Australian Government

Department of Agriculture, Water and the Environment

SUPERVISING SCIENTIST

ANNUAL TECHNICAL REPORT

2020 - 2021

This report should be attributed as Supervising Scientist 2021. *Annual Technical Report 2020–21*, Commonwealth of Australia 2021.

ISSN: 2207-7758 (Print)
ISSN: 2207-7766 (Online)

Supervising Scientist Branch is part of the Australian Government Department of Agriculture, Water and the Environment

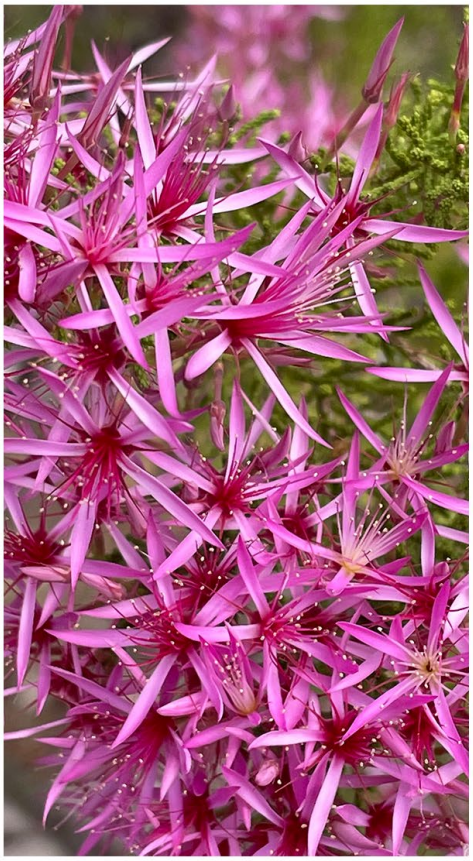
ABN 34190894983

Contact

Supervising Scientist Branch
Department of Agriculture, Water and the Environment
Street: Pederson Road/Fenton Court, Eaton NT 0820 Australia

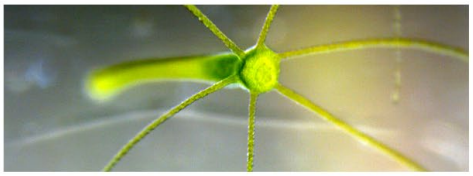
Telephone +61 8 8920 1100
Facsimile +61 8 8920 1199
awe.gov.au/science-research/supervising-scientist

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 respect to their elders past, present and emerging.








Photos (clockwise spiral from top left): *Calytrix exstipulata*, Turkey Bush. Investigating passive samplers as advanced monitoring tools, SSB Laboratory. Field work, Gulungul Billabong. Ground-truth mapping of tree canopy species. Gamma radiation monitoring on Pit 1, Ranger Mine. Under the microscope, *Paraplea* sp, Jim Jim Creek, Kakadu National Park. *Hydra viridissima* and *Amerianna cumingi*, ecotoxicology testing, SSB Laboratory.

TABLE OF CONTENTS

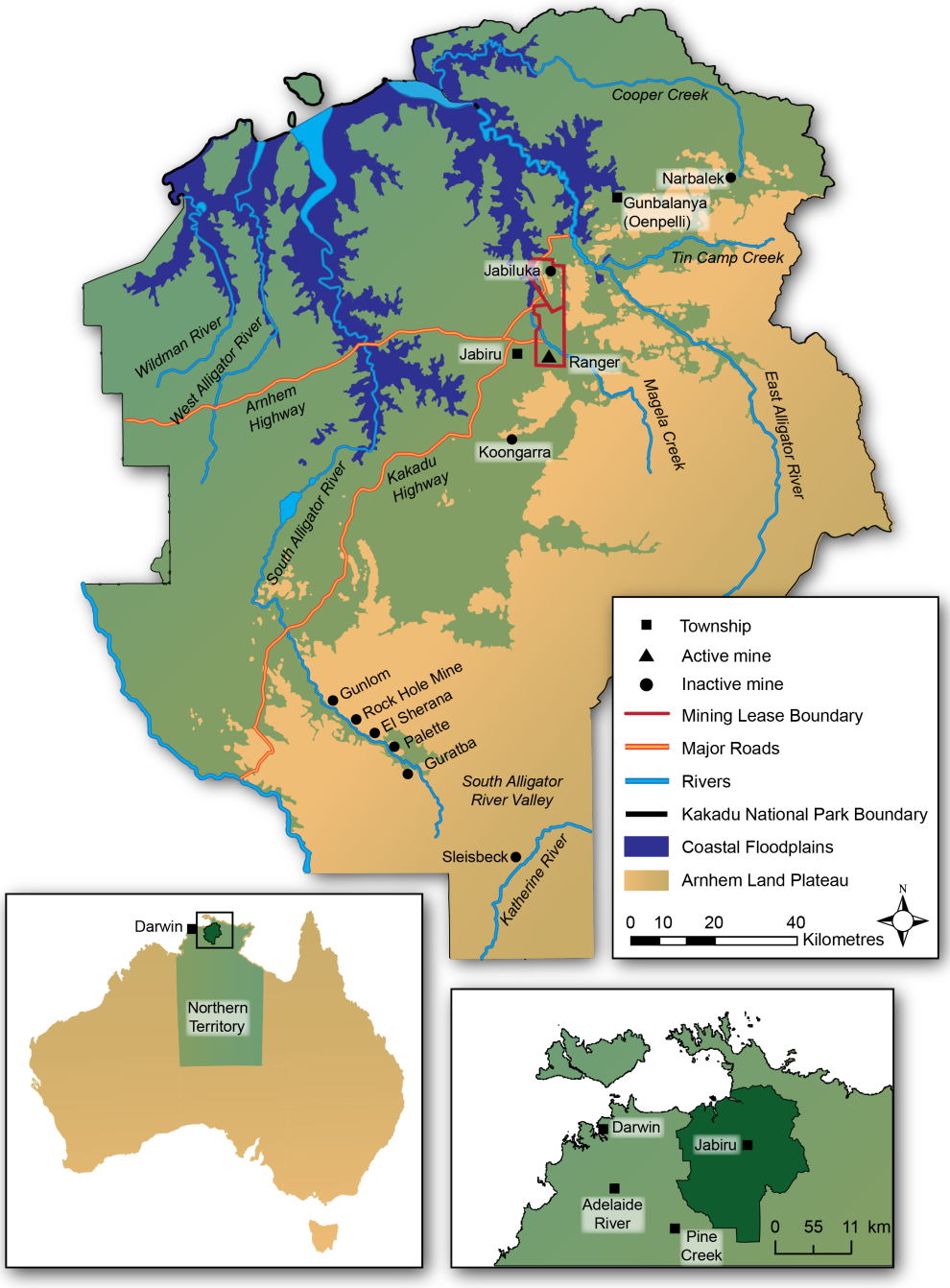


Figure 1 The Alligator Rivers Region

Image 1 Georgetown Billabong, Ranger Mine, Alligator Rivers Region

SUPERVISING SCIENTIST'S OVERVIEW

Despite disruptions throughout 2020-21 due to the COVID-19 pandemic we completed our environmental monitoring program as scheduled and demonstrated that the people and environment of Kakadu National Park remained protected from the effects of uranium mining. It is a testament to all current and former staff of the Supervising Scientist that such a high level of protection has been sustained through-out the entire operating period of the Ranger uranium mine.

Forty-two years of uranium production in the Alligator Rivers Region drew to a close on the 8th of January 2021 with the closure of the processing plant at Ranger. The closure of Ranger is significant milestone for the region and marks the transition to full-time rehabilitation works.

Several key rehabilitation milestones were achieved at Ranger during 2020-21, including: completion of the backfill of Pit 1, completion of dredging of tailings in the Tailings Storage Facility, completion of make-safe activities in the processing area and the commencement of backfill of the Ranger 3 Deeps underground mine. During the reporting period SSB commenced a detailed rehabilitation verification project in order to ensure rehabilitation works at Ranger are completed in accordance with regulatory approvals. This program will continue for the duration of major rehabilitation works.

In support of ongoing rehabilitation activities at Ranger the Supervising Scientist Branch has been making good progress in completing key research work and rehabilitation related assessments, including a detailed assessment of the 2020 Ranger Mine Closure Plan. In addition, we have been working with ERA and traditional owner representative

groups to finalise closure criteria and collaborating on rehabilitation-related monitoring activities.

The closure of Ranger will require a revision of our monitoring programs from a focus on detecting and preventing impacts from short-term changes in water quality, to a multi-decadal program which is focused on detecting seasonal-scale water quality effects from diffuse sources. Through the application of omics techniques, drones and artificial intelligence we are developing leading edge monitoring technologies which are safer, more efficient and provide vastly more data.

SSB has now established an omics laboratory and have successfully operationalised our fish videography artificial intelligence-based monitoring program for the first time. Through our BRUVNet program 185 citizen scientists from 34 countries have now labelled over 25 thousand images to assist in training our fish identification artificial intelligence model. We are now adapting our fish identification model to assist colleagues in the Biosecurity Group to identify imported fish at the border.

SSB is also providing technical support to the wider Department in a range of fields including the formalisation of the role of Chief Remote Pilot with oversight of all Departmental drone operations, and the establishment of Departmental Communities of Practice in Omics, Artificial Intelligence and Drones. We continue to provide technical advice to inform assessments conducted under the *Environment Protection and Biodiversity Conservation Act*, including the assessment of the National Radioactive Waste Management Facility. The Supervising Scientist has taken on management responsibility for the South Alligator Disposal Facility on behalf of the Director of National Parks and has agreed to do the same for the Koongarra site in Kakadu.

External to the Department we continue to engage widely, including participation in working groups with the International Atomic Energy Agency and the OECD Nuclear Energy Agency. SSB staff presented our work at a range of technical conferences and played a key role in the organisation of the Society for Ecological Restoration conference held in Darwin.

I would like to thank all the staff of the Supervising Scientist Branch for their hard work and dedication throughout 2020-21, their achievements are all the more remarkable given the difficult circumstances brought about by COVID-19. It remains a pleasure and a privilege to lead such a fantastic team.

Keith Tayler

Supervising Scientist

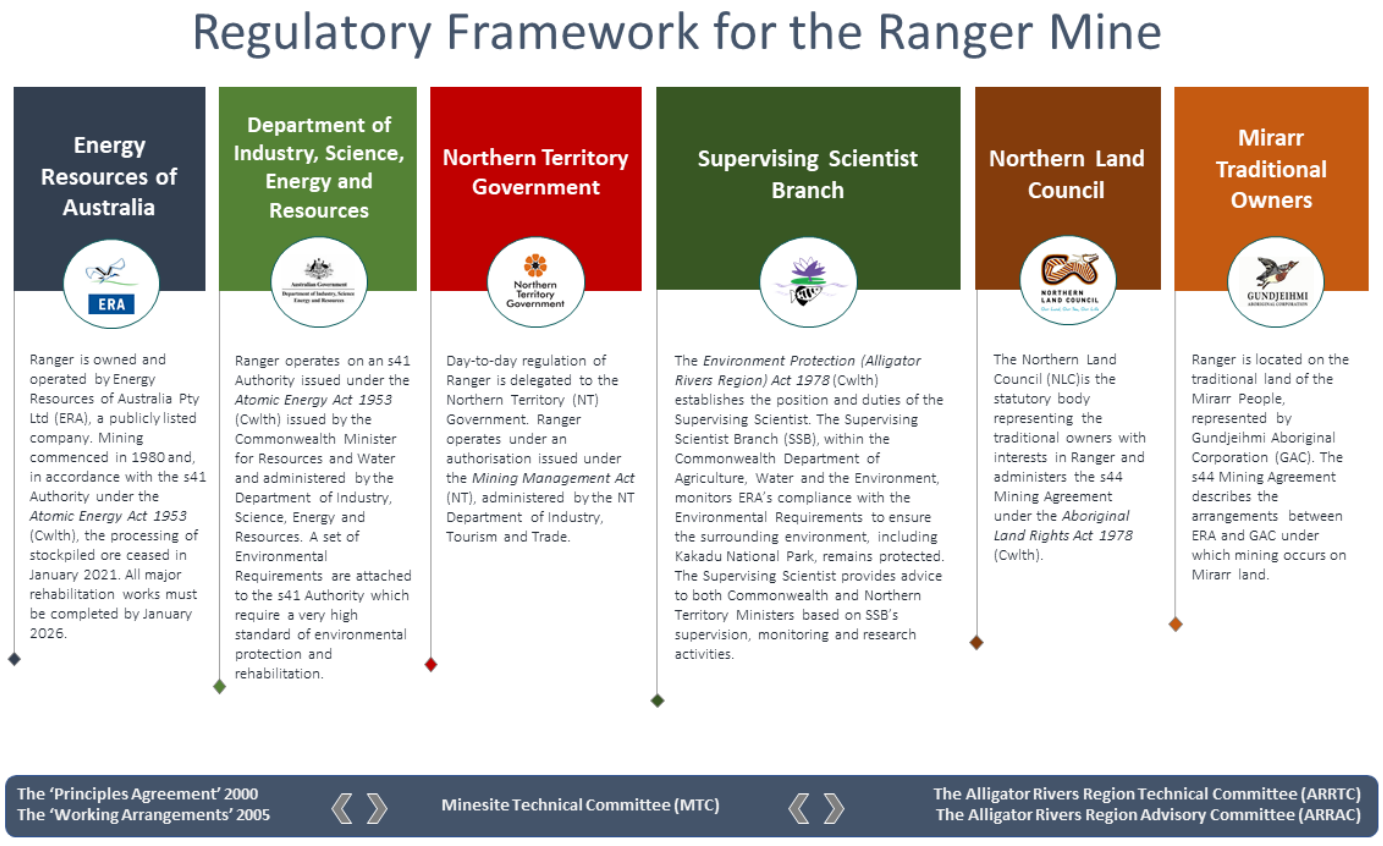


Figure 2 Regulatory framework for Ranger uranium mine

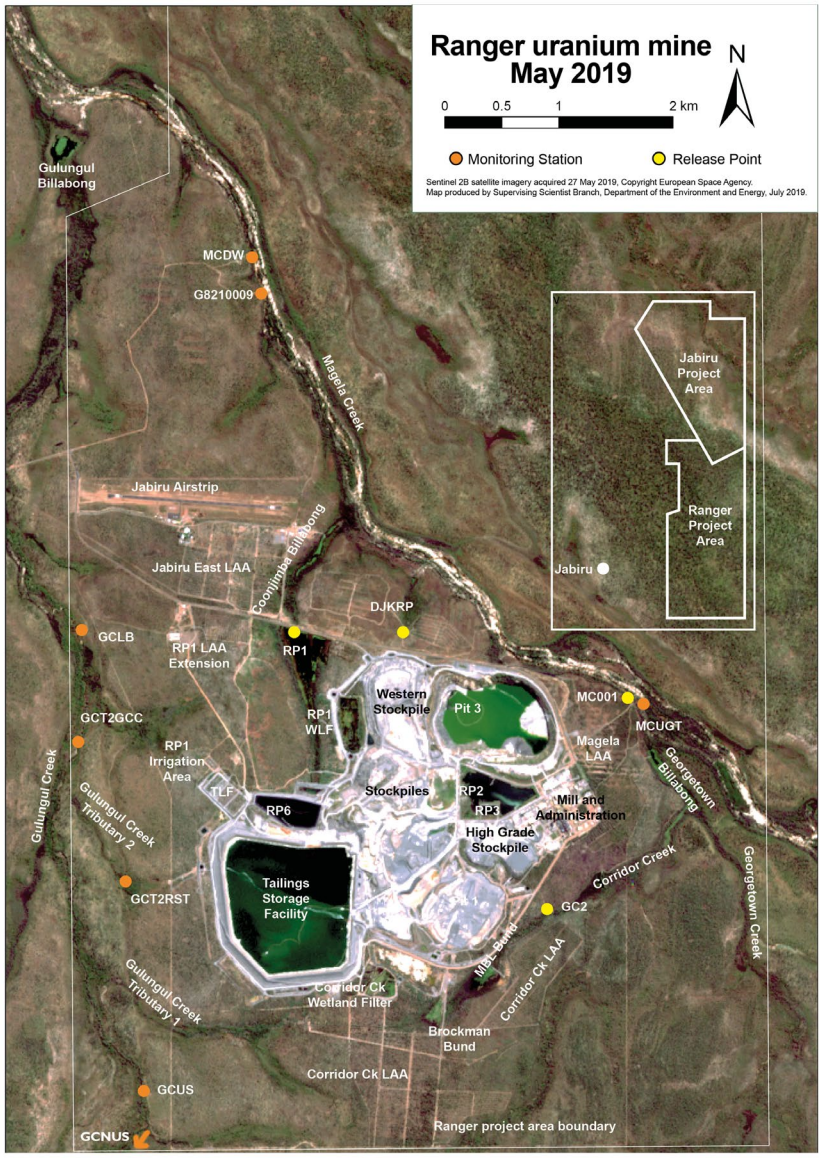


Figure 3 Ranger mine site including location of water release points and SSB monitoring sites

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		

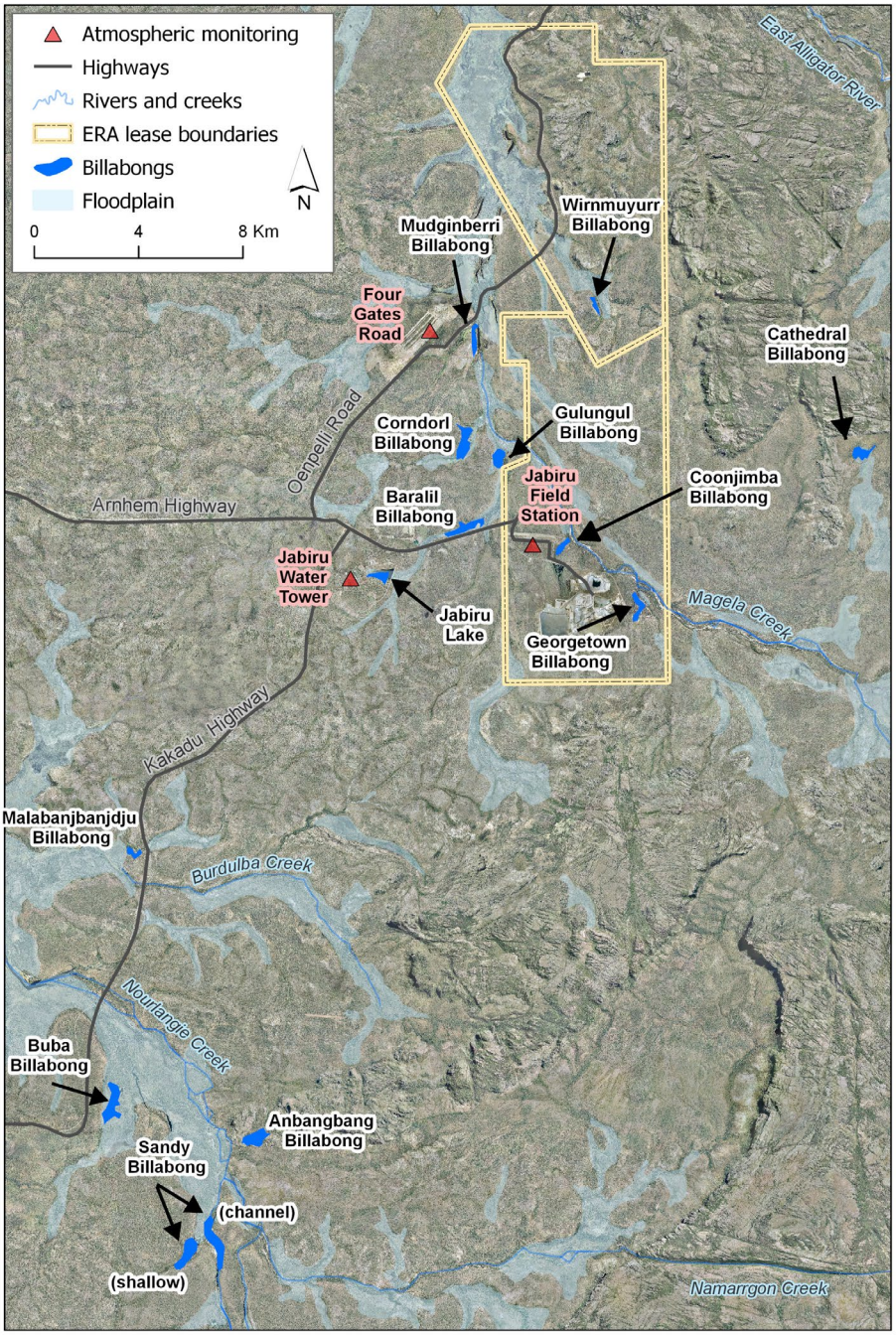


Figure 4 Location of waterbodies in the Supervising Scientist Branch's environmental research and monitoring programs

Image 2 Georgetown Billabong, Ranger Mine, Alligator Rivers Region

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 (SSB) in the Department of Agriculture, Water, and the Environment, situated within the Heritage, Reef and Wildlife Trade Division.

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 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.

There are no longer any operational uranium mines in the ARR. Mining at Ranger ceased in 2012, and processing of stockpiled ceased on 8 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 mine sites 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 status of each of these sites and the activities undertaken by SSB for the 2020–21 reporting period.

Image 3 View from Ubirr, Kakadu National Park

2 ASSURANCE AND ENGAGEMENT

Ongoing COVID restrictions throughout the reporting period impacted the ability of SSB to participate in many face to face engagement opportunities. Despite this, we were still able to communicate the outcomes of the Branch's research and monitoring activities throughout the year via a range of, mostly virtual, 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 is comprised of representatives of government and regulatory bodies, stakeholder organisations, and companies involved in uranium mining activities in the region.

The 54th ARRAC meeting was held in Jabiru on 17 September 2020. 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. ERA provided an overview on the company's operational performance, health and safety, process safety, environmental performance, water management, progressive rehabilitation and studies and approvals for the reporting period.

The committee convened its 55th meeting in Darwin on 22 April 2021. Updates provided included information on the SBB rehabilitation verification program, new monitoring methods being developed and wider collaboration initiatives such as the South Alligator Disposal Facility management by SSB on behalf of Parks. The NT Department of Environment, Parks and Water presented on the detection of browsing ants at Ranger mine and details of the extent of the infestation and the ongoing surveillance and treatment program. The Department of Industry, Science, Energy and Resources noted that work to amend *Atomic Energy Act 1953* was underway.

Further updates and reports were provided by committee members including ERA, the Northern Land Council (NLC), the Australian Radiation Protection and Nuclear Safety Agency.

The minutes of ARRAC meetings are available on the Department's website at: http://www.awe.gov.au/science-research/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 45th ARRTC meeting was held 'virtually' on the 9th-11th of November 2020 due to travel restrictions relating to the COVID-19 pandemic. The meeting focussed on the research program required to inform and underpin closure and ecological restoration of the Ranger mine. ERA presented on their review of reference ecosystem sites required to set closure criteria for Ranger mine. SSB provided the Committee with an update on SSB's assessment of the impact of landscape-scale processes on the stability of the rehabilitated landform.

Due to the continuing impact of the COVID-19 pandemic on interstate travel, the 46th ARRTC meeting was again held virtually from the 14th-15th of February 2021. The frequency of ARRTC meetings have increased in 2021 due to the number of Key Knowledge Needs (KKNs) and associated projects required to be closed out ahead of regulatory milestones in late 2021. At the meeting, the Committee reflected on the significant milestone of the cessation of processing activities at Ranger mine on 8 January 2021, and the transition to full scale rehabilitation. ERA provided updates on surface water modelling and soil assessment of Ranger mine Land Application Areas. SSB

presented on the developments towards an agreed conceptual reference ecosystem and quantitative closure criteria for the 2021 Ranger Mine Closure Plan.

ARRTC 47 was held as a hybrid meeting on the 24th-25th of May 2021. Darwin-based stakeholders (SSB, NLC/GAC, ERA and DITT) were represented in person. The ARRTC landform specialist also attended the meeting in person so that he could undertake a visit to Ranger, while the other ARRTC members joined the meeting virtually. At the meeting ARRTC:

- endorsed the close-out of several KKNs and projects,
- noted, that with the cessation of operations at Ranger, it expected that in future there would be focus on ecological risk assessment and adaptive management supported by strategic and targeted monitoring, and
- requested more reporting on other mine and legacy sites in the Alligator Rivers Region.

The minutes of ARRTC meetings are available on the Department's website at: www.awe.gov.au/science-research/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 SSB's Jabiru Field Station plays an important role in keeping the Mirarr and other regional Indigenous stakeholders informed about the SSB's research and monitoring work. This includes consulting with the Gundjeihmi Board of Management as required, and the Kakadu Board of Management as described in protocols for research in Kakadu National Park agreed between the Director of National Parks and the Supervising Scientist.

SSB is exploring opportunities to further engage Gundjeihmi Aboriginal Corporation (GAC), Djurrubu Rangers, and other Traditional Owner groups in our work, with a long-term vision of including Indigenous ranger groups in post-rehabilitation monitoring.

The Djurrubu Rangers and Supervising Scientist collaborated on the Baralil Creek water monitoring project and undertook numerous sampling campaigns together in early 2020. The purpose of this collaboration was to provide a mechanism to share knowledge between parties and to build capacity and skills within the Djurrubu Ranger group. Results from this monitoring program will be provided at the September 2021 ARRAC meeting.

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:

- SSB scientists and field staff held a community BBQ at Mudginberri Billabong in October 2020 to demonstrate freshwater mussel collecting techniques. SSB

provided assurance to residents of Mudginberri that 2019 sampling and testing showed that the mussels continue to be safe to eat.

- Staff from SSB and ERA participated in a visit to some proposed vegetation reference sites with Mirarr Traditional Owners and the NLC to ensure these sites are representative of stakeholder views on the reference ecosystem for Ranger rehabilitation.
- SSB held some on country consultations at the former Nabarlek mine site with Traditional owners and the Northern Land Council to discuss ecosystem restoration activities.

2.4 Public engagement

To support our public assurance role and maintain the reputation of the SSB for the provision of independent advice underpinned by high-quality science, staff participate in several public engagement and communication activities.

SSB staff visited the Jabiru Area School in September and November 2020 to launch the BRUVNet citizen science project (www.bruvnet.org) and get the local community involved in identifying fish to train our artificial intelligence model. A number of school visits were also conducted in Darwin by the Ecosystem Restoration and Landform team, and the SSB hosted a work experience student from a local Darwin high school in April 2021.

SSB produced a water quality report card at the completion of the 2020-21 wet season monitoring program that was distributed around the Jabiru community. This communicated the summary outcomes of our water quality monitoring programs which demonstrated that the water quality in the creeks surrounding Ranger remained well below prescribed limits.

The SSB launched its official Facebook page (www.facebook.com/SSBgov/) in October 2020 to engage with the broader community by posting information about the work of the SSB. The page has attracted many unique views and shares of our information and has provided significantly greater reach than traditional communication channels (Table 1). Social media has increased the SSB's engagement with the public and has become a mainstream element of communication of our work. We will shortly be expanding our presence to Instagram and LinkedIn to further promote our leading practice science.

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.awe.gov.au/science-research/supervising-scientist/publications).

TABLE 1 PERFORMANCE METRICS OF SSB FACEBOOK PAGE OCTOBER 2020 TO 30 JUNE 2021

Total Page Followers	385 (64% Female, 36% Male)
Total Page Reach	19672
Total Post Shares (The number of times posts have been shared by another person)	159
Total Post Likes and Reactions (Number of times posts have been liked by another person)	2416

2.5 International Engagement

SSB maintains strong relationships and engagement with the international environmental protection, mining remediation and scientific communities. This engagement serves to benchmark our programs against leading practice and creates opportunities to contribute to the development of international guidelines and standards.

The Radiation team continued its involvement in the International Atomic Energy Agency (IAEA) Modelling and Data for Radiological Impact Assessments (MODARIA II) program and made significant contributions to the working group on 'radionuclide transfer processes and data for radiological impact assessment'. This included lead authorship on a journal paper describing the development of a revised IAEA data compilation for estimating root uptake of radionuclides by crops in tropical environments. The data are intended to be used internationally to support screening assessments of radiation doses to the public from planned facilities and activities discharging radioactivity to the environment in tropical regions of the world.

The Water and Sediment Quality team participated in the OECD Environment Directorate's Test Guidelines Programme, providing feedback on test guideline development, and participated in a virtual workshop about Adverse Outcome Pathways. The team also contributed to a multi-institutional and multi-national project funded by the International Zinc Association. The project is led by CSIRO and aims to improve predictions of zinc toxicity in freshwater ecosystems based on water quality. Finally, the team continued its engagement with the Asia-Pacific board and World Council for the Society of Environmental Toxicology and Chemistry. Two face-to-face key events, the SETAC World Congress and Omics Workshop have been postponed due to COVID-19 but are rescheduled for 2022.

The Ecosystem Restoration and Landform team continued ongoing collaboration with Professor Tom Coulthard from the University of Hull on the use of CAESAR for landform evolution modelling. Work continued with the United States Geological Survey's (USGS) National Unmanned Aircraft Systems Project Office (NUPO) investigating the use of drone-based radar doppler to measure surface water velocity. Collaboration was also undertaken with Kim Calders (Ghent University, Belgium) and Harm Bartholomeus

(Wageningen University, The Netherlands) on the application of drone-based LiDAR to survey savanna ecosystems.

The Supervising Scientist continued his participation in the OECD Nuclear Energy Agency (NEA) Expert Group on Uranium Mining and Economic Development, including assisting in the finalisation of the NEA publication *Maximising uranium mining's social and economic benefits: a guide for stakeholders.*

2.6 Engagement Across DAWE

Throughout 2020-21 SSB contributed to a range of broader Departmental programs and priorities, leveraging our ability to collaborate across DAWE and provide high quality scientific support and advice.

We continued to provide technical advice to the Environmental Assessment Division on *Environment Protection and Biodiversity Conservation Act 1999* assessments, particularly those triggered as nuclear actions under the Act. The Rum Jungle Rehabilitation Project and the establishment of a National Radioactive Waste Facility were key highlights.

Several staff participated in a departmental process to establish DAWE's Purpose, Objectives and Priorities and to develop the future "Blueprint" for the department's science capability. To further support and develop this capability, the Supervising Scientist and Director of ERISS are also members of the DAWE Science Council and participated in the development of the Science Strategy Action Plan (SSAP). The Director of ERISS lead one of the sub-groups and both participated in a number of discoveries, integration and improvement activities.

The position of Chief Remote Pilot for DAWE is held by Dr Renee Bartolo of SSB who has responsibilities under Civil Aviation Safety Authority (CASA) legislation for all departmental Drone operations. To ensure compliance, build capacity and support application development and testing, SSB has developed a Drone Policy and operational framework for the Department, and leads the DAWE Community of Practice on Drones. SSB also leads the Departmental Communities of Practice on Artificial Intelligence (AI) and Omics, all of which are further discussed in Chapter 4 "Centres of Excellence in Science Application".

SSB continued its close engagement with Parks Australia and continues to support research and monitoring in Kakadu National Park. The Supervising Scientist is a member of the Kakadu Research and Management Advisory Committee which provides advice to the Kakadu Board of Management on research priorities for Kakadu.

2.7 Engagement with other Australian Government Departments and entities

SSB staff continue to provide specialist technical expertise and advice through participation in several Inter Departmental Committees (IDC) and Government funded programs.

The Supervising Scientist and representatives from the SSB participate in the Nuclear Agencies Consultative Committee (an IDC that shares information and provides networking opportunities) and the Radioactive Waste Committee which helps facilitate information on the progression of the development of a National Radioactive Waste Management Facility.

2020-21 saw the completion of the National Environmental Science Program (NESP) Northern Australia Environmental Resources (NAER) Hub's version 4. The NESP V4 research plan commenced in 2018 and included three projects that were focused on Ranger mine closure and rehabilitation.

These projects are:

1. *Rehabilitation of faunal assemblages at Ranger uranium mine* (Ecosystem Restoration closure theme) – Completed 2019 (see ATR 2020)
2. *Ecohydrology and sensitivity of riparian vegetation* (Water and Sediment closure theme) – Completed 2021 (see Appendix 3)
3. *Effects of surface and ground water egress of mining-related solutes on aquatic ecological connectivity, Magela Creek* (Water and Sediment closure theme) – Completed 2021 (see Appendix 3)

These projects represent a significant resource investment by NESP and have provided valuable information for SSB and ERA to inform the rehabilitation of Ranger.

SSB participated in the development of the Research Plan for the 2021 National Environmental Science Program (NESP2) and is working with collaborators on projects in the Resilient Landscapes, Sustainable Communities and Waste, and Climate System Hubs.

SSB is also a member of and provides in-kind support to the Commonwealth Department of Industry's Cooperative Research Centre (CRC) on Transformations in Mining Economies (CRC TiME). In particular, SSB leads Project 3.2 Transforming disparate approaches to remote sensing and monitoring to industry best practice and is contributing to a variety of other projects.

Image 4 Pit 3, Ranger Mine, Alligator Rivers Region

3 SITES

3.1 Ranger

Energy Resources of Australia Ltd (ERA) operates the Ranger uranium mine, which is located 8 km east of the township of Jabiru. The mine lies within the 78 km^2 Ranger Project Area (RPA) and is adjacent to Magela Creek, a tributary of the East Alligator River. Ranger is an open cut mine which produced uranium oxide (U_3O_8) via acid leach extraction between 1981 and 2021. Mining at Ranger ceased in 2012 and processing of stockpiled ore ceased on 8 January 2021. The cessation of processing at Ranger on 8 January 2021 was mandated by Ranger's mining Authority issued under s41 of the *Atomic Energy Act 1953* (Cwlth).

The s41 Authority issued under the *Atomic Energy Act 1953* is administered by the Commonwealth Minister for Resources and Water. The Authority also contains the Commonwealth's environmental protection conditions as 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 the key environmental objectives for mining operations and rehabilitation. Whilst the Commonwealth Minister retains overall responsibility, day-to-day regulation of uranium mining in the Northern Territory (NT) has been delegated to the NT Government and is given effect under the *Mining Management Act*, administered by the NT Department of Industry, Tourism and Trade (DITT). Figure 2 provides an overview of the regulatory framework for Ranger. The Supervising Scientist provides advice to both the Commonwealth Minister for Resources and Water and the NT Minister for Mining and Industry based on the Supervising Scientist Branch's supervision, monitoring and research activities.

Further information on historical activity at Ranger is provided in Appendix 1.

3.1.1 Site Developments

Processing of ore at Ranger ceased on 8 January 2021 and representatives from SSB were onsite to confirm the final closure of the processing plant. Cleaning and de-energisation works continue in the processing area in preparation for future

deconstruction. ERA has now transitioned from a processing to a rehabilitation-focussed operation, including managing a reduction in workforce and changing risk profile.

