publications to date (if applicable)

Canham CA, Cavalieri OY, Setterfield SA, Freestone FL & Hutley LB. 2020. Effect of elevated magnesium sulfate on two riparian tree species potentially impacted by mine site contamination. Scientific Reports 10, 2880. https://doi.org/10.1038/s41598-020-59390-9

Project Title	Guiding ecological restoration at Ranger uranium mine with drone derived indicators of ecosystem health		
KKN Theme	Ecosystem Restoration		
KKN Title	ESR9. Developing best-practice monitoring methods for ecosystem restoration		
KKN Question	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?		
Project Status	Active		
Project number	RES-2019-014	**Project commencement date**	5/02/2020
Project duration (months)	32	**Estimated completion date**	30/09/2022
Lead team	ERL	**Date required**	1/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	UQ: Mitchel Rudge, Peter Erskine CSIRO: Shaun Levick
Resources 2020-21 (person weeks)	7		

Aims

- To explore the measurement of key plant functional traits in reference ecosystems in Kakadu National Park using drones equipped with LiDAR and hyperspectral sensors. Traits of interest include: foliar chlorophyll, nitrogen and phosphorus content; demographic traits (recruitment/mortality); phenology; and plant stress.
- To explore the ecological roles of these traits within the reference ecosystem.
- To apply these traits where successfully developed to assessment of key ecosystem processes and functions on the restored ecosystems at Ranger Uranium Mine.
- To explore the use of functional trait-based vegetation targets as an alternative to, or in conjunction with, species composition targets.

Background

The *Environmental Requirements* stipulate that the Ranger Project Area is to be restored to an ecosystem similar to those in surrounding areas of Kakadu National Park. To set targets for ecosystem similarity, SSB is using the reference ecosystem framework as outlined by the Society for Ecological Restoration Australasia (SERA) standards. The savanna ecosystems that dominate the landscape around Ranger are spatially variable, which makes similarity targets difficult to quantify. By including landscape scale patchiness, large scale surveys would be the best approach to characterise the reference ecosystems. However, an unrealistic number of ground surveys would be required to cover a sufficiently large area, and traditional remote sensing lacks the resolution that would be required to derive restoration targets. Drone based remote sensing is a new ecological tool that can provide very high spatial resolution measurements over large areas. Drone based remote sensing could be used to inform restoration targets, through the use of large scale reference ecosystem surveys that include landscape scale variability. Such surveys could also be used to monitor restoration progress against these targets, which would greatly increase monitoring accuracy while reducing costs. However, the accuracy of drone-based vegetation surveys needs to be proven at the plot scale before they can be applied to set and monitor restoration targets.

Progress against plan

- PhD Confirmation completed
- Work has commenced on drafting a review manuscript on the use of drones to monitor ecosystem health indicators for restoration projects
- Testing of processing methods for hyperspectral data and LiDAR data sets

Key findings

Nil to date

Workplan for 2020-21

- Collection of LiDAR and hyperspectral data from reference ecosystems around Ranger Mine (September 2020-June 2021)
- Collection of plant samples for laboratory analysis to determine chemical composition

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A method and information informing use of plant functional traits and phenology for species composition measures.

- A monitoring tool to assess plant health at various stages of ecosystem restoration.

The outcome that this project will achieve is:

- Drone-based methods for measuring ecosystem health parameters relevant to the sustainability indicators from SSB's Ecosystem Restoration Standard. This will enable ecosystem health to be measured at large scales at the individual tree level.

Planned communication activities

- Presentations to ARRTC.
- Presentations to stakeholders including the Ecosystem Restoration Working Group.
- Conference presentation at the Advancing Earth Observation Forum (August 2021)

Project publications to date (if applicable)

Nil to date

CROSS-THEMES

Project Title	Cumulative risk assessment for Ranger mine site rehabilitation and closure- Phase 2 (aquatic pathways)		
KKN Theme	Cross theme		
KKN Title	CT1. Assessing the cumulative risks to the success of rehabilitation on-site and to the protection of the off-site environment.		
KKN Question	CT1A. What are the cumulative risks to the success of rehabilitation on-site and to the off-site environment?		
Project Status	Complete		
Project number	RES-2017-032	**Project commencement date**	01/03/2018
Project duration (months)	22	**Estimated completion date**	01/10/2020
Lead team	WASQ	**Date required**	01/03/2022
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	1		

Aims

- To develop qualitative and quantitative risk models that assess the cumulative risks to on-site and off-site aquatic ecosystems during the decommissioning and post-decommissioning phases of the Ranger uranium mine.

