

Alligator Rivers Region
Technical Committee

Key Knowledge Needs

Uranium Mining in the
Alligator Rivers Region



Supervising Scientist



Australian Government

Department of the Environment and Energy

Supervising Scientist

The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

It is Supervising Scientist policy for reports in the SSR series to be reviewed as part of the publications process. Whilst not externally peer-reviewed, this report was reviewed and endorsed by the Alligator Rivers Region Technical Committee, which provides independent advice on the direction and quality of the research and monitoring programs undertaken to ensure the protection of the Alligator Rivers Region from the impacts of uranium mining.

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Foreword

The rehabilitation of the Ranger uranium mine in the Alligator Rivers Region of northern Australia is a significant and complex process that needs to be completed by January 2026. The Alligator Rivers Region Technical Committee is required to review the quality, adequacy and appropriateness of the science undertaken by the Supervising Scientist, Energy Resources of Australia Ltd and other relevant stakeholder organisations that underpins the mine's rehabilitation.

At its meeting in May 2015, the Alligator Rivers Region Technical Committee determined that, in order to perform its statutory role, the existing Key Knowledge Needs should be revised to focus on the environmental risks associated with rehabilitation activities at Ranger. It was agreed that the revised Key Knowledge Needs should be mapped out against the specific scientific knowledge requirements and timelines for key rehabilitation decisions. This would enable the Committee to identify risks not yet considered, comment on the scientific research required to better understand and mitigate these risks, and to advise on relative research priorities.

The Supervising Scientist and Energy Resources of Australia Ltd have worked together to perform this assessment. This report is the culmination of this major undertaking. It presents the Key Knowledge Needs required to sufficiently understand and manage the risks to the off-site environment and successful rehabilitation on-site, including the completion of a comprehensive ecological risk assessment. The Alligator Rivers Region Technical Committee commends the authors and endorses the report as a benchmark for the systematic acquisition of the knowledge needed to ensure the success of rehabilitation and the protection of the environment of the Alligator Rivers Region.

Dr Simon Barry

Chair

Alligator Rivers Region Technical Committee

Introduction

What are the Key Knowledge Needs?

The Alligator Rivers Region Technical Committee (ARRTC) Key Knowledge Needs (KKNs) articulate the relevant knowledge and tools required, primarily through research and monitoring, to ensure:

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

The KKNs provide the basis upon which the stakeholders, primarily the Supervising Scientist and Energy Resources of Australia Ltd (ERA), determine their environmental research programs. Whilst the KKNs also inform monitoring programs, the nature of these programs is also informed by regulatory requirements, operational investigations and emerging issues.

Scope

The KKNs encompass the knowledge needs for all past, present and prospective uranium mining activities in the ARR. These include the rehabilitated Nabarlek mine and mines of the South Alligator Valley, Jabiluka and exploration sites. However, the focus at present remains firmly on the operational Ranger uranium mine, in operation since 1981, and this emphasis is reflected in the KKNs.

The current KKNs supersede the 2008-2010 KKNs, which remained in operation until the current revision was completed.

The state of mining operations in the ARR

In assessing the KKNs for research and monitoring in the ARR, the current mining plans in the region and the standards for environmental protection and rehabilitation determined by the Commonwealth have been taken into account. The status for uranium mining operations in the region is as follows:

Ranger mine

- Ranger mine completed mining in Pit 3 in 2012, and is currently scheduled to cease milling of stockpiled ore by early January 2021 and complete rehabilitation works by 2026. Consequently, there is an increasing focus on rehabilitation-related knowledge needs, whilst at the same time also maintaining the ability to ensure current operations do not adversely impact the off-site environment.
- The rehabilitation and closure of Ranger mine will occur in three distinct phases: *decommissioning, stabilisation and monitoring*, and *post closure*.
 - *Decommissioning*: Decommissioning is the general works associated with infrastructure removal, rehabilitating the site to an agreed standard of environmental protection, including containment of tailings and process water brines, and the re-contouring and revegetation of the final landform. The decommissioning stage has already commenced (in parallel with milling operations), and will further escalate at the completion of processing plant operation by early January 2021. Decommissioning is expected to be completed by 2026.