Rainfall at Jabiru Airport for the 2020-21 wet season, was 1635 mm for the period of Sept 2020-June 2021. This was above the mean annual rainfall for this site (1548 mm). Over the 2020-21 wet season, 1196 ML of treated water has been actively released. This is significantly more than the 296 ML actively released over the 2019–20 wet season and is partly attributable to the above average wet season.

The rate of process water treatment through the brine concentrator was below target and treatment volumes were reduced during the reporting period due to the commissioning of critical upgrades to increase capacity in the longer term. Treatment of process water through the high-density sludge plant recommenced following the approval of a restart application on 7 January 2021. ERA is also trailing brine squeezer technology to increase process water treatment capacity. Pond water treatment occurred throughout the wet season based on operational needs.

ERA made significant progress on rehabilitation activities during the reporting period. The dredging of tailings from the TSF was completed on 15 February 2021 with remnant tailings from the floor and the walls, that could not be dredged, currently being trucked to Pit 3 for disposal.

ERA completed the backfill of Pit 1 on 17 August 2020 and, prior to the 2020-21 wet season, constructed a release/diversion system to manage water coming off the Pit 1 landform based upon quality. The 2020-21 wet season was the first opportunity to observe sediment dynamics and water quality on a completed landform at Ranger. No water was released from the rehabilitated Pit 1 landform over the 2020-21 wet season due to elevated turbidity and electrical conductivity.

Revegetation commenced on Pit 1 with 6,660 tube stock planted from 25 March to 8 April 2021. Further plantings also occurred at the former Stage 13 stockpile area in November 2020 to complement the original plantings in April 2020. These trials are a valuable opportunity to refine ecosystem establishment plans for major revegetation works in 2025.

ERA continued to monitor and treat the introduced weed *Spigelia anthelmia* on site in consultation with the NT Government Weeds Branch. This weed has been contained to the RPA with no infestations identified in the wider Kakadu National Park. The invasive, exotic browsing ant *(Lepisiota frauenfeldiare)* was also identified on site during the reporting period. The National Browsing Ant Eradication Program NT are working with ERA to conduct a surveillance and eradication program on site.

During the reporting period ERA progressed several studies integrating sampling, monitoring, modelling and risk assessment, such as PFAS sampling, an acid sulfate sediment assessment, surface water modelling and groundwater source term conceptual modelling which will inform future rehabilitation applications.

Further information on these activities is included in Appendix 1.

3.1.2 Supervision

The Supervising Scientist oversees the regulation of Ranger uranium mine through the assessment of plans, reports and applications made by ERA. SSB also carries out a program of routine periodic mine site inspections (RPIs) and annual environmental audits for Ranger mine. During the reporting period, SSB commenced a verification program to monitor rehabilitation activities on site. These processes allow stakeholders to review ERA's environmental performance, assess all reported environmental incidents, ensure adequate systems are in place to manage critical on-site risks and ensure effective maintenance and upkeep of mine infrastructure. SSB also conducts investigations to answer questions that arise from water quality and other monitoring observations around Ranger mine.

The Ranger Minesite Technical Committees (MTC) provides a forum for the mine operator to discuss environmental management and regulatory issues with regulators and key stakeholders. The Ranger MTC met twice during the 2020–21 reporting period. Significant agenda items discussed at the meeting included:

- Cessation of processing
- Updating the Ranger Authorisation
- Planned and current assessment activities.

SSB has been engaging with DITT on the frequency of MTC meetings which will occur quarterly as a minimum in future.

3.1.2.1 Assessments and approvals

SSB assesses documents submitted by ERA in accordance with the Environmental Requirements and the Ranger mine Authorisation. SSB assess routine and non-routine reports as well as applications for new or changed activities on site. SSB provides advice to the regulator, mine operator and key stakeholders to help ensure that the environmental management activities undertaken by ERA will achieve the Environmental Requirements and remain in compliance with the Authorisation.

Table 2 shows the assessments undertaken by SSB during the reporting period with significant historical assessments summarised in Appendix 1.

TABLE 2 2020-21 ASSESSMENT ACTIVITIES

Document Title	SSB Assessment Outcome*
Proposals	
Tailings Storage Facility – Plan for Removal of Remnant Tailings	Under assessment
TSF Remnant Tailings Transfer – Pit 3 Pre-Cap Trucking Notification	Supported acceptance
Updated R3Deeps Decommissioning Plan	Noted update
TSF Subfloor Material Management	Supported acceptance
TSF notching works	Supported acceptance
Routine Reports and Plans	
Ranger Wet Season Report 2019/20	Supported acceptance
Ranger Radiation Management Plan 2020	Supported acceptance
Ranger Mining Management Plan 2019/20	Supported acceptance
Ranger Mine Closure Plan 2020	Supported acceptance
TSF Inspection Report	Supported acceptance
TSF Operations and Maintenance Manual	Provided advice
Ranger Water Management Plan 2020-21	Supported acceptance
Ranger Water Monitoring Strategy 2020-21	Supported acceptance
Ranger Annual Groundwater Report 2019/20	Supported acceptance
Radiation and Atmospheric Monitoring Report 2020	Supported acceptance
Non-Routine Reports and Plans	
Pit 1 Interim Water Management Plan	Supported acceptance
ALARA and BPT for Ranger Mine Closure	Provided advice
TSF ramps engineers report	Provided advice
Ranger Land Application Areas Soil Assessment Report	Provided advice
Preliminary Site Wide Acid Sulfate Sediment Conceptual Model	Provided advice
Acid Sulfate Soil Interpretive Report	Provided advice
Metals in Soil Interpretive Report	Under assessment
Ranger Climate Change Risk Assessment	Provided advice
Consolidation and modelling reports relating to Pit 1 and Pit 3	Ongoing advice
Ranger Surface Water Model	Ongoing advice
Groundwater Source Term Conceptual Model	Provided advice
Groundwater Uncertainty Analysis	Provided advice
CCLAA review report	Provided advice
GCT2 Interception System Report	Provided advice
Pit 1 Construction Monitoring Plan	Provided advice
Pit 1 Ecosystem Establishment Monitoring Plan	Ongoing advice
2019/2020 Contaminated sites investigation	Provided advice
HDS Restart Trial Report and Direct Treatment Application	Supported acceptance
R3Deeps – Material Movement Plan	Provide advice

**Supported acceptance* – SSB endorsed statutory reports or proposals; *Provided advice* – SSB provided feedback to inform future applications or ERA activities; *Ongoing advice* – SSB is providing ongoing feedback on iterations of the model or report; *Under assessment* – Assessment outcomes have yet to be finalised.

3.1.2.2 Ranger Mine Closure Plan

Rehabilitation planning for Ranger has been underway for many years. ERA is required to submit a Ranger Mine Closure Plan (RMCP) annually for approval, under both Commonwealth and NT legislation. The RMCP must detail ERA's approach for the planning and implementation of rehabilitation activities and demonstrate that these activities will achieve the Environmental Requirements. The RMCP requires approval by the respective Commonwealth and NT Ministers, with advice from the Supervising Scientist. ERA has submitted a RMCP annually since 2016. Several rehabilitation activities have already been executed according to the RMCP, and all major rehabilitation works are intended to be completed by 2026.

The 2020 RMCP was submitted for assessment on 1 October 2020 and included updates on the status of rehabilitation activities and addressed some of the feedback provided on the 2019 version of the plan by SSB and other stakeholders. SSB undertook a detailed technical review of the plan and published an Assessment Report in December 2020 (https://www.awe.gov.au/science-research/supervising-scientist/publications/internal-reports/ir664).

SSB's assessment of the 2020 RMCP found that the broad rehabilitation strategy remains acceptable and noted an improvement over the previous version through extensive work undertaken over the preceding year. However, the Supervising Scientist noted several areas where further information was required, including:

- Information on the management of residual contamination beneath the TSF.
- Further work on a detailed long-term (post-closure) monitoring plan.
- Detailed plans for full ecosystem establishment, 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 and clarity around what level of environmental effect within the RPA would be considered "As Low as Reasonably Achievable".

At the end of the reporting period the 2020 RMCP remained under review by the Minister for Resources and Water.

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. Several less complex rehabilitation activities will be approved within the RMCP itself while more technically complex activities will require a stand-alone approval process outside of the RMCP. This stand-alone approval process will require the submission of specific applications that include all relevant information related to the 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 Tailings Storage Facility Applications

On 16 March 2020 ERA submitted an application to leave the contaminated material at the base of the TSF in place, as opposed to moving the material to Pit 3. Groundwater modelling supporting the application concluded that transferring the material to Pit 3 would result in a worse environmental outcome than leaving the material *in situ*. This is due to disturbance of the subfloor material increasing the mobilisation of contaminants through the groundwater pathway and into surface water systems. Following assessment, SSB supported the proposal but noted that significant uncertainty remained on the magnitude of the contaminant loads from site including the TSF. This uncertainty would need to be addressed as part of the future TSF deconstruction plan and potential remediation of the contaminant plume may be required. The application was approved by DITT on 5 August 2020.

Since 2018, ERA has submitted several applications to construct notches, construct internal access ramps in the TSF embankments and reduce the TSF crest height. Each application has been assessed by SSB with advice from specialist geotechnical consultants. Further information on these historical assessments is provided in Appendix 1. On 2 June 2020, ERA submitted a proposal for construction of two new notches and internal TSF wall ramps to provide access to the TSF floor. The proposed works and associated engineering designs were assessed by SSB, and it was concluded they did not pose a risk to the integrity of the TSF walls.

On 21 April 2021 ERA submitted a proposed method to remove remnant tailings from the TSF walls and floors to satisfy the requirements of ER 11.2 which requires all tailings be placed in mined out pits by the end of operations. This proposal included a quality control procedure to measure and verify the extent to which the TSF has been cleaned of visible remnant tailings. SSB provided comments on the proposed verification techniques on 11 May 2021, which are being considered by ERA.

On 14 May 2021 ERA submitted a notification for the use of haul trucks to transfer residual tailings from the TSF to Pit 3. The notification proposed depositing the tailings down a lined dump face on the north-west wall of Pit 3. The proposal presented groundwater modelling of various disposal option in Pit 3 to demonstrate that depositing the tailings prior to laying geofabric and depositing waste rock would result in the best environmental outcome. SSB supported acceptance of the proposed approach on 29 June 2021.

3.1.2.4 Ranger 3 Deeps Backfill

The updated bulk backfill work program for the Ranger 3 Deeps exploration decline and ventilation shaft was approved by DITT on 5 March 2021 following advice from SBB, with works commencing shortly after. This update describes the material movement requirements provided conceptually in the original decommissioning plan approved on 15 April 2019. The backfill works entail removing remaining infrastructure and backfilling

the top 350 m of the decline and the ventilation shaft with waste rock. Additionally, the top 10 m of the ventilation shaft will be plugged with a mixture of concrete and waste rock to minimise the risks from subsidence. These works will be completed later in 2021.

SSB has developed a comprehensive verification program (section 3.1.3) to monitor these backfill works and ensure activities are undertaken in accordance with approval conditions.

3.1.2.5 Pit 1 Progressive Rehabilitation

ERA's Pit 1 Interim Water Management Plan was approved on 9 December 2020 following assessment by SSB. This plan established release criteria for water shed from the Pit 1 landform and describes how water from the Pit 1 catchment will be managed until the whole-of-site final landform is completed. ERA constructed a drainage system to direct all surface water from Pit 1 to the Corridor Road Sump, which has been upgraded with electrically actuated culvert gates and additional pumping capacity. Water in Corridor Road Sump will be released to Corridor Creek if it is within specification or pumped to on-site waterbodies if it is not of release quality.

SSB has commenced the rehabilitation verification process for Pit 1 as detailed in Section 3.1.3 below.

ERA commenced planting for revegetation trials in the central region of Pit 1 in March and April 2021. Further trial planting also occurred at the former Stage 13 stockpile area in November 2020 to complement the original plantings in April 2020. These trials are a valuable opportunity to inform ecosystem establishment plans for major revegetation works in 2025.

SSB participated in the development of a water, sediment, ecosystem re-establishment and radiation monitoring plan for the Pit 1 area with monitoring activities described within this plan being conducted by both ERA and SSB. ERA's implementation of their commitments in this plan will be audited during the July 2021 RPI and SSB will continue to review results of the monitoring and any changes to the monitoring program through routine inspections.

3.1.2.6 Audit

The 2020 annual environmental audit on behalf of external stakeholders of Ranger mine was undertaken on site from 21 to 25 September 2020.

The subject of the 2020 audit was ERA's planning and preparation for transitioning from an operational mine site to a rehabilitation and closure focussed operation. ERA's strategies were assessed to evaluate how environmental protection will be assured and to ensure that key environmental risks continue to be managed during the transition.

The audit assessed how six environment-related activities will be managed during the transition, namely:

- Revegetation and ecosystem restoration
- Pit backfill and closure

- Water management and treatment
- Groundwater and surface water monitoring
- Weed management
- Radiation protection.

The audit comprised six high-level questions applied to each environmental activity. Each high-level question targeted a component of ERA's environmental management system (EMS). These EMS components included transition planning, statutory compliance, performance monitoring, communication strategies, resources for environmental management and records management.

The grading for each question was assigned based on the status of management strategies being developed and in place, taking into consideration potential consequences to the environment and/or rehabilitation, and closure timeframes.

The audit found that planning for the transition had commenced. ERA demonstrated awareness of the potential risks associated with the transition and had processes and systems in place, or in train, to manage those risks. Thus, no non-compliances were identified during the audit.

Eight conditional findings were identified where additional evidence is required to demonstrate that planning and transitioning activities are being completed.

- Six of these related to transition activities which were in progress but not yet completed:
    - knowledge transfer templates where key environmental responsibilities are being handed over between managers and/or superintendents
    - the update of the closure obligations register
    - the integration of the closure and operational risk registers
    - the update of standard operating procedures for tasks that manage key environmental risks (in light of changed reporting lines or management practices)
    - the completion of document control-related tasks in the transition plan
    - the revision of the Radiation Management Plan.
- The audit identified several resourcing pressure points which should be monitored to ensure that environmental risks are managed.
- Given that much of the future rehabilitation works will be based on experience gained during earlier work and trials, ERA should implement a schedule of progressive monitoring and evaluation to ensure that lessons learned are integrated into later stages of projects.

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

Stakeholders followed up on the significant findings of this audit through the Routine Periodic Inspection (RPI) program. The 2021 annual environmental audit is scheduled

for August 2021 and will focus on environment and land use management including weed, fire, water, and radiation management.

3.1.2.7 Inspections

Routine Periodic Inspections were carried out monthly as scheduled during the reporting period. The 2021 Ranger RPI and audit program was agreed to by stakeholders in December 2020. Each RPI in the program has a theme aligned with relevant activities on-site. With the cessation of processing on 8 January 2021, the schedule for 2021 has a significant focus on rehabilitation preparation activities and rehabilitation execution. Routine operational activities such as site water management are still included in the program. Table 3 shows the focus areas for each of the RPIs completed during the reporting period.

TABLE 3 2020-21 RANGER ROUTINE PERIODIC INSPECTION PROGRAM

Month	Theme	Primary areas inspected
2020		
July	Hydrocarbons and waste management Water treatment and management	Pit 3 controlled waste disposal area, Pit 3 temporary laydown area, bulk diesel and VivaSol storage area Water treatment plant 1, HDS plant
August	Revegetation and Ecosystem Restoration Preparation Groundwater monitoring and management and contaminated sites	Pit 1 landform, nursery Western Stockpile Interception System, GCT2, CRS and Pit 1 diversion system, Pit 3 rim
September	Annual Environmental Audit	No inspections were conducted
October	Crushing circuit, mill, and processing area	Processing area (primary and fine crushing areas, coarse tailings stockpile, grinding wheels, CCD, SX, calciner, product packing area), Pit 3, Pit 1 diversion system
November	Major rehabilitation activities and wet season preparation and Jabiluka pre wet season inspection	TSF wall integrity and inspection program, piezometer monitoring trends, notching activities, dredging and wall cleaning, Pit 3, Pit 1 diversion system, Stage 13.1A and Stage 13.1B revegetation trials
December	Audit follow-up and preparations for cessation of processing	No physical inspections were conducted
2021		
January	Cessation of Processing	Calciner, product packing area
	Continued Audit Follow-Up 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	Make Safe for Crushing Circuit, Mill and Processing area	Processing area (primary and fine crushing areas, acid tanks, clarifier tanks, SX dump tank, ammonia storage area)

TABLE 3 2020-21 RANGER ROUTINE PERIODIC INSPECTION PROGRAM

Month	Theme	Primary areas inspected
March	Land use management (Weed and Fire management)	Pit 3, Stockpiles to NW of TSF, Stage 13, Pit 1, TSF, Northern CCLAA, CRS Sump
April	Revegetation, nursery, and ecosystem re-establishment (focus on Pit 1 monitoring)	Nursery, seed storage rooms, Pit 1 revegetation trial plantings, Stage 13.1 A and B
May	Ranger TSF Annual Inspection (incorporating post wet season inspection) and Jabiluka post wet season inspection	TSF crest road, west wall notch and western access ramp, TSF floor, north wall notch
June	Water treatment and brines and release management	High Density Sludge (HDS) Plant, Water Treatment Plant 1, Brine Squeezer, Brine Concentrator, Pit 3
July	Pit 1 Monitoring and Ecosystem Establishment Plan	Pit 1 landform, CRS sump, Stage 13.1, TSF

3.1.2.8 Environmental incidents

From 1 July 2020 to 30 June 2021, ERA reported 16 environmental incidents to stakeholders. This represents a reduction in reported incidents from the same period in 2019–20 during which 29 incidents were reported. This reduction is partly attributable to reduced activities on site during the reporting period including the cessation of processing. An annual comparison of incidents reported over the past six years is shown in Figure 5.

The number of process water-, tailings- and hydrocarbon-related incidents notified to stakeholder in 2020–21 is consistent with the number reported in 2019–20 (Figure 6). Process water and hydrocarbon related incidents accounted for most incidents reported during 2020-21 with almost all being minor, with no impact or residual risk to the environment.

All incidents were investigated by SSB through the RPI process and were considered to have been satisfactorily resolved. ERA implemented several improvements in response to incidents.

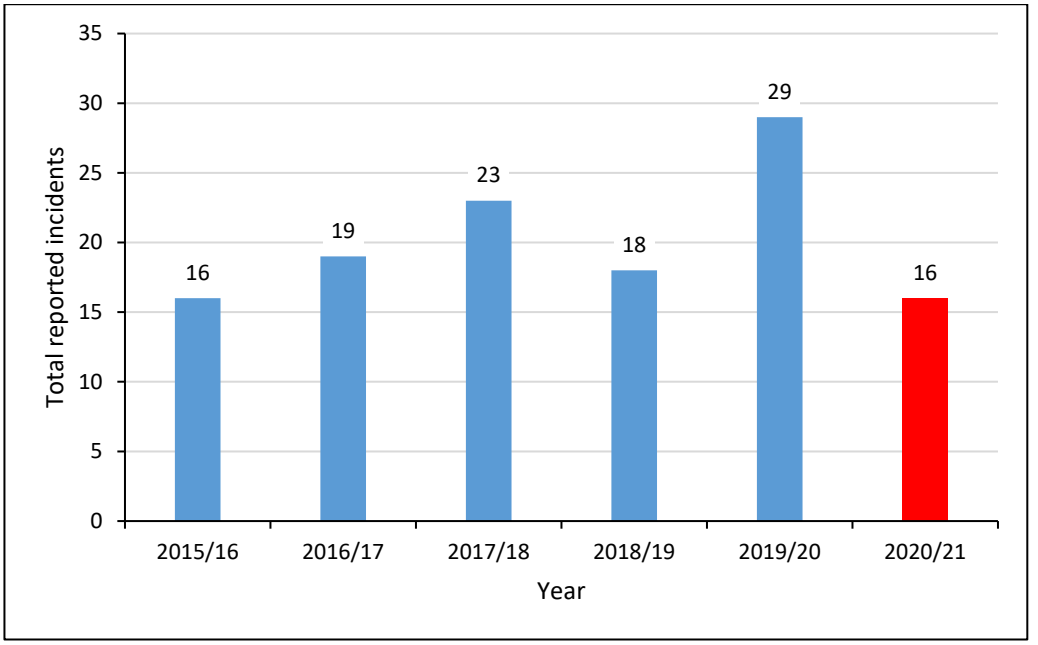


Figure 5 Ranger mine reported environmental incidents by year.

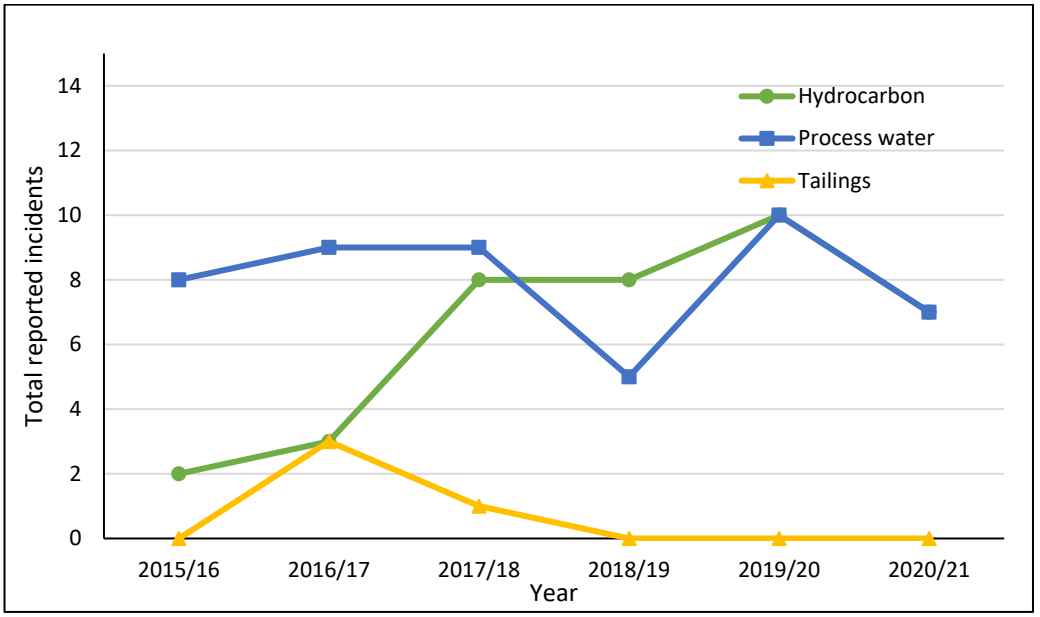


Figure 6 Hydrocarbon, process water and tailings incidents by year.

3.1.2.9 Significant Incidents

One significant incident was identified during the reporting period.

Browsing ants

Browsing ants were detected at the Ranger mine site. Browsing ants (*Lepisiota frauenfeldiare*) are an exotic ant to Australia. They are invasive, have potential to displace native ants and are a declared pest.

Browsing ants were previously detected in Darwin in 2015. The National Browsing Ant Eradication Program NT was formed to undertake surveillance and eradication. The National Browsing Ant Eradication Program NT detected browsing ants at a commercial premise in East Arm in June 2020. Through analysis of cargo movements, it was identified that shipment of cargo to Ranger mine had occurred.

The National Browsing Ant Eradication Program NT subsequently commenced a comprehensive surveillance program at Ranger and detected Browsing Ants in and around the processing area in October 2020. ERA is assisting staff from the National Browsing Ant Eradication Program NT to conduct treatment and further surveillance activities and SSB is monitoring the progress of the eradication program through routine inspections and direct communication with the National Browsing Ant Eradication Program NT.

Table 4 provides a summary of the significant incidents that have occurred since 2013.

TABLE 4 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.

TABLE 4 SUMMARY OF SIGNIFICANT INCIDENTS

Year	Incident	Outcome
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.
2019	**Detection of *Spigelia anthelmia*** On 17 April 2019, ERA notified stakeholders that *Spigelia anthelmia* (West Indian Pinkroot) had been found on site. This weed had not previously been recorded in Australia and ERA surveys confirmed that the infestation is currently restricted to the Ranger mine operational areas.	In consultation with the NT Weeds Branch, ERA developed a weed management plan including surveys, internal and external communication, the establishment of control zones and a treatment and monitoring program. ERA aim to eradicate the weed. Stakeholders are monitoring the implementation and outcomes of the weed management plan during RPIs.
2020	**Detection of *Lepisiota frauenfeldiare*** In October 2020, *Lepisiota frauenfeldiare* (Browsing ants) were identified at the Ranger mine site. Browsing ants are an exotic ant to Australia, are invasive and have potential to displace native ants.	The National Browsing Ant Eradication Program NT is conducting a comprehensive surveillance and treatment program. This program is ongoing and SSB are monitoring its progress through routine inspections and direct communication with the National Browsing Ant Eradication Program NT.

3.1.2.10 Investigations

Leach Tank 5 Leak Investigation

In the early hours of 11 November 2020, a leak from Leach Tank 5 was noted during a routine inspection of the tank. Process slurry was spraying into the bund and a mist was spraying onto the ground outside the bund. Leach Tank 5 was immediately taken offline, and the level of the tank was lowered. In 2013, a similar leak occurred in a leach tank immediately prior to a catastrophic failure of the leach tank. Following the 2013 incident, ERA implemented a comprehensive inspection and monitoring program to prevent recurrence.

Considering the precedent, representatives from SSB and DITT conducted an inspection of the incident location on 17 November 2020. Upon inspection, the tank had been emptied and the agitator blades had been removed. The location of the leak was visible from the outside of the tank. ERA advised that the hole was small (20 mm × 10 mm), oblong and did not appear to be near other holes or areas of lining or tank thinning.

Stakeholders viewed the results of an ultrasonic scan conducted in March-April 2020 which showed no significant thinning in the area of the leak. Following that scan, in August 2020, the tank had undergone an opportunistic refurbishment of areas of

concern noted during the previous scan. The tank had remained offline from March to September 2020. The tank was put back online in October 2020 and had been online for around a month when the leak occurred.

ERA's investigation concluded that the hole was initiated by localised internal corrosion of the tank's shell which occurred when a bubble in the rubber membrane ruptured. The root cause of the rubber rupture is not clear but could potentially be related to repairs conducted in August 2020.

From inspection and ERA's investigation, stakeholders were satisfied that the hole was likely to be an isolated occurrence and not a wider general concern with the ongoing integrity of the tanks.

Following the cessation of processing operations on 8 January 2021 all leach tanks have been permanently drained and there is now no risk of any future tank failure.

Gulungul Creek Tributary 2 Investigation

During the 2013-14 wet season, SSB observed a significant elevation in EC at the downstream compliance site in Gulungul Creek (GCLB). Subsequently, SSB initiated discussions with ERA and investigations began to determine the source of contamination, the contamination pathway and impacts of the elevated EC. The source of elevated EC was determined to be a groundwater seep at the head of the Gulungul Creek Tributary 2 (GCT2) to the west of the TSF.

As a result of these investigations, the Supervising Scientist recommended that ERA restrict the movement of solutes into the Gulungul Creek catchment by upgrading its water management systems to the west of the TSF. Subsequently, ERA constructed a groundwater interception system comprising a shallow groundwater seepage interception trench, a clay barrier, and a series of groundwater extraction wells. The interception trench was constructed in the dry season 2014 whilst the barrier and wells were completed in late 2015.

Following the initial investigation, and in response to exceedances of the Ranger Water Quality Objectives electrical conductivity trigger value SSB took the opportunity to conduct a study assessing the effectiveness of the magnesium water quality guideline value. A direct toxicity assessment (DTA) of water sourced from a groundwater seep along GCT2 was conducted with local tropical freshwater species whilst an *in-situ* toxicity assessment using local freshwater snails was carried out in the creek receiving the diluted groundwater. The results, published in Trenfield et al (2018)[1], found no effect on reproduction of the snails exposed to an average of approximately 5 mg/L Mg. However, a very small but significant suppression in reproduction relative to upstream was noted

[1] Trenfield M, Harford A, Mooney T, Ellis M, Humphrey C & van Dam R 2018. Integrating Laboratory and Field Studies to Assess Impacts of Discharge from a Uranium Mine and Validate a Water Quality Guideline Value for Magnesium. Integrated Environmental Assessment and Management 15 (1), 64-76.

closer to the groundwater source, probably associated with contaminants other than magnesium.

In response to the elevated solutes being detected, an additional site close to where Gulungul Tributary 2 enters Gulungul Creek proper (GCT2GCC) was added to the SSB macroinvertebrate monitoring program. The results from the last several years of monitoring (2015 – present) show that despite macroinvertebrate exposure to mine waters with high solute concentrations over 2-3 seasons, no impairment to macroinvertebrate communities has been observed (See Appendix 6 – Macroinvertebrate Communities).

SSB has also conducted continuous monitoring over multiple wet seasons (2014-15 to 2019-20) in the GCT2 tributary to monitor EC and to confirm the effectiveness of ERA's mitigation measures. EC was measured at a site called GCT2 Radon Springs Track (GCT2RST), which is located downstream of the interception system and dewatering bores. The EC distribution at GCT2RST has reduced across wet seasons and the average EC of the base flow in the GCT2 tributary has maintained a downwards trend since mitigation measures were installed. Since the 2017-18 wet season the baseline EC has ranged from 150 µS/cm to 300 µS/cm, with higher values associated with first flush conditions and lower values associated with dilution from rainfall events. The median EC of groundwater collected from bores in the same hydrolithic unit as GCT2 (shallow weathered Nanambu) is 275 µS/cm (mean = 967 µS/cm), suggesting the EC observed at the surface is close to what would have been observed historically through natural processes.

The reduction in WQO exceedances at GCLB and the return to seasonal EC trends consistent with historical data (collected at downstream site GCDS) also suggests the expression of high solute groundwater from this site has returned to natural levels (Figure 7).

The environmental investigation, summarised above, indicates no short or long-term harm to the Gulungul ecosystem for the period of elevated solutes expressed in GCT2. In addition, water quality monitoring has shown ERA's mitigation to be effective in managing surface and shallow groundwater quality in the GCT2 tributary across consecutive wet seasons.

Whilst ERA maintains the current water management infrastructure and performance monitoring regime, continued monitoring of GCT2RST by SSB is not required. However, as rehabilitation of Ranger mine progresses, and water management priorities change across site, this will need to be reviewed.

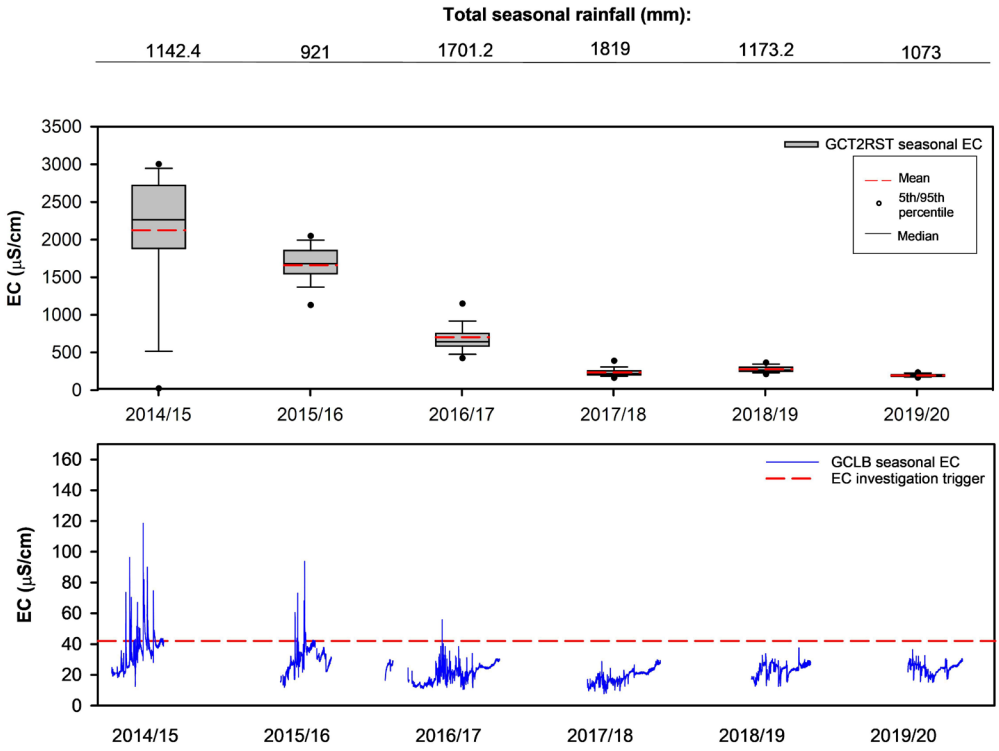


Figure 7 Electrical conductivity measured within Gulungul Creek Tributary 2 (GCT2RST) (top)[2] and Gulungul Creek downstream compliance site (GCLB), and total seasonal rainfall.

While this investigation has concluded, SSB will continue to monitor water quality in Gulungul Creek (GCLB) and review the need for future *in situ* monitoring at GCT2RST based on seasonal results. SSB will also continue to review ERA's monitoring of the GCT2 interception system as part of the Ranger Water Monitoring Strategy.

Upper Gulungul Catchment Investigation

From 2004 to 2015, an increase in electrical conductivity (EC) was observed at the upstream Gulungul catchment monitoring site (GCUS). Subsequently, SSB began investigations to determine potential sources and initial chemistry samples taken determined that Gulungul Creek Tributary South (GCTS) was contributing to the high EC observed in upper Gulungul Creek. To ensure an unimpacted reference site was

[2] The lower and upper boundaries of the boxplots above 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).

available if a mine signature was identified, SSB installed a new site (GCNUS), located upstream of GCUS in 2015.

In response to stakeholder concerns, ERA initiated their own investigations, and engaged Environmental Resources Management Australia (ERM) to assess the historical groundwater data from the southwestern Corridor Creek Land Application Area. In 2017, ERM developed a conceptual hydrologic model to infer groundwater levels to the south of the CCLAA and to determine the potential for irrigation activities to have affected water quality in one of the upper Gulungul tributaries. ERM concluded that the elevated groundwater had the potential to intersect the ground surface at low lying areas and that evapotranspiration due to the shallow water table was the likely mechanism for elevated EC in surface water. ERM hypothesised that groundwater sourced from the CCLAA was likely to express to surface water in the north-eastern flowline (site GCTS-7). ERM found groundwater elevations had increased from May 2010 to June 2015, and subsequently declined with the cessation of dry season irrigation in the southern CCLAA in 2015. Elevated sulfate was observed in several bores and ERM surmised that it had probably been introduced to the groundwater through irrigation of pond quality water from 2007 to 2012. Sulfate concentrations had decreased or stabilised in bores after the improvement in irrigation water quality since 2012. The early findings of SSB monitoring and the ERM report indicated that the CCLAA was a potential source of the elevated solutes although the pathway could not be confirmed based on the lack of groundwater bores to the south of the CCLAA.