Background

At the completion of mining, Energy Resources of Australia Ltd is required to close Ranger uranium mine (RUM) and meet the Environmental Requirements (ERs) stated in the mine's Authorisation. A robust screening-level ecological risk assessment process has identified a number of environmental risks and knowledge gaps for the rehabilitation of the mine-site. However, these risks were assessed in isolation of one another, and the interaction and cumulative impact of the risks was outside the scope of the risk-screening process. Hence, there is a need to

conduct a cumulative ecological risk assessment (CERA) process. Phase 1 of the CERA project focused on the risks to the on-site terrestrial environment, in particular, risks that might result in failed revegetation of the mine-site.

For the next phase (2) of the CERA project, the Supervising Scientist Branch requires risk model(s) that are capable of assessing the cumulative effects of multiple-stressors on the aquatic ecosystems surrounding Ranger uranium mine at multiple-scales (spatial and temporal). The modelling needs to be spatially-explicit and able to assess the risks arising during the decommissioning and post-decommissioning phases. The model will be used to assess if adverse environmental impacts will result from exposure scenarios derived from ERA's groundwater and surface water modelling, which is scheduled for completion in Q3 2020. The spatial and temporal resolution of the model(s) should align with the assessment tasks that are required to determine if ERA can meet the ERs. The modelling will need to include the riparian zones of the creeks as these were omitted from CERA Phase 1. Depending on further scope discussions, the model may also need to quantify risks to the health of Aboriginal communities downstream of the mine.

Stressors that will need to be included in the model include: magnesium, uranium, manganese, ammonia, turbidity/suspended sediment, bedload, sulfate (in the context of acid sulfate soils) and a number of other trace metals (e.g. copper, zinc, cadmium, etc.). Where applicable, the model needs to be able to predict risks to surface water and sediment biotic communities.

A mixtures toxicity project was recently completed (see RES-2017-001) to assess the extent and nature of interactions amongst the major contaminants of potential concern in surface and ground waters around the mine site (which would be reflective of contaminated waters entering the creeks during decommissioning and post-decommissioning). The results of the mixtures toxicity project will inform the necessary level of model complexity.

This phase of the CERA project will build on the methods and lessons learnt from the phase 1 CERA). There are also a number of data sources that it can draw-on including toxicity and field-effects data for some contaminants of potential concern, and whole-effluent toxicity test results. This phase of the CERA will be run jointly with ERA.

Progress against plan

- CSIRO was engaged under a cost-sharing arrangement between SSB and ERA
- Key aquatic ecology experts and stakeholders participated in a workshop held at SSB on 28 May 2018, in order to construct a qualitative model of the Magela catchment aquatic ecosystem processes. The model was used to test

the important links in the ecosystems and the effect of perturbations. A report has been completed.
- A comprehensive review of relevant datasets has been conducted. The datasets have been collated and catalogued.
- A quantitative cumulative risk assessment model has been built and was tested using historical exposure datasets.

Key findings

The qualitative modelling provided knowledge concerning the cumulative impacts to aquatic ecosystems arising from trophic interaction perturbations:

- A trophic level and habitat-based qualitative model indicated that the higher-level Environmental Values could be adversely affected by impacts to some lower trophic-level-group organisms.
- It highlighted the trophic groups that have potential as key indicators of whole-of-ecosystem health, e.g. phytoplankton.

The quantitative modelling provided knowledge about cumulative impacts associated with combined multiple stressors:

- The additive model combines all the risks of the contaminants of potential concern (COPCs) for which there are existing biological effects data.
- It was tested with historical exposures and showed no cumulative risk from the COPCs discharged from the mine-site.
- It can be used to calculate the additive risk of COPCs predicted to enter the creek in the future, if needed and appropriate.