- *Stabilisation and monitoring:* The stabilisation and monitoring phase of the mine will commence post 2026, when the rehabilitated site is stabilising and has commenced the slow progression towards the achievement of a long-term viable ecosystem and of closure criteria. The timeframe for this phase is likely to be in the order of decades. This phase may require significant initial management to address issues such as water treatment, landform subsidence, erosion and vegetation mortality. Post-decommissioning monitoring will then commence.
- *Post closure:* The post closure phase will commence once the monitoring and modelling has demonstrated that all closure criteria have been achieved, a close-out certificate has been issued, and the site's operator (ERA) is released from its responsibility for the site. It is in this period that the site may be returned to the traditional owners who may elect to have it incorporated into Kakadu National Park. This period spans indefinitely from the time of issue of the close-out certificate.

Nabarlek

- Nabarlek is partly decommissioned but has not yet reached a status where the Northern Territory Government can agree to issue a close-out certificate to the mine operator. Minor exploration activities are still being undertaken at the site. Further assessment of the success of rehabilitation at Nabarlek is required, and may provide valuable data for consideration in the design and implementation of rehabilitation at Ranger. There are no agreed closure criteria for the site and further rehabilitation work is outstanding with infrastructure remaining on site. The Nabarlek lease expires in 2034.

Jabiluka

- In recent years, the Jabiluka site has undergone significant rehabilitation works, primarily the removal of the Interim Water Management Pond, revegetation of the disturbed footprint and most of the site infrastructure removed. ERA, the project owner, has stated that further mining will not occur without the agreement of the traditional owners. It appears likely that Jabiluka will remain in care and maintenance. The Jabiluka lease expires in 2024.

South Alligator Valley

- Historical uranium mine workings from the 1950s and 1960s in the South Alligator Valley (SAV) were mostly rehabilitated by the Australian Government between 2006 and 2009. This included the construction of a radiological containment facility at the old El Sherana airstrip for the final disposal of historic uranium mining waste associated with the rehabilitation works. Remediation and monitoring of the SAV sites is the responsibility of the Australian Government's Director of National Parks, although the Supervising Scientist will continue to assist with this role into the future.

Koongarra

- The Koongarra project area was incorporated into the Kakadu National Park World Heritage area in 2011. Commonwealth legislation incorporating the Koongarra project area into Kakadu National Park came into effect in March 2013.

Uranium exploration

- The Supervising Scientist undertakes an annual program of site inspections and audits of uranium exploration operations in western Arnhem Land.

The above summary of the state of mining operations in the ARR is considered to be a reasonable basis on which to base plans for research and monitoring, but such plans may need to be amended if mining plans change in the future. The Supervising Scientist and ERA will work with ARRTC to ensure the research and monitoring strategy is flexible enough to accommodate any new knowledge needs.

Ranger Environmental Requirements

The Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine (ERs), attached to the Ranger Authority issued under s.41 of the *Atomic Energy Act 1953*, set out the Commonwealth's environmental protection conditions with which the company must comply. The ERs are also given effect through the Ranger Authorisation issued under the Northern Territory *Mining Management Act*.

The Ranger ERs specify primary and secondary environmental objectives to be achieved during the life of the mine and following closure. The primary environmental protection objectives focus on maintaining the World Heritage attributes of Kakadu and the ecosystem health of the wetlands for which Kakadu is listed as a Ramsar site, protecting the health of people living in the region and the biological diversity and ecological processes in the region. Impacts within the Ranger Project Area are to be as low as reasonably achievable.

The ERs for rehabilitation are, in summary, to establish an environment with habitats and erosion characteristics similar to the adjacent areas of Kakadu National Park and stable radiological conditions with doses that are in line with national requirements and as low as reasonably achievable. Tailings must be placed into the mined-out pits in a way that ensures physical isolation from the environment for at least 10,000 years and no detrimental environmental impacts from tailings contaminants for at least 10,000 years. Moreover, surface or ground waters arising or discharging from the Ranger Project Area during or following rehabilitation must not compromise the achievement of the above primary environmental objectives.