SSB also deployed conductivity, temperature, and pressure loggers at numerous locations throughout the upper Gulungul tributaries to monitor EC at a refined spatial resolution. The data indicated a source of solutes in the north-eastern headwaters of GCTS (as reported in the Supervising Scientist Annual Technical Report 2016-17). This was consistent with the locations where ERM (2017) initially hypothesised groundwater sourced from the CCLAA was likely to express to surface water.

SSB has continued to monitor EC at a reduced number of locations along GCTS to track changes in solute expression over time. The EC distribution across the surface water sites (Figure 8) shows a reduction in EC between GCTS-7 and GCTS-3 before increasing again at GCTS-8. The increased EC at GCTS-8 suggests natural processes are also contributing to elevated solutes leaving GCTS into Gulungul Creek. SSB also installed a piezometer in the north easter headwaters (GCTS-7P) to assist with interpretation of the groundwater contribution to the surface water at that location. As expected, higher EC was recorded in groundwater at this location confirming groundwater as a source of solutes to the surface water in addition to potential evapoconcentration effects later in the wet season.

In 2020, ERM conducted an additional review of the impacts of CCLAA on Gulungul and found no evidence that irrigation at CCLAA was contributing to elevated EC in Gulungul Creek. An ionic signature from the CCLAA was not observed in surface water in upper Gulungul creek and at GCTS-7/GCTS-7P. Additionally, whilst groundwater flow towards Gulungul from the southern modules of CCLAA was possible, it was considered to be

unlikely due to the presence of a topographic divide and a groundwater divide to the west of CCLAA. The report instead suggested the elevated EC at GCT7 was related to local groundwater expression.

Upon review of ERM's report and the additional data collected since 2017, which shows relatively stable groundwater solute expression over several years and the potential for natural processes to contribute to elevated EC in GCTS, SSB will cease monitoring in the upper Gulungul tributaries. While this investigation has concluded, SSB will continue to monitor water quality in upstream Gulungul Creek (GCUS) and review the need for future monitoring if water quality deteriorates in Gulungul Creek.

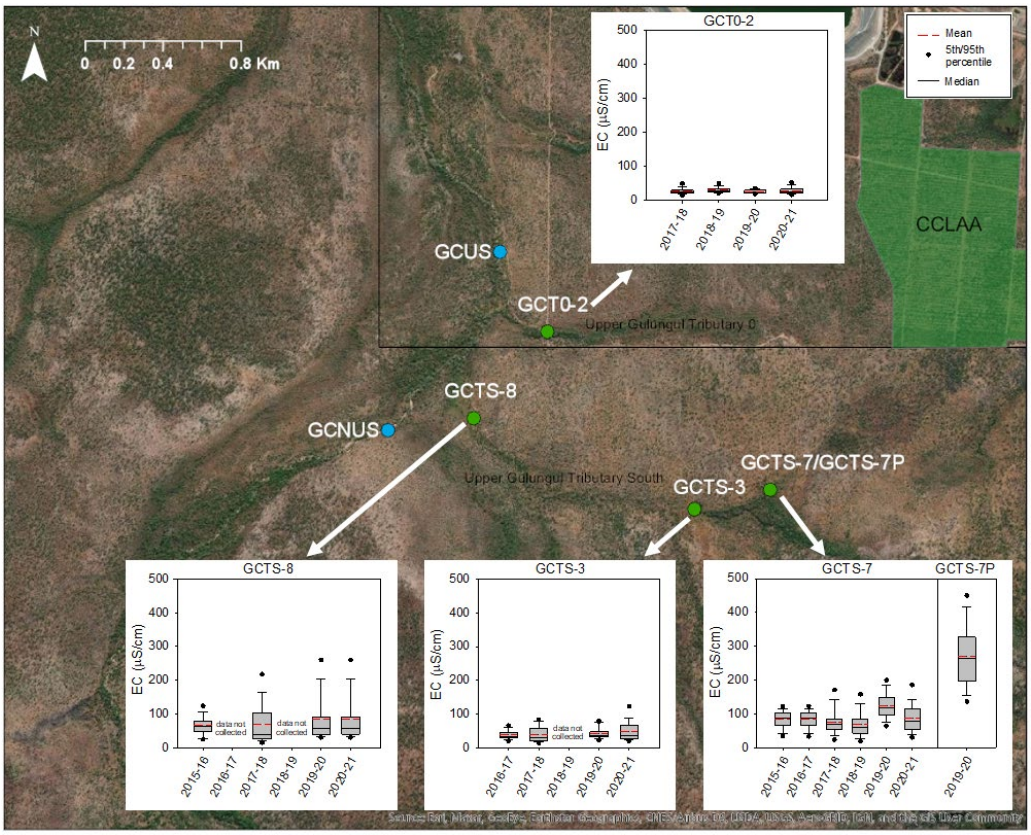


Figure 8 Map of GCT monitoring sites with continuous EC box plots from multiple wet seasons (2015-16 to 2020-21)

ERA maintains groundwater level trigger values to inform irrigation practices in the southern modules of the CCLAA and SSB will also continue to review ERA's monitoring of the groundwater bores in the CCLAA as part of the routine review of the Ranger Water Management Plan and Water Monitoring Strategy.

Downstream Magela Investigation

In response to the detection of elevated solutes downstream of the Gulungul confluence in Magela Creek, SSB has implemented a monitoring investigation to understand and characterise additional solute sources downstream of Ranger mine. Periods of elevated EC have been observed at the Magela downstream of Gulungul Creek confluence (MCDSGCC) site since 2018-19 wet season, and at Gulungul Creek Crossing (GCX) in 2019-20 and 2020-21. A map of monitoring sites with their corresponding EC in box plots is shown in Figure 9.

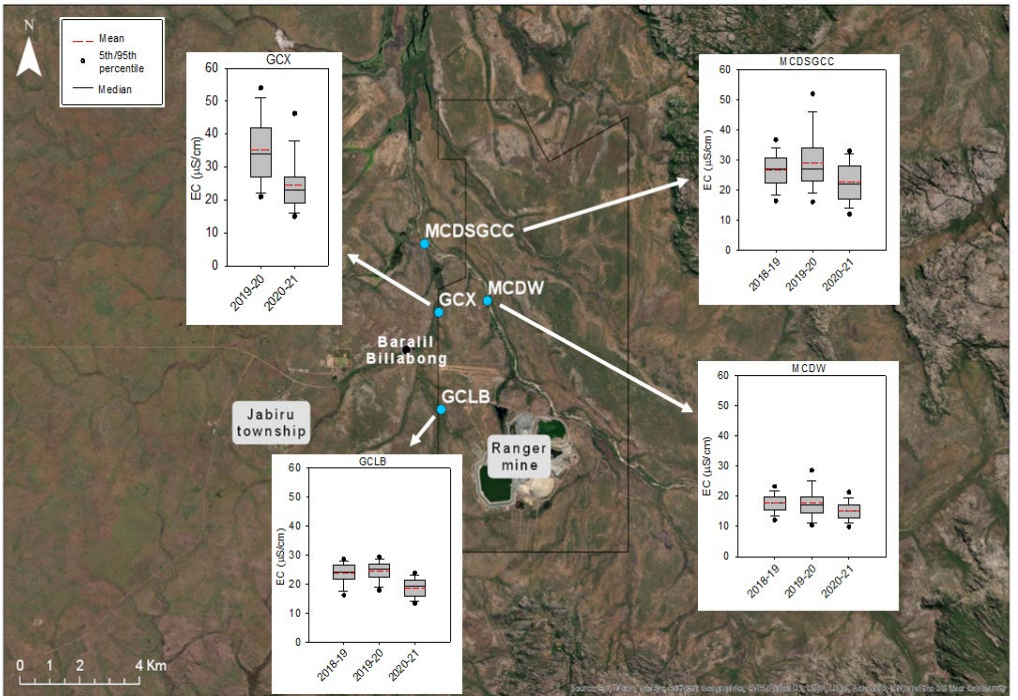


Figure 9 Map of monitoring sites with continuous EC box plots from 2018-19, 2019-20 and 2020-21

The box plots reveal that higher EC is observed downstream at GCX and MCDSGCC compared to GCLB and MCDW across multiple wet seasons. The increase in EC between GCLB and GCX indicate these effects are not mine-related but suggests Baralil Creek as a potential source of elevated EC as Baralil Creek flows into Gulungul Creek between the two sites. Chemistry samples taken at MCDSGCC and GCX showed ionic composition varied with flow conditions throughout the wet season. However, magnesium concentrations at Baralil Billabong from samples collected in 2019-20 were greater than concentrations at MCDSGCC, GCX and downstream compliance sites, MCDW and GCLB. Therefore, it is likely that the Baralil catchment is inputting solutes into Gulungul Creek influencing EC downstream of the Baralil confluence.

This investigation is on-going, and monitoring loggers and chemistry samples will continue to be collected during the 2021-22 wet season.

Regional Snapshot of Per- and Polyfluoroalkyl Substances (PFAS)

Surface water sampling was undertaken during the recessional flow period in 2020-21 wet season to determine PFAS concentrations in the region surrounding Jabiru township and Ranger mine. Findings of this investigation are still under analysis and will be reported in the Supervising Scientist Annual Technical Report 2021-22.

3.1.3 Verification

A verification process has been developed by SSB to monitor the execution of rehabilitation activities at Ranger mine. The purpose of verification is to ensure rehabilitation activities are executed by ERA in accordance with relevant approval conditions and commitments described in approved rehabilitation plans.

Verification that these works are completed satisfactorily is carried out by identifying critical points in the rehabilitation activity and obtaining evidence through physical inspections, independent SSB verification and/or assessment of information (such as data, surveys, and tests). A verification report is produced once a rehabilitation activity is completed which details the outcomes of the verification activity and collates all information and evidence collected during the verification execution.

SSB is developing working protocols with ERA for verification activities. These arrangements include the collaborative development of verification protocols and drafting verification plans for specific rehabilitation activities.

Three verification projects commenced during the reporting period as shown in Table 5.

TABLE 5 STATUS OF VERIFICATION ACTIVITIES

Area	Activity	Status as of 30 June 2021
Ranger 3 Deeps	Decline Final Closure and Backfill	Ongoing – completion expected end of August 2021
TSF	TSF walls and floor cleaning and Pit 3 Pre-Cap Trucking	Ongoing – approx. 95% of tailings are turned over and 65% are ready for transfer.
Pit 1	As-built construction of Pit 1 landform	Currently being prepared by ERA. SSB expect to review the report in August 2021.

3.1.4 Monitoring

3.1.4.1 Early detection water quality monitoring in Magela Creek

Magela Creek flows to the northwest of Ranger mine and receives mine site runoff and treated mine waters. EC and stage (water level) are continuously monitored in the creek upstream and downstream of the mine throughout the wet season. Elevated EC may indicate the presence of contaminants in the creek.

The EC measured in Magela Creek over the 2020-21 wet season was comparable to previous wet seasons (Figure 10) and values at the monitoring site downstream of

Ranger remained below the trigger value of 42 µS/cm. The EC for the 2020-21 season followed the same trends typical for previous wet seasons, i.e. fluctuation throughout the earlier part of the season corresponding with rainfall and (for the downstream site) passive and active mine-water discharges, followed by smoothing and evapoconcentration later in the season as rainfall declined and recessional flows commenced (Figure 11). All Water Quality Objectives for Magela Creek were met for the 2020-21 wet season (see https://www.awe.gov.au/science-research/supervising-scientist/publications#monitoringdata).

SSB also monitors radium (Ra^{226}) in Magela creek, upstream and downstream of the mine. The Ra^{226} Limit of 3 mBq/L is assessed by calculating the difference in the geometric mean of concentrations upstream and downstream of the mine. Radium samples collected over the 2020-21 wet season were within the historical range (Figure 12) and the geometric mean difference was below the Limit and close to zero.

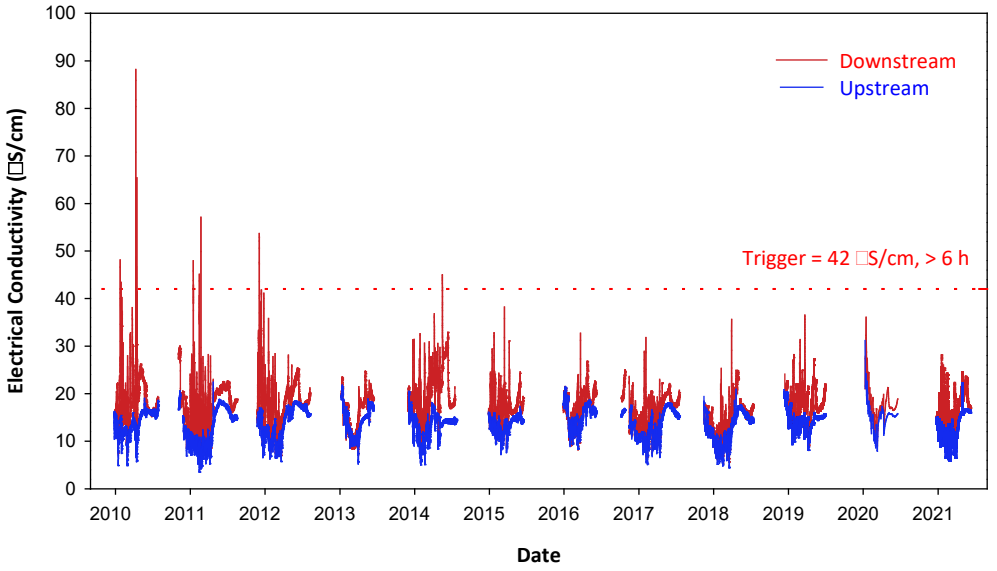


Figure 10 Long term wet season electrical conductivity in Magela Creek (2010-2021)

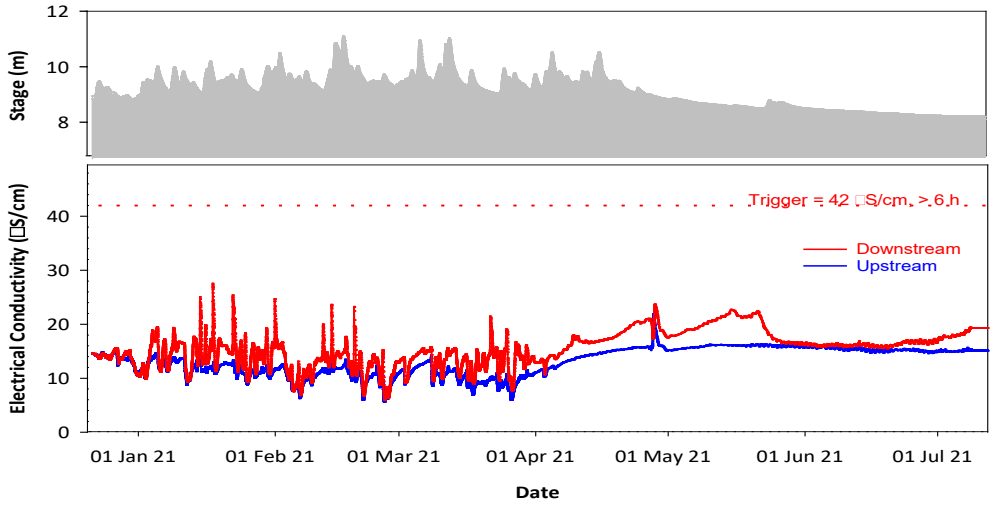


Figure 11 Magela Creek electrical conductivity and water level (stage) for the 2020-21 wet season

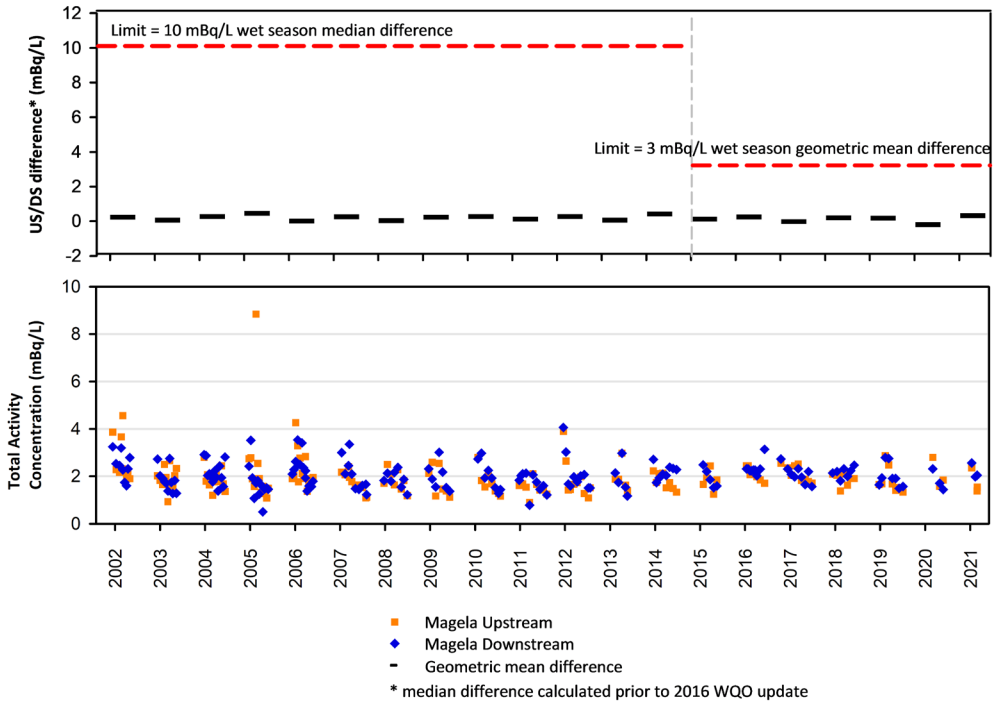


Figure 12 Long term wet season radium concentrations measured in Magela Creek (2002-2021)

3.1.4.2 Early detection monitoring in Gulungul Creek

Gulungul Creek flows along the western boundary of the RPA. ERA does not actively discharge mine water into Gulungul Creek, but the creek receives passive surface runoff and shallow groundwater flows from the mine site. Variable water quality in Gulungul Creek over the 2013-16 period was associated with mine water influences from the Upper Gulungul Creek tributaries and Gulungul Creek Tributary 2 (Figure 13). Since then, there has been greater active ERA management of mine water inputs. The EC measured in Gulungul Creek over the 2020-21 wet season was comparable to values recorded in the past three wet seasons (Figure 13) and remained below the trigger value of 42 µS/cm.

The EC for the 2020-21 season followed similar trends as observed for previous wet seasons, i.e. fluctuation throughout the earlier part of the season corresponding with rainfall followed by general smoothing and evapoconcentration later in the season as rainfall declined and recessional flows commenced (Figure 14). All Water Quality Objectives for Gulungul Creek were met for the 2020-21 wet season (see https://www.awe.gov.au/science-research/supervising-scientist/publications#monitoringdata).

SSB also monitor radium (Ra^{226}) in Gulungul creek upstream and downstream of the mine. The Ra^{226} Limit of 3 mBq/L is assessed by calculating the difference in the geometric mean of concentrations upstream and downstream of the mine. Radium samples collected over the 2020-21 wet season were within the historical range (Figure 15) and the geometric mean difference was well below the Limit.

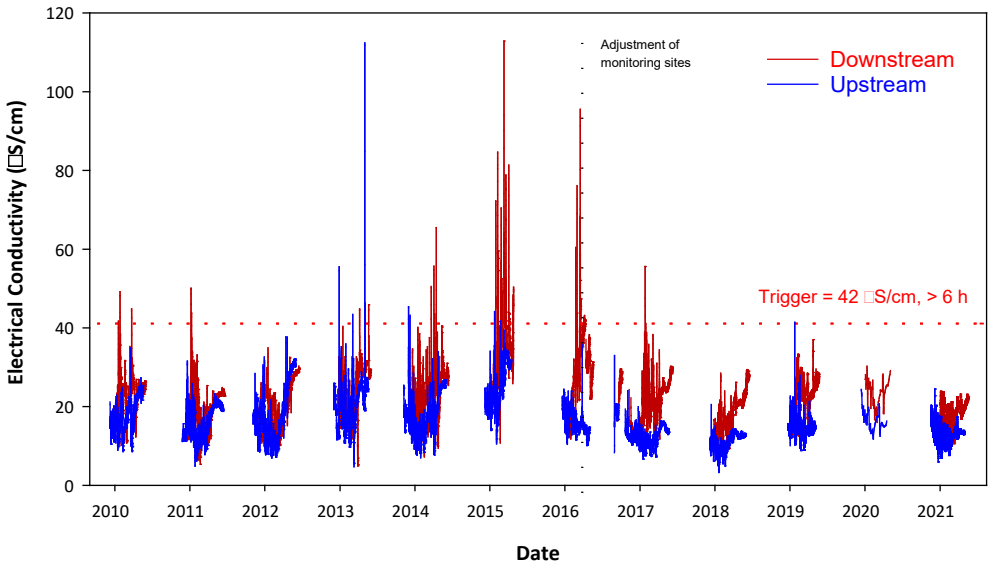


Figure 13 Long term wet season electrical conductivity in Gulungul Creek (2010-2021)

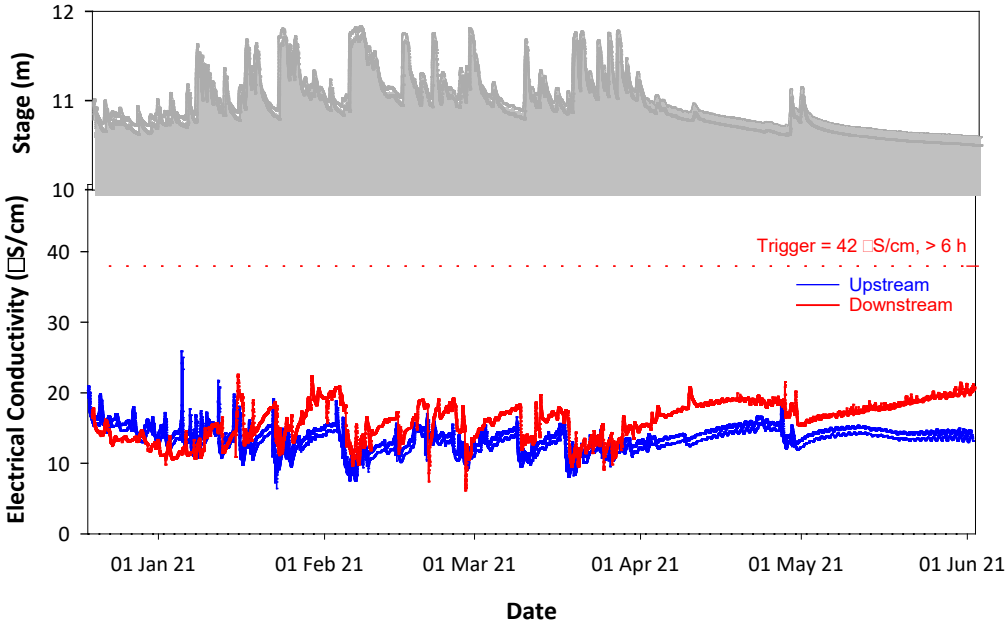


Figure 14 Gulungul Creek electrical conductivity and water level (stage) for the 2020-21 wet season

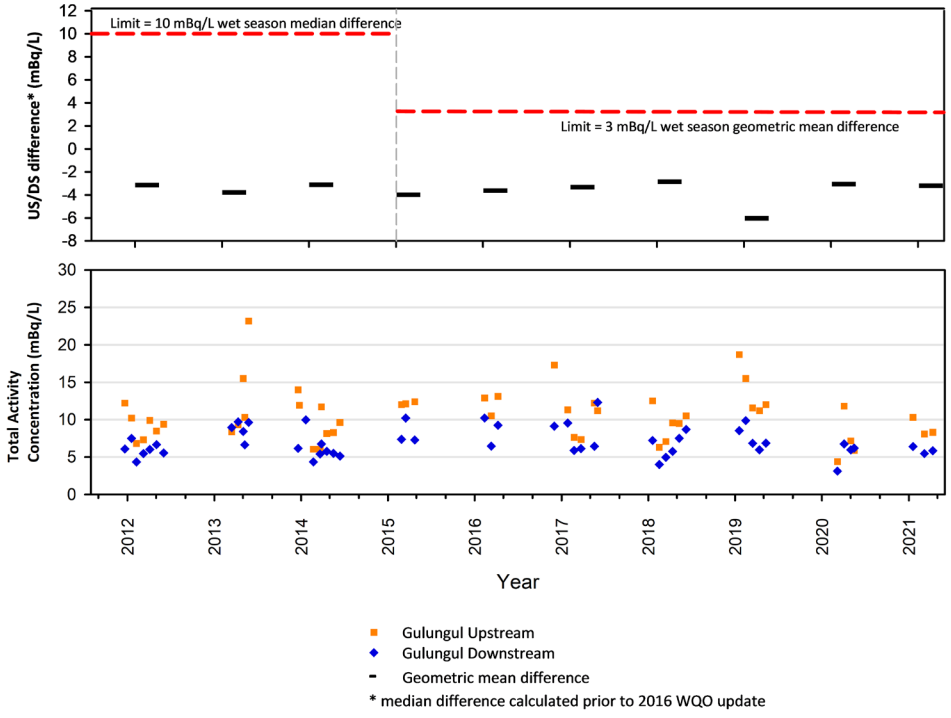


Figure 15 Long term wet season radium concentrations measured in Gulungul Creek (2002-2021)

3.1.4.3 Biological monitoring using fish communities

Fish communities in deep channel billabongs are assessed for mining-related impacts annually, at the wet-dry season transition. Historically, SSB has compared fish community structures in Mudginberri Billabong (directly exposed site downstream of Ranger in Magela Creek catchment) to those in Sandy Billabong (control site in Nourlangie Creek catchment). Dissimilarity measures depict the degree of similarity in fish communities between the two locations (paired sites). Annual mean paired-site dissimilarity for 2021 was within the range of values reported in all previous years (Figure 16), indicating no mine-related changes to the fish communities in Mudginberri Billabong downstream of Ranger over the 2020-21 wet season. Appendix 6 contains a full statistical analysis of these monitoring data with associated Figures.

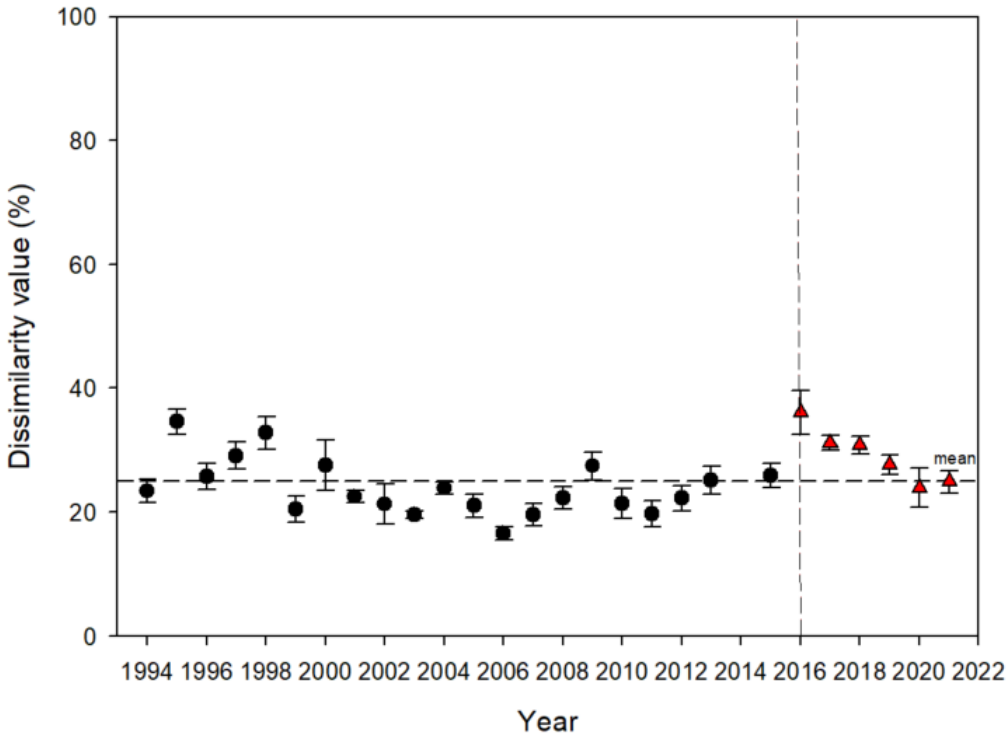


Figure 16 Paired control-exposed dissimilarity values for fish community structure in channel billabongs. Dissimilarity values calculated using the Bray-Curtis measure, for community structure of fish in Mudginberri ('exposed') and Sandy ('control') Billabongs. Values are means (± standard error) of 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 triangles).

3.1.4.4 Biological monitoring using macroinvertebrate communities

During the recessional flow period of the 2020-21 wet season, macroinvertebrate communities were sampled in 'exposed' streams, Magela and Gulungul creeks at sites upstream and downstream of the mine, and from the same paired-site configuration in control streams, Burdulba and Nourlangie creeks. As described for fish communities (section 3.1.3.3 above), (dis)similarity measures are used to depict the degree of similarity in macroinvertebrates between the upstream and downstream locations (paired sites) in each stream. Annual, mean paired-site dissimilarity for the four streams is shown in Figure 17 with results discussed as follows:

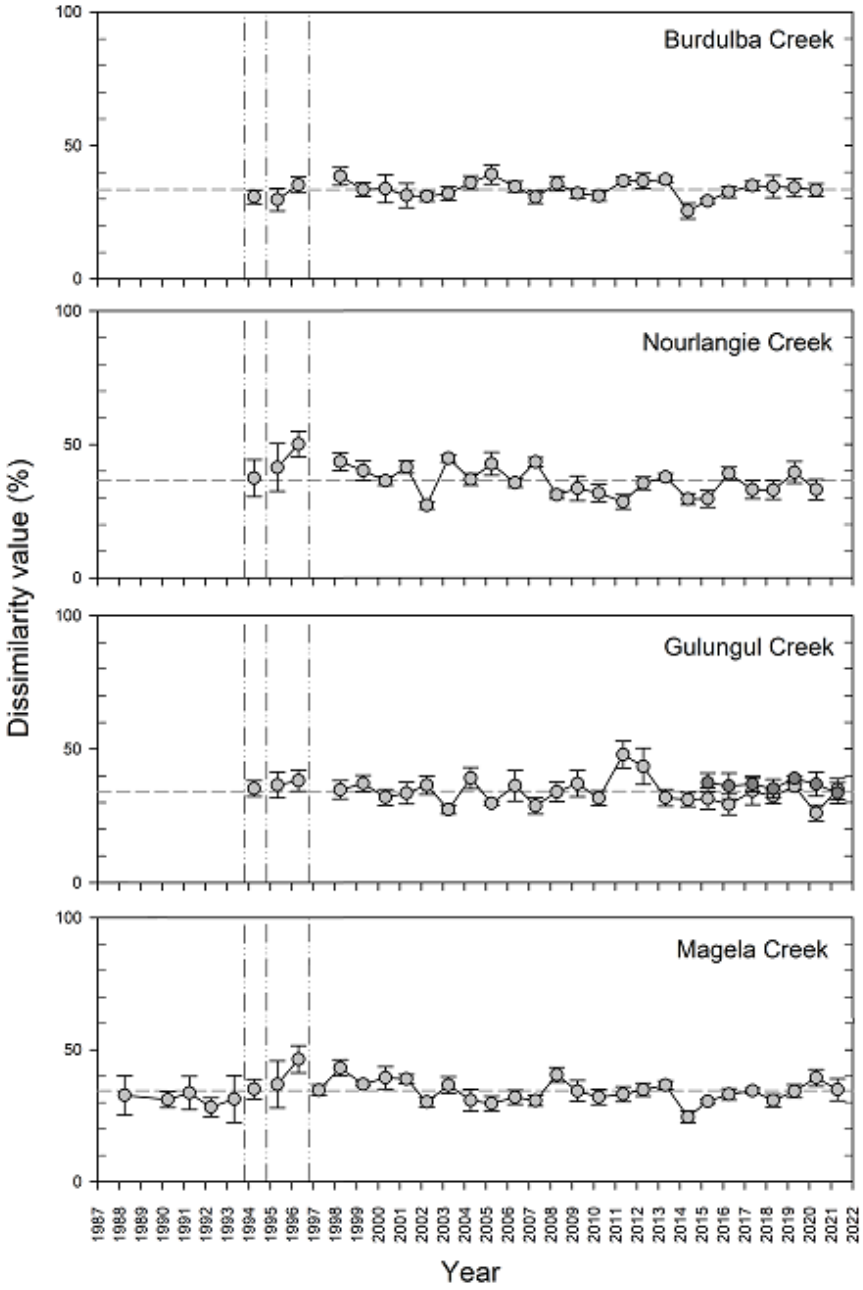


Figure 17 Paired upstream-downstream Bray-Curtis dissimilarity values using family-level (log transformed) data for macroinvertebrate community structure.

Dark grey 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

Results for the full 2019-20 data

In last year's Annual Technical Report, the complete 2019-20 recessional flow data set (i.e., including control streams Nourlangie and Burdulba creeks) was not available for reporting, with only exposed streams, Magela and Gulungul Creeks, being reported on at the time. Compilation and analysis of the full macroinvertebrate dataset from 1988 to 2020 has now been completed. Annual mean paired-site dissimilarity for both of the exposed streams in 2020 was within the range of values reported in all previous years (Figure 17) and were similar to values reported for control streams in 2020 and previous years. This confirms the preliminary results reported in the previous Annual Technical Report (2019-20), i.e., no evidence of mine-related changes to the macroinvertebrate communities in Magela and Gulungul Creeks downstream of Ranger over the 2019-20 wet season.

Results for Magela and Gulungul Creeks 2020-21

At the time of report preparation, only data for exposed streams Magela and Gulungul creeks sampled during the 2020-21 wet season were available for analysis. Annual mean paired-site dissimilarity for both of the exposed streams in 2021 was within the range of values for the same streams reported in all previous years (Figure 17), indicating that any changes to water quality downstream of Ranger as a consequence of mining activities during 2021 had not adversely affected macroinvertebrate communities in the creeks.

Appendix 6 contains a full statistical analysis of these monitoring data (2019-20 and 2020-21) with associated Figures.

3.1.4.5 Radiation exposure to 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 mine site, while the ingestion pathway is caused by the uptake of radionuclides into bush foods from the Magela Creek system downstream of the mine.

Ingestion pathway

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

Freshwater mussels were collected from Mudginberri Billabong in October 2020. Figure 18 shows ^{226}Ra activity concentrations 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 2020 were within the range of previously measured values.