Workplan for 2020-21

- Complete journal paper

Planned project outputs and associated outcomes

The primary outputs for the project are:

- Qualitative and quantitative risk models that assess the cumulative risks to on-site and off-site aquatic ecosystems during the decommissioning and post-decommissioning phases of Ranger rehabilitation.
- Assessment of the surface water concentrations of stressors during post-decommissioning and if they are likely to result in ecological impacts.
- Identification of interactions amongst risks and how these can affect risks as a whole.

The outcome that this project will achieve is:

- The knowledge will be used to determine if there are risks to the off-site environment following mine site closure and to determine if and/or when impacts will be expected on-site.

Planned communication activities

The primary communication activities for the project are:

- Presentation to ARRTC.
- Journal articles arising from the qualitative and quantitative modelling.
- Relevant communication products for the different stakeholder groups, developed with the Public Assurance and Advice team.

Project publications to date (if applicable)

Harford AJ et al., (in prep) Qualitative Mathematical Models to Support Ecological Risk Assessment for Rehabilitation and Closure of Ranger Uranium Mine, Australia. *Integrated Environmental Assessment and Management.*

Project Title	Cataloguing the natural World Heritage values on the Ranger Project Area		
KKN Theme	Cross theme		
KKN Title	CT2. Characterising key conservation and biodiversity values of the Ranger Project Area		
KKN Question	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?		
Project Status	Active		
Project number	RES-2017-004	**Project commencement date**	01/07/2017
Project duration (months)	23	**Estimated completion date**	30/08/2020
Lead team	ERL	**Date required**	01/08/2020
In-house or outsourced	In-house	**Supporting team(s)**	
Resources 2020-21 (person weeks)	1		

Aims

- To collate spatial data and undertake analysis to quantify the locations and spatial extent of natural values on the Ranger Project Area (RPA) that map to the World Heritage values for which Kakadu National Park is listed.
- To identify threatened and significant species that may utilise the habitats in the RPA, as determined through cataloguing the natural values.

Background

The Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger uranium mine outline the Commonwealth's environmental protection conditions for Ranger mine. The Ranger Project Area must be rehabilitated to establish an environment that could be incorporated into the Kakadu National Park.

Kakadu National Park is inscribed on the World Heritage List for five criteria: three physical and two cultural. Some of the features for which Kakadu is listed are

also present on the Ranger Project Area. In particular, elements of most of the natural World Heritage Values present in Kakadu are also present on the Ranger Project Area. This project will outline the elements of natural World Heritage values for which Kakadu is listed that are also present within the Ranger Project Area.

Progress against plan

- Draft report under final review.

Key findings

- The current natural values for which Kakadu National Park were inscribed on the World Heritage List were assessed for their occurrence on the Ranger Project Area using GIS data layers. Each natural value found on the RPA was reported against the relevant World Heritage criterion as follows:
  - Criterion vii) To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance – represented by landscapes, view fields, integrity of the site, vegetation and habitats, and scale of undisturbed landscape.
  - Criterion ix) To be outstanding examples representing significant ongoing ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals – represented by floodplains and wetlands, waterways, landscapes, integrity of the site, vegetation and habitats, diversity of species, and ecological processes.
  - Criterion x) To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation – represented by vegetation and habitats, flora and fauna species of conservation significance, and endemic species.
- The focus of this work was on the natural World Heritage values. Further work should be undertaken to account for the cultural World Heritage values, and any other relevant conservation and biodiversity values.

Workplan for 2020-21

- Finalise internal review of report

Planned project outputs and associated outcomes

The primary outputs for the project are:

- A report on the locations and spatial extent of natural values (for which Kakadu National Park is World Heritage listed for) occurring on the Ranger Project Area.
- Spatial database of core datasets used in the project

The outcome that this project will achieve is:

- Listed and quantified natural World Heritage values currently present on the Ranger Project Area that inform the potential incorporation of the site post-closure into Kakadu National Park.