Ranger closure criteria

While the ERs describe the broad objectives for rehabilitation, specific criteria are required to determine when these objectives have been met. Consequently, the development of closure criteria is a key component of rehabilitation and closure planning for Ranger. They represent a measurable quantification of the ERs, and will form the basis for issuing of a close-out certificate. ERA is required to propose closure criteria for approval by the relevant Northern Territory and Commonwealth Ministers, with the advice of the Supervising Scientist.

Closure criteria are the performance benchmarks against which the long-term success and sustainability of rehabilitation will be measured. The scientific basis for these criteria are identified, reviewed and agreed within the framework of the KKNs. That is, the knowledge required to develop closure criteria, and assess whether closure criteria are likely to be met and how they will be monitored, is identified through the KKN risk-based framework described below and, subsequently, explicitly captured within the KKNs themselves. Importantly, traditional ecological knowledge and traditional owners' views will also be taken into account during the development of closure criteria.

There are three aspects of closure criteria related research:

1. Development of closure criteria
2. Demonstrating closure criteria are achievable; and
3. Monitoring to assess closure criteria.

Closure criteria are being developed by ERA under six themes:

1. Water and sediment
2. Radiation
3. Landform
4. Flora and fauna
5. Soils
6. Cultural

Research to inform the development and monitoring of closure criteria is largely undertaken by SSB, while research (including assessment) to demonstrate closure criteria can be achieved is largely undertaken by ERA.

A risk-based framework for KKNs

Previous versions of the KKNs, whilst targeted and comprehensive, had no clear conceptual underpinning, thus, making it difficult to track the origin of, and basis for, specific KKNs. Consequently, at its 28th meeting in April 2012, ARRTC agreed that a revised set of KKNs should be underpinned by a risk-based framework that would enable KKNs to be identified and prioritised in a strategic, transparent and rigorous manner. In acknowledging that resources were limited, ARRTC agreed that the process should have a strong emphasis on Ranger rehabilitation and closure-related risks and knowledge needs. Consequently, the KKN risk-based framework was developed as part of the rehabilitation and closure ecological risk assessment, which is described below. The framework has been used to capture all KKNs, including Ranger current operations and other sites in the region.

Ranger operational phase stressor pathways screening level assessment

A screening level assessment of the key stressor pathways during the operational phase at Ranger was completed in 2013¹. The assessment: (i) developed conceptual models of all the operational phase stressor pathways, (ii) described the associated existing knowledge base, including uncertainties, and (iii) assessed the pathways' relative importance in terms of potential to result in off-site impacts. The operational phase KKNs described in Section 1 of this document are drawn from this risk-based assessment, as well as from the 2008-2010 KKNs, several other key reports (referenced where relevant) and knowledge on current environmental issues on-site.

Ranger rehabilitation and closure screening level ecological risk assessment

The rehabilitation and closure ecological risk assessment project (Bartolo et al 2017a²), addressed the following two 2008-2010 KKNs:

¹ Bartolo R, Parker S, van Dam R, Bollhöfer A, Kai-Nielsen K, Erskine W, Humphrey C & Jones D 2013. Conceptual models of stressor pathways for the operational phase of Ranger Uranium Mine. Internal Report 612, January, Supervising Scientist, Darwin.

² Bartolo RE, Harford AJ, Iles M & van Dam RA 2017a. Rehabilitation and closure ecological risk assessment for Ranger Uranium Mine: Part 1 – Risk Screening. Supervising Scientist Report (in preparation), Supervising Scientist, Darwin.

KKN 2.7.1 Ecological risk assessments of the rehabilitation and post rehabilitation phases.

and

KKN 5.1.1 Develop a landscape-scale ecological risk assessment framework for the Magela catchment that incorporates, and places into context, uranium mining activities and relevant regional landscape processes and threats, and that builds on previous work for the Magela floodplain.

The risk assessment was a pathways-based screening level assessment that was based on conceptual models that captured the key stressors, sources, pathways, receptors/measurement endpoints, assessment endpoints and management goals. It aimed to identify the risks to, and inform programs of research targeted to ensure the success of, (i) off-site environmental protection and (ii) a successful rehabilitation on-site. The assessment covered multiple spatial (on-site, off-site) and temporal (decommissioning, post-decommissioning) scales of rehabilitation, and considered both unmitigated and mitigated (i.e. residual) risks.