The annual committed effective dose from ^{226}Ra in mussels has been calculated to be 0.167 mSv for a 10-year-old child who eats 2 kg (wet mass) of mussel flesh based on the 2020 measurement results collected from Mudginberri Billabong.

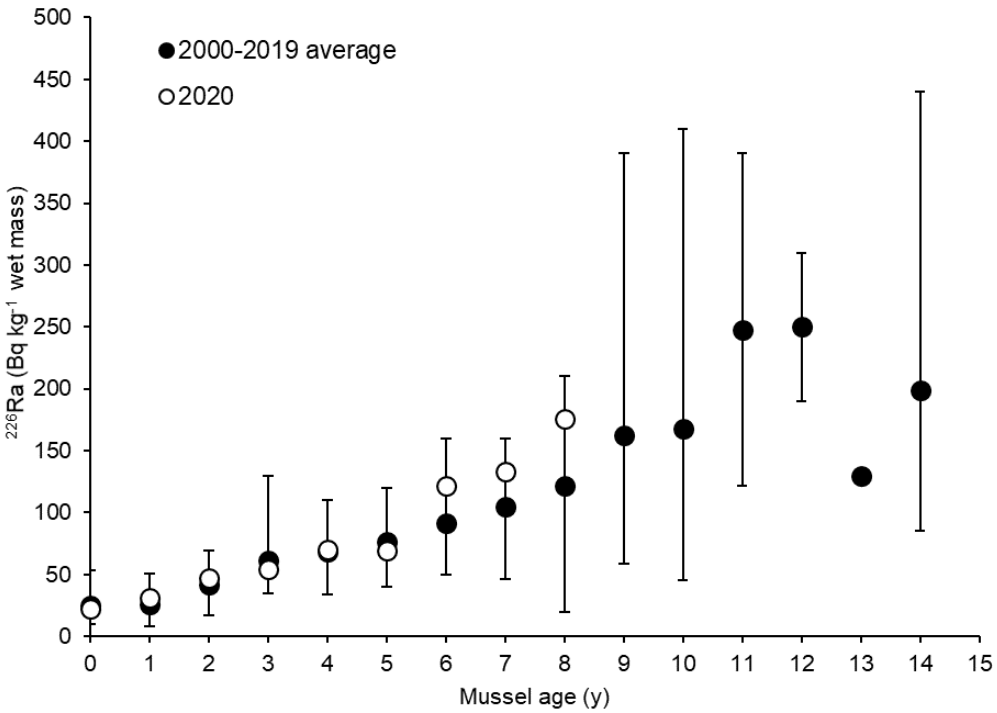


Figure 18 Flesh ^{226}Ra activity concentrations in mussels collected from Mudginberri Billabong. The error bars represent the ^{226}Ra activity concentration range in each age class.

By comparison, the annual committed effective dose from ^{226}Ra in mussels based on the average of all Mudginberri Billabong measurement results from 2000 to 2019 has been calculated as 0.176 mSv, with a range from 0.07 mSv to 0.39 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 assertion can be made since: (1) the difference between ^{226}Ra activity concentrations measured in 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.

Inhalation pathway

At the beginning of 2021, after a 5-year pause, SSB recommenced atmospheric monitoring for radioactivity associated with radon gas and dust at Four Gates Road (Mudginberri), Jabiru water tower (Jabiru) and Jabiru Field Station (JFS). This monitoring was recommenced to provide assurance that significant onsite earthworks during the decommissioning and rehabilitation phases of the Ranger mine do not result in increased concentrations of airborne radioactivity and radiation doses to the public through inhalation.

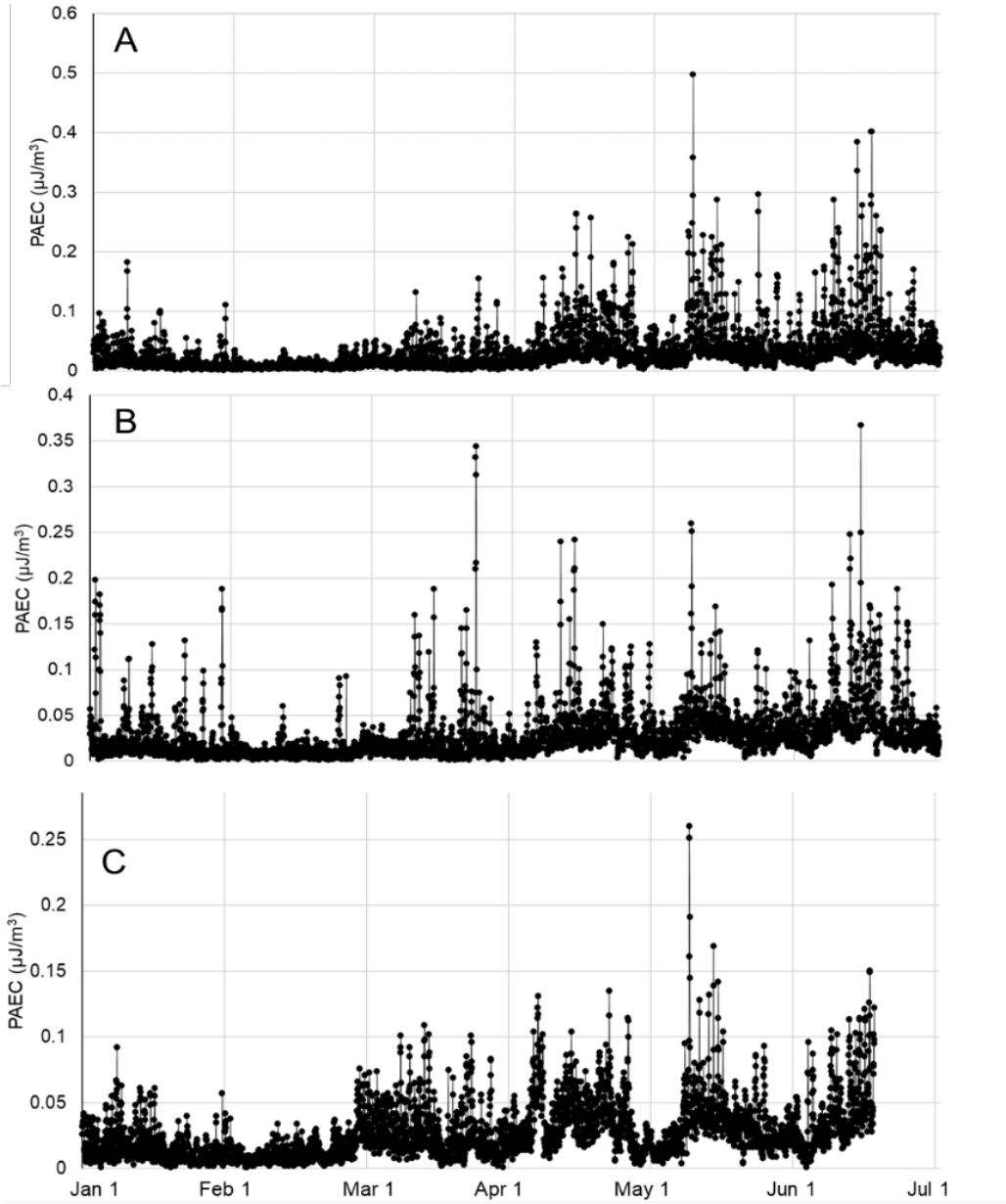


Figure 19 Hourly radon progeny potential alpha energy concentrations (PAEC) between January 2021 – July 2021 at A) Jabiru field station, B) Jabiru, C) Mudginberri.

Figure 19 shows hourly radon progeny potential alpha energy concentration (PAEC) monitoring data from JFS, Jabiru and Mudginberri (A-C respectively). Instrument uptime was 100% for both JFS and Jabiru monitoring stations, and 92% at the Mudginberri monitoring station due to an equipment malfunction which occurred in mid-June 2021. The large variations in PAEC seen in Figure 19 are due to diurnal (day-night) changes. Typically, higher PAEC are observed around sunrise when the atmospheric conditions

(wind and temperature) are most stable. This allows for the radon gas (which is exhaled from soil and rock) to remain close to ground level without dispersing. As the ambient temperature increases, the air becomes mixed through solar convection and wind which dilutes the radon gas and its progeny into a wider atmospheric volume. All three radon monitoring stations also show lower average PAEC over the first three months of the year where wet season rainfall was recorded. Moist soil due to rain suppresses radon exhalation and therefore decreases PAEC in the air. This trend is also evident in the dust radioactivity measurements where lower long-lived alpha activity (LLAA) concentrations were measured in the first quarter of 2021 due to rain limiting of dust movement during wet periods.

Quarterly averages for PAEC and LLAA are presented in Figure 20 and Figure 21 respectively. These results were similar to measurements conducted between 2012 – 2015. As only 6 months of data has been collected since atmospheric radiation monitoring was recommenced, an annual inhalation dose calculation was not performed. Although, since both PAEC and LLAA quarterly averages were comparable to previous measurements taken, the radiation dose is expected to be similar to previous annual doses, and therefore well below the public dose limit.

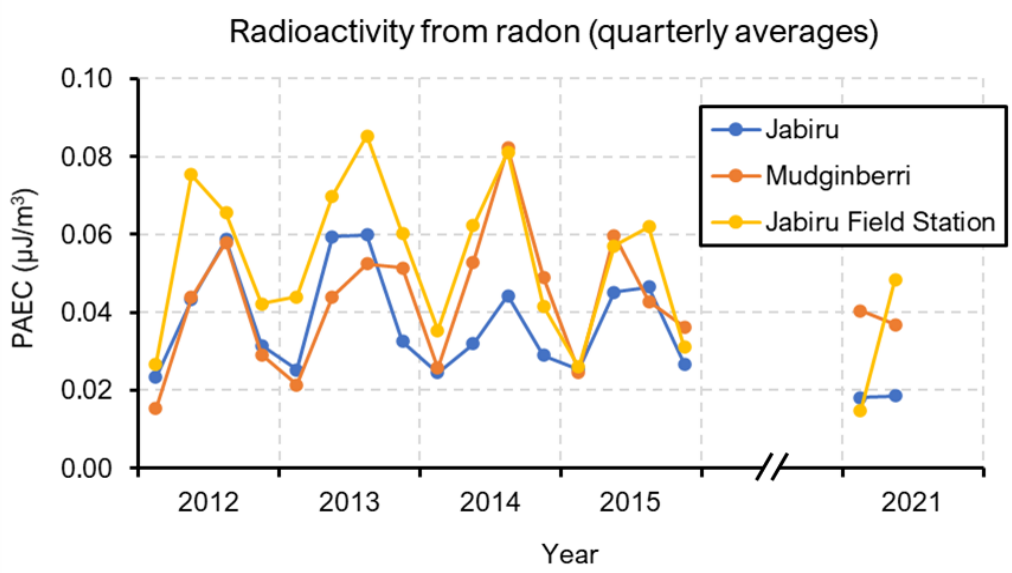


Figure 20 Quarterly average PAEC from radon progeny between 2012 – 2015 and the first half of 2021

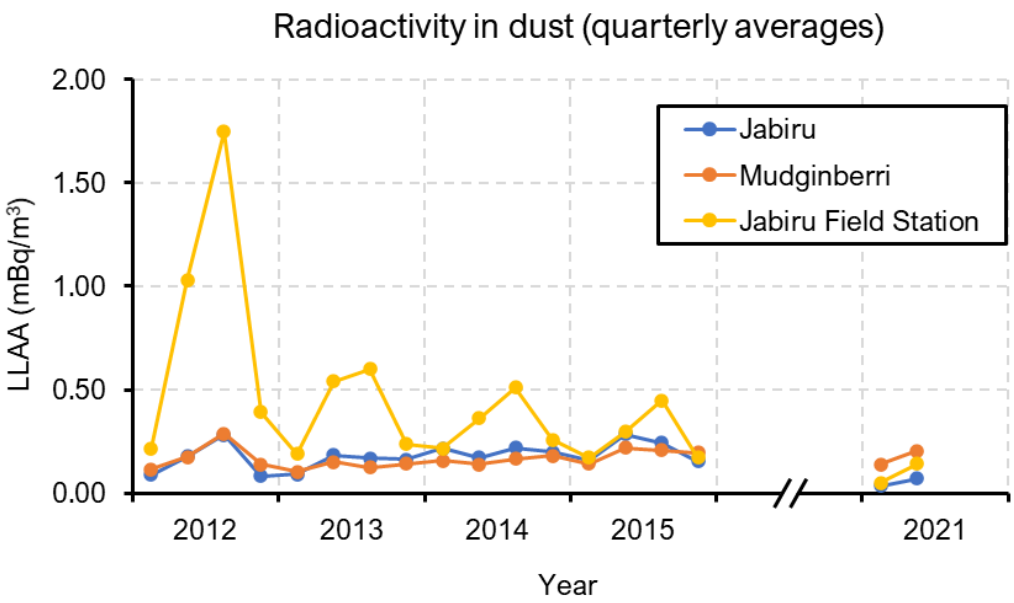


Figure 21 Quarterly average dust LLAA concentrations between 2012 – 2015 and the first half of 2021

ERA radiation monitoring

Given SSB has only recently recommenced its atmospheric monitoring program, ERA's annual dose assessment results for the 2020 calendar-year are discussed.

In accordance with the Ranger mine Authorisation, ERA measures concentrations of radon progeny and dust bound 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 6 provides a summary of annual average radon progeny potential alpha energy concentration (PAEC) in air and estimated doses to the public in 2020. In 2020 the mine-derived annual dose from radon progeny in air was 0.013 mSv. This dose is dependent on wind direction and has been estimated from the difference between 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 revisions have yet to be formally adopted in Australia. It is likely that when adopted, the new dose conversion factors will increase the reported annual dose and mine derived dose from radon progeny, but the mine derived dose will remain well below the dose limit of 1 mSv.

TABLE 6 RADON PROGENY PAEC IN AIR AND ESTIMATED DOSES TO THE PUBLIC AT JABIRU TOWN

	2020	2019
Annual average PAEC [µJ m-3]	0.034	0.054
Total annual dose [mSv]	0.328	0.520
Mine-derived dose [mSv]	0.013	0.000 [1]

[1] The radon progeny PAEC difference used in the mine-derived dose calculation was 0.017 µJ/m3 for 2018 and -0.013 µJ/m3 for 2019. As the 2019 dose calculation was negative, and hence meaningless, it was regarded as 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 7 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 0.004 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 7 LLAA RADIONUCLIDE CONCENTRATIONS IN AIR AND ESTIMATED DOSES TO THE PUBLIC AT JABIRU TOWN

	2020	2019
Annual average concentration ($Bq_{\alpha}^{-1}m^{-3}$)	8.8×10^{-5}	9.7×10^{-5}
Total annual dose (mSv)	0.004	0.004
Mine-derived dose* (mSv)	$1.6 \text{ x} \times 10^{-4}$	0.000

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

3.1.5 Research

3.1.5.1 Introduction

The Environmental Research Institute of the Supervising Scientist (ERISS) conducts research into developing standards and leading practice technologies for monitoring and assessing the environmental impact of uranium mining in the ARR. ERISS' current research program is primarily focussed on the decommissioning, rehabilitation, and ecosystem restoration of the Ranger mine site. This includes comprehensive baseline studies of the ecosystem in the surrounding Kakadu National Park.

An ecological risk assessment was carried out some years ago, which identified the Key Knowledge Needs (KKNs) for the decommissioning and rehabilitation of Ranger mine. The assessment identified a total of 33 KKNs, across five rehabilitation themes (i.e., landform; water and sediment; health impacts of radiation and contaminants; ecosystem restoration; and cross-themes). Each KKN has one or more associated components/questions (total of 119 questions). The KKNs underpin SSB and ERA's environmental research programs. KKNs and their associated projects have been allocated to ERA, SSB or designated as joint projects.

SSB was initially allocated 126 projects. As knowledge has been accumulated, further information gaps have been identified, and additional projects have been added to the program of work. During FY2021, SSB's total project allocation increased to 154 projects. Of these, 84 have been completed, 40 are active and 29 are pending. Figure 22 shows that SSB completed more projects than it gained in FY2021.

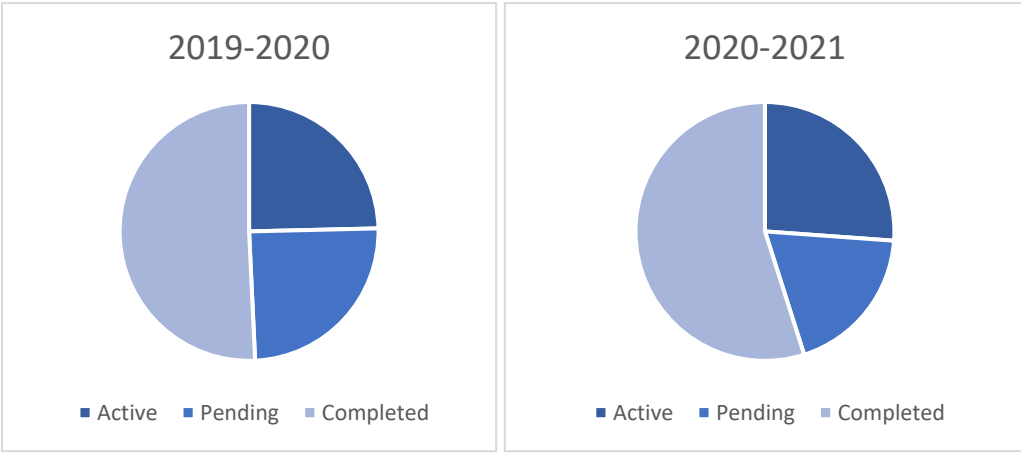


Figure 22 Comparison of completed, pending and active projects from FY2019-20 and FY2020-21. In this reporting period, a) the total number of projects has increased, b) the number of completions has increased and c) the total number of pending projects has increased.

SSB prioritises the commencement and completion of projects in alignment with ERA's work schedule, and timeline for submission of major applications. Figure 24 gives an overview of SSB's current research schedule and indicates that all projects will be completed by 2026. This aligns with when all major engineering rehabilitation works at the Ranger site are scheduled to be completed. Figure 23 shows a forecast of active projects to 2026.

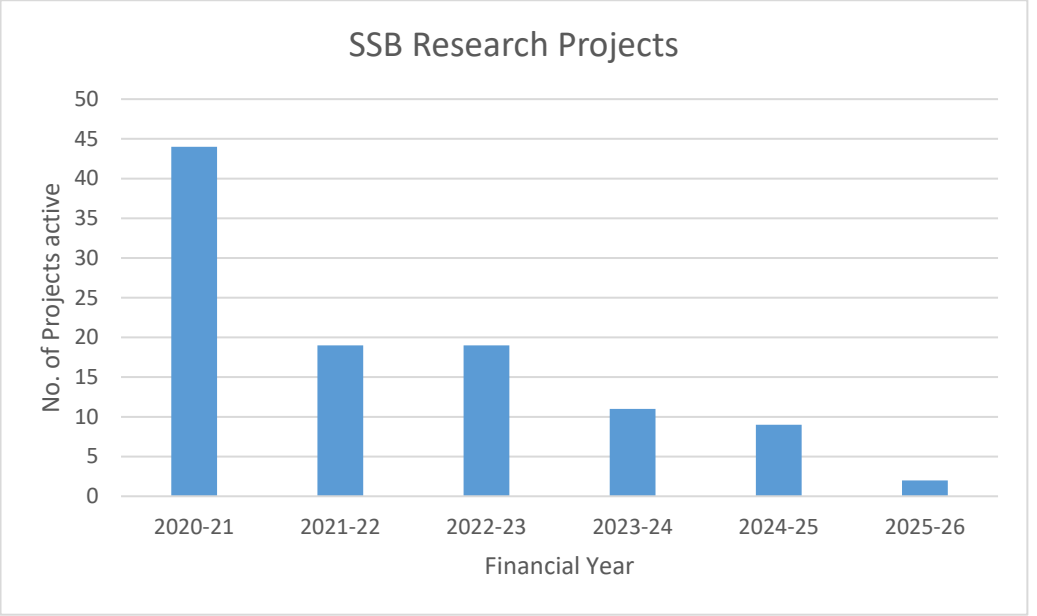


Figure 23 Forecast active projects by financial year

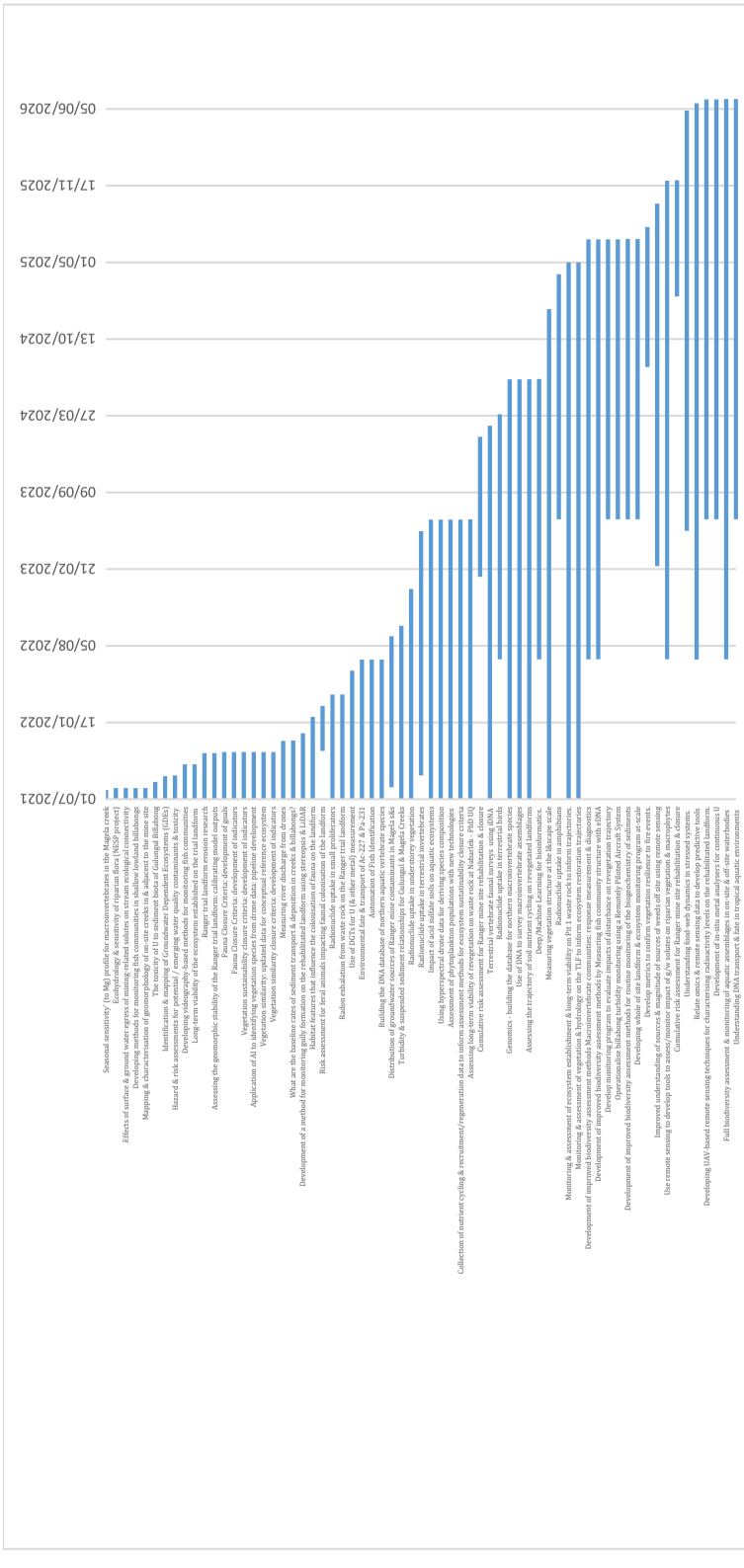


Figure 24 Research Project Schedule

3.1.5.2 Research outcomes

Appendix 2 includes all scientific publications issued during the reporting period and those pertinent to the projects discussed in this report. Appendix 3 provides maps of the KKNs for each of the research themes and gives details about each of the research projects that were current in 2020-21. Appendix 5 lists Technical Advice Memoranda issued during the reporting period.

3.1.5.3 Close-outs in 2020-21

As research projects are completed and the required knowledge is obtained the projects are "closed out". KKNs are closed out once all their subordinate projects are completed. When either a project or a KKN is closed out, SSB (and ERA) provide documentary evidence to Alligator Rivers Region Technical Committee (ARRTC) and request their endorsement that the project/KKN has provided the necessary information to address the requisite question(s).

During the 2020-21 reporting period, ARRTC endorsed the close out of 6 SSB KKNs and 13 SSB projects.

3.1.5.4 Research highlights

This section provides three case studies which demonstrate the applied and innovated nature of SSB's research.

Identifying savanna tree species from drones using artificial intelligence

With the objective of reducing personnel time in extreme outdoor environments while greatly expanding capacity to measure and identify trees across the landscape the SSB Ecosystem Restoration and Landform (ERL) team have combined drones with artificial intelligence (AI).

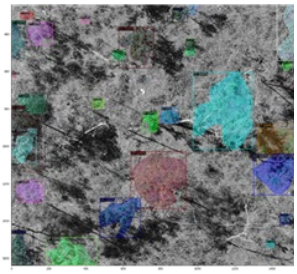
With the ready availability of commercial off-the-shelf drones, there has been a rapid uptake in their use for collecting ecological data. The increased resolution of imagery obtained by drones allows us to observe, measure, and potentially identify individual trees at an unprecedented scale across the landscape. However, advanced analytic tools are required to extract information from the large datasets collected by drones.

The ERL team have partnered with Microsoft to develop the data capture methods, workflows, and deep learning pipelines to automate savanna tree species identification from drone imagery. This has resulted in improved capacity which informs the metrics and assessment methods for our ecosystem restoration standard. We are developing methods and deep learning pipelines using the most readily available drones and sensors (e.g. Phantom Pro 4) and working through to our more complex sensors (e.g. LiDAR) to demonstrate what can be achieved as it relates to platform cost and deployability.

To date, we have developed data collection methods by leveraging the expertise of our botanists who identify tree species in near real time to coincide with our drone image

captures. These datasets serve as a library of labelled tree imagery that forms the training data essential to building and deploying deep learning models. Once the trees at a location have been identified by species, we can re-acquire drone imagery over time to capture seasonal differences in flowering and fruiting to further train the model. Our methods and deep learning pipelines will be publicly available through a GitHub repository.





Images 5-7 (L to R): Image 5, Pre-flight check for drone-based image capture; Image 6, Turkey Bush (*Calytrix exstipulate*) in flower; Image 7: Tree species identification using deep learning

Characterising the release of radioactive radon gas from a rehabilitated landform

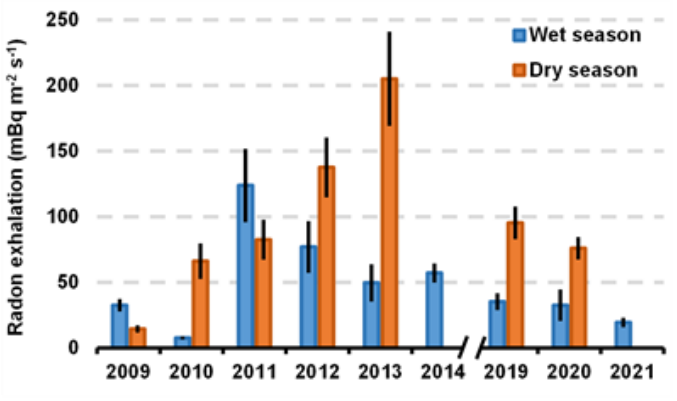
To predict radiation dose to the public from the Ranger final landform, the SSB Radiation team is studying radon release ('exhalation') from waste rock to understand its seasonal and longer-term behaviour.

Radon is a radioactive gas produced and released to the air by rocks and soils containing uranium. It can be transported by wind over distances of several kilometres or more from its point of origin before decaying and can give a radiation dose to people along its path. It is one of several radiation exposure pathways to the public from uranium mining, with other exposure pathways being radioactivity in dust, radioactivity accumulated in bush food and external gamma radiation. The radon pathway was the main pathway of radiation exposure to the public from the operation of the Ranger mine and is expected to be important for the Ranger final landform due to the use of low uranium grade waste rock as the surface cover.

Radon exhaling from waste rock is sampled using passive devices filled with granulated carbon which are deployed on a trial rehabilitated landform at the Ranger mine each wet and dry season. They are then measured for radioactivity in our laboratory. The measurements allow us to characterise the relationship between radon exhalation and waste rock uranium content, which is then used in predictive modelling of the radon pathway and associated doses to the public from the Ranger final landform.

Radon exhalation on the trial landform was originally measured in the dry and wet seasons over each of six years in the period 2009–2014. The results showed a year-on-year increase in dry season radon exhalation. Additional dry and wet season measurements are being conducted over each of the three years 2019–2021 to confirm the longer-term behaviour. So far, these additional measurements show a fall in dry

season radon exhalation. A further dry season measurement will be made in August 2021.



Images 8-9 (left to right): Image 8, Passive sampling device for radon exhalation; Image 9, measurement results to date

Building the genomics database for northern macroinvertebrate species

To improve our long-standing biomonitoring programs, increase the information collected, reduce costs, and reduce personnel time in hot, crocodile-rich environments, the SSB Water and Sediment Quality (WASQ) team is developing expertise in genomic sequencing and developing a genomic database.

Biomonitoring using macroinvertebrate communities is commonly used to assess the health of freshwater ecosystems. Such "bioindicators" have been essential for monitoring the potential impacts of mining in receiving waters of the Alligator Rivers Region (ARR). A limitation to their use is the labour-intensive processing of samples and the specialist expertise needed for accurate identification of the diverse groups.

High-throughput genomic sequencing technologies are now being used to characterise environmental DNA (eDNA), representing a new, vastly improved, and cost-effective approach for environmental monitoring. DNA metabarcoding can provide accurate and simultaneous species-level identifications from bulk macroinvertebrate samples by DNA barcodes. In common with efforts globally, the WASQ team is building a regional DNA-barcode library that can be used to identify the macroinvertebrates present in samples, provide a basis for research being undertaken in other projects, and assist similar work in northern Australia.

With NT Government and Macquarie University researchers, SSB has completed a 3-year project that developed methods for extracting and sequencing high quality DNA from macroinvertebrates near Ranger mine. Usually, approaches to identifying species from DNA-barcoding focus on 1 or 2 specific genes but our project sequenced the *whole* maternal (mitochondrial) genomes of specimens. Our genomic database now contains multiple target genes, which allows exploration of target sequences for the design of DNA "photocopying" experiments, improving the identification of species, and future-

proofing the usefulness of the data. Macroinvertebrates from three diverse taxonomic Orders were initially targeted: caddisflies (Trichoptera), mayflies (Ephemeroptera), and non-biting midges (Diptera, family Chironomidae). SSB will fill gaps in the library, expanding to include other key groups. A genomics laboratory has been established at the Darwin facilities, improving the capacity of SSB to conduct eDNA biological monitoring through deriving extraction and Polymerase Chain Reaction (PCR) amplification methods that are tailored for tropical Top End species.

Images 10-11 (L to R): Image 10, Field collection of macroinvertebrates and Image 11, microscope image of *Macromia tillyardi* (dragonfly larvae)

3.1.5.5 Rehabilitation Standards

Our Rehabilitation Standards 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. Most of the Standards were published on SSB's website in September 2018. Since then and apart from minor revisions to existing Standards, the following additions or major revisions have occurred:

- The addition of three new Standards under the Water and sediment theme:
  - Uranium in Sediments
  - Copper and Zinc in Surface Water (replacing the former "Other metals" Standard)
  - Turbidity
- Major revision to the Landform – stability and erosion Standard
- Major revision to the Ecosystem restoration Standard (near completion)

A complete list of SSB's Rehabilitation Standards by closure theme is provided in Table 8.

TABLE 8 REHABILITATION STANDARDS

Closure theme	Rehabilitation standard
Water and sediment	Magnesium (surface water)
	Uranium and Manganese (surface water)
	Ammonia (surface water)
	Sulfate – acid sulfate soils (surface water)
	Copper and zinc (surface water)
	Turbidity
	Uranium in Sediments
Landform	Landform – stability and erosion
Ecosystem restoration	Ecosystem restoration (flora, fauna, ecological processes) *Under review*
Radiation	Environmental Radiation Protection
	Public Radiation Protection

3.2 Nabarlek

The former Nabarlek mine is located 280 kilometres east of Darwin and operated from 1979 to 1988. More information about the history of operations and uranium production at Nabarlek can be found in Appendix 1. Rehabilitation and exploration activities are currently being undertaken at Nabarlek by the authorised operator DevEx Resources.

3.2.1 Supervision

SSB, the regulator and key stakeholders including the NLC monitor and assess exploration activities and performance of the ongoing rehabilitation and revegetation program at Nabarlek. A description of past rehabilitation and SSB historical supervisory activities on at Nabarlek are included in Appendix 1.

An updated MMP detailing the status of rehabilitation activities at Nabarlek was submitted on 13 July 2020. No significant disturbances were proposed with the focus being on the remediation of the Radiologically Anomalous Area (RAA) as discussed below. The MMP was approved by DITT on 9 November 2020. However, work to remediate the RAA and weed mapping proposed in the MMP was delayed during 2020-21 due to the COVID-19 pandemic and West Arnhem access restrictions.

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. A weed spraying campaign occurred in late February/early March 2021. Results from the campaign were not available at the time of report preparation.

The Nabarlek MTC met on 15 September 2020 and continues to monitor and advise on the implementation of fire, weed, revegetation and radiation management on site.

There were no environmental incidents reported for Nabarlek during 2020-21.

3.2.1.1 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 mine site. Historically, the RAA has also contributed the majority of the radionuclide flux from the site via the erosion pathway (more detail is provided in Supervising Scientist Annual Report 2004–05).

DevEx submitted a plan for the remediation of the RAA in conjunction with the 2020 MMP. SSB assessed the application and following discussions and presentations by DevEx at the Nabarlek Minesite Technical Committee on 15 September 2020, and the subsequent submission of updated information, supported the proposed RAA remediation strategy. The remediation strategy 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. The remediation works are currently scheduled for late 2021, subject to contractor availability and site access. SSB intends to be on site during construction to verify that the works are completed as approved.

3.2.1.2 Exploration

No exploration activities occurred during 2020-21. An MMP for 2021-22 was provided to SSB for review on 28 June 2021 which includes exploration drilling of prospective targets and is currently under assessment.

3.2.2 Monitoring

DevEx conducted groundwater sampling in November 2020. Results were consistent with previous 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 below levels that are likely to cause environmental impact to surface water quality.