Planned communication activities

The primary communication activities for the project are:

- Internal report
- Presentations to for a, closure working groups and ARRTC
- Input to workshops determining ALARA and BPT on the RPA

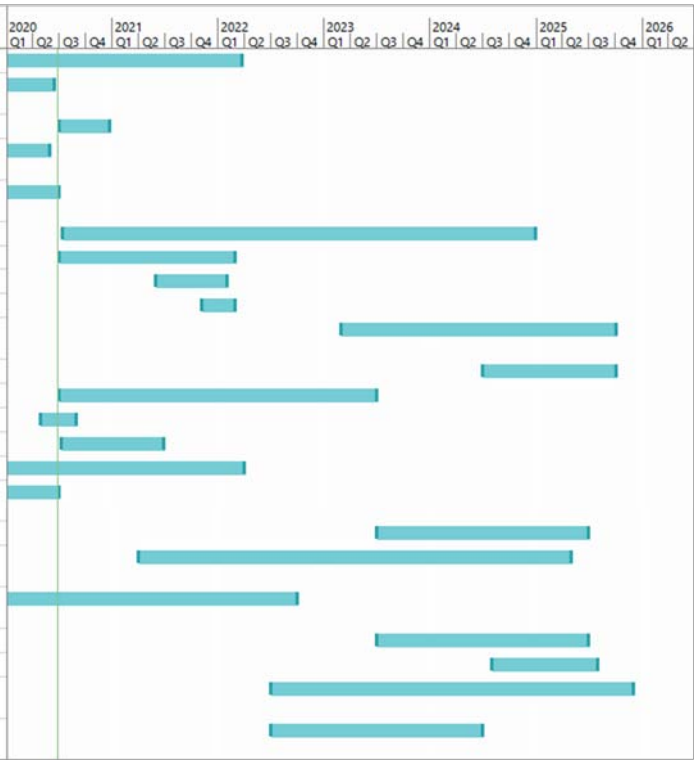
Project publications to date (if applicable)

Nil

Appendix 3 Supervising Scientist Branch draft research project schedule, 2020-2026

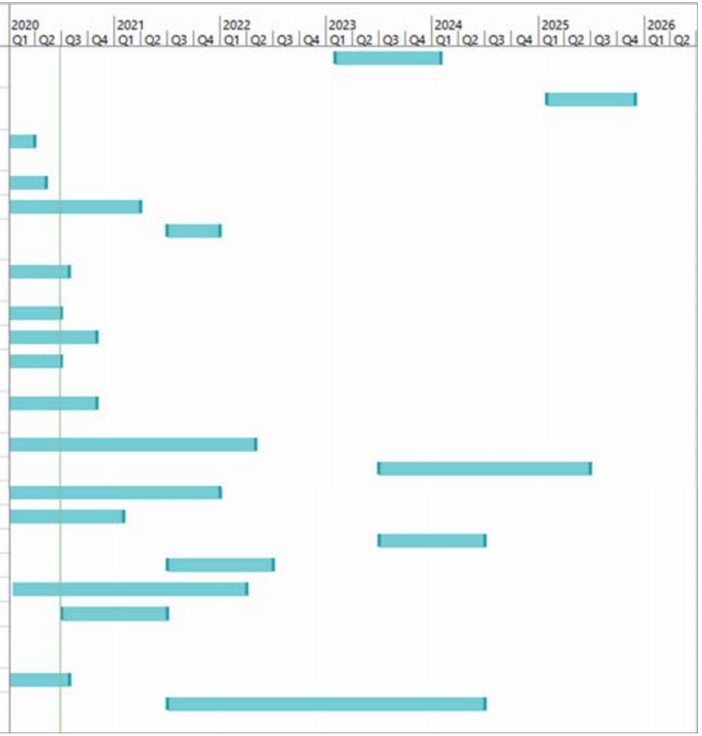
Projects against Ecosystem Restoration (ESR) Key Knowledge Needs