KKN identification and initial prioritisation

Following the completion of the rehabilitation and closure risk assessment, a process was developed to identify KKNs based on the risk outcomes (Bartolo et al 2017b³). This process was initially applied to the risks identified as being critical or high. For decommissioning, only critical/high mitigated (residual) risks were assessed, while for post-decommissioning, the critical/high unmitigated risks were assessed (see Bartolo et al 2017a for details). Relevant experts from the key stakeholder groups, including ARRTC members, participated in the process, which involved identifying knowledge needs through structured interrogation of the conceptual models that formed the original basis of the risks that were identified and subsequently assessed. The final conceptual models that form the basis of the KKNs will be published in Bartolo et al (2017b). Several subsequent activities also informed the KKNs. In particular, separate technical workshops in late 2016 relating to groundwater modelling and revegetation knowledge needs helped refine and consolidate KKNs in those areas.

A high level, preliminary prioritisation of the resultant KKNs was undertaken to provide an indication of their importance, in order to inform research program planning. Each KKN has been assigned a priority based on the necessity of the KKN, determined as follows:

- *Essential* – the knowledge need represents best practice science that is required for the associated provision of best practice advice for ensuring environmental protection associated with the current operations, rehabilitation and/or closure of Ranger mine; and
- *Desirable* – the knowledge need will improve understanding and knowledge, but is not necessary for ensuring best practice science has been undertaken and/or best practice advice has been provided.

‘Best practice’ is viewed as the approach that is the most effective and produces optimum or superior results to other approaches. It represents the benchmark, and requires a commitment to using all the knowledge that can be acquired. For Ranger mine,

³ Bartolo RE, Harford AJ, Iles M & van Dam RA 2017b. Rehabilitation and closure ecological risk assessment for Ranger Uranium Mine: Part 2 – Analysis of risk assessment outcomes and identification of Key Knowledge Needs (KKNs). Supervising Scientist Report (in preparation), Supervising Scientist, Darwin.

and in the context of the significant conservation and cultural values of the surrounding region, implementation of best practice is essential to ensure the success of rehabilitation and associated protection of the off-site environment. Best practice is likely to change over time and, as a result, knowledge needs also may change over this time. Examples of changing best practice in environmental assessment include the move to landscape scale metrics over plot scale metrics for ecological surveys and monitoring, and the inclusion of non-human biota into radiological dose assessments.

The preliminary prioritisation originally took into account the timeframes in which the knowledge is required. However, as those timeframes have subsequently shifted due to ERA refining its closure planning, the timeframe component was removed from the prioritisation reported here. More appropriately, the relevance of a piece of knowledge, the timeframe in which it is required, and the associated lead time to acquire it, are formally considered when determining the priority of research projects through existing research program planning processes.

Cross-mapping

Where applicable, these KKNs have been cross-mapped against the *2008–2010 KKNs*, *Ranger Closure Criteria Record of Development by the Closure Criteria Working Group* and *Ranger closure timeline and SSB/ERA research projects spreadsheet*, to ensure no essential knowledge needs have been inadvertently omitted. Previous knowledge needs that were not also identified through the current KKN revision, and which were incomplete and still considered essential, were subsequently included in the current KKNs under the relevant risk.

Structure of KKNs

The KKNs are presented in summary tables and structured according to the phase of mining. Each KKN comprises a short title, key question and short rationale for the KKN. For each KKN, the relevant spatial scale (*on-site* – disturbed footprint of the Ranger mine; *off-site* – areas outside the disturbed footprint of the Ranger mine; *landscape* – on-site and off-site) and the priority are indicated.

The operational and decommissioning phase KKNs are combined and presented first, followed by the post-decommissioning KKNs. The operational and decommissioning phases were combined because they will typically occur in parallel, and are not distinctly different in their risk profile, due to active management of hazards during the phases. The operational and decommissioning phase KKNs are separated into:

1. the development and validation of standards;
2. issue identification and impact assessment; and
3. monitoring and assessment needs.