SSB has installed conductivity, temperature, and pressure loggers (Divers) at three surface water locations since the 2016-17 wet season. These sites are: Kadjirrikamarnda Creek (KCW) downstream of the former mine site and two sites in Cooper Creek, upstream (CCUS) and downstream (CCDS) of the former mine site. The EC measurements were consistent with DevEx monitoring data reported in previous MMPs and provide a baseline of current seasonal EC trends which can be used to assess changes over time. Divers have been re-deployed for 2020-21 and will be collected during the next Nabarlek inspection.

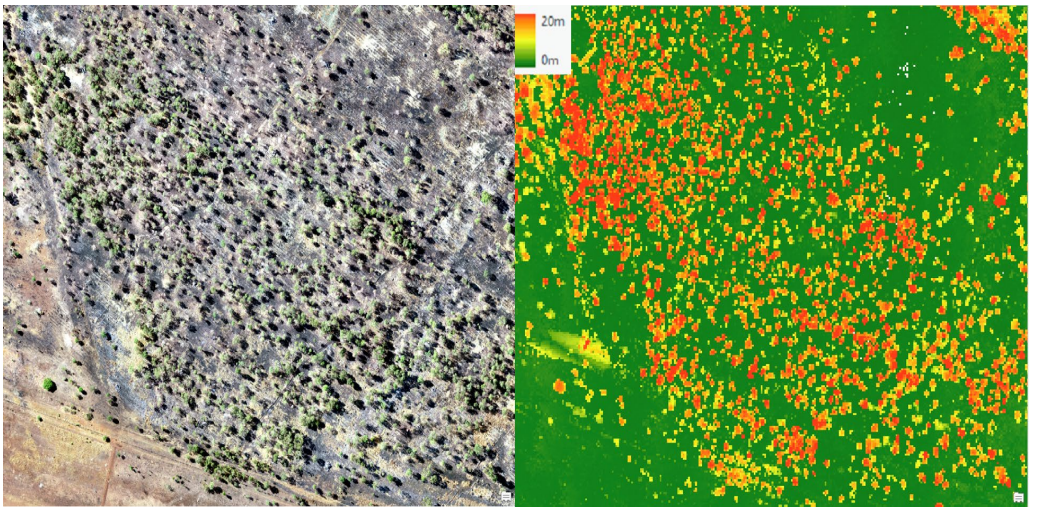
SSB proposes to expand our water chemistry monitoring program at Nabarlek over the coming wet seasons to include periodic water chemistry grab-samples. This additional data will be compared to historical baseline and used to assess the progress of site rehabilitation and inform future research needs.

3.2.3 Research

SSB is supporting a PhD project at Nabarlek which is being undertaken through the Centre for Mined Land Rehabilitation at the University of Queensland. The focus of this research is developing and investigating ecosystem restoration trajectories for a site that is located in a similar savanna ecosystem and had similar mining method as Ranger mine. The scope of the research is targeted on aspects related to ecosystem restoration planning for Ranger mine.

Preliminary seasonal ecological surveys (which have been supported by the Ecosystem Restoration and Landform (ERL) team) have been undertaken in 2020-21. These surveys can be compared with historical surveys which has enabled preliminary ecosystem trajectories to be developed. The ERL team have also collected drone-based LiDAR across the site to inform vegetation structure surveys at the whole of site scale. Traditional Owners have participated in site visits through the support of the Northern Land Council.

Site context information is currently being collated to aid in the interpretation of the ecosystem trajectories and will include the investigation of management interventions and the effect these have had on the ecosystem trajectories for the site.



Images 12-13: Drone data of Nabarlek mine site collected in August 2020. Standard Red, Green, Blue (RGB) camera data (left) and LiDAR derived canopy height model (right) with red indicating the tree canopy tops.

3.3 Jabiluka

The ERA-owned Jabiluka Mineral Lease abuts the northern boundary of the RPA, with the former Jabiluka mine site situated 20 km north of the Ranger mine site. Information about the history of Jabiluka and SSB historical oversight activities can be found at Appendix 1. The site is currently in care and maintenance and ERA are conducting and monitoring revegetation trials at the site.

3.3.1 Supervision

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. The 2019-20 Jabiluka Environmental Interpretive Report was submitted by ERA in December 2020 in line with the requirements of the Jabiluka Authorisation 0140-05. ERA reports on the outcomes of their weed, fire, and revegetation management programs through this annual submission.

ERA uses herbicide to actively manage weeds at the Jabiluka Mineral Lease. ERA have been collaborating with Kakadu Native Plants Pty to conduct weed management activities. During the reporting period ERA and Kakadu Native Plants staff conducted 273 hours of weed spraying activities at the Jabiluka and Djarr Djarr sites, which is a decrease from the 326 hours of weed spraying activity were undertaken during 2019-20. In 2019-20, one new weed patch has been identified (and mapped) adjacent to Oenpelli Road between Jabiluka and Djarr Djarr, against the escarpment wall.

ERA undertakes annual fuel-reduction burning around the Djarr Djarr and Jabiluka sites to reduce the effects of wildfires on the revegetated areas. Two hazard reduction burns were completed in the second quarter of 2021.

SSB in conjunction with other MTC stakeholders conduct pre- and post-wet season inspections to identify and assess emerging issues (e.g., erosion, weeds) and monitor the progress of revegetation. The 2020–21 pre-wet season inspection was conducted on 20 November 2020 and the post-wet season inspection was conducted on 10 June 2021. Stakeholders inspected revegetating areas, assessed landform stability, and verified the status of groundwater and surface water monitoring sites. Observations from these inspections include:

- Stakeholders noted that the eastern fence line track was overgrown with some grass and native vegetation and noted that the area should be cleared to ensure it can continue to act as a firebreak.
- Erosion control measures put in place to manage a shallow gully forming in a preferential drainage line in an area south-western section of the former Integrated Water Management Pond appear to be performing well. Sand and gravel are building up and juvenile vegetation is establishing in the gully.
- Surface water monitoring weirs continue to fill with sand and detritus each wet season. ERA has agreed to clear the weirs before the beginning of the 2021-22 wet season.

- Stakeholders visited the vent shaft to inspect the installation of water monitoring equipment. Water monitoring data will be reviewed in the Jabiluka wet season report to be submitted in Q3 2021.
- Djarr Djarr appeared to have been burned without the knowledge of ERA in June 2021 and stakeholders have recommended a process be implemented to ensure burns by all stakeholders are managed strategically an in consultation with each other.

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.

No environmental incidents have been reported for Jabiluka during 2020–21.

3.3.2 Monitoring

Given the low environmental risk posed by the site, SSB ceased routine water quality monitoring prior to the 2015-16 wet season. ERA submits a Jabiluka Wet Season Report which is assessed by stakeholders. 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. The 2020-21 Wet Season Report is currently under review.

3.4 South Alligator Disposal Facility

During the 1950s and 1960s several small uranium mines and milling facilities operated in the South Alligator River Valley. These sites were simply abandoned in the 1970s when uranium mining was no longer providing an economic return. In May 2006 the Australian Government provided funding over four years for their rehabilitation and subsequently a radiological containment facility was constructed in 2009 at the old El Sherana airstrip. This facility provided for the final disposal of historic uranium mining waste recovered from several sites throughout the South Alligator Valley. After its construction, the South Alligator Disposal Facility (SADF) was granted a license by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), of which the Director of National Parks is the license holder. In 2020, the Supervising Scientist became the license nominee, managing the ARPANSA facility license on behalf of the Director of National Parks.

An inspection of SADF was conducted by ARPANSA on the 15 October 2020, as per the current license conditions. Several areas for improvement were identified and the licence nominee committed to rectifying all findings from the inspection.

3.4.1 Supervision

The current *Plans and Arrangements* for SADF, approved by ARPANSA on the 30 April 2021, defines the requirement for an annual inspection of the facility at the start of each dry season. The purpose of this inspection is to ensure there have been no changes to the integrity of the containment, to observe and record site maintenance requirements and to ensure there has been no unauthorised access to the facility.

A formal inspection of the facility was conducted by members of SSB on 7 June 2021. The inspection found that the containment cover continues to be stable, with surface cracks identified in 2017 'self-healing' with the infill of mobile soil. All three rock lined drains along the southern wall of the containment continue to divert surface water as required. The surface of the containment surrounding the soil monitoring stations continues to experience consolidation and was infilled prior to the 2020-21 wet season to prevent ponding. Parks Australia continue to conduct controlled burns and targeted weed spraying campaigns at the request of SSB.

As SSB are now actively involved in all components of the environmental monitoring for SADF, there are more opportunities to observe and informally inspect the facility for any maintenance requirements.

3.4.2 Monitoring

The SADF environmental monitoring program, required under the facility license conditions, was updated by SSB, and approved by ARPANSA as part of the facility's *Plans and Arrangements*. Significant changes to the monitoring program include: the reduced frequency of surface radioactivity monitoring from 2-yearly to 5-yearly, the removal of surface run-off monitoring, and the reduction of vegetation monitoring requirements.

The South Alligator Disposal Facility - Environmental Monitoring Report 2020 – 2021 was submitted to ARPANSA on 28 July 2021 as per the license conditions. The results of the annual monitoring report provide confidence that the waste contained in the Disposal Facility does not pose a risk to people or the environment. Average gamma dose rates and radon-222 exhalation flux densities taken on site in June 2021 continue to be at or below baseline measurements. While the data collected from the soil monitoring stations indicates that there continues to be an ingress of water into the waste material, the groundwater monitoring results from samples collected in November 2020 and April 2021 showed there had been no movement of contaminants into the surrounding groundwater monitoring bores. Both radium-226 and uranium levels in groundwater samples consistently fall below the original (pre-build) levels recorded in 2007.

SSB has committed to undertaking a detailed review of the environmental monitoring program to ensure monitoring objectives and outcomes to are appropriate to assess the performance of the disposal facility and risk to the surrounding environment. This review will include an environmental risk assessment, a detailed review of the current groundwater monitoring program, an assessment of the suitability of the current vegetation analysis and an investigation into the options to mitigate data loss from the monitoring stations.

3.5 Koongarra

Koongarra is a former uranium exploration site, incorporated into the Kakadu National Park in 2013 after the special mining lease application was revoked. It is now under the management control of Parks Australia as the Australian Government organisation responsible for Kakadu.

The Koongarra site is located approximately 250km east of Darwin and 30km south of the township of Jabiru. Public access to Koongarra is prohibited, with a locked fence and gate preventing unauthorised access to the area.

3.5.1 Supervision and monitoring

The Koongarra site was inspected by members of SSB, NLC and ARPANSA on 15 October 2020. Legacy structures at Koongarra include sheds, concrete pads, fuel storage tanks and five shipping containers. The shipping containers are located within a fenced compound and contain drill core and rock samples with elevated levels of natural uranium (U-nat).

During the October inspection, SSB conducted a dose rate assessment around the exterior of the shipping containers. Contact dose rates at exterior surfaces are typically 1-3µSv/h, with some localised hot spots along container walls exceeding 10µSv/h. Dose rates 1m back from the midpoint of each container are in the range of 0.3-1.6µSv/h. Consultation with ARPANSA determined that a source license is required for the shipping containers located at Koongarra.

The SSB is currently drafting a source license application for the shipping containers at Koongarra and will investigate remediation options for Koongarra in consultation with the senior traditional owner.

3.6 Exploration Projects in the ARR

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

On 1 March 2018 Cameco entered into an agreement with Vimy Resources Ltd to acquire Cameco's ARR exploration projects with Cameco effectively ceasing its exploration activities in the region.

Representatives from SSB and NLC conducted an inspection of the Wellington Range and King River Joint Venture (WRKRJV) on 29-30 September 2020. This inspection focussed on following up on the 2018 audit findings and verifying the progress of drill pad rehabilitation detailed in Vimy's 2018 Rehabilitation Report and 2020 Mining Management Plan. From this site inspection, SSB and NLC were able to support the close-out of the rehabilitated drill sites which were included in Vimy's 2018 Rehabilitation Report. The inspection found that most of the 2018 audit findings could be closed out, while noting that several actions were yet to be addressed.

The 2020 WRKRJV MMP, submitted in July 2020, proposed 45 reverse circulation exploration drill holes. This plan was supported by SSB in September 2020.

3.6.2 DevEx West Arnhem Joint Venture

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.

An updated MMP for the 2020 field season was submitted by DevEx in September 2020 and following assessment by SSB, approved by DITT in November 2020. This work program proposed drilling at the Black Bream prospect, non-invasive geophysical work, stream sediment sampling, a review of geophysics and reanalysis of pulps in storage.

3.6.3 Alligator Energy Tin Camp Creek Project and Beatrice Project

Alligator Energy did not submit an MMP in the reporting period and as such SSB has not performed any assessment or inspection activities for the Tin Camp Creek Project or Beatrice Project during the 2020-21 reporting period.

3.6.4 UXA Resources Nabarlek Group Project

UXA Resources did not submit an MMP in the reporting period and as such SSB has not performed any assessment or inspection activities for the Nabarlek Group Project during the 2020-21 reporting period.

3.6.5 Eclipse Metals Devil's Elbow Project

Eclipse Metals is a new exploration company in the ARR. Eclipse Metals submitted an MMP in June 2020, which SSB and DITT provided feedback on. The MMP proposed a program of rock chip and heli-borne diamond drilling, as well as ground proofing of historical exploration work. No updated MMP has been received for assessment since this draft submission.

Image 14 Ground-truth mapping of tree canopy species to be used for automated AI classification of vegetation cover in the surrounding region of Ranger uranium mine

4 KEY ENABLING TECHNOLOGIES

SSB continues to apply leading-edge technologies to improve the safety and efficiency of our research and monitoring programs. SSB continues to develop and apply leading-edge technologies to improve the safety and efficiency of our research and monitoring programs. SSB has established expertise and capability in three rapidly evolving technologies: drones and associated imagery, Artificial Intelligence (AI) and Omics.

The following three sections describe SSB's drivers for the use and development the three technologies, SSB's current applications of the technologies and SSB's leadership and engagement activities associated with each of these technologies.

4.1 Drones

SSB have been using drones to develop faster, safer, and more effective environmental monitoring for over seven years through collaborating with industry, academia and government partners.

The ability to conduct landscape-scale surveys has informed the development of revegetation closure criteria for Ranger mine by measuring the level of natural variability in the surrounding landscape. To conduct landscape-scale vegetation surveys SSB has recently acquired large Vertical Take-off and Landing drone platforms which are able to cover larger areas in the Alligator Rivers Region.

The use of drones in combination with multispectral and LiDAR sensors has provided unprecedented information for ecosystem establishment monitoring on mine sites – greatly reducing the time required whilst simultaneously increasing the amount of information that can be collected.

Drone pilots in the Department are required to operate under a remotely piloted aircraft operator's certificate (ReOC) issued by the Civil Aviation Safety Authority, which allows departmental pilots to conduct a range of drone operations. The administration of the Department's ReOc and management of the drone pilots and platforms is undertaken by SSB, including the roles of the Chief Remote Pilot, Maintenance Controller and Drone Compliance and Policy Manager.

The SSB drone team assists areas in the Department commencing drone operations, including developing and undertaking proof-of concept projects, and provide technical advice on contracted services and projects.

SSB established and leads the Department's Drone Community of Practice (CoP) and holds regular meetings of drone pilots, personnel contracting drone services, and those involved in policy aspects with the aim of managing the use of drones in the Department. The CoP provides an opportunity to:

- foster a culture of continuous improvement to apply more effective safety practices in drone operations;
- discuss new types of drone operations to meet Department business objectives; and
- facilitate collaboration between areas in the Department on the scientific and operational use of drones.

In many respects drones and AI are interdependent technologies, with AI methods required to process the very large amounts of data generated by drone platforms operating at the landscape scale.

4.2 Artificial Intelligence

The Supervising Scientist is applying AI methods, primarily Deep Learning (DL), to improve the accuracy, performance and cost effectiveness of its research and monitoring programs.

SSB is collaborating with Microsoft to develop data pipelines for processing drone and underwater-based camera imagery in a DL workflow. These tools are being developed with open-source products that can be made publicly available to enable others.

Two projects are currently well advanced at SSB: (1) automating fish species identification from underwater videography and (2) automating tree species identification from drone derived imagery.

SSB has developed a citizen science initiative to assist with the arduous task of generating an annotated and labelled dataset for training the fish identification AI. This project, called BRUVNet, allows citizen scientists to receive a discrete dataset of fish images to annotate and label. Images undergo quality control by SSB fish ecologists before being combined with the master dataset. More information can be found at www.bruvnet.org. To date, 185 citizen scientists from 34 countries have engaged with the BRUVNet project resulting in 25,848 annotations of fish, greatly improving the accuracy of fish identification using AI.

SSB established and leads the AI Community of Practice within DAWE which aims to promote a culture of innovation and collaboration to assist other areas of the Department to develop and operationalise business solutions using artificial intelligence. Learnings, experience, and solutions are shared to ensure duplication of effort is not occurring and new projects build on work that has already been undertaken.

4.3 Omics

The SSB is investing in an omics capability to improve our research and monitoring outcomes by making environmental monitoring easier, cheaper, more comprehensive, and more efficient. This approach will advance environmental monitoring in Australia and allow the uptake of omics to a range of other Departmental and national projects.

SSB has a range of active projects using omics related tools, including:

- Building a DNA database for northern aquatic macroinvertebrate and vertebrate species
- Use of DNA to survey aquatic macroinvertebrate assemblages
- Terrestrial vertebrate faunal surveys using invertebrate derived DNA
- Assessing the trajectory of soil nutrient cycling on revegetated landforms

SSB has founded an Omics and eDNA Community of within the Department which aims to promote a culture of collaboration to advance the use of omics tools across a broad range of areas such as biodiversity, conservation, biosecurity, agriculture, and environmental management. Through sharing information with colleagues within the Department, experiences and solutions can be shared to avoid duplication of effort and to build on the work of others.

APPENDIX 1 MINING ACTIVITIES BACKGROUND INFORMATION

Image 15 Ranger Mine, Alligator Rivers Region

Appendix 1.1 Ranger

History and Overview

The Ranger mine deposits were discovered in 1969 through an aerial radiometric survey. Further drilling confirmed the viability of two ore bodies termed Ranger 1 and Ranger 3. In 1978, title to the land underlying the Ranger Project Area (RPA) was granted to the Kakadu Aboriginal Land Trust, in accordance with the Commonwealth *Aboriginal Land Rights (Northern Territory) Act 1976* (*Aboriginal Land Rights Act*) and the Commonwealth Government entered an agreement with the Northern Land Council (NLC) to permit mining to proceed.

Construction of the Ranger Mine began in January 1979 and the mine came into full production in October 1981. Mining of orebody Ranger 1 was completed in December 1994 and orebody Range 3 completed in 2012. Since 2012 ERA has been producing uranium from stockpiled ore. Processing of this ore ceased on 8 January 2021 with major rehabilitation works on site due for completion by 2026.

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 is 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 9

TABLE 9 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

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 high quality distillate that can be released off-site. Details of water treatment volumes using the brine concentrator are shown in Table 10.

TABLE 10 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
2020-21	326	1503

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 when constructed had a nominal capacity to treat 1830 ML of process water per year and forms an integral part of ERA's rehabilitation strategy. Through ongoing improvement initiatives and a fan upgrade completed in early 2021, the brine concentrator is currently operating at approximately 120% of the nominal capacity.

To provide additional process water treatment capacity, ERA applied to recommission a High-Density Sludge (HDS) treatment plant located on site. The HDS plant uses 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. The HDS treatment of process water for release to the pond water circuit was approved in February 2020 following assessment by SSB. In December 2020, SSB endorsed direct release of HDS product

water treated through WTP1 as ERA provided data from trials which indicated that the permeate was of a similar or better quality than historical release water. Brines from the HDS plant are currently disposed of in the Pit 3 tailings mass. ERA is investigating alternative disposal options for the HDS sludge once Pit 3 is backfilled with waste rock. ERA's preferred option will be the subject of a standalone application.

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 for treatment of pond water brines was completed in early 2020. ERA is investigating opportunities to utilise the brine squeezer for the direct treatment of process water. An application to conduct process water treatment trials was approved in June 2020 following assessment by SSB. These trials are ongoing.

Other initiatives to reduce the volume of process water on-site include 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 11 shows the annual total volumes of pond water treated and resulting permeate produced. The volume of pond water treated over the reporting period is significantly higher than that treated in recent years due to the above average 2020-21 wet season to date and reduced pond water requirements with the cessation of processing activities.

TABLE 11 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
2020-21	3449	2493

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). SSB 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 the impacts of HDS treatment on permeate are better understood.

In May 2018 ERA trialled the use of two mechanical evaporators (turbomisters) on the eastern side of RP1 using permeate and distillate. Following completion of this trial an additional 12 turbomisters were installed in 2018-2019. These turbomisters will be used as a contingency to dispose of permeate and distillate during future dry seasons as land application areas are rehabilitated. 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 12 shows the total volume of water actively released from the site since 2013–14 (noting that water released passively is not quantified). Over the 2020-21 wet season, 1196 ML has been actively released. This is significantly more than the 296 ML actively released over the 2019–20 wet season. This is partly attributable to the above average rainfall over the 2020-21 wet season to date and the need to retain water on site in 2019-20 for trialling of water treatment technologies.

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 proposals to ensure the adequacy of all controls and contingency measures.

TABLE 12 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
2020-21	1196

Tailings and waste management

Table 13 summarises the management of mill tailings over time. As part of the site rehabilitation process ERA is currently focussing on the transfer 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 tailings delivered to the pit from both the processing mill and from the TSF (via dredging). Bulk tailings dredging was completed in October 2021. There are approximately 1.3 Mm^3 of tailings remaining in the TSF which need to be transferred to Pit 3 from the TSF.

TABLE 13 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	2015-21
Tailings transfer from TSF to Pit 3	2016-

The primary mechanisms for disposal of controlled wastes (wastes which originate from a controlled area or has been in contact with process water) is disposal in Pit 3. Non-hazardous wastes are disposed of either through disposal to landfill or off-site recycling.

Rehabilitation

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 and Water 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.awe.gov.au/science-research/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 site-specificity of the water quality standards for metals. An improved and simplified method for assessing erosion of the rehabilitated landform was also incorporated into a revision of the Landform stability Standard and a new Turbidity Standard was introduced. 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.

Current status of rehabilitation

Approved progressive rehabilitation works are being undertaken on-site including tailings deposition into the mined-out pits and subsequent backfill with waste rock before construction of the final landform. Table 14 shows the performance metrics as at the end of February 2021 for major rehabilitation activities currently occurring or recently completed on-site. These are discussed in the following sections. Table 15 summarises the approvals related to rehabilitation and Table 16 summarises the rehabilitation works that have been carried out to date.

TABLE 14 KEY REHABILITATION METRICS

Activity	Completed	Remaining
Transfer of TSF tailings to Pit 3[1]	22.3 Mm^3	1.3 Mm^3
Pit 1 Backfill[1]	3.4 Mt	Completed
Brine injection	92 ML	NA

[1] Reported for the 2020 calendar year. Backfill was completed in August 2020.

TABLE 15 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
Pit 1 ecosystem establishment plan	2021
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
Ranger 3 Deeps exploration decline decommissioning – update	2021
Water treatment and release	
Application to change permeate discharge conditions	2019
Brine squeezer pond water treatment	2019
Brine squeezer process water treatment trials	2020
High Density Sludge process water treatment- indirect treatment	2020
High Density Sludge process water treatment- direct treatment	2021
Site-wide activities	
Ranger Mine Closure Plan	2018

TABLE 16 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 commence	2019
Waste rock backfill – completion of bulk backfill and final landform surface	2020
Interim water management systems completed	2021
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
Completion of mill tailings deposition	2021
TSF	
Tailings dredging commenced	2016
Commissioning of a second tailings dredge	2019
Tailings dredging completed	2021

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 was installed to accelerate consolidation and dewatering. 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. 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 https://www.awe.gov.au/science-research/supervising-scientist/publications/internal-reports/ir651 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 at the proposed level was low, compared to the cumulative risk associated with the whole rehabilitated mine site.

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. Following review by SSB and the submission of a progressive rehabilitation monitoring framework, the application to proceed to final landform was approved in May 2019. The proposed monitoring framework is designed to ensure critical data are 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. Final backfill of Pit 1 was completed in August 2020.

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. Sub-aerial deposition of mill tailings commenced in February 2015 and sub-aerial deposition of tailings via dredging from the TSF commenced in January 2016. In August 2019 amendments to the deposition strategy were approved to allow tailings from dredging to be deposited via subaqueous deposition, and mill tailing to continue to be deposited sub-aerially but from additional locations around the pit. Sub-aerial deposition of mill tailings from the processing circuit was completed with the cessation of processing in January 2021. The bulk transfer of tailings from the TSF to Pit 3 via dredging was completed in February 2021. The assessments undertaken to date on tailings deposition are listed in Table 15.

During the dredging of tailings, the process water levels in Pit 3 and the TSF were managed in a closed circuit to ensure that the water in the TSF was maintained at an optimal depth for operation of the tailings dredges. With the completion of dredging in February 2021, ERA is in the process of transferring all remaining process water from the TSF to Pit 3 to allow the clean out of all residual tailings in the TSF. A maximum operating level (MOL) for water in Pit 3 of +3.5 mRL has been established to maintain the groundwater hydraulic gradient towards the pit and ensure process water is contained within Pit 3.

During the reporting period SSB, ERA and subject matter experts have formed working groups to assist in developing and refining groundwater and surface water modelling and predictions which will inform Pit 3 closure.

Tailings Storage Facility

Tailings stored in the TSF are currently being transferred to Pit 3, the final disposal location. Dredging of the TSF tailings commenced in 2016 with a second dredge commissioned in the TSF in June 2019. The incorporation of a second dredge increased the tailings dredging rate and helped to ensure tailings dredging from the TSF to Pit 3 was completed on schedule (Q1 2021). As discussed in Section 3.1.2.5 above, all remaining process water is now being transferred to Pit 3. Concurrently, work is

underway to prepare the TSF so that it can be used as a process water storage dam in the future. This includes scraping residual tailings from the TSF walls and the assessment of options to transfer residual tailings to Pit 3 while ensuring tailings management complies with regulatory expectations. ERA estimates that approximately 1 Mt of tailings remains to be transferred to Pit 3. These TSF preparatory works were routinely inspected by SSB and other stakeholders during the reporting period through the RPI program discussed further in Section 3.1.3.3.

In March 2020 ERA applied to leave the contaminated material at the base of the TSF in place, as opposed to disposing of this material in Pit 3. Groundwater modelling supporting the application concluded that transferring the material to Pit 3 would result in a worse environmental outcome than leaving the material in-situ. This is due to disturbance of the subfloor material increasing the mobilisation of contaminants through the groundwater pathway and into surface water systems. Following assessment, SSB supported the proposal but noted that significant uncertainty remained on the magnitude of the contaminant loads from site including the TSF. This uncertainty would need to be addressed as part of the future TSF deconstruction plan and potential remediation of the contaminant plume may be required. The application was approved by DITT in July 2020.

Since 2018, ERA has submitted several applications to construct notches in the TSF embankments and reduce the TSF crest height. Each application has been assessed by SSB with advice from specialist geotechnical consultants. Further information on these historical assessments is shown in Table 15. In June 2020, ERA submitted a proposal for construction of two new notches and internal TSF wall ramps to provide access to the TSF floor. The proposed works were assessed by SSB, and it was concluded they did not pose a risk to the integrity of the TSF walls.

Radiation protection at Ranger

ERA monitors radiation doses to workers and the public. The monitoring results from the 2019-20 radiation protection and atmospheric monitoring program 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 17.

TABLE 17 2020 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

SSB reviews the results of ERA's monitoring annually. The data presented below is summarised from ERA's 2020 radiation protection and atmospheric monitoring program.

For both designated workers and non-designated workers, the 2020 dose was comparable to the 2019 dose as shown in Table 18 and Table 19 respectively.

TABLE 18 2020 DESIGNATED WORKER DOSE (MSV)

	2020	2019
Occupational dose limit	20	20
Mean annual effective dose (% of dose limit)	1.01 (5.0%)	1.07 (5.4%)
Maximum annual effective dose (% dose limit)	2.76 (13.8%)	3.58 (17.9%)

TABLE 19 2020 NON-DESIGNATED WORKER DOSE (MSV)

	2020	2019
Occupational dose limit	20	20
Mean annual effective dose (% of dose limit)	0.13 (0.65%)	0.13 (0.65%)
Maximum annual effective dose (% dose limit)	1.31 (6.5%)	1.18 (5.9%)

Appendix 1.2 Nabarlek

History

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.

Rehabilitation

Revegetation, weed and fire management

To help protect revegetated areas, DevEx has repaired the mine perimeter fence and is managing feral animals within the fenced area. Consultation regarding revegetation with Kakadu Native Plants and the Njanjma Rangers is ongoing. DevEx has advised it intends to develop a revegetation plan and engage with rangers for its execution. The 2021 priority area is the waste rock run-off pond.

Annual fire management activities are undertaken in conjunction with the local Njanjma Rangers from Gunbalanya as recommended during the 2015 stakeholder audit. Fire management usually occurs concurrently with weed spraying activities on-site. A cool burn was carried out by Njanjma Rangers in February 2019. DevEx wishes to re-establish a cool burn protocol and are collaborating with local rangers to do so.

DevEx engaged Kakadu Native Plants and Njanjma Rangers to conduct weed mapping, which has been completed in accordance with NT weed mapping guidelines. No class A weed species were found while four class B species were identified in the latest weed surveys.

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 mine site. Historically, the RAA has also contributed 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 submitted an application for the remediation of the RAA in conjunction with the 2020 MMP. The remediation strategy 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. SSB supported the proposed RAA remediation strategy.

Recent exploration

During 2019, six holes were drilled. All holes were rehabilitated in October 2019. SSB and DITT inspected the rehabilitation of these drill holes in December 2019 and were satisfied with the level of rehabilitation to date.

Appendix 1.3 Jabiluka

History

The ERA-owned Jabiluka mineral lease abuts the northern boundary of the Ranger Project Area, with the former Jabiluka mine site situated 20 km north of the Ranger mine site. 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. In 2003 it was agreed that the Jabiluka site would not be mined, and the site was placed in long-term care and maintenance. While in long-term care and maintenance, revegetation activities have been undertaken by ERA. The lease will expire in August 2024. However, this may be subject to renewal.

Rehabilitation

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. While the density of original planted individuals at Jabiluka had decreased since 2015, there has been an overall increase in density of stems. This indicates that recruitment is occurring, albeit of primarily non-target (i.e., non-Eucalypt) species.

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 now sampling the vent shaft once a month, taking a sample from depth and a sample from the surface. The results so far have not shown a large difference between the depth and surface samples. This data may potentially be used to assess groundwater flow direction and for monitoring purposes in lieu of having to access the mine valley bores.

APPENDIX 2 PUBLICATIONS JUL 2020-JUNE 2021

Chandler L, Harford AJ, Hose GC, Humphrey CL, Chariton A, Greenfield P & Davis J 2021. Saline mine-water alters the structure and function of prokaryote communities in shallow groundwater below a tropical stream. *Environmental Pollution* 284, 117318. https://doi.org/10.1016/j.envpol.2021.117318

D'hont B, Calders K, Bartholomeus H, Whiteside T, Bartolo R, Levick S, Krishna Moorthy SM, Terryn L & Verbeeck H 2021. Characterising termite mounds in a tropical savanna with UAV laser scanning, *Remote Sensing*, 13(3), 476. doi:10.3390/rs13030476

Doering C, Twining J, Rout S, Iurian A-R & Howard B 2021. A revised IAEA data compilation for estimating the soil to plant transfer of radionuclides in tropical environments. *Journal of Environmental Radioactivity* 232, 106570. https://doi.org/10.1016/j.jenvrad.2021.106570

Fischer S, Edwards AC, Weber P, Garnett ST & Whiteside TG 2021. The bird assemblage of the Darwin region (Australia): What is the effect of twenty years of urbanisation? *Diversity*, 13(7), 294. doi: 10.3390/d13070294

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.

Hancock G & Lowry J 2021.Quantifying the influence of rainfall, vegetation and animals on soil erosion and hillslope connectivity in the monsoonal tropics of northern Australia, *Earth Surface Processes and Landforms*, https://doi.org/10.1002/esp.5147

Hernandez-Santin l, Rudge ML, Bartolo RE, Whiteside TG & Erskine PD 2020 Reference site selection protocols for mine site ecosystem restoration, *Restoration Ecology*, 29(1), e13278. doi:10.1111/rec.13278

Joyce KE, Anderson K & Bartolo RE 2021. Of Course We Fly Unmanned—We're Women! *Drones* 5(1):21. https://doi.org/10.3390/drones5010021

Levick S, Whiteside T, Loewensteiner D, Rudge M & Bartolo R 2021. Leveraging TLS as a Calibration and Validation Tool for MLS and ULS Mapping of Savanna Structure and Biomass at Landscape-Scales, *Remote Sensing*, 13(2), 257. doi: 10.3390/rs13020257

Lowensteiner D, Bartolo R, Whiteside T, Esparon A & Humphrey C 2021 Measuring savanna woody cover at scale to inform ecosystem restoration, *Ecosphere*,12(3), e03437. doi:10.1002/ecs2.3437

McMaster SA, Noller BN, Humphrey CL, Trenfield MA & Harford AJ 2020. Speciation and partitioning of uranium in waterbodies near Ranger Uranium Mine. *Environmental Chemistry* 18, 12–19. https://doi.org/10.1071/EN20096

Mooney TJ, McCullough CD, Jansen A, Chandler L, Douglas M, Harford AJ, van Dam R & Humphrey C 2020. Elevated magnesium concentrations altered freshwater assemblage structures in a mesocosm experiment. *Environmental Toxicology and Chemistry* 39(10), 1973-1987.

Pease CJ, Trenfield MA, Mooney T, van Dam RA, Walker S, Tanneberger C & Harford AJ 2021. Development of a Sublethal Chronic Toxicity Test for the Northern Trout Gudgeon, Mogurnda mogurnda, and Application to Uranium, Magnesium, and Manganese. *Environmental Toxicology and Chemistry, 40*, 1596-1605.

Pfitzner K, Bartolo R, Whiteside T, Loewensteiner D & Esparon A. 2021. Hyperspectral Monitoring of Non-Native Tropical Grasses over Phenological Seasons. *Remote Sensing* 13(4):738. https://doi.org/10.3390/rs13040738

Pfitzner J & McMaster S 2021. Radon-222 diffusion from acrylic containers used in ERISS gamma spectrometry analysis. Internal Report 662, Supervising Scientist, Darwin.

Rudge MLM, Levick SR, Bartolo RE & Erskine PD 2021. Modelling the Diameter Distribution of Savanna Trees with Drone-Based LiDAR. *Remote Sensing* 13(7):1266. https://doi.org/10.3390/rs13071266

Saynor M, Wasson R, Erskine W & Lam D 2020. Holocene palaeohydrology of the East Alligator River, for application to mine site rehabilitation, Northern Australia, Quaternary Reviews, 249, https://doi.org/10.1016/j.quascirev.2020.106552

Trenfield MA, Pease CJ, Walker SL, Mooney T, 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 6*, 1-80.