Project Title	KKN No.
Using hyperspectral drone data for deriving species composition	ESR1A
Assessing the effect spatial scale has on species composition and community structure for revegetation planning	ESR1A
Quantifying spatial and temporal change in seasonally-inundated savanna	ESR1A
Deriving species composition measures and their environmental correlates to assess ecosystem restoration similarity	ESR1C
Deriving vegetation community structural attributes that inform the conceptual reference ecosystem	ESR1C
Deriving similarity metrics for ecosystem restoration at the scale of the Ranger rehabilitation	ESR1C
Applying patch metrics to characterise 'natural' distribution of vegetation	ESR1C
Habitat features that influence the colonisation of fauna on the landform	ESR2B
Risk assessment for feral animals impacting faunal colonisation of the landform	ESR2C
Improved understanding of sources and magnitude of sources of weeds off site using remote sensing	ESR4A
Assess the occurrence and density of feral animal species in the adjacent off-site environment	ESR4A
Assessing long-term viability of revegetation on waste rock at Nabarlek.	ESR5A
Determining the key terrestrial ecological processes required for ecosystem restoration	ESR5A
Ecosystem development on Nabarlek waste rock to inform tractories	ESR5A
Long-term viability of the ecosystem established on the trial landform	ESR5B
Developing restoration trajectories to predict when the restored site will move to a sustainable ecosystem	ESR5B
Develop monitoring program to evaluate impacts of disturbance on revegetation trajectory	ESR5B
Monitoring and assessment of ecosystem establishment and long-term viability on Pit 1 waste rock to inform trajectories.	ESR5B
Guiding ecological restoration at Ranger uranium mine with drone derived indicators of ecosystem health	ESR9A
Developing whole of site landform and ecosystem monitoring program at-scale	ESR9A
Develop metrics to confirm vegetation resilience to fire events.	ESR9A
Develop diagnostic tool to assessing/ monitoring impact of g/w solutes on riparian vegetation and aquatic macrophytes using remote sensing	ESR9A
Determining measures of nutrient cycling in reference sites to be used in developing closure criteria and revegetation monitoring.	ESR9A