The KKNs are then structured according to their respective closure criteria themes and then by the key stressor pathways (e.g. risks via the surface water pathway) that were identified in the conceptual models for the operational (Bartolo et al 2013) and decommissioning phases (Bartolo et al 2017b).

The post-decommissioning KKNs include a separate section covering over-arching KKNs, to capture knowledge needs that cross multiple, if not all, rehabilitation-related risks. The KKNs are structured according to:

1. overarching knowledge needs;
2. development and validation of closure criteria;

3. demonstrating closure criteria are achievable; and
4. monitoring to assess closure criteria.

Within this, the KKNs are structured according their respective closure criteria themes and then the key stressor pathways (e.g. risks via the surface water pathway) that were identified in the ecological risk assessment (Bartolo et al 2017b).

The risk-based scientific justification for each KKN is presented in Appendix A. The KKN summary tables contain hyperlinks to the relevant contextual information within Appendix A. This enables the KKNs to be traced back to their origins within the ecological risk assessment. It is important to note that the management goals and assessment endpoints articulated in the ecological risk assessment covered the requirements of both the Ranger closure objectives and the ERs. The links between these aspects are provided in Appendix A. Finally, non-Ranger related KKNs have been similarly structured, albeit without a formal risk assessment having been undertaken for these other sites, which are known to be of lower priority at this stage. However, knowledge needs for the other sites will need to be properly identified in the near future, especially for Nabarlek.

Review of KKNs

The KKNs for Ranger are based on the risks that were identified as being critical or high. Although the majority of the moderate and low risks are considered unlikely to be of significant concern, they will, nevertheless, be screened in a systematic manner and assessed as necessary to ensure that any further essential knowledge needs are identified and captured in subsequent updates to these KKNs. For example, risks assigned a high uncertainty might require additional knowledge in order to increase confidence in the risk predictions. Alternatively, new scientific knowledge acquired as part of the SSB or ERA research programs, or from elsewhere, may identify that some KKNs are no longer required.

Review of the KKNs will comprise:

- an ongoing ability to review the necessity or otherwise of new and existing KKNs as relevant information arises; and
- a formal review of the KKNs every 2-3 years, based on revisiting the risk assessment and associated conceptual models.

This process will enable timely addition or removal of KKNs in a robust and transparent manner. Moreover, project priorities are reviewed quarterly and, more formally, annually.

Current operations and decommissioning

1 The development and validation of standards

1.1 Water and Sediment

1.1.1 Risks via the surface water pathway

KKN#		Spatial scale	Priority
1.1.1a	Improving confidence in the ammonia water quality limit <i>What is the toxicity of ammonia to local species, and what is an appropriate ammonia water quality limit?</i> An interim water quality guideline value (GV) was derived using a generic international toxicity dataset published by the US EPA. To derive a final site-specific water quality limit, the effects of ammonia on local species under local conditions need to be quantified. The ammonia toxicity literature also indicates that freshwater mussels are particularly sensitive to ammonia. As freshwater mussels are an important component of the local aquatic ecosystem, and are a highly-valued food source for traditional owners, they should be represented in the dataset used to derive the site-specific water quality limit, which can replace the interim guideline value. This knowledge need relates also to the development of a closure criterion for ammonia (see KKN 5.1.1e, page 22).	Off-site	Essential
1.1.1b	Validating the application of multiple single toxicant water quality limits <i>Is the regulatory use of multiple water quality limits, each based on single contaminant toxicity, sufficiently/overly protective of an environment where multiple contaminants occur together and in varying proportions?</i> Much effort has been invested in deriving water quality limits for individual toxicants. However, this approach does not incorporate potential interactive (e.g. additive, synergistic, antagonistic) effects of toxicant mixtures or other modifying effects occurring in the field. As additional limits for new toxicants (e.g. ammonia) are included in the regulatory framework, the continuing rigour of this approach needs to be tested in laboratory and field settings to ensure that it is appropriately protective of the aquatic environment. This knowledge need will also inform the development and application of closure criteria for toxicants.	Off-site	Essential