Trenfield MA, Pease CJ, Walker SL, Humphrey C, van Dam R, Markich S & Harford AJ 2021. Assessing the toxicity of mine-water mixtures and the effectiveness of water quality guideline values in protecting local aquatic species. *Environmental Toxicology and Chemistry, 40*, 2334-2346. doi:DOI: 10.1002/etc.5103

Wasson RJ, Saynor MJ & Lowry JBC 2021 The natural denudation rate of the lowlands near the Ranger mine, Australia: A target for mine site rehabilitation. *Geomorphology* 389 (2021) 107823.

Wilson GDF & Humphrey CL 2020. The *Eophreatoicus* Nicholls, 1926 species flock from Kakadu and Arnhem Land, with a description of a new genus of Amphisopidae (Crustacea : Isopoda : Phreatoicidea). *Zootaxa* Sep 25, 4854(1).

APPENDIX 3 CURRENT RESEARCH PROJECTS BY THEME

Image 16 Mistletoe, *Decaisnina signata*, Kakadu National Park

Appendix 3.1 Introduction

This appendix is divided into 5 sections which reflect ERISS's 4 research themes (Water and Sediment, Environmental Radiation, Landform and Ecosystem Restoration) and a final section provides detail on a cross theme project. Sections 2 to 5 begin with a diagram which outlines the relationship between all the KKNs under that theme and then gives details on each of the projects which were active in 2020/21.

Appendix 3.2 Water and Sediment

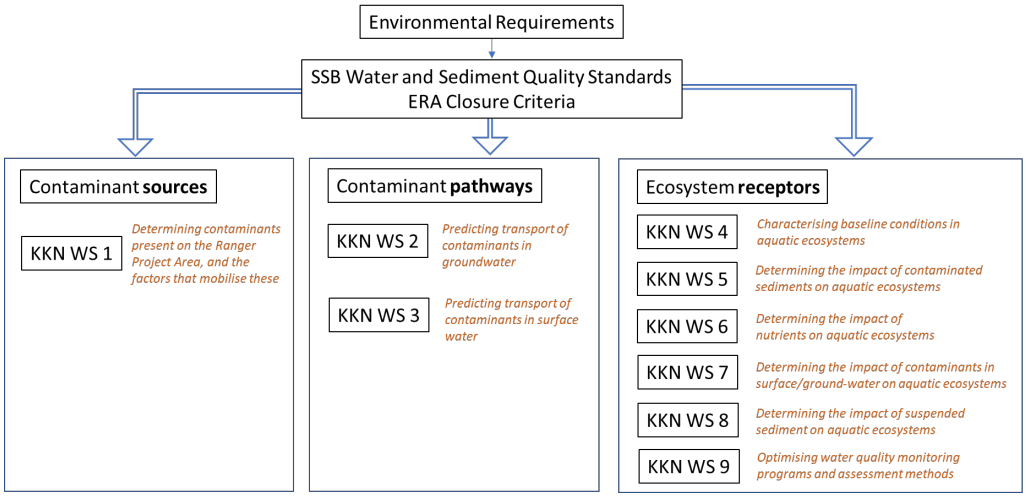


Image 17 Aquatic vegetation (*Eleocharis* spp. and *Nymphoides* spp.) at Wirnmuyurr Billabong, Kakadu National Park

Monitoring surface water and sediment chemistry of Gulungul and Mudginberri Billabong

KKN WS3

Predicting transport of contaminants in surface water

KKN Question for WS3B

What concentrations of contaminants from the rehabilitated site will aquatic (surface and ground-water dependent) ecosystems be exposed to?

Application

Baseline Water chemistry data are needed to validate Intera's Surface Water Model for Ranger mine. So, key contaminants (Mg, Mn, U, TAN), aluminium, sulfate, nutrients, chlorophyll and in situ water quality parameters are being monitored in Gulungul and Mudginberri Billabong over a two-year period.

Background

Gulungul and Mudginberri billabongs have been identified as primary potential offsite ecosystem receptors for the rehabilitated Ranger mine site but there are currently no useful baseline data to assess future changes in water quality to receiving water billabongs. Available water quality data from the 1970s and 1980s differ from contemporary water quality data (in part due to removal of wallowing water buffalo from the local areas), and contemporary water quality of other backflow billabongs (Georgetown and Coonjimba), cannot be used as an analogue for Gulungul Billabong because of mine contamination. The behaviour of solutes under contemporary seasonal conditions is also unknown.

Project aims

- To gather a two-year, monthly baseline of water chemistry data for the billabongs that will enable mine contributions of contaminants to be identified, and for this information to be used to validate the Surface Water Model developed by Intera for ERA.
- To ensure sediment contaminants are characterised, including examination of any natural seasonal changes.

Project scope and methods

- To collect data for key contaminants, nutrients, and chlorophyll monthly from two sites in each billabong for a two-year period.
- To have continuous EC measured by divers deployed at each of the sites
- To measure in situ water parameters at site visits and take sediment samples to analyse opportunistically for contaminants.

Publications

No publications to date

Predicting uranium accumulation in sediments

KKN WS3

Predicting transport of contaminants in surface water

KKN Question for WS3G

To what extent will the interaction of contaminants between sediment and surface water affect their respective qualities?

Application

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. Modelling showed that if aqueous U [Uaq] reaches the water quality guideline maximum of 2.8 µg/L, the sediment concentration was predicted to be 46 mg/kg (AEM), which is below the Sediment Quality Guideline Value.

Background

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.

Detailed project aim

- 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).

Project scope and methods

- Using the available datasets and literature 1) Assess the potential for U to accumulate in sediments when water concentration is 2.8 µg U/L 2) Assess the potential for U concentration to increase in the water column if sediment concentration is 94 mg U/kg.

Publications

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.

Identification and mapping of Groundwater Dependent Ecosystems (GDEs)

KKN Title for WS4

Characterising baseline aquatic biodiversity and ecosystem health

KKN Question for 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?

Application

Mapping of the spatial coverage of groundwater dependent ecosystems GDEs on the RPA is needed to inform risk assessments of exposure of riparian communities to mine-derived contaminants. The information gained will be used as a tool to assess the need for mitigation measures for GDEs on the RPA. It will provide a greater level of confidence in the assessment of the achievement of closure criteria for ecosystem sustainability.

Background

Previous research in the wet-dry tropics of northern Australia has identified that some riparian vegetation is dependent upon groundwater during the dry season. Known as Groundwater Dependent Ecosystems (GDEs), these are important environments that provide numerous environmental services. These ecosystems could be at high risk of impacts from any mine-derived contaminants that may be transported via groundwater, therefore the identification and mapping of these environments is vital for their management and protection. Whilst methods of mapping GDEs have been developed, they are limited in the wet-dry tropics. In Australia, a national GDE Atlas has been developed which encompasses the wet-dry tropics, however the scale of the method, and data limitations associated with the region, results in coarse scale potential GDEs being mapped. This project adapted an existing method developed for semi-arid regions to the wet-dry tropics and evaluated the results against the existing national GDE Atlas

Detailed project aims

- To identify and map potential 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.
- To collect ultra-high resolution and multi-temporal and ground-truth data to validate the GDEs identified through the historical analysis.

Project scope and methods

- GDE mapping used six time points of Landsat 5 imagery captured over a 20-year period. Time points were selected based upon annual rainfall in the region which resulted in 219 images being used to analyse vegetation dynamics using the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI).
- The NDMI was found to more accurately detect potential GDEs compared to the NDVI. The resulting maps captured a greater spatial extent and smaller size of potential GDEs than the existing National GDE Atlas. To visualise the potential extent of GDEs surrounding Ranger, high likelihood GDE sites were clipped to the boundaries of the Ranger Project Area.

Publications

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. 30pp.

Assess the ecological risks of mine water contaminants in the dry season, subsurface waters of Magela sand channel

KKN Title for WS4

Characterising baseline aquatic biodiversity and ecosystem health

KKN Question for 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?

Application

Assess the impact of mine-water inputs to groundwater communities in Magela Creek

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 (Mg) and sulfate (SO_4) derived from the waste rock landform and pit capping. Solute egress modelling predicts that within 10 years of closure, groundwater with Mg 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 Mg concentrations and other COPCs on these communities.

Stygofauna are particularly sensitive to groundwater environment disturbance because they are adapted to near steady-state environment conditions and have very narrow spatial distributions. 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.

Detailed project 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 mine site.
- To investigate the implications for ecological functions provided in Magela subsurface sands of elevated contaminants of potential concern arising from Ranger mine site.

Project scope and methods

- Piezometers were installed within the Magela Creek channel during the dry season, to a maximum depth of approximately 2 m
- 18 sites within the creek were visited monthly during the dry seasons (August-November) of 2017 and 2018, and samples were collected for;
  - Stygofauna
  - Environmental DNA (eDNA), and
  - Water chemistry and physical parameters such as hydraulic conductivity.
- The eukaryote and prokaryote community composition and function were characterised using Illumina sequencing of the 16S (prokaryotes), 18S and COI (eukaryotes) amplicons.
- Targeted ecotoxicological investigations will be conducted to evaluate the sensitivity of groundwater biota to elevated concentrations of contaminants

Publications

Chandler, L., Harford, A.J., Hose, G.C., Humphrey, C.L., Chariton, A., Greenfield, P., Davis, J., 2021. Saline mine-water alters the structure and function of prokaryote communities in shallow groundwater below a tropical stream. Environmental Pollution 284, 117318. https://doi.org/10.1016/j.envpol.2021.117318

The toxicity of U to sediment biota of Gulungul Billabong

KKN Title for WS5

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

KKN Question for WS5A

Will contaminants in sediments result in biological impacts, including the effects of acid sulfate sediments?

Application

Experimental field exposures and field macroinvertebrate studies were used to determine the bioavailability and toxicity of uranium in billabong sediments.It was found that a sediment quality guideline value of 100 mg U/kg (whole sediment, dry weight) is an appropriate Standard.

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.

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 used to derive a sediment quality Guideline Value (GV) for U for current operations and closure of the mine and this GV was the basis of a Rehabilitation Standard for U in sediments . The results will soon be published in peer-reviewed journals.

Detailed project aim

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

Project scope and methods

- The ecological effects of U contamination of sediment were studied in a series of field-based experiments aimed at deriving a candidate sediment quality guideline value.
- Sediments spiked with U were deployed in an unimpacted billabong (Gulungul) for the duration of a wet season.
- They were retrieved and sub-sampled for the analysis of microbes, including bacteria and archaea (prokaryotes), and micro- and macro-invertebrates (eukaryotes) using a combination of genomic and traditional microscopic extraction and identification methods. Only genomics-based results were used in guideline derivation.

Publications

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.

Supervising Scientist 2021. Uranium in Sediments — Rehabilitation Standard for the Ranger uranium mine (version 1). Supervising Scientist Branch, Darwin, NT. http://www.awe.gov.au/science-research/supervising-scientist/publications/ss-rehabilitation-standards. Cited.

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.

Assessing the toxicity of mine water mixtures for operational and closure scenarios

KKN Title for WS7

Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health

KKN Question for WS7A

Are current guideline values appropriate given the potential for variability in toxicity due to mixtures, modifying factors and different exposure scenarios?

Application

Mine water released during operation or via ground and surface water after rehabilitation will contain a mixture of contaminants, so this study was undertaken to determine the effects of combinations of contaminants. The study found that the toxicity of four tested site waters was generally less than expected, based on the sum of toxicity of individual contaminants. This antagonism suggests that existing individual Guideline Values (GVs) for contaminants will be adequately protective for ecosystems downstream of the mine in the event of exposure to a mixture of the contaminants of concern.

Background

Site-specific guideline values have been derived for individual contaminants of concern: uranium, manganese, magnesium, ammonia, copper, and zinc. However, scant toxicity data was available for local species exposed to mixtures of these contaminants. Contaminants in mixtures can in some cases be synergistic (more toxic than the sum of the toxicity of the individual contaminants). A Direct Toxicity Assessment of site waters was required to assess whether the individual GVs would be protective if aquatic organisms were exposed to a mixture of contaminants (as would be case for an environmental exposure scenario).

Project aim

- To assess the toxicity of mine water mixtures and determine if site-specific guideline values for individual contaminants would be protective for aquatic ecosystems downstream of Ranger mine.

Project scope and methods

- The toxicity of mine waters from various sources on the Ranger mine-site were tested using six local species
- Each mine water was assessed on two separate occasions across a range of dilutions using Magela Creek water as the diluent

- Mixture toxicity models were used to compare observed toxicity of the mixtures with predicted toxicity (based on the sum of individual contaminant toxicity)
- Metal speciation and potential bioavailability of the contaminants were modelled to see if this improved the agreement between observed and predicted toxicity

Findings

The study found for Ranger mine site waters (TDWW, PJ, RP2, SIS2) that the combined effect of contaminant mixtures cannot be predicted by summing the toxicity of the individual contaminants, as potential interactions can occur amongst contaminants. The toxicity of site waters was generally less than expected based on the sum of toxicity of individual contaminants. This antagonism suggests that existing individual GVs for contaminants would be adequately protective for ecosystems downstream of the mine in the event of exposure to a mixture of the contaminants of concern.

Publications

Trenfield MA, Pease CJ, Walker SL, Humphrey C, van Dam R, Markich S, Harford AJ. 2021. Assessing the toxicity of mine-water mixtures and the effectiveness of water quality guideline values in protecting local aquatic species. *Environmental Toxicology and Chemistry, 40*, 2334-2346. doi:DOI: 10.1002/etc.5103

Deriving site-specific guideline values for copper and zinc

KKN Title for WS7

Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health

KKN Question for WS7A

Are current guideline values appropriate given the potential for variability in toxicity due to mixtures, modifying factors and different exposure scenarios?

Application

Site-specific water quality guidelines values for copper and zinc in Ranger mine water have been determined to provide the highest level of protection to the off-site environment (Kakadu National Park). The determined site-specific GVs will be included in the relevant Supervising Scientist Rehabilitation Standard.

Background

A recent study investigating the toxicity of site water mixtures from Ranger mine identified copper and zinc as contaminants of concern. Default national GVs for these metals exist but these were derived using non-local species and based on toxicity data generated in hard water (not relevant to the characteristics of Magela Creek water; extremely soft, low in dissolved organic carbon which, can enhance metal toxicity).

Detailed project aim

- To assess the toxicity of copper and zinc to seven local species in Magela Creek water and derive site-specific guideline values for these metals.

Project scope and methods

- Chronic toxicity data was generated for Cu and Zn using seven local species
- A Species Sensitivity Distribution (SSD) was produced by fitting a log normal distribution to the data (ShinyApp tool)
- Due to the poor fit of the model to the Zn data, the local data was combined with that from 22 additional species. As a result, the GV is classified as 'site-adapted' rather than 'site-specific' due to the incorporation of a large proportion of adjusted, non-site-specific data.

Findings

Site-specific and 'site-adapted' guideline values (GVs) have been derived for Cu and Zn, respectively. These GVs have been derived under tropical testing conditions and account for the characteristics of Magela Creek water (low hardness, buffering capacity and organic material). Both GVs are based on a 72-h moving average of the dissolved metal (0.45 µm fraction) and confer protection to 99% of local aquatic species. The GVs will be

included in the relevant Supervising Scientist Rehabilitation Standard for Ranger uranium mine and will form the basis of SSB's advice on closure criteria for the site.

Publications

Supervising Scientist 2021. Copper and zinc in surface water — Rehabilitation Standard for the Ranger uranium mine. Supervising Scientist Branch, Darwin, NT. http://www.awe.gov.au/science-research/supervising-scientist/publications/ss-rehabilitation-standards. Cited 10/08/2021.

Hazard and risk assessments for emerging aquatic contaminants

KKN Title for WS7

Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health

KKN Question for WS7B

What is the risk associated with emerging contaminants?

Application

Emerging contaminants identified for the Ranger mine; herbicides, hydrocarbons, major ions, nutrients and per- and polyfluoroalkyl substances (PFAS), were assessed based on source, pathway, and receptor (toxicity) information. Hydrocarbons were considered low risk to the offsite environment based on their minimal source area and limited pathway to the offsite environment. While the risk from herbicides, major ions, and nutrients were considered low, more data and information are being collected to support this assessment. PFAS is now subsequently being addressed through a separate investigation.

Background

Contaminant research for the Ranger Project Area has been prioritised on a risk basis. However, as the mine transitions into a rehabilitated site, potential emerging contaminants need to be considered, for which there may not be exposure or effects data available. The contaminant-based hazards listed above needed to be considered based on the spatial and temporal extent of potential impact, the likelihood of recovery by aquatic species following exposure, and the relevant closure objectives (both on-site and off-site). Each of these considerations were addressed separately for each potential emerging contaminant within the following categories: *Size of the contaminant source*, *Pathway, and mobility* (i.e., connectivity between source and receptor), and *Toxicity* and *Persistence* (Receptor) of each emerging contaminant. If necessary, a systematic Weight of Evidence approach can be used to both identify and manage contaminants that may be a potential risk to the off-site environment or to the success of on-site ecosystem management.

Project aim

- To assess the risk of potential emerging contaminants from Ranger mine and determine if further investigation is required to quantify their potential risks to the aquatic environment.

Project scope and methods

- Each of the emerging contaminants was assessed using a Source, Pathway, Receptor approach
- Scoring relating to *Size of source* and *Pathway* was made based on information provided by ERA.
- A desktop review of toxicity data was carried out for each of the emerging contaminants to determine scores relating to *Toxicity*
- A workshop was held in September 2020 between ERA and SSB to discuss the risk for each of the contaminant groups
- More data and information are being collected

Publications

No publications to date

Effects of surface and ground water egress of mining-related solutes on stream ecological connectivity (NESP fish migration)

KKN Title for WS7

Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health

KKN Question for WS7F

Can a contaminant plume in creek channels from a barrier that inhibits organism migration and connectivity (e.g. fish migration, invertebrate drift, gene flow)?

Application

Historical data (Bishop et al. 1995) and the most up-to-date methods available (sonar, videography, electronic tagging) have been used to develop a comprehensive understanding of fish migration dynamics in the Magela Creek region. Results showing significant movement and residence of fish in the sand channel and onsite billabongs together with associated water quality data will be directly linked to surface and ground water solute modelling to assess risks.

Background

The research described in this report builds upon the previous work by SSB to develop a comprehensive understanding of fish migration dynamics in the Ranger Mine Project Area/Magela Creek region. Acoustic telemetry was employed to characterise individual-level patterns of spatial and temporal residency of different species in the Magela Creek sand channels from upstream (Bowerbird Billabong) and downstream (Mudginberri Billabong/Magela crossing) sources. High-resolution sonar was also used to quantify seasonal changes in fish assemblage composition, size class distribution, and relative abundance in Bowerbird and Mudginberri billabongs, thus allowing for inference regarding the consequences of fish migration at the population and assemblage levels. The data collected during the study will be used to assess the risks to fish populations associated with mine-derived solute egress to Magela Creek after mine closure and rehabilitation of Ranger. Finally, we use learnings from the study to make recommendations regarding monitoring methods for ongoing assessment of fish populations in Magela Creek.

Detailed project 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.

Project scope and methods

- Acoustic telemetry was used to examine movements of fish collected from bowerbird and Mudginberri billabongs
- Sonar imaging was used to measure abundance and biomass in bowerbird and Mudginberri billabongs
- Fish behaviour was examined at active mine-water release sites.

Publications

David Crook, Dion Wedd, Brendan Adair, Alison King, Tom Mooney, Andrew Harford, Chris Humphrey (2021). Fish migration in Magela Creek and potential impacts of mining-related solutes. Charles Darwin University, Darwin.

Ecohydrology and sensitivity of riparian flora (NESP project)

KKN Title for WS7

Determining the impact of contaminants in surface and groundwater on aquatic biodiversity and ecosystem health

KKN Question for WS7H

What concentrations of contaminants will be detrimental to the health of aquatic vegetation?

Application

The outcomes from this project will be used to assess the potential impacts of modelled Mg concentrations in groundwater on riparian trees.

Background

Riparian vegetation, particularly that growing along the banks of the major drainage lines (Magela and Gulungul creeks) may be seasonally exposed to elevated concentrations of contaminants in shallow groundwater after mine site rehabilitation. An assessment of the potential sub-lethal impacts of Mg in particular, on germination and early growth of representative species through pot trials, will assist in determining if healthy riparian habitats can be maintained following rehabilitation

Detailed project aim

- Assess the potential impacts of modelled Mg concentrations in groundwater on riparian trees by 1) assessing the proportion of groundwater sources used by riparian trees, using stable isotope and tritium analyses and 2) assessing the effect of magnesium sulfate ($MgSO_4$) on the growth of riparian trees.

Project scope and methods

- 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.
- To undertake pot trials to examine the sensitivity of dominant riparian woody species to MgSO4).
- To assess the implications to riparian vegetation of groundwater solute expressing to Magela and Gulungul Creeks and determine the salt tolerances of key riparian species.

Publications

Lindsay B. Hutley, Clément Duvert, Samantha A. Setterfield, Adam Bourke, Caroline A. Canham, Fiona L. Freestone, Ornela O. Cavalieri, Diego Alvarez-Cortez, Michael Brand (2021). Ecohydrology and sensitivity of riparian flora, Magela Creek, Ranger

Uranium Mine, Final Report, NESP North Australian Hub, Charles Darwin University, 57 pages.

Use of DGTs for uranium (and other metal) measurement

KKN WS9

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

Passive samplers or Diffusive Gradients in Thin Films (DGTs) are being investigated a potential cost-effective means of measuring bioavailable concentrations of chemical contaminants in surface waters.

Background

This project builds on work undertaken in a commercial collaboration with Hydrobiology, which investigated whether copper (Cu) and nickel (Ni) measured by DGTs were equivalent to the bioavailable concentration of these metals that cause toxicity, to the microalgae, *Chlorella* sp., under varying dissolved organic carbon concentrations. This earlier work found that DGTs can be used as a conservative tool to monitor bioavailable Cu and Ni in the moderately hard river waters of Queensland. However, the creeks surrounding Ranger Mine are unique in their low hardness, low ionic content, and pH. Thus, the viability of using DGTs for environmental monitoring in these soft waters needs to be investigated.

Uranium (U) and manganese (Mn) are contaminants of potential concern for the mine. Little work has been done with DGTs for either of these metals, and none of the existing DGT data for Mg and Mn has been conducted in conjunction with toxicity testing. This information is needed to determine the relationship between DGT metal concentrations and aquatic toxicity.

Detailed project aim

- The aim of this project is to test the use of DGTs for the measurement of bioavailable uranium (and potentially manganese) in discharged mine waters and determine if DGTs would be an appropriate tool to monitor environmental risk of these metals to Magela and Gulungul Creek.

Project scope and methods

The project will investigate the use of DGTs for the measurement of bioavailable uranium, (and possibly manganese). The influence of water quality conditions (DOC, pH and hardness) will also be investigated to aid in the interpretation of the data.

The project has four main components/methodology steps:

- Different DGT resin layers will be trialled to determine which is the most appropriate for use for detecting U in the low ionic strength, soft waters of the waterbodies surrounding Ranger mine.
- Determine the influence of water quality conditions DOC, pH and hardness on U uptake and DGT effectiveness.
- Compare DGT and predicted U measurements with U toxicity to biota
- Field trials to develop a methodology for field deployment of the DGT for in-situ environmental monitoring.

Publications

No publications to date

Acoustic backscatter sensors for total suspended sediment monitoring

KKNWS9A

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

Acoustic backscatter (ABS) sensors are being deployed in parallel with traditional NTU sensors to see if they are more effective at distinguishing natural and mine derived sediment loads in Magela and Gulungul Creeks.

Background

SSB currently uses optical (NTU) sensors to monitor turbidity as a proxy for total suspended solids (TSS). Historical NTU data from the Trial Landform showed that it is difficult to ascertain the relationship between turbidity and suspended sediments from mine-site waste rock surface run-off, likely due to the nature of the particles. ABS sensors present many advantages over NTU sensors such as sensitivity to grain size changes, detection of a greater grain size range, tolerance to biofouling, and reduced maintenance.

Detailed project aims

- To determine if acoustic backscatter sensors are effective at detecting total suspended solids in low ionic waters.
- To determine if ABS sensors will give better insights than traditional methods as to the origin of suspended sediment in Magela, and Gulungul Creeks.

Project scope and methods

- A 3-year trial is being conducted wherein ABS sensors are being deployed in parallel with traditional NTU sensors.
- The ABS sensors will be integrated into existing surface water monitoring infrastructure, upstream and downstream in Magela and Gulungul Creeks.
- The 3-year term of the trial will capture variability across wet seasons.

Publications

No publications to date

Building the metabarcode database for northern macroinvertebrate species

KKN WS9A

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

New generation genomic techniques are being adapted and used to develop a DNA barcode library of local invertebrates common to the Alligator Rivers Region (ARR). This library will be an important national asset and provide a benchmark for environmental management in the region.

The new techniques employed will initially complement and eventually potentially replace traditional morphological processing of macroinvertebrate samples.

Background

Macroinvertebrate communities are a commonly employed biological monitoring group in freshwater ecosystems, including monitoring and assessment of potential mine impact 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 (eDNA, ecogenomics) offer vastly improved and cost-effective approaches to deriving accurate species-level information for macroinvertebrate samples. In partnership with NT Government and Macquarie University, SSB are developing a DNA barcode library of freshwater macroinvertebrates which will be used to identify macroinvertebrates species from samples.

Detailed project aims

To build a baseline DNA barcode library for freshwater macroinvertebrate species from ARR streams, commencing with 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

Project scope and methods

- Macroinvertebrate material for this study is being collected from NT Top End streams, billabongs and other waterways, including those located in the ARR.
- Macroinvertebrate species will be shotgun sequenced to determine the whole metagenome.
- Sequences will be made available in a publicly accessible DNA barcode library

Publications

No publications to date

Use of DNA to survey macroinvertebrate assemblages

KKN WS9A

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

Adapted new generation genomics techniques and a DNA barcode library of macroinvertebrates will be used to identify the presence of macroinvertebrate species in bulk samples collected during routine monitoring.

Background

The Supervising Scientist Branch (SSB) has been assessing macroinvertebrate communities downstream of Ranger Mine for potential mine derived impact since 1988. This annual biomonitoring program involves collecting macroinvertebrate samples, upstream and downstream in four seasonally flowing streams. Macroinvertebrates are currently identified morphologically, which is labour-intensive and time consuming. Furthermore, macroinvertebrates are typically identified to family level as species level processing can be an arduous task, requiring specially trained staff. Emerging genetic techniques (eDNA, metabarcoding) have the potential to transform the way we assess aquatic ecosystem health and offer a potentially more cost-effective approach to deriving accurate, species-level presence data for aquatic assemblages.

Detailed project aims

The aim of this project is to use DNA metabarcoding techniques in routine monitoring to identify macroinvertebrate species present in bulk samples.
To achieve this the project will address the following aims:

- Determine appropriate sample preparation and primers for extracting macroinvertebrate DNA from bulk unsorted samples.
- Determine an appropriate bioinformatics pipeline for processing DNA data from bulk samples and use the DNA barcode database for species-level identification of macroinvertebrate species.
- Understand the difference in macroinvertebrate assemblage data collected using traditional morphological methods and genomic techniques.

Project scope and methods

- DNA will be extracted from bulk field collected macroinvertebrate samples
- The macroinvertebrate DNA barcode library will be used to assign species to each operational taxonomic unit (OTU).
- Assemblage data will be compared between sample processing methods, i.e., traditional sorting and DNA identification (shotgun sequencing and PCR).

Publications

No publications to date

Building the DNA database of northern aquatic vertebrate species

KKN WS9A

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

To be able to better audit and monitor biodiversity in Northern Australia, a DNA database will be established using Next Generation Sequencing technologies.
This project will provide data of national significance and the opportunity to develop linkages with researchers, regulators, industry, and government to research and the assess the use of eDNA tropical waters.

Background

Fish and other aquatic vertebrates are commonly used in biological monitoring and ecological assessments for freshwater ecosystems. Emerging genetic techniques in biological monitoring (eDNA, metabarcoding) have the potential to transform the way we assess aquatic ecosystem health and offer a complementary and potentially a more cost-effective approach to deriving accurate, species-level presence data for aquatic assemblages. This technique could be used alongside current biological monitoring methods to provide greater resolution in the identification of rare, threatened, cryptic and pest species.
To exploit this approach, it is pivotal to be to able discriminate organisms at the species level. Internationally, the necessary research is being undertaken to build regional baseline DNA barcode libraries for a range of taxonomic groups. Currently, DNA databases have a limited number of northern Australian aquatic vertebrate species, making them inadequate for species level biodiversity surveys in the top end. Before we can effectively use this technology to enhance current biological monitoring techniques we need to establish and maintain regionally specific DNA barcode libraries for taxonomic groups of interest.

Detailed project aim

- Develop a customised, publicly available whole-mitochondrial genetic database derived from the fish and other aquatic vertebrates from northern Australia with particular focus on the Magela catchment.

Project scope and methods

- Build a database of whole-mitochondrial sequences for northern Australian aquatic vertebrates.
- Samples will be provided by NT museum and shotgun sequenced by CDU

Publications

No publications to date

Measuring river discharge from drones

KKN Title for WS9

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

This project seeks to operationalise the use of drone-mounted radar to measure water flow rates and volumes in remote or dangerous places, noting that a great deal of preliminary work will be needed to lay the foundation for meaningful results. If successful, the flow measurements could be used to assess closure criteria related to suspended sediment transport and solute loads leaving the Ranger site.

Background

The US Geological Survey (USGS) hydrologists and National Unmanned Aircraft System Project Office (NUPO) are developing new technology 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 ephemeral streams of the wet-dry tropics.

Flow data is needed for surface water modelling, suspended sediment monitoring, and 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. 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 provide a unique opportunity to build on international relationships when developing leading monitoring technology.

Detailed project aims

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

Project scope and methods

- The project will require targeted data collection and data analysis prior to drone based measurements being collected. This will consist of targeted flow measurements at the 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 developed and stable rating curves.

Publications

No publications to date

Automation of Fish Identification

KKN WS9

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

The project will create a Deep Neural Network model that can be used to identify freshwater fish assemblages from the Alligators Rivers Region, including an annotated library of fish images that can be shared in a national database and be used for deep learning workflows.

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 measure fish community structure. Videography methods result in the acquisition of significant hours of video that a technician is required to observe and extract identifications and counts from on a computer. Advancement of Deep Learning techniques in the field of computer vision 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 fish identification from videography collected for SSB's monitoring activities.

Detailed project aim

- To develop a deep learning model that can count and identify freshwater fish from videography.

Project scope and methods

- Develop a deep learning workflow using open-sourced tools for automating fish species identification. This workflow will enable fish videography to be annotated and labelled and generate a gold standard training dataset of fish. The dataset will be in a format that can be used to train deep learning models, both locally on a desktop and using cloud compute. The workflow will enable predictions of new videography using deep learning models and visualisation of results.
- All workflows will be made publicly available to enable others.

- A bounding box annotated dataset will be generated from channel billabong fish videography and a polygon annotated dataset will be generated from shallow lowland billabong fish videography.
- Both datasets will be tested against unseen monitoring datasets and compared with human fish counts to determine the performance of automation methods.
- Citizen science will be used to assist with generating the training dataset. All training data that can be used for deep learning will be compiled into one dataset called BRUVNet. More information can be found at www.bruvnet.org.

Publications

No publications to date

Developing methods for monitoring fish communities in shallow lowland billabongs

KKN WS9

Optimisation of water quality monitoring programs and assessment methods

KKN Question for WS9A

How do we optimise methods to monitor and assess ecosystem health and surface and groundwater quality?

Application

New approach methodologies (underwater cameras, aerial imagery and AI) are being optimised for characterisation of fish and vegetation assemblages in shallow lowland backflow 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.

Detailed project aim

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

- Determine the optimal time of day for sampling and asses the methods ability to detect spatial heterogeneity, key landscape and habitat variables that influence fish assemblages

Project scope and methods

- Using existing methods developed for surveying channel billabongs with underwater cameras, an approach to deploy cameras in the littoral zones of backflow billabongs will be developed.
- This project will survey backflow billabongs at different time intervals in the day (morning, midday, and afternoon) to determine if there is an optimal time of day for sampling fish using underwater cameras.
- Drones will be used to collect RGB and multi-spectral imagery to map vegetation at the scale of the billabong using remote sensing tools.
- The method will be expanded to the six billabongs originally sampled in the pop-netting program to determine if spatial patterns in fish assemblages are captured using underwater cameras.
- Multiple years of fish assemblage data will be collected to determine if temporal patterns in fish assemblages are captured using underwater cameras.

Publications

No publications to date

Appendix 3.3 Environmental Radiation

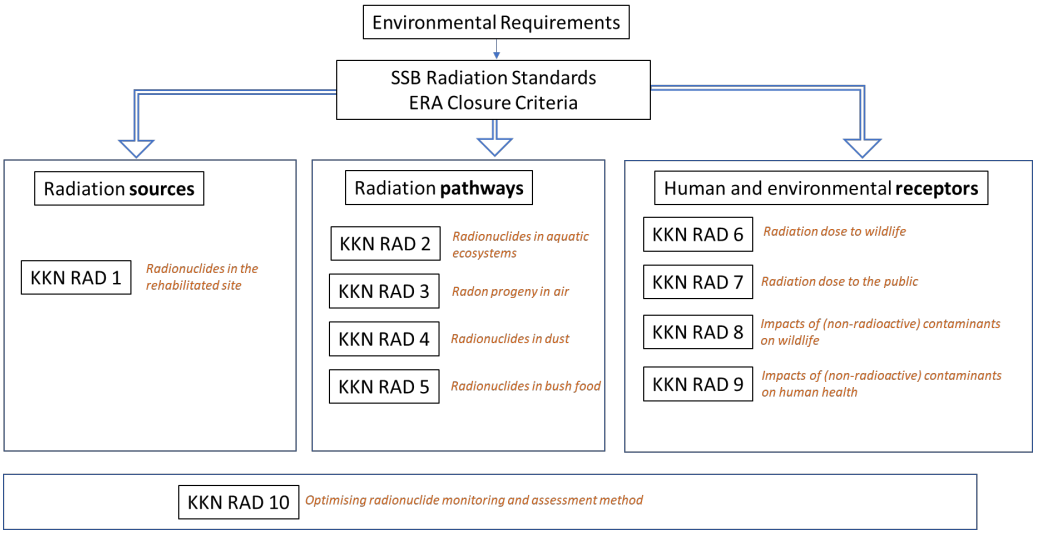


Image 18 SSB staff collecting freshwater mussel samples for bioaccumulation monitoring, Mudginberri Billabong

Radon exhalation from waste rock on the Ranger trial landform

KKN Title for RAD3

Radon progeny in air

KKN Question for RAD3A

What is the above-background concentration of radon and radon progeny in air from the rehabilitated site?