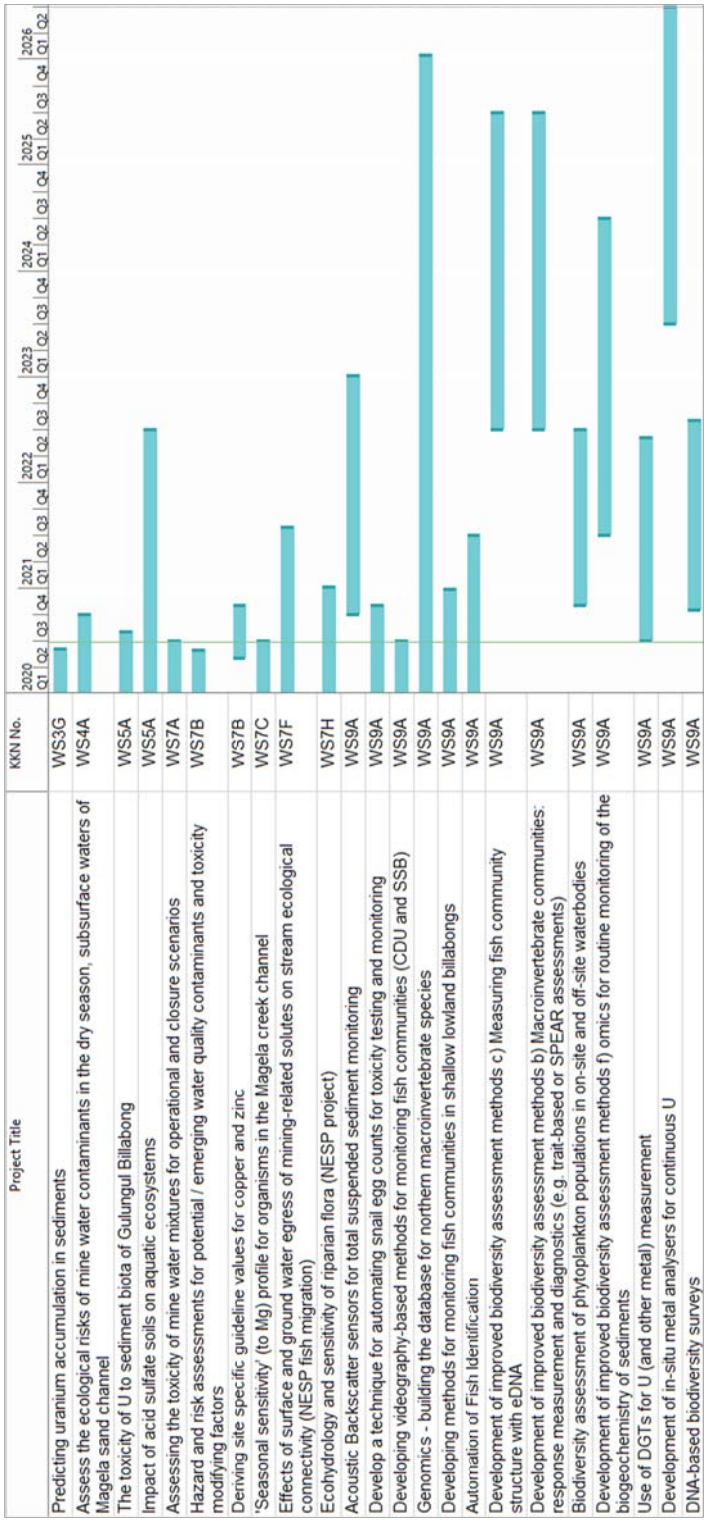


Projects against Cross-theme (CT), Landform (LAN) and Health Impacts of Radiation and Contaminants (RAD) Key Knowledge Needs

Project Title	KKN No.
Cumulative risk assessment for Ranger mine site rehabilitation and closure- Periodic review and update (2024)	CT1A
Cumulative risk assessment for Ranger mine site rehabilitation and closure- Periodic review and update (2026)	CT1A
Cumulative risk assessment for Ranger mine site rehabilitation and closure- Phase 2 (aquatic pathways)	CT1A
Cataloguing the natural World Heritage values on the Ranger Project Area	CT2A
What are the baseline rates of sediment transport and deposition in creeks and billabongs?	LAN1A
Determine baseline extent, size and rate movement of gullies in undisturbed areas surrounding the mine site	LAN1A
Mapping and characterisation of geomorphology of on-site creeks in and adjacent to the mine site, including historical change	LAN1B
Assessing the geomorphic stability of the Ranger trial landform: calibrating model outputs	LAN3C
Ranger trial landform erosion research	LAN3C
Determining and testing representativeness of long-term rainfall patterns for use in final landform modelling	LAN3C
Development of a method for monitoring gully formation on the rehabilitated landform using stereopsis and LiDAR	LAN4A
Turbidity & suspended sediment relationships for Gulungul and Magela Creeks	LAN5A
Operationalise billabong turbidity monitoring using a Remotely Piloted Aircraft System (RPAS)	LAN5A
Radon exhalation from waste rock on the Ranger trial landform	RAD3A
Environmental fate and transport of Ac-227 and Pa-231	RAD5A
Radionuclide uptake in amphibians	RAD6B
Radionuclide uptake in terrestrial invertebrates	RAD6B
Radionuclide uptake in understorey vegetation	RAD6B
Radionuclide uptake in small proliferators	RAD6B
Deriving site-specific concentration factors for metals in bush foods to inform human health risk assessments for the Ranger final landform	RAD9B
Quantifying radon retention characteristics of ERISS acrylic gamma spectroscopy containers	RAD10A
Developing UAV-based remote sensing techniques for characterising radioactivity levels on the rehabilitated landform.	RAD10A