1.1.2 Risks via the groundwater pathway

KKN#		Spatial scale	Priority
1.1.2a	Potential ameliorative effects on magnesium toxicity <i>Will the current Mg limit be protective (or apply to) mine water quality predicted to be released from site, e.g. how will its Mg:Ca ratios vary? Would a better understanding of the effect of Ca on Mg toxicity help derive more accurate GVs?</i> Direct toxicity testing of expressed groundwater in the Gulungul Creek Catchment showed no effects at concentrations well above the GV for Mg. This was thought to be due to ameliorating factors in the groundwater, primarily Ca, as the Mg:Ca ratios were lower than those used to derive the GV. Hence, an understanding of the Mg:Ca ratio of seepage water from various sources and how this affects toxicity is required. The gathering of field (or semi-field) effects data for mine released waters (including groundwater sources) mixed with receiving waters would provide supporting evidence.	Off-site	Essential

2 Issue identification and impact assessment

2.1 Water and Sediment

2.1.1 Risks via the surface water pathway

KKN#		Spatial scale	Priority
2.1.1a	<p>Source and cause of acidification events in Coonjimba Billabong</p> <p><i>What is the source and cause of acidification events in Coonjimba Billabong?</i> Since about 2002, Coonjimba Billabong has experienced significant early wet season acidification events, with concomitant increases in dissolved metals including manganese and uranium concentrations. Although these water quality perturbations have not resulted in unacceptable water quality at the downstream monitoring point in Magela Creek, this may not be the case in the future. Thus, the source (including potential groundwater sources) and cause of these events needs to be determined in order to understand and manage any risks to the off-site aquatic environment. This knowledge need will also inform requirements for remediation of Coonjimba Billabong during rehabilitation (see KKN 6.1.1i and j, page 27).</p>	On-site	Essential
2.1.1b	<p>Importance of contaminants associated with suspended sediments</p> <p><i>Are there likely to be off-site impacts associated with mobilisation of uranium and other contaminants from mine-derived sediments in downstream wetlands/deposition zones?</i> Some work has been done to quantify concentrations of uranium and other mine-related contaminants associated with sediments in Magela and Gulungul creeks. Long-term turbidity monitoring has shown that the operational mine is not a significant source of suspended sediment to the creek systems, however suspended sediment delivery to the creeks may increase significantly during and after rehabilitation. This work will enable ongoing assessment of loads of sediment-bound contaminants transported off the minesite, giving an indication of the potential for off-site impacts related to remobilisation of these contaminants in sensitive downstream sediment deposition zones, such as wetlands.</p>	Off-site	Essential
2.1.1c	<p>Temporal trends in sediment uranium concentrations in Georgetown and Coonjimba billabongs</p> <p><i>How do U concentrations change over time?</i> Uranium is the key Contaminant Of Potential Concern (COPC) in billabong sediments and readily binds to organic matter and benthic sediments. An analysis of the temporal trends in U concentrations in the sediments of the two on-site backfill billabongs will provide useful information to help assess if closure criteria for sediment quality will be met.</p>	On-site	Essential
2.1.1d	<p>Identification and assessment of emerging contaminants of potential concern</p> <p><i>Are there any emerging contaminants of potential concern and what is their risk to the environment?</i> Contaminant research has been prioritised on a risk basis, but the continued gathering of contaminant knowledge before and during the mine's transition into a rehabilitated site may result in the identification of new or emerging contaminants of potential concern. Where such contaminants are identified, they need to be assessed using a tiered, risk-based approach.</p>	Off-site	Essential