Application

This project provides information on the long-term behaviour of radon exhalation from a landform covered by low uranium grade waste rock. The information will be used to estimate radon doses to the public from the Ranger final landform and will inform our assessment of radiation protection of the public against our public radiation rehabilitation standard for the Ranger mine.

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 from waste rock to be quantified. The Ranger trial landform provides a unique opportunity to acquire site-specific data on radon exhalation from waste rock, including its seasonal and long-term variability. Measurements of radon exhalation on the trial landform from 2009 to 2014 showed a year-on-year increase in dry season values. Further measurements are needed to confirm whether this behaviour is sustained over the long-term, as it will have implications for public dose estimates.

Detailed project 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 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.

Project scope and methods

- Measure dry and wet season radon exhalation flux density from waste rock on the Ranger trial landform during 2019–2021.
- Collect waste rock samples from the trial landform and analyse them for radium-226.
- Calculate dry and wet season $R_{E\text{-}R}$ values from the radon exhalation and waste rock radium-226 measurements.

Publications

No publications to date

Environmental fate and transport of Ac-227 and Pa-231

KKN Title for RAD5A

Radionuclides in bushfoods

KKN Question for RAD5A

What are the concentration ratios of actinium-227 and protactinium-231 in bush foods?

Application

This project develops new methods for measuring actinium-227 and protactinium-231 in environmental samples and provides information on the uptake of these radionuclides in bush food and biota. The information will be used to inform our assessments of radiation protection of the public and the environment against our public and environmental radiation rehabilitation standards for the Ranger mine.

Background

Radiological assessments for uranium mining and milling do not often consider radionuclides in the uranium-235 decay series. This is because of the low abundance of uranium-235 compared to uranium-238 and technical difficulties in measuring uranium-235 decay series radionuclides at environmental levels. Actinium-227 and protactinium-231 are two radionuclides in the uranium-235 decay series with relatively high dose coefficients which could potentially contribute to dose if they have high uptake in bush foods or biota. However, there is currently a lack of measurement data for these radionuclides to make a quantitative assessment of their importance to dose.

Detailed project 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.

Project scope and methods

- Develop new radiochemistry methods for measuring actinium-227 and protactinium-231 in environmental samples.
- Apply the newly developed methods to process and analyse samples for actinium-227 and protactinium-231.
- Determine radionuclide concentration ratios between bush food, biota and soil or water.
- Use the newly determined concentration ratio values to estimate doses to the public and to wildlife from actinium-227 and protactinium-231.

Publications

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.

Radionuclide uptake in small proliferators

KKN Title for RAD6

Radiation dose to wildlife

KKN Question for RAD6B

What are the whole-organism concentration ratios of uranium and actinium series radionuclides in wildlife represented by the representative organism groups?

Application

This project provides information that can be used to predict radionuclide activity concentrations in algae growing in waterbodies downstream of the Ranger final landform. The information will inform our assessment of radiation protection of the environment for the Ranger final landform against our environmental radiation rehabilitation standard.

Background

Prospective assessments of radiation doses to wildlife use whole organism concentration ratio values to predict radionuclide activity concentrations in wildlife from those in soil or water. Site-specific values are preferable to international default values to ensure the assessment best represents local species and environmental conditions. There are currently no site-specific concentration ratio values available for uranium decay series radionuclides in small proliferators such as algae which is a weakness of the current wildlife dose assessment for the Ranger final landform.

Detailed project aims

- To measure uranium decay series radionuclides in algae and water.
- To derive radionuclide concentration ratios between algae and water.
- To update the current wildlife radiation dose assessment for the Ranger final landform using new site-specific concentration ratio data for algae.

Project scope and methods

- Collect algae and water samples from billabongs in the Alligator Rivers Region.
- Analyse samples for radionuclides.
- Determine radionuclide concentration ratios between algae and water from the sample analysis.
- Use the new site-specific concentration ratio values to update the current wildlife dose assessment for the Ranger final landform.

Publications

No publications to date

Radionuclide uptake in understorey vegetation

KKN Title for RAD6

Radiation dose to wildlife

KKN Question for RAD6B

What are the whole-organism concentration ratios of uranium and actinium series radionuclides in wildlife represented by the representative organism groups?

Application

This project provides information that can be used to predict radionuclide activity concentrations in understorey vegetation (e.g. grasses, herbs and shrubs) growing on the Ranger final landform. The information will inform our assessment of radiation protection of the environment against our environmental radiation rehabilitation standard for the Ranger mine.

Background

Prospective assessments of radiation doses to wildlife use whole organism concentration ratio values to predict radionuclide activity concentrations in wildlife from those in soil or water. Site-specific values are preferable to international default values to ensure the assessment best represents local species and environmental conditions. There are currently no site-specific concentration ratio values available for uranium decay series radionuclides in understorey vegetation which is a weakness of the current wildlife dose assessment for the Ranger final landform.

Detailed project aims

- To measure uranium decay series radionuclides in understorey vegetation and soil.
- To derive radionuclide concentration ratios between understorey vegetation and soil.
- To update the current wildlife dose assessment for the Ranger final landform using new site-specific concentration ratio data for understorey vegetation.

Project scope and methods

- Collect understorey vegetation and soil samples from three reference sites in Kakadu and analyse samples for radionuclides.
- Determine radionuclide concentration ratios between vegetation and soil from the sample analysis.
- Use the new site-specific concentration ratio values to update the current wildlife dose assessment for the Ranger final landform.

Publications

No publications to date

Deriving site-specific concentration factors for metals in bush foods to inform human health risk assessments for the Ranger final landform

KKN Title for RAD9

Impacts of contaminants on human health

KKN Question for RAD9B

What are the concentration factors for contaminants in bush foods?

Application

This project provides site-specific information on metal concentration factors for bush foods. The information can be used to predict metal concentrations in bush foods and inform human health risk assessments for rehabilitation of the Ranger mine.

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 (HILs) 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.

Detailed project aims

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

Project scope and methods

- Conduct a desktop analysis of existing metal data for bush food, soil and water to derive concentration factors.
- Investigate the suitability of the concentration factors for deriving HILs based on the NEPM methodology.

Publications

Doering C (in review). Metal concentration factors in Aboriginal bush foods. Internal Report, Supervising Scientist, Darwin.

Quantifying radon retention characteristics of ERISS acrylic gamma spectroscopy containers

KKN Title for RAD10

Optimisation of radionuclide monitoring and assessment methods

KKN Question for RAD10A

How do we optimise methods to monitor and assess radionuclides?

Application

This project provides information on radon leakage from acrylic containers used by ERISS for gamma spectrometry analysis of environmental samples. The information will be used to verify the accuracy of the analytical method for radium-226 determination and to provide assurance of the correctness of our measurements.

Background

Radium-226 can be difficult to measure directly by gamma spectrometry because of its low gamma emission intensity and interference from other natural radionuclides at similar energy. The preferred radium-226 analysis method is to measure the gamma emissions of the progeny of radioactive radon gas (lead-214 and bismuth-214) which are of higher intensity. This method requires that samples be sealed in airtight containers so that the radon progeny can reach equilibrium with radium-226, a process that takes about 1 month to occur.

The containers currently used 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 radon gas 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.

Detailed project aims

- To measure radon diffusion from the acrylic gamma spectrometry containers.
- To assess the impact of variations in radon diffusion on the accuracy of the radium-226 analysis.
- To investigate methods for improving the radon retention of the acrylic containers

Project scope and methods

- Measure the diffusion of radon from acrylic gamma spectrometry containers using a RAD7 radon detector.
- Apply model fits to the measurement data to determine the fractional loss of radon from the containers.

Publications

Pfitzner J & McMaster S 2021. Radon-222 diffusion from acrylic containers used in ERISS gamma spectrometry analysis. Internal Report 662, Supervising Scientist, Darwin.

Appendix 3.4 Landform

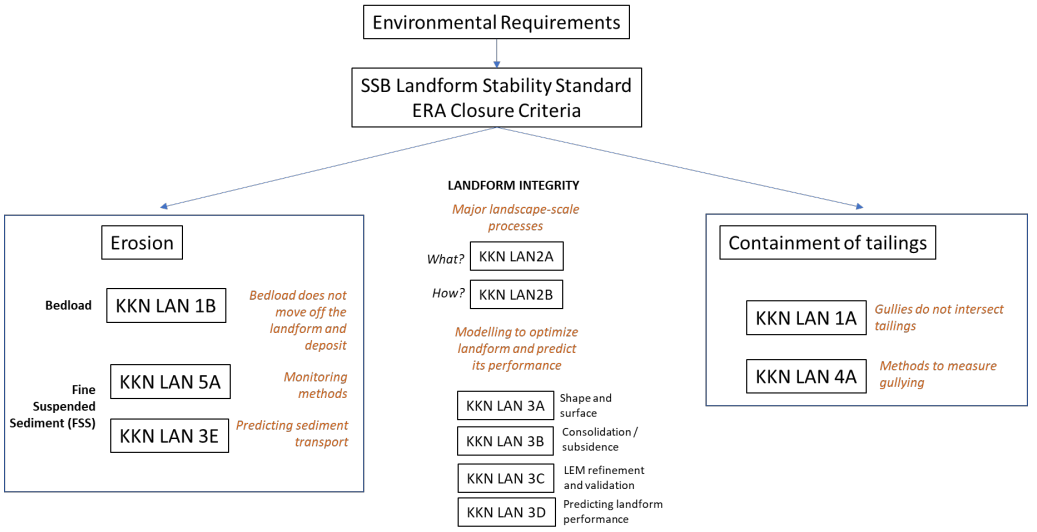


Image 19 Magela Creek catchment below Arnhem Land escarpment, Alligator Rivers Region, Kakadu National Park

What are the baseline rates of sediment transport and deposition in creeks and billabongs?

KKN Title for LAN1

Determining baseline erosion and sediment transport characteristics in areas surrounding the RPA

KKN Question for LAN1B

What are the baseline rates of gully formation for areas surrounding the RPA?

Application

This project will provide information about the natural sedimentation rates in backflow billabongs downstream of the Ranger mine site. This knowledge will be used to assist in determining whether erosion of the rehabilitated Ranger site causes any increase in sedimentation rates in the billabongs. Information will be collected 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.

Background

Three backflow billabongs (Georgetown, Coonjimba and Gulungul Billabongs) 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 and provide a 2021 baseline.

Detailed project 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.

Project scope and methods

- Collect sediment cores from 3 backflow billabongs (Georgetown, Coonjimba & Gulungul) downstream of the Ranger Mine site.
- Describe the cores stratigraphically and sample for dating using the fallout radionuclides ^{210}Pb(ex) and ^{137}Cs which will be undertaken in the environmental radiation laboratory in the Darwin office of the SSB.
- Explore the possibility of dating the older sections of the cores by ^{14}C and Optically Stimulated Luminescence (OSL).
- Depending upon the utility of the results from the fallout radionuclides, determine if Pu isotopes would add further value to the chronology.
- Undertake Bathymetric surveys and/or UAV surveys to compare with surveys collected in the 1980's and determine a 2021 baseline

Publications

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

Sedimentation rates in billabongs downstream of the Ranger uranium mine, Northern Australia: a pilot study (In prep) Wasson RJ, Pfitzner J, Saynor MJ, Trinh K, McMaster S, McDonnell , Spooner N.

Mapping and characterisation of geomorphology of on-site creeks in and adjacent to the mine site, including historical change

KKN Title for LAN1

Determining baseline erosion and sediment transport characteristics in areas surrounding the RPA

KKN Question for LAN1B

LAN1B. What are the baseline rates of sediment transport and deposition in creeks and billabongs?

Application

Mapping and characterisation of geomorphological features (water bodies, creek lines, grass and sandy beds) from historic data will provide a baseline dataset that will allow future geomorphic changes to be accurately ascribed to natural variation or to mine influence.

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 geomorphological changes to these receiving waters associated with the rehabilitated mine. Specifically, it will allow for detection of changes in tributaries, including visualisation of increased sediment and can potentially provide indication of gully formation.

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). 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.

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

Detailed project aim

- 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.

Project scope and methods

- Use historical aerial imagery and satellite photos to see if there has been historical change in the creeks adjacent to the mine and to determine a baseline geomorphic map from the latest imagery.

Publications

Lowry J, Saynor M & Muller S (in Prep). Mapping and characterisation of geomorphology of on-sites creeks in and adjacent to the Ranger mine site, including historical change. Internal Report XYZ, August 2021, Supervising Scientist, Darwin.

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

Assessing the geomorphic stability of the Ranger trial landform: calibrating model outputs

KKN Title for LAN3

Predicting erosion of the rehabilitated landform

KKN Question for 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)?

Application

Optimisation of the landform evolution model will provide improved confidence in modelling of the long term (>10,000 year) performance of the landform.
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.
This information will increase 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.

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.

Detailed project aim

- 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.

Project scope and methods

- Use data from the trial landform to inform model outputs to better parameterise model simulations.

Publications

Coulthard T 2019. Final report for the Supervising Scientist Branch, Department of the Environment and Energy in fulfillment of Contract 3600001290, CAESAR sensitivity analysis. University of Hull, Hull, United Kingdom.

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 2020. A comparison of landform evolution model predictions with multi-year observations from a rehabilitated landform. Internal Report 663, December, 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.

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.

Determining and testing representativeness of long-term rainfall patterns for use in final landform modelling

KKN Title for LAN3

Predicting erosion of the rehabilitated landform

KKN Question for 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)?

Application

To optimise the landform evolution model, data from the March 2007 rainfall event (which represents a >1:1,000-year occurrence) has been incorporated into extreme wet rainfall scenario model simulations.

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 slack water 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.

Detailed project aim

- To determine historic extreme floods on the East Alligator River, using flood deposits called slack water deposits.

Project scope and methods

- To use slack water 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.

Publications

Saynor M, Wasson R, Erskine W & Lam D 2020. Holocene palaeohydrology of the East Alligator River, for application to mine site rehabilitation, Northern Australia, Quaternary Reviews, 249, https://doi.org/10.1016/j.quascirev.2020.106552

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 slack water 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.

Ranger trial landform erosion research

KKN Title for LAN3

Predicting erosion of the rehabilitated landform

KKN Question for 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)?

Application

Data derived from the trial landform (TLF) were used to optimize the physical parameters used in the CAESAR-Lisflood landform evolution model.
Hydrology and particle size measurements have allowed

- comparison of the suitability of different surface treatments and vegetation establishment strategies and
- identified knowledge needs for assessing plant available water.

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.

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 tube stock, 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 several 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.

Detailed project 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.

Project scope and methods

- Use data collected from the trial landform to provide information on hydrology (rainfall and runoff) and erosion that is occurring on the surface.
- Erosion plots with automated gauging stations collecting rainfall and runoff were established during the dry season of 2009.
- Suspended sediment, EC and bedload was collected in the first 4 years and bedload has been collected at least annually to present.
- Collect rainfall and runoff each wet season 2009-2010.

Publications

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.

Development of a method for monitoring gully formation on the rehabilitated landform using stereopsis and LiDAR

KKN Title for LAN4

Development of remote sensing methods for monitoring erosion

KKN Question for LAN4A

How do we optimise methods to measure gully formation on the rehabilitated landform?

Application

This project will develop a robust and cost-effective method for use in detecting and assessing gully development on the Ranger rehabilitated landform.

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.

Detailed project 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.

Project scope and methods

- Use different RPAS platforms and sensors to collect data on erosion gullies to determine the most accurate and cost-effective method to quantifying gully erosion on the Ranger rehabilitated landform.

Publications

No publications to date

Turbidity and suspended sediment relationships for Gulungul and Magela Creeks

KKN Title for LAN5

Development of water quality monitoring methods for assessing landform erosion

KKN Question for LAN5A

How can we use suspended sediment in surface water (or turbidity as a surrogate) as an indicator for erosion on the final landform?

Application

This project will be used to determine site specific suspended sediment and turbidity relationships that will enable continuous suspended sediment loads to be determined. It will be used for the 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.

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.

Detailed project 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

Project scope and methods

- Assessment of mine site erosion using annual net turbidity compared to baseline/background. Determination of site-specific suspended sediment and turbidity relationships that will enable continuous suspended sediment loads to be determined.

Publications

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.

Appendix 3.5 Ecosystem Restoration

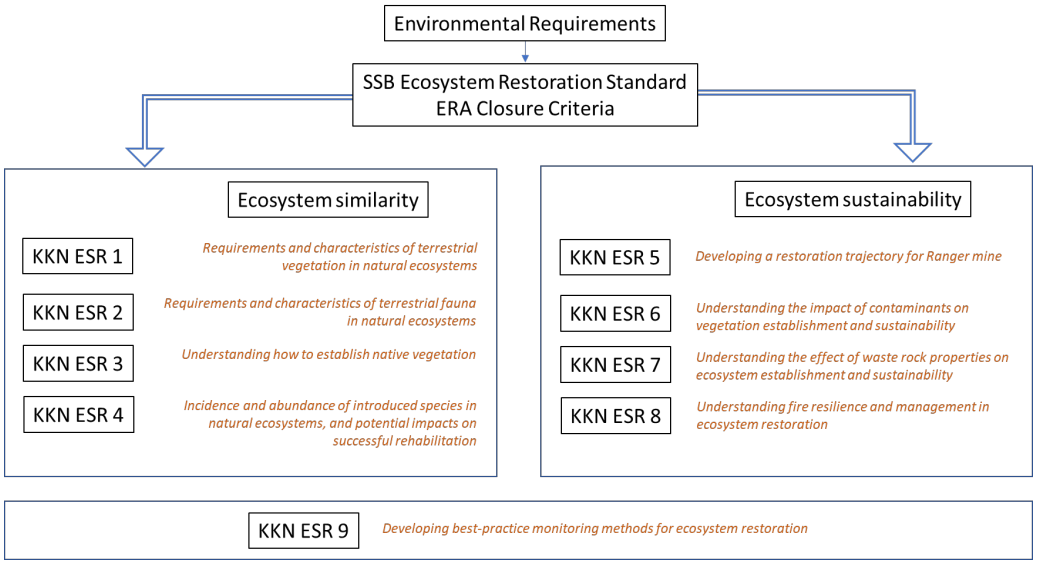


Image 20 Revegetation on the Pit 1 landform, Ranger uranium mine

Using hyperspectral drone data for deriving species composition

KKN Title for ESR1

Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the mine site, including Kakadu National Park.

KKN Question for 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?

Application

Hyperspectral data will be used to establish and measure several metrics associated with ecosystem restoration 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.

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.

Detailed project aim

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

Project scope and methods

- Undertake review of previous SSB hyperspectral work as well as RPAS based hyperspectral research;
- Establishment of spectral calibration laboratory and procedures to characterise and calibrate spectral sensors and targets;
- Capture of hyperspectral imagery of over the reference sites at intervals coinciding with key phenological stages over a 2-year time frame;
- Collect irradiance data at the same time;
- Collection of spectra in field for validation;
- Development of procedures to calibrate imagery to surface reflectance including corrections for irradiance;
- Establishment of a spectral library for future plant ID and functional trait research.

Publications

Pfitzner KS, Bartolo RE, Loewensteiner DA, Esparon AJ, & Whiteside TG 2021 Hyperspectral monitoring of non-native grass over phenological seasons. *Remote Sensing*, 13(4): 738. https://doi.org/10.3390/rs13040738

Pfitzner KS, Bartolo RE, Whiteside TG & Loewensteiner DA (submitted) The spectral reflectance of tropical savanna understorey species and recommendations for drone-based hyperspectral remote sensing for mine site closure planning. *International Journal of Applied Earth Observation and Geo-information, --.*

Vegetation similarity: updated data for conceptual reference ecosystem

KKN Title for ESR1

Determining the requirements and characteristics of terrestrial vegetation in natural ecosystems adjacent to the mine site, including Kakadu National Park.

KKN Question for 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?

Application

In accordance with the Ranger Environmental Requirements, vegetation communities on the rehabilitated mine site need to be similar to surrounding areas. The outputs from this project will enable the further development of the savanna reference ecosystem, upon which the closure criteria pertaining to vegetation similarity will be assessed in future. The vegetation data collected from reference areas will also directly inform the development of ERAs revegetation plan (species selection and densities).

Background

Based on continuing stakeholder discussion, it was agreed that more data from additional vegetation reference plots were required in order to develop the reference ecosystem. Additional 1-hectare plots were established in the Georgetown area on the Ranger Project area. The new plots were intended to (i) alleviate the discrepancy between plot sizes and scaling up of vegetation information from 20 x 20 m plots (400 m^2) to 1 hectare (10,000 m^2) and (ii) survey savanna woodland with a suite of species in densities similar to that of the surrounding vicinity of Ranger.

Detailed project aims

- Establish two additional 1-hectare reference survey plots in the Georgetown area to expand the current savanna woodland data and to standardise reference plot sizes informing the conceptual reference ecosystem
- Update the conceptual reference ecosystem for savanna and reach consensus between stakeholders that this is appropriate for revegetation of the Ranger Project Area.

Project scope and methods

- Select two additional appropriate sites for plot establishment in the Georgetown area, in consultation with relevant stakeholders.
- Survey the two new sites using established sampling methodologies

Publications

Supervising Scientist 2021. Updated Conceptual Reference Ecosystem data. Technical Advice 041. Supervising Scientist, Darwin.

Vegetation similarity closure criteria: development of indicators

KKN Title for ESR1

Determining the characteristics of ecosystems in the areas surrounding the RPA.

KKN Question for ESR1B

Which indicators of similarity should be used to assess revegetation success?

Application

This project will directly inform the development of vegetation similarity closure criteria (to ensure the rehabilitation at Ranger mine is in accordance with the Environmental Requirements) and promote agreement amongst stakeholders on appropriate criteria.

Background

In accordance with Ranger Environmental Requirements, vegetation communities on the rehabilitated mine site need to be similar to surrounding areas. This project is focussed on development and agreement of the indicators for vegetation similarity closure criteria.
This project will primarily be undertaken via desktop review, with substantial consultation with key stakeholders (i.e. ERA and Traditional Owner representatives) and inputs from local experts as required.

Detailed project aims

- Develop and gain stakeholder agreement on indicators that will inform the assessment of each of the closure criteria goals;
- Where possible and within project timeframe and resources, identify assessment methods for each indicator and identify and prioritise any data collection requirements that are required to inform the development of assessment methods.

Project scope and methods

- Undertake a desktop literature review to identify candidate indicators for each of the vegetation similarity goals - this will include consideration of the following for each indicator: how they may interact with other indicators; identification of any that may be more/less important; and identification of those that may be more practicable to measure.
- As part of the above desktop review, identify any (or the most) suitable assessment method(s) for a given indicator. Where there is no available existing information and/or when it is identified as needing site specific information, recommendations will be made for future data collection needs and prioritised.
- Regular and close consultation with ERA and Traditional Owner representatives on gaining agreement on suitable closure criteria indicators. This consultation

will take the form of regular fortnightly meetings and other topic-specific specific meetings/workshops as required.

Publications

No publications to date

Deriving species composition measures and their environmental correlates to assess ecosystem restoration similarity

KKN Title for ESR1

Determining the characteristics of ecosystems in the areas surrounding the RPA.

KKN Question for ESR1C

What values should be prescribed to each indicator of similarity to demonstrate revegetation success?

Application

The data generated by this project will be used to determine interim species composition closure measures (including species specific stem densities where appropriate) for both overstorey and understory at 1 ha scale, which can in turn be used in nursery planning.

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. 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. These differences make the 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 anddo not capture the necessary inherent seasonal and inter-annual changes and variability required for specifying several 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, this project will collect new data at appropriate sampling scales that can be used to derive and assess revegetation closure criteria for Ranger mine site. This 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.

Detailed project 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.

Project scope and methods

- The project will establish a sufficient number of 1 ha permanent plots in areas of Kakadu National Park adjacent to Ranger mine site and undisturbed areas of the Ranger Project Area (a 10km buffer around the mine and restricted to appropriate land units) to capture the inherent plant community variability in the region. The AusPlots Rangelands Survey Protocols (a national standard developed by the government funded Terrestrial Ecosystem Research Network, TERN) will be used to survey the plots (including the collection of soil samples).
- The plots will be established and surveyed at various times of the year, particularly in March- April, when the understorey in the savanna is at peak biomass.
- Existing plot data from Kakadu National Park (60 sampling plots from early 2018, and the temporally monitored fire plots (100 plots)) and the Georgetown studies will be used to determine: 1) whether the 1ha plots have captured the spatial variation of plant communities present in the environment; 2) species accumulation curves to be used in assessing species richness; 3) environmental correlates for species composition; and 4) temporal variation in plant species. The information collected through the AusPlots survey method will also be used in determining environmental correlates.
- These 1 ha plots will be used to derive other rehabilitation standard measures for ecosystem restoration, including those related to fauna, vegetation structure and ecosystem sustainability. Method development for using drones to measure rehabilitation standard attributes where possible will also be undertaken using these plots.

Publications

Hernandez-Santin l, Rudge ML, Bartolo RE, Whiteside TG & Erskine PD 2020 Reference site selection protocols for mine site ecosystem restoration, *Restoration Ecology*, 29(1), e13278. doi:10.1111/rec.13278.

Loewensteiner DA, Nicholson JD, Whiteside TG, Rudge M, Erskine P, Bartolo RE (in draft) The practical development of a reference ecosystem to inform mine site restoration, journal

Nicholson JD, Hernandez-Santin L, Rudge ML, Ufer NG, Erskine PD, Bartolo RE (in draft). Assessing understorey vegetation diversity of tropical savanna to inform mine site restoration in northern Australia.

Supervising Scientist 2019. Species richness and composition indicator values for assessing ecosystem similarity for savanna woodland. Technical Advice 006. Supervising Scientist, Darwin.

Supervising Scientist 2020. Functional diversity of savanna surrounding Ranger. Technical Advice 028. Supervising Scientist, Darwin.

Supervising Scientist 2020. Intermittent flooding savanna species composition. Technical Advice 029. Supervising Scientist, Darwin.

Supervising Scientist 2020. Proportion of forest types surrounding Ranger. Technical Advice 017. Supervising Scientist, Darwin.

Supervising Scientist 2020. Ranger *Eucalyptus miniata/tetrodonta* open forest reference ecosystem soil physical and chemical properties. Technical Advice 023. Supervising Scientist, Darwin.

Supervising Scientist 2020. Reference site selection protocols for mine site ecosystem restoration. Technical Advice 024. Supervising Scientist, Darwin.

Fauna Closure Criteria: development of goals

KKN Title for ESR2

Determining the requirements to support a terrestrial faunal community similar to areas surrounding the RPA.

KKN Question for ESR2A

What faunal community structure (composition, relative abundance, functional groups) is present in the areas surrounding the RPA?

Application

The project identifies meaningful, measurable and practical criteria that will be used for the development of rehabilitation standards that are aligned with the Environmental Requirements with respect to fauna colonization and habitation of RPA following rehabilitation.

Background

SSB has committed to developing and proposing a set of high-level goals for the fauna colonization and habitation for Ranger uranium mine that align with the Environmental Requirements for rehabilitation of the site. A key facet of these requirements is that fauna colonisation and utilisation of the site is similar to the surrounds of Kakadu National Park. The biodiversity, relative abundances, status (i.e. threatened, endangered) and range of life forms that are expected to colonise and utilise the site (and that inhabit the surrounds of Kakadu National Park) necessitates a process of careful consideration with regards to setting meaningful, practical and measurable closure criteria for fauna. This process should evaluate the current best practices in fauna monitoring as well as identifying fauna (and groups of fauna) that are both important indicators of the progress of rehabilitation as well as key drivers of that progress.

There has been decades of research and monitoring of a range of fauna groups in Kakadu National Park and similar ecosystems across the Top End. This body of research and monitoring provides a foundation for SSB to evaluate and identify a set of fauna groups and approaches that can serve as attributes for setting closure criteria. The identification of attributes is similar to the process that SSB used to reach consensus for the setting of flora closure criteria attributes.

In this project we will conduct a literature and scientific report review (e.g. the NESP research), summarise current practices in the industry and solicit expert opinion from key fauna ecologists who have decades of experience in the region. This information will be collated and analysed to develop a set of attributes that are meaningful, measurable and practical. In order to build consensus, the process of deriving these attributes will be shared with key stakeholders through effective communications. Consultation throughout this process will be undertaken with ERA and their consultants.

Detailed project aims

- To assemble knowledge from expert fauna scientists, relevant reports and scientific literature to make an informed decision about how to develop fauna closure criteria at Ranger uranium mine.
- To produce clear, concise and interpretable descriptions of fauna closure criteria attributes that are aligned with the Environmental Requirements for Rehabilitation of Ranger uranium mine.
- To begin the process of consensus building of fauna attributes amongst key stakeholders (ERA, NLC, ARRTC members, NT Government, SSB). This consensus building will continue with the 2 subsequent flow on projects.

Project scope and methods

- This project synthesizes existing reports and publications to understand the current status of knowledge available to inform the development of rehabilitation standards specific to fauna colonization and habitation of the RPA. We will collate the various measures and metrics of fauna (i.e., abundance, diversity) that are used to monitor and assess fauna in relevant habitats in the region.
- This information will then form the starting point for developing a series of workshops to assess the utility and applicability of these metrics in the context of the Environmental Requirements as they relate to fauna colonization and habitation of the RPA.

Publications

No publications to date

Fauna Closure Criteria: development of indicators

KKN Title for ESR2

Determining the requirements to support a terrestrial faunal community similar to areas surrounding the RPA

KKN Question for ESR2A

What faunal community structure (composition, relative abundance, functional groups) is present in the areas surrounding the RPA?

Application

The project identifies meaningful, measurable and practical criteria that will be used for the development of rehabilitation standards that are aligned with the Environmental Requirements with respect to fauna colonization and habitation of RPA following rehabilitation.

Background

SSB has committed to developing and proposing closure criteria for Ranger uranium mine that align with the Environmental Requirements for rehabilitation of the site. A key facet of these requirements is that fauna colonisation and utilisation of the site is similar to the surrounds of Kakadu National Park. The biodiversity, relative abundances, status (i.e. threatened, endangered) and range of life forms that are expected to colonise and utilise the site (and that inhabit the surrounds of Kakadu National Park) means that the specific metrics used to evaluate closure criteria must be carefully considered. The first step in this process is to develop descriptive key attributes that broadly describe aspects of faunal colonisation and site utilisation that are meaningful and measurable in the context of ecosystem rehabilitation of the mine. From these attributes, we will develop and evaluate the effectiveness of a range metrics in order to identify those metrics that most suitable for being used to assess the achievement of closure criteria. This process will provide confidence that these metrics will perform as designed; to evaluate fauna colonisation and site utilisation at the rehabilitated Ranger mine with respect to agreed closure criteria as well as being capable of informing the trajectory of rehabilitation at the site.

There has been decades of research and monitoring of a range of fauna groups in Kakadu National Park and similar ecosystems across the Top End. Additionally, there are a range of novel technologies and analytical techniques that are showing promise in improving our ability to accurately monitor and assess fauna. SSB will evaluate existing research and monitoring techniques, as well as novel approaches to identify a set of metrics that can be used to assess fauna closure criteria. We will develop a robust assessment methodology with respect to fauna closure criteria. The process of identifying metrics to evaluate closure criteria is similar to that used by SSB to reach consensus for the setting of metrics to assess flora closure criteria.

Detailed project aims

- To assemble knowledge from expert fauna scientists, relevant reports, technology reviews and scientific literature to make an informed decision about how to measure fauna closure criteria at Ranger uranium mine.
- To produce clear, concise and interpretable metrics of fauna groups and how those metrics are effective at assessing fauna closure criteria for Ranger uranium mine.
- To continue the process of consensus building of fauna metrics amongst key stakeholders (ERA, NLC, ARRTC members, NT Government, SSB). This consensus building continues from the preceding Fauna Attributes Project and will continue with the subsequent fauna data provision project.

Project scope and methods

- This project will collate the results of a series of workshops assembled to reach consensus amongst fauna experts and key stakeholders into a set of metrics that are to be measured and used as the basis for the aspects of the Restoration Standard that directly concern fauna colonization and habitation of the rehabilitated RPA.
- These workshop results will go through an iterative process in order identify metrics that are agreed upon by key stakeholders as well as those metrics that require further refinement and/or research prior to their inclusion in the Standard.

Publications

No publications to date

Long-term viability of the ecosystem established on the trial landform

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for 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?

Application

This project will refine the State and Transition Models being developed for revegetation by providing information that can be used to assess the long-term sustainability of the ecosystem being established on Ranger waste rock.

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.

Detailed project 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.

Project scope and methods

- This project focuses on the collection, processing and analysis of data (mostly remote sensing) that can be used to derive key metrics to inform an assessment of sustainability on the TLF. This involves periodic drone flights over the TLF (at least twice yearly) along with associated field data collection over the project's duration.
- The remote sensed data to be collected will include RGB and multispectral imagery, as well as LiDAR point clouds.
- The data will be processed to geometrically accurate point clouds and orthomosaics that will enable comparison between dates.
- Analysis will create products that will help inform changes in vegetation over time such as canopy height models (CHMs) from point clouds and normalised difference vegetation index (NDVI) from multispectral mosaics.
- Data products (point clouds, CHMs, orthomosaics and NDVI maps) and brief analysis will be provided to ERA.

Publications

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.

Assessing long-term viability of revegetation on waste rock at Nabarlek - PhD UQ

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for ESR5B

How can we develop restoration trajectories (flora and fauna) to predict when the rehabilitated site will move to a sustainable ecosystem without further management intervention (e.g. different fire and weed scenarios)?

Application

The Nabarlek mine site, which was rehabilitated nearly 25 years ago, is being studied to collect information pertinent of the rehabilitation of the Ranger Project Area. This project will allow quantitative assessment of key indicators of the sustainability (including soil formation) of the plant community on waste rock in the long term. The collected data will assist in refining the State and Transition Model developed for Ranger revegetation, inform trajectories, and create an understanding of the likelihood of achievement of flora closure criteria at Ranger.

Background

Rehabilitation of Nabarlek commenced over 20 years ago. Since then, management efforts have been ad hoc and disturbances such as fire, feral animals and weeds have influenced the area. Most research on waste rock ecosystem establishment at Ranger has been undertaken on much shorter time frames and many of these areas (apart from the Trial Landform) have since been cleared or covered in stockpiles. Therefore, Nabarlek provides a valuable 'baseline' for the assessment of revegetation efforts on waste rock over a long-term period (20+ years), within the Alligator Rivers Region. This project will use quantitative methods to assess the long-term viability of the ecosystem that has been established on waste rock. It will contribute to informing whether closure criteria for the Ranger rehabilitated landform are likely to be met.