Projects against Water and Sediment (WS) Key Knowledge Needs


Project Title
KKN No.
2020 Q1 Q2 Q3 Q4
2021 Q1 Q2 Q3 Q4
2022 Q1 Q2 Q3 Q4
2023 Q1 Q2 Q3 Q4
2024 Q1 Q2 Q3 Q4
2025 Q1 Q2 Q3 Q4
2026 Q1 Q2
Predicting uranium accumulation in sediments WS3G
Assess the ecological risks of mine water contaminants in the dry season, subsurface waters of Magela sand channel WS4A
The toxicity of U to sediment biota of Gulungul Billabong WS5A
Impact of acid sulfate soils on aquatic ecosystems WS5A
Assessing the toxicity of mine water mixtures for operational and closure scenarios WS7A
Hazard and risk assessments for potential / emerging water quality contaminants and toxicity modifying factors WS7B
Deriving site specific guideline values for copper and zinc WS7B
*Seasonal sensitivity (to Mg) profile for organisms in the Magela creek channel WS7C
Effects of surface and ground water egress of mining-related solutes on stream ecological connectivity (NESP fish migration) WS7F
Ecohydrology and sensitivity of riparian flora (NESP project) WS7H
Acoustic Backscatter sensors for total suspended sediment monitoring WS9A
Develop a technique for automating snail egg counts for toxicity testing and monitoring WS9A
Developing videography-based methods for monitoring fish communities (CDU and SSB) WS9A
Genomics - building the database for northern macroinvertebrate species WS9A
Developing methods for monitoring fish communities in shallow lowland billabongs WS9A
Automation of Fish Identification WS9A
Development of improved biodiversity assessment methods c) Measuring fish community structure with eDNA WS9A
Development of improved biodiversity assessment methods b) Macroinvertebrate communities: response measurement and diagnostics (e.g. trait-based or SPEAR assessments) WS9A
Biodiversity assessment of phytoplankton populations in on-site and off-site waterbodies WS9A
Development of improved biodiversity assessment methods f) omics for routine monitoring of the biogeochemistry of sediments WS9A
Use of DGTs for U (and other metal) measurement WS9A
Development of in-situ metal analysers for continuous U WS9A
DNA-based biodiversity surveys WS9A

Appendix 4 Technical Advice Memoranda

Technical Advice No.	Date of issue	Title
1	03/01/2019	Feedback on INTERA numerical groundwater model presentations at ARRTC #41
2	03/01/2019	Runoff coefficients relevant to the Ranger waste rock landforms
3	03/01/2019	Potential risks associated with compaction layers
4	21/02/2019	Initial assessment of the FLV6.2 landform
5	24/04/2019	Particle size on the trial landform
6	24/05/2019	Species richness and composition indicator values for assessing ecosystem similarity for savanna woodland
7	21/06/2019	Vegetation strata, woody plant species size class distribution and total basal area data for use as indicator values
8	TBA*	Canopy cover indicator value for assessing ecosystem similarity for savanna woodland
9	TBA*	Functional traits analyses of reference sites
10	13/09/2019	Updated assessment of the FLV6.2 landform
11	31/03/2020	Water chemistry and biological communities of shallow groundwater in Magela Creek
12	01/06/2020	Rn226 monitoring on the trial landform
13	22/06/2020	DATA SHARE - Investigation into CCLAA influence on Gulungul Creek
14	16/07/2020	Mg Standard supporting lines of evidence

* Currently being finalised

Glossary of terms, abbreviations and acronyms

ANOVA	Analysis of Variance testing
application	A document stating how the mining operator proposes to change the conditions set out in the mining Authorisation. These changes need to be approved by all MTC stakeholders.
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ARR	Alligator Rivers Region
ARRAC	Alligator Rivers Region Advisory Committee
ARRTC	Alligator Rivers Region Technical Committee
authorisation	For mining activities authorisation is required under the Northern Territory *Mining Management Act 2008* (MMA*)* for activities that will result in substantial disturbance of the ground. It details the authorised operations of a mine, based on the submitted mining management plan and any other conditions that the Northern Territory Minister considers appropriate.
concentration factor	The metal or radionuclide activity concentration measured in biota divided by the respective concentration measured in the underlying soil (for terrestrial biota) or water (for aquatic biota).
CCLAA	Corridor Creek Land Application Area
CAESAR-Lisflood	landform evolution modelling software
Cumec	a cubic metre per second, as a unit of rate of flow of water.
dose constraint	The International Commission on Radiation Protection (ICRP) defines dose constraint as '*a prospective restriction on anticipated dose, primarily intended to be used to discard undesirable options in an optimisation calculation*' for assessing site remediation options.
DPIR	Northern Territory Department of Primary Industry and Energy (formerly Northern Territory Department of Mines and Energy)
early detection	Measurable early warning biological, physical or chemical response in relation to a particular stress, prior to significant adverse effects occurring on the system of interest.
EC (electrical conductivity)	A measure of the total concentration of salts dissolved in water.
ERA	Energy Resources of Australia Ltd
ERISS	Environmental Research Institute of the Supervising Scientist