Detailed project aim

- Use remote sensing and field-based methods to undertake a quantitative assessment of the long-term sustainability of the ecosystem established on waste rock areas of Nabarlek, including the monitoring of vegetation health, survival and recruitment, and soil development and evolution of nutrient cycling.

Project scope and methods

- This project is being undertaken via a PhD placement in collaboration with the Centre for Mined Land Rehabilitation (University of Queensland).

Publications

No publications to date

Monitoring and assessment of ecosystem establishment and long-term viability on Pit 1 waste rock to inform trajectories

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for ESR5B

How can we develop restoration trajectories (flora and fauna) to predict when the rehabilitated site will move to a sustainable ecosystem without further management intervention (e.g. different fire and weed scenarios)?

Application

This project will help refine the State and Transition Model for Ranger and inform recommendations on drone-based monitoring tools for ecosystem establishment, specifically the most appropriate tool for monitoring the specific parameters of survival, health, growth, flowering and fruiting and contextual data.

Background

Key aspects of ecosystem establishment that should be monitored during the initial period following revegetation planting on the Pit 1 landform are plant survival, health and growth. It is expected that following this initial period, other aspects will be introduced to the monitoring program, including comparison of ecosystem similarity and sustainability to reference sites.

Ecosystem sustainability processes specific to the vegetation itself (i.e. as opposed to other ecosystem functions e.g. nutrient cycling) include evidence of plant sexual reproduction (i.e. flowering and fruiting) and recruitment. Whilst it is not expected that these processes will be prevalent during the initial period following revegetation, they may be present. Monitoring should therefore include these processes, where practical and efficient to do so.

Combined with ground-based survey methods, drones can capture data (optical imagery and light-detection-and-ranging (LiDAR)) that can be used to assess a variety of ecosystem establishment parameters, with the benefit of whole of site coverage in a timely and cost-effective manner. Contextual data can also be collected, for example through the use of thermal imagery to identify contextual information such as operational issues (e.g. leaks in irrigation systems) and environmental variables (e.g. soil surface temperature) that affect plant survival, health and growth. Ground-based LiDAR (terrestrial laser scanning (TLS) and mobile laser scanning (MLS) can be used to capture further detail in the early stages of revegetation and to calibrate drone-based LIDAR.

Detailed project aims

- To develop drone and ground-based survey techniques and test methods for assessing sustainability of the vegetation planted on the Pit 1 landform.
- To apply drone and ground-based survey techniques to assess the initial establishment of revegetation on the Pit 1 landform and inform the Ranger rehabilitation trajectory.

Project scope and methods

Vegetation data will be collected using from drone-based sensors and ground-based LiDAR to gather information on:

- Survival and health - Monthly collection of red, green and blue (RGB) in conjunction with qualitative rapid assessment.
- Growth – Quarterly surveys using LIDAR and MLS for first 12 months and then biannually for next 4 years. Annually thereafter.
- Flowering and fruiting – Using high resolution RGB data when key framework species flower or fruit
- Contextual information (e.g. irrigation leaks, soil surface temperatures) – Monthly collection of thermal imagery, in conjunction with other drone-based surveys.

Publications

No publications to date

Deriving vegetation community structural attributes that inform the conceptual reference ecosystem

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for 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?

Application

The outputs of this project will be used to develop interim community structure closure measures for both overstorey and understorey at 1 ha scale, which can in turn be used in revegetation planning.

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'). Some of the most applicable datasets are more than 20 years old and represent point surveys in time. For the development of some closure criteria, especially vegetation structural components, 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.

Detailed project 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.

Project scope and methods

- The project will survey the 1 ha permanent plots in areas of Kakadu National Park adjacent to Ranger mine site and undisturbed areas of the Ranger Project Area (a 10km buffer around the mine and restricted to appropriate land units) to capture the inherent plant structural variability in the region. The AusPlots Rangelands Survey Protocols (a national standard developed by the government funded Terrestrial Ecosystem Research Network, TERN) will be used to survey the plots.
- Existing structural data from Georgetown and other studies within the Alligator Rivers Region will be used to determine whether the structural variability of the savanna woodland has been adequately described.
- These 1 ha plots will be used to derive other rehabilitation standard measures for ecosystem restoration, including those related to fauna, vegetation composition and ecosystem sustainability. Method development for using drones to measure structural attributes where possible will also be undertaken using these plots.

Publications

Hernandez-Santin l, Rudge ML, Bartolo RE, Whiteside TG & Erskine PD 2020 Reference site selection protocols for mine site ecosystem restoration, *Restoration Ecology*, 29(1), e13278. doi:10.1111/rec.13278.

Levick SR, Whiteside T, Loewensteiner DA, Rudge M & Bartolo R. 2021. Leveraging TLS as a calibration and validation tool for MLS and ULS mapping of savanna structure and biomass at landscape-scales. *Remote Sensing*, *13*(2), p.257.

Loewensteiner DA, Bartolo RE, Whiteside TG, Esparon AJ & Humphrey CL, 2021. Measuring savanna woody cover at scale to inform ecosystem restoration. *Ecosphere*, *12*(3), p.e03437.

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.

Supervising Scientist 2020. Canopy cover indicator value for assessing ecosystem similarity for savanna woodland. Technical Advice 008. Supervising Scientist, Darwin.

Supervising Scientist 2020. Reference site selection protocols for mine site ecosystem restoration Technical Advice 024. Supervising Scientist, Darwin.

Supervising Scientist 2021. Using LiDAR tools for measuring savanna structure at landscape scales. Technical Advice 034. Supervising Scientist, Darwin.

Developing restoration trajectories to predict when the restored site will move to a sustainable ecosystem

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for 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?

Application

This project will identify ecosystem restoration trajectories that ensure the rehabilitated site will move to a sustainable ecosystem after closure without management interventions that are significantly different from those applied to surrounding natural ecosystems. It will specifically address the requirements for an ecosystem restoration trajectory approach as outlined in the Supervising Scientist Ecosystem Restoration Standard.

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 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?".

Detailed project aims

- To develop ecosystem restoration trajectories for Ranger mine site using a state and transition modelling 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.

Project scope and methods

- This project is focussed on describing the likely trajectories (both desired and undesired) of ecosystem development from initial ecosystem establishment to end state on the Ranger mine site.
- The ecosystem restoration trajectory will be compiled through an expert elicitation process to identify likely ecosystem states and transitions along the restoration trajectory, and management actions to maintain the desired trajectory.
- Experts will provide responses on the likelihood of transitions between states and the associated consequences for ecosystem restoration. These responses will be used to assess the risk of deviating from a desired trajectory using a Bayesian Belief Network (BBN) to identify knowledge gaps for the management of undesired states and where uncertainty remains around the effectiveness of management interventions.

Publications

Richards A, Bartolo, R, Loewensteiner, D & Warnick, A (2020). Rehabilitation trajectories for Ranger mine, Final report. CSIRO, Australia.

Vegetation sustainability closure criteria: development of indicators

KKN Title for ESR5

Develop a restoration trajectory for Ranger mine

KKN Question for ESR5A

What are the key sustainability indicators that should be used to measure restoration success?

Application

The outputs from this project will directly inform the development and agreement amongst key stakeholders on vegetation sustainability closure criteria, to ensure the rehabilitation at Ranger mine is in accordance with the Environmental Requirements.

Background

In accordance with the relevant regulations for ecosystem restoration at Ranger, vegetation communities on the rehabilitated mine site need to be a) similar to surrounding areas and b) resilient and self-sustaining. This project is focussed on development and agreement of the indicators for vegetation sustainability closure criteria.

This project will primarily be undertaken via desktop review, with substantial consultation with key stakeholders (i.e. ERA and Traditional Owner representatives) and inputs from local experts as required.

Detailed project aims

- Develop and gain stakeholder agreement on indicators that will inform the assessment of each of the closure criteria goals;
- Where possible and within project timeframe and resources, identify assessment methods for each indicator and identify and prioritise any data collection requirements that are required to inform the development of assessment methods.
- Collect soil samples for nutrients and nutrient cycling laboratory analyses from current reference plots

Project scope and methods

- With assistance from expert consultants, undertake a desktop literature review to identify candidate indicators/ for each of the vegetation sustainability goals - this will include consideration of the following for each indicator: how they may interact with other indicators; identification of any that may be more/less important; and identification of those that may be more practicable to measure.

- As part of the above desktop review, identify any (or the most) suitable assessment method(s) for a given indicator. Where there is no available existing information and/or when it is identified as needing site specific information, recommendations will be made for future data collection needs and prioritised.
- Regular and close consultation with ERA and Traditional Owner representatives on gaining agreement on suitable closure criteria indicators. This consultation will take the form of regular fortnightly meetings and other topic-specific specific meetings/workshops as required.
- Collection and analysis of soil samples from up to 14 of the existing 1ha reference sites. Sampling depth, replication and selection of parameters will be selected in consultation with experts (e.g. SSB and ERA personnel/consultants).

Publications

Richards AE, Welch M, Paramjyothi Venugopal H and Bartolo R (2021) Ecosystem sustainability indicators for Ranger mine restoration. CSIRO, Australia.

Application of AI to identifying vegetation species from drone data: pipeline development

KKN Title for ESR9

Developing best-practice monitoring methods for ecosystem restoration

KKN Question for 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?

Application

This project will inform a larger project to determine the most efficient combination of sensors required to measure composition and structure attributes. Examples of equipment include, high resolution cameras, and multispectral, hyperspectral and LiDAR sensors.

Background

Collecting drone data with a range of sensors to provide measures of composition and structure has increased the complexity, size and type of data, requiring advanced computing power and analysis algorithms in order to derive species level metrics. With the new Vertical Take Off and Landing (VTOL) drone ERISS will be generating significant volumes of spatial data and require automated processes to analyse this data which are robust, reliable and scalable.

Deep Neural Networks (DNN), a derivative of Artificial Intelligence (AI), can determine complex patterns in non-linear data with high predictive performance, and are already being used to detect and identify vegetation in imagery with varying degrees of success. DNN's require a pipeline which defines how data is configured and processed in an end-to-end consistent manner. Pipelines are often unique for different applications of AI, requiring customization or building new tooling to achieve a project aim.

There are currently no data analysis pipelines available to automate processing of large spatial datasets and identify tree species found in the savanna of Northern Australia. In collaboration with Microsoft deep learning engineers, this project will aim to develop a pipeline for ingesting, labelling, training and scoring spatial data to identify vegetation species. We will determine how to label tree species from aerial imagery and define 'quality' training data for use in a DNN. We will build novel DNN models capable of inputting 3 – 10 bands of spectral data in the first instance and determine which bands can be used to identify framework species. Ultimately this project will inform a larger project to determine the most efficient combination of sensors required to measure composition and structure attributes e.g. high-resolution camera, multispectral, hyperspectral and LiDAR sensors.

Detailed project aims

- develop an automated deep learning approach to identify the framework tree species in savanna adjacent to Ranger mine.
- develop a tree species dataset and model weights for savanna of northern Australia that can be used for deep learning workflows.
- build a pipeline that will utilise cloud computing and automate analysis of drone imagery to derive tree-level metrics at the landscape scale.

Project scope and methods

- An automated deep learning pipeline will be developed using open-sourced libraries such as python, tensorflow and jupyter notebooks.
- A labelled tree dataset will be generated through field campaigns to reference plots in Kakadu National Park. High-resolution RGB imagery will be collected using drones for image labelling.
- These tools for training and scoring drone imagery to identify tree species will be configured for deployment in Azure to scale with cloud computing.

Publications

Three abstracts for this project have been submitted to the Ecological Society of Australia 2021 conference in Darwin.

Guiding ecological restoration at Ranger uranium mine with drone derived indicators of ecosystem health

KKN Title for ESR9

Developing best-practice monitoring methods for ecosystem restoration

KKN Question for 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?

Application

Drone-based methods for measuring ecosystem health parameters relevant to the sustainability indicators from SSB's Ecosystem Restoration Standard are being developed. These techniques will enable the assessment of ecosystem health across large areas based on information detail at the individual tree level.

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.

Detailed project 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.

Project scope and methods

This research project will aim to use drones to measure key plant traits that relate to ecosystem function. The permanent one-hectare Ausplots that have been established around Ranger mine will be the primary field sites for this project. Drones equipped with LiDAR and hyperspectral sensors will capture data over the vegetation of the reference sites and develop models of ecosystem health based on field measurements.

Publications

Rudge MLM, Levick SR, Bartolo RE, Erskine PD. 2021. Modelling the Diameter Distribution of Savanna Trees with Drone-Based LiDAR. *Remote Sensing* 13(7):1266. https://doi.org/10.3390/rs13071266

Assessing the trajectory of soil nutrient cycling on revegetated landforms using soil microbial communities

KKN Title for ESR9

Developing best-practice monitoring methods for ecosystem restoration

KKN Question for 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?

Application

This project will develop a rapid and cost-effective omics-based tool for monitoring nutrient cycling trajectories (through measuring soil microbial communities) on the rehabilitated landform at Ranger.

Background

A key focus for SSB is to develop and gain stakeholder agreement on ecosystem restoration closure criteria, for inclusion and regulatory approval in the 2021 RMCP. In accordance with the Rehabilitation Standard and relevant ERs for ecosystem restoration, vegetation communities on the rehabilitated Ranger mine site need to be a) similar to surrounding areas and b) resilient and self-sustaining.

Understanding of soil ecosystem services is a fundamental component of developing measures of success of rehabilitation of the final landform. Soil ecosystem services are dependent on structure (i.e. biotic and abiotic components and the interactions within and between them) and function (e.g. primary production and nutrient cycling). It will be affected by the revegetation strategies used on the final landform, which ultimately need to sustain perpetual nutrient cycling processes.

Currently, the non-molecular methods used to assess nutrient cycling in soils are non-definitive. Molecular techniques, like analysis of environmental DNA, provide the knowledge needed to understand the processes involved in nutrient cycling, which non-molecular methods, such as assessment of soil chemistry, cannot achieve. Metagenome sequencing provides profile the abundance of gene within a soil community, providing specific information to help unravel links between microbial communities and soil ecosystem services, particularly in little studied regions like Kakadu where soil communities are likely to have novel taxa.
This project will develop cost-effective omics-based methods for the rapid assessment of soil ecosystem function (specifically nutrient cycling). To achieve this, it will characterise soil microbial assemblages and quantify the abundance of genes present, establishing a link between microbial structure and function. Genomic and chemical data will be collected from reference and disturbed sites, encompassing a range of vegetation structures, to build a model that predicts the development and sustainability

of nutrient cycling. The model will be used to assess the trajectory of nutrient cycling development on the rehabilitated landform and to test the success of treatments and mitigations.

Detailed project aims

- Measure and monitor soil microbial communities using a number of methods including:
    - community level metagenomics (i.e., environmental DNA) using amplicon sequencing (i.e., fungal and 16S rRNA) and PCR;
    - whole-metagenome sequencing (shotgun sequencing)/Meta transcriptomics of soil assemblages. (Strategic subset of samples); and
    - other non-molecular analyses i.e., Biolog plates will be used to examine microbial functional processes and validate omics functional information.
- Develop a cost-effective tool that predicts nutrient cycling from genomics and chemical data.
- To assess the sustainability of functions involved in nutrient cycling on the rehabilitated landform to
    - Test treatments in Pit 1 trials and adaptive management options
    - Determine the trajectory of nutrient cycling on the rehabilitated landform

Project scope and methods

- Collection of samples from 18 reference plots around the Ranger Mine Project Area, as well as a number of sites at varying stages of rehabilitation (i.e., Ranger Pit 1, Trial Landform, Jabiluka, SAV, Nabarlek). Samples will be collected in both wet season and dry seasons over a three-year period to address any temporal variability.
- Proposed sampling and extraction methods will be based on the Australian Microbiome Initiative (AMI) protocols. The AMI also has sampling sites within Kakadu National Park (KNP) that would be potentially useful as extra reference sites, and scope exists to collaborate with AMI and KNP in terms of collecting reference information.
- Collaboration with Flinders University (as part of a CRC-TiME project) to build a predictive tool using whole metagenome sequencing and chemical data. This will develop targeted assays for genes associated with nutrient cycling to provide rapid assessment of soil nutrient cycling.
- Assess ecosystem function for different revegetation treatments on Pit 1 landform at Ranger.
- Specifically, we will collect and extract DNA from at least 2 pooled samples per plot from 2 different depths (0-10cm and 20-30cm). Soil chemistry analysis will also be undertaken on these samples. DNA will be extracted in triplicate, then sequenced using both amplicons (for Fungi, Bacteria and Archaea) and shotgun sequencing.

Publications

No publications to date

Image 21 SSB staff collecting macro-invertebrates at Burdulba Creek, Kakadu National Park

Appendix 3.6 Cross Theme Project

Cumulative risk assessment for Ranger mine site rehabilitation and closure- Phase 2 (aquatic pathways)

KKN Title for CT1

Assessing the cumulative risks to the success of rehabilitation on-site and to the protection of the off-site environment.

KKN Question for CT1A

What are the cumulative risks to the success of rehabilitation on-site and to the off-site environment?

Application

The knowledge from this project will be used to determine if there are cumulative risks to the off-site environment following mine site closure and to determine if and/or when impacts will be expected on-site. This will inform the Surface Water Pathways Risk Assessment.

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.

Detailed project aim

- 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.

Project scope and methods

- Qualitative risk models will be used to identify of interactions amongst risks and how these can affect risks.
- Quantitative models will be used to assess the cumulative COPC 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.

Publications

Harford AJ et al., (submitted) Qualitative Mathematical Models to Support Ecological Risk Assessment for Rehabilitation and Closure of Ranger Uranium Mine, Australia. *Journal of Environmental Management and Assessment.*

Cataloguing the natural World Heritage values on the Ranger Project Area

KKN Title for CT2

Characterising key conservation and biodiversity values of the Ranger Project Area

KKN Question for CTA2

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?

Application

This project will list and quantify 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.

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.

Detailed project 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.

Project scope and methods

A spatial analysis of the natural values on the RPA aligned with World Heritage criteria will be undertaken via the following process:

1. Identify stakeholders and areas with information
2. Identify the natural values listed for Kakadu National Park World Heritage as spatially explicit components and quantifiable elements.

3. Collate spatial data to map the natural values aligned with World Heritage criteria on the Ranger Project Area.
4. Identify threatened and other significant species that have been recorded in the Ranger Project Area and surrounding areas.
5. Site survey to ground truth examples of natural World Heritage values within the Ranger Project Area

Publications

Everett R, Bartolo R, Edgar S & Whiteside T (2021). Cataloguing the natural World Heritage values on the Ranger Project Area. Internal Report 657, August, Supervising Scientist, Darwin.

APPENDIX 4 TECHNICAL ADVICE MEMORANDA

Advice No#	Date sent to ERA	Subject
001	3/01/2019	Feedback on INTERA numerical groundwater model presentations at ARRTC #41
002	3/01/2019	Runoff coefficients relevant to the Ranger waste rock landforms
003	3/01/2019	Potential risks associated with compaction layers
004	21/02/2019	Initial Assessment of the FLV6.2 Landform
005	24/04/2019	Particle Size on the Trial landform
006	24/05/2019	Species richness and composition indicator values for assessing ecosystem similarity for savanna woodland
007	21/06/2019	Vegetation strata, woody plant species size class distribution and total basal area data for use as indicator values
008	1/10/2020	Canopy cover indicator value for assessing ecosystem similarity for savanna woodland
009	13/10/2020	Factors affecting change and variability in savanna woodlands
010	13/09/2019	Updated assessment of the FLV6.2 landform
011	31/03/2020	Water chemistry and biological communities of shallow groundwater in Magela Creek
012	1/06/2020	Recommencement of radon-222 exhalation measurements on the Ranger trial landform
013	22/06/2020	Investigation into CCLAA influence on Gulungul Creek
014	16/07/2020	Mg Standard supporting lines of evidence
015	30/07/2020	Magela Sands Continuous data for ERA's SW/GW conceptualisation
016	7/09/2020	Extreme Rainfall & Floods in the East Alligator catchment
017	8/09/2020	Proportions of forest types surrounding Ranger
018	21/09/2020	Site-specific Guideline value for copper
019	21/09/2020	Aqueous/sediment U partitioning modelling for KKN WS3G
020	25/09/2020	Assessing the chronic toxicity of aquatic contaminant mixtures for Ranger uranium mine
021	2/10/2020	Ecosystem Restoration Activities for Ranger Mine
022	13/10/2020	Updated assessment of the FLV6.2 landform part 2
023	23/10/2020	Reference ecosystem soil physical and chemical properties
024	27/10/2020	Reference Site Selection Protocol
025	25/11/2020	Interim report - NESP Ecohydrology
026	2/12/2020	Interim report - ASS Data Summary
027	4/12/2020	Billabong Water Chemistry - ERA Data request
028	9/12/2020	Functional diversity of savanna near Ranger

Advice No#	Date sent to ERA	Subject
029	10/12/2020	Intermittent Flooding Savanna species composition
030	10/12/2020	Site adapted zinc guideline value
031	10/12/2020	Revised denudation rate
032	10/12/2020	Particle Size on the Trial landform - 2020 update
033	22/12/2020	On-site Waterbodies 2020
034	11/01/2021	Using LiDAR tools for measuring savanna structure at landscape scales
035	18/01/2021	GDE Mapping
036	22/01/2021	Fish Migration
037	1/02/2021	Cataloguing WH values
038	14/05/2021	Pit 1 radiation verification
039	14/05/2021	Radionuclide concentration ratios in algae
040	18/05/2021	Cumulative ecological risk assessment

Image 22 Saratoga (*Scleropages jardinii),* Fish Monitoring in Mudginberri Billabong, Kakadu National Park

APPENDIX 5 BIOLOGICAL MONITORING

A high-level description of biological monitoring results for Ranger for the 2020-21 period was provided in Sections 3.1.3.3 and 3.1.3.4 of this Annual Technical Report, together with key supporting figures. The following descriptions contain further detail, full statistical analyses of the monitoring data, and additional supporting Figures. (Some figure references refer to Sections 3.1.3.3 and 3.1.3.4.)

Fish communities

Shallow lowland billabongs

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 under "Developing methods for monitoring fish communities in shallow lowland billabongs", Appendix 3).

Deep channel billabongs

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.

Multivariate dissimilarity

As reported in Section 3.1.3.3, annual mean, paired-site dissimilarity for 2021 (Figure 16) 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 collected between 2016 and 2021.

The fish community structure data for the 2016 and 2021 period have been analysed using a nested three-factor PERMANOVA model, with Before/After (BA), Year (nested within BA) and Exposure (Ex) as factors[3]. In this model, BA tests whether data for the year of interest (2021) are consistent with the range of values reported in previous years (2016 to 2020), 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 2021 show no significant difference between 2021 and previous years (2016 to 2020) 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.

Rainbowfish abundances

Rainbowfish (*Melanotaenia splendida inornata*) are numerically the most dominant fish species in Mudginberri Billabong. During the period of monitoring using visual observations (1989-2015), a negative correlation between rainbowfish abundance in Mudginberri Billabong and the magnitude of antecedent wet season rainfall (and by inference, discharge in Magela Creek) was observed (Figure A6.1). Possible causes of this natural relationship were described in the 2008-09 Supervising Scientist Annual Report; primarily, high rainfall (and stream flow) years are thought to stimulate upstream movement of rainbowfish past Mudginberri, leaving comparatively fewer fish in the billabong, compared to low rainfall (and stream flow) years where lack of flow stimuli lead to congregation of fish in the billabong. (This same relationship is not evident for rainbowfish in Sandy Billabong, Figure A6.1.)

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

Too few sampling years are available for the videography dataset to confirm this relationship (where fish abundance is depicted as average maximum number of fish in the imagery frame, "MaxN"), although the pattern for Mudginberri Billabong (of a negative relationship between rainbowfish abundance and rainfall) is evident (Figure A6.1). The 2021 results for Mudginberri Billabong are also consistent with the relationship.

Across the entire dataset (visual observations and videography), for pairs of consecutive years where rainfall is below average (including 2002 and 2003, and 2019 and 2020), rainbowfish abundance in Mudginberri in the second year (i.e. 2003 and 2020) was lower than expected (light blue symbols in Figure A6.1). As described in the 2019-20 Annual Technical Report, any two consecutive years with below average rainfall may have reduced recruitment in the second year because of the smaller population pool in upper reaches of Magela catchment as well as the smaller breeding population of these relatively short-lived fishes in the catchment overall.

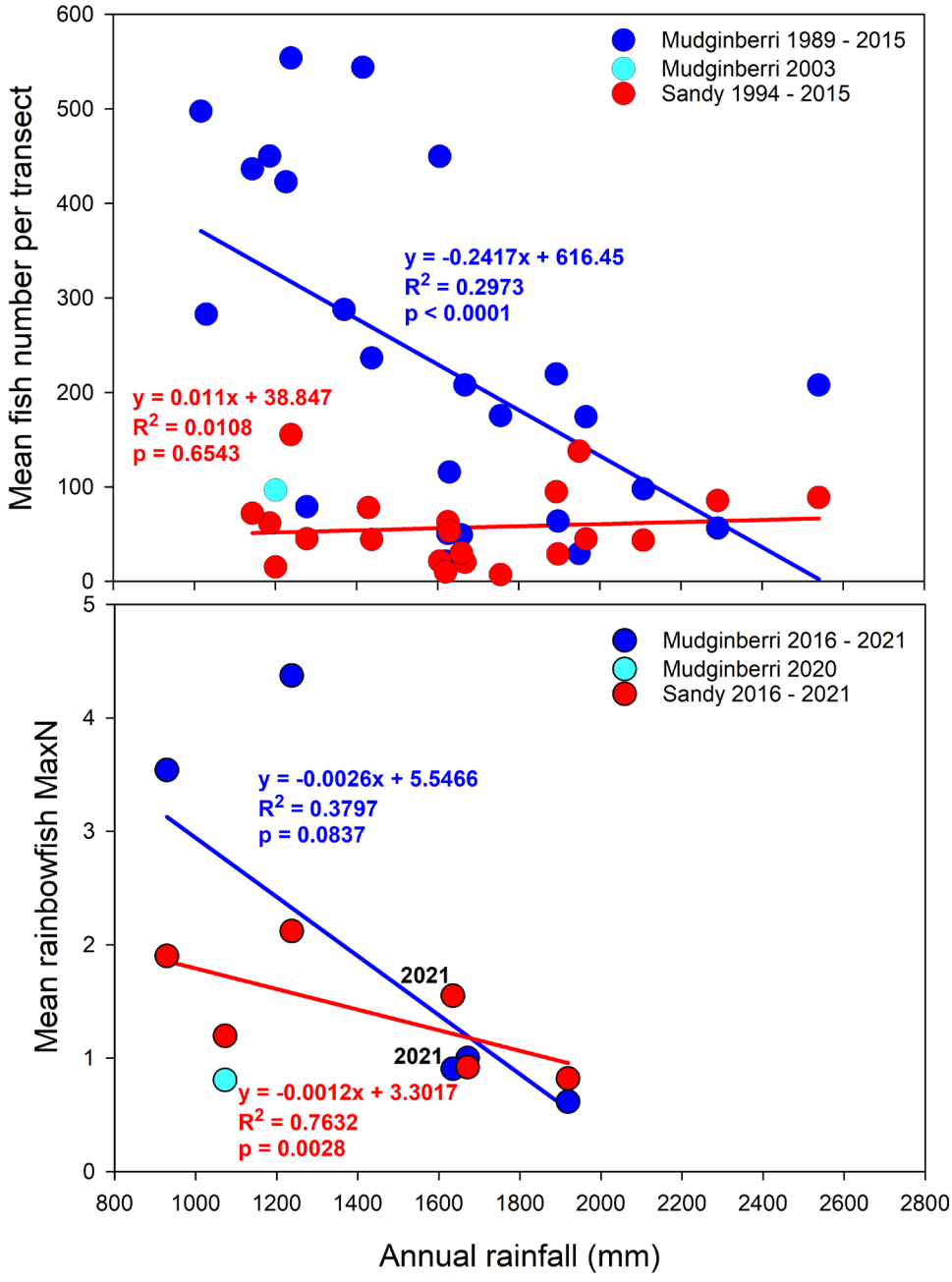


Figure A6.1 Relative abundance of chequered rainbowfish in Mudginberri and Sandy Billabongs in relation to antecedent annual wet season rainfall recorded at Jabiru Airport: *Top figure*: results from 1989 to 2015 using visual observations; *Bottom figure*: results for mean abundance (MaxN) from 2016 to 2021 using videography

Macroinvertebrate communities

As described in Section 3.1.3.4, during the recessional flow period of the 2020-21 wet season, macroinvertebrate communities were sampled in 'exposed' streams, Magela and Gulungul creeks at sites upstream and downstream of the mine, and from the same paired-site configuration in control streams, 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.

Results for the full 2019-20 data

In last year's Annual Technical Report, the complete 2019-20 data set (i.e. including control sites in Nourlangie and Burdulba creeks) were not available for reporting, with only exposed sites, Magela and Gulungul Creek being reported on at the time. Compilation and analysis of the full macroinvertebrate dataset from 1988 to 2020 has now been completed. In previous reports, both a four-factor ANOVA on paired-site dissimilarity values and five-factor PERMANOVA on individual replicates were performed. The PERMANOVA approach has a distinct advantage over the ANOVA because a) the influence of individual sites can be determined, and b) the direction of change in multivariate space is evident (i.e. if a change in a paired site dissimilarity value occurs, it is not possible to determine which of the sites may have changed in community composition). The analysis in this report, and hereafter, uses only PERMANOVA, with the data visualised using paired-site dissimilarity plots, and Multivariate Dimensional Scaling (MDS) ordination to illustrate any changes observed between exposed and control sites.

Figure 17 (Section 3.1.3.4) shows the paired-site dissimilarity values using family-level (log transformed) data, for the two 'exposed' streams and the two 'control' streams. Dissimilarity values for 2020 Magela and Gulungul paired sites depicted in Figure 2 were comparable to those from that year's control streams and previous years, indicating that no significant alteration to macroinvertebrate communities has occurred at the downstream exposed sites from the before (pre-2020) to the after (2020) periods. Confirming this, PERMANOVA testing conducted on the replicate data from all available years and sites (excluding GCT2GCC) showed the upstream and downstream sites across streams and within each exposure group were similar between the before (pre-2020) and the after (2020) periods, indicating no mine influence on macroinvertebrate communities at the exposed downstream sites.

These collective results provide good evidence that any changes to water quality downstream of Ranger as a consequence of mining during period 1994 to 2020 have not adversely affected macroinvertebrate communities in the creeks.

Results for Magela and Gulungul Creek 2020-21

At the time of report preparation only data from Magela and Gulungul creeks collected during the 2020-21 wet season were available for analysis. Without comparable data from the two control streams, it is not possible to run the full PERMANOVA testing for the 2020-21 wet season. Instead, a modified PERMANOVA model was used to examine the exposed creeks, Magela and Gulungul, to determine if any change in these streams had occurred over time. The PERMANOVA results showed no significant change from the before (pre-2021) to the after (2021) periods in the magnitude of upstream-downstream dissimilarity across both 'exposed' streams and within each exposure group (excluding GCT2GCC). These outcomes were unsurprising given the dissimilarity values for both 'exposed' creeks in 2021 plot at similar values to those recorded in most previous years (Figure 17, Section 3.1.3.4).

Figure A6.2 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 2021), 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).

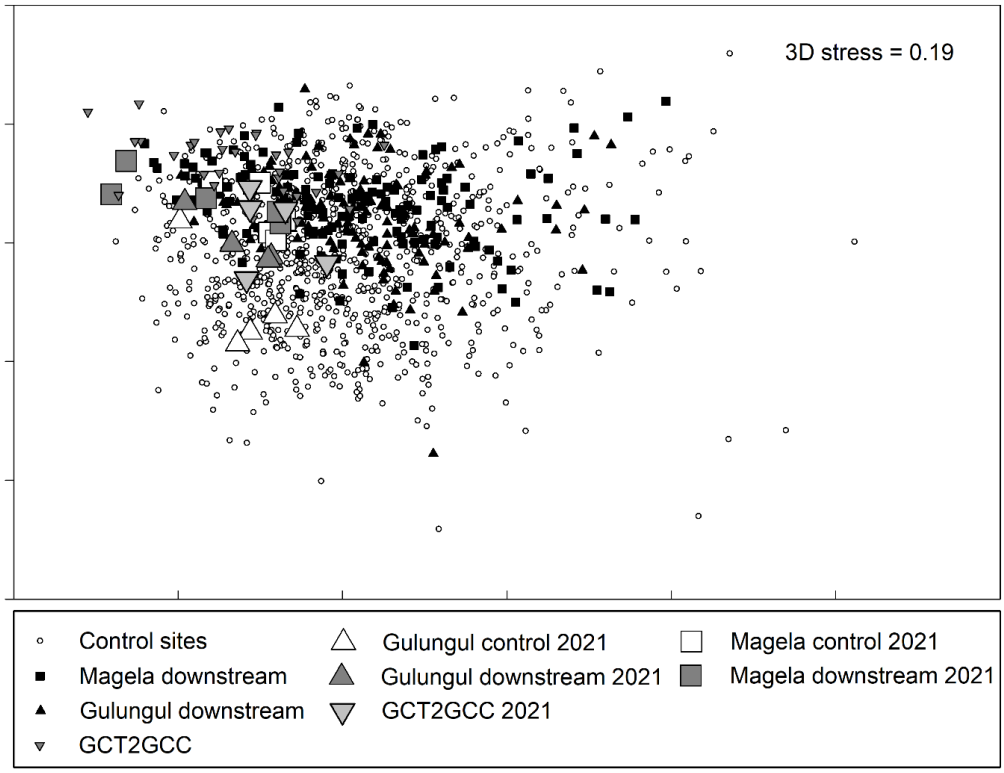


Figure A6.2 Ordination plot (axis 1 and 2) of macroinvertebrate community structure to 2021 in Ranger exposed and control streams

Data points associated with the 2021 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 top left-hand corner of the ordination where two replicates from Magela Creek downstream have separated slightly from the main cluster (Figure A6.2). Data for these replicates were examined and were characterised by higher total abundances of macroinvertebrates, particularly of some families of detritovores, when compared to the other three replicates from 2021 and previous years. Considering that the amount of detritus recorded from these two replicates in 2021 was higher than the other three replicates, the difference in their macroinvertebrate assemblages can be attributed to natural habitat variation and not a mine related influence. The PERMANOVA and paired dissimilarity results for the current year, as reported above, further supports this.

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 the regulator.
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.
designated worker	A worker who works in a work category where the work conditions are such that they may individually receive an annual effective dose greater than 5 mSv per year.
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.
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	metres Reference Level – a specific elevation relative to mean sea level.
MTC	Mine site 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 waste product consisting of 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).
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 (tailings dam)
UEL	Uranium Equities Ltd
WTP	Water Treatment Plant