GCT2	Gulungul Creek Tributary 2
GCUS	Gulungul Creek Upstream (upstream monitoring site)
ICRP	International Commission on Radiological Protection
ionising radiation	Sub-atomic particles (α, β) or electromagnetic (γ, x-rays) radiation that have enough energy to knock out an electron from the electron shell of molecules or atoms, thereby ionising them.
in situ	A Latin phrase that translates to 'on-site' and identifies tests been conducted in the creeks in the vicinity of the mine-site.
JFS	Jabiru Field Station
KKN	Key Knowledge Needs
laterite	In the Ranger mine context, laterite is a local term used to describe well weathered rock and soil profile material that consists primarily of a mixture of sand and silt/clay size particles. It may or may not exhibit characteristics of a fully-developed laterite profile.
LLAA	Long-lived alpha activity
mRL	Reduced Level metres
MTC	Minesite Technical Committee
NT	Northern Territory
ore	A type of rock that bears minerals, or metals, which can be extracted.
PAEC	Potential alpha energy concentration
PERMANOVA	PERmutational Multivariate Analysis Of Variance testing
permeate	The higher purity stream produced by passage of water through a reverse osmosis (RO) treatment process.
pH	A measure of the acidity or alkalinity of an aqueous solution
pond water	Water derived from seepage and surface water runoff from mineralised rock stockpiles as well as runoff from the processing areas that are not part of the process water circuit.
process water	Water that has passed through the uranium extraction circuit, and all water that has come into contact with the circuit. It has a relatively high dissolved salt load constituting the most impacted water class on-site.
RAA	Radiologically Anomalous Area. Area that displays significantly above background levels of radioactivity.

radionuclide	An atom with an unstable nucleus that loses its excess energy via radioactive decay. There are natural and artificial radionuclides. Natural radionuclides are those in the uranium (^{238}U), actinium (^{235}U) and thorium (^{232}Th) decay series for example, which are characteristic of the naturally occurring radioactive material in uranium orebodies.
RPAS	Remotely Piloted Aircraft System
RPI	Routine Periodic Inspection
RP1	Retention Pond 1
RP2	Retention Pond 2
RP3	Retention Pond 3
RP6	Retention Pond 6
sievert (Sv)	Unit for equivalent dose and effective dose 1 Sievert = 1 Joule·kg^{-1}. In contrast to the Gray, the Sievert takes into account both the type of radiation and the radiological sensitivities of the organs irradiated, by introducing dimensionless radiation and tissue weighting factors, respectively.
tailings	A slurry of ground rock and process effluents left over once the target product, in this case uranium, has been extracted from mineralised ore.
toxicity monitoring	The means by which the toxicity of a chemical or other test material is determined in the field over time. The monitoring comprises field toxicity tests which are used to measure the degree of response produced by exposure to a specific level of stimulus (or concentration of chemical).
mRL	metres Reference Level – a specific elevation relative to mean sea level.
toxicity testing	The use of a standardised protocol, in the laboratory or the field, to determine the effects of a toxicant on an organism.
trigger values	Concentrations (or loads) of the key performance indicators measured for an ecosystem, below which there exists a low risk that adverse biological (ecological) effects will occur. They indicate a risk of impact if exceeded and should 'trigger' some action, either further ecosystem specific investigations or implementation of management/remedial actions.
TSF	Tailings Storage Facility
UEL	Uranium Equities Ltd
WTP	Water Treatment Plant