2.1.2 Risks via the groundwater pathway		
KKN#		<div>Spatial scale</div> <div>Priority</div>
2.1.2a	<p>A hydrogeological conceptual whole-of-site model for current operations</p> <p><i>How does the current hydrogeological and hydrogeochemical condition of the minesite aquifers define the nature and extent of groundwater movement, groundwater/surface water interaction, existing contaminant plumes and geochemical reactivity, and as such enable identification of key groundwater pathways for mine contaminants?</i> A significant amount of groundwater data and information has been collected throughout the mining phase at Ranger, however this data and information has not been well integrated for the purpose of assessment of key hydrogeological functions (such as groundwater/surface water interactions) nor the definition and clear delineation of existing groundwater contamination. This needs to be done in association with the current operational minesite, taking into account, amongst other things, appropriate background concentrations, the effects of open pits and rock stockpiles on groundwater head across the site. This work would include preparation of potentiometric groundwater maps. Once this model has been completed it will provide the basis for numerical modelling (e.g. solute transport modelling) and further conceptualisation throughout the decommissioning of the site and the effects that changes to surface structures may have on groundwater movement. This knowledge need will feed into similar needs for the post-decommissioning phase also (see KKNs 6.1.1b, page 26).</p>	<div>On-site</div> <div>Essential</div>
2.1.2b	<p>Dry season sub-surface water quality in the Magela Creek channel sand bed</p> <p><i>What is the source, extent (longitudinal, lateral, depth), rate of movement and residence times of current mine solute contamination in the sub-surface dry season flows in Magela sand channel downstream of Ranger, are there impacts associated with this contamination, and how might this information inform knowledge needs for closure?</i> Mine-derived solutes have been measured at elevated concentrations in the sub-surface dry season flows in Magela sand channel downstream of Ranger. In the case of Mg, values exceeded surface water limits at MCDW in December 2015. Detailed spatial characterisation is required to determine the extent of this contamination, and to determine whether it is seasonal only, or indicative of long-term residency along the creek channel and through the sand depth profile. Characterisation of the hyporheic fauna and possible stygofauna present in the sands is also required for impact and risk assessment. Information arising from a study of current contamination should serve as important knowledge for assessing risks associated with groundwater expression of contaminants in Magela Creek predicted in the long-term (peaking 300 years after closure) from Pit 3 closure modelling.</p>	<div>Off-site</div> <div>Essential</div>
2.1.2c	<p>Source and potential off-site impacts of contaminated groundwaters in the upper Gulungul Creek catchment</p> <p><i>What is the source of groundwater contamination in the GCT2 tributary and what are the off-site impacts of expression of this water into the surface waters of Gulungul Creek?</i></p> <p>Expression of contaminated groundwater from the GCT2 tributary has recently impacted the water quality of Gulungul Creek where high electrical conductivities were measured at downstream sites throughout the 2014/15 wet season. Whilst extensive investigations have been carried out to date more work is required to ensure that the impacts of the groundwater expression are adequately assessed.</p>	<div>Landscape</div> <div>Essential</div>
2.1.2d	<p>Characterisation of groundwater changes due to irrigation of Land Application Areas</p> <p><i>What are the processes by which contamination in the Land Application Areas (LAAs) can be mobilised and what are the likely consequences to the off-site environment during the decommissioning phase?</i> Mine waters high in solutes have been measured near Corridor Creek LAAs, although they did not have a typical mine signal, i.e. they did not have high MgSO_4. An understanding of this issue would inform changes to water management practices that reduce the risks of solutes leaving site?</p>	<div>On-site</div> <div>Essential</div>

2.1.2e	Characterisation, delineation and assessment of current groundwater contamination plumes in minesite aquifers <i>What is the current state of groundwater quality in the minesite aquifers in the vicinity of the key contaminant sources, including the Tailings Storage Facility, the processing plant, ponds, waste disposal areas, etc.?</i> Current groundwater contamination plumes in minesite aquifers need to be hydrologically and geochemically characterised and spatially delineated. This information can then be used in conjunction with the conceptual whole-of-site model to determine key groundwater pathways for transport of solutes off-site, and for assessing risks where necessary.	Landscape	Essential
2.1.2f	Characterising groundwater quality and movement during decommissioning of water management systems <i>What will happen to groundwater flow once the site's through-flow water and shallow groundwater interception systems are dismantled? Consideration needs to be given to the hydrological and hydrogeochemical interaction between site waters, including those currently captured by interception systems, and groundwater during decommissioning, which might lead to solutes being transported off-site during the decommissioning phase. This will require concentrations of COPCs in water that has interacted with waste rock to be determined and agreed. The timeframes for the progressive dismantling of these systems needs to be considered in the modelling.</i>	Landscape	Essential
2.1.2g	The contribution of waste rock to groundwater solutes during decommissioning <i>Could waste rock be a significant source of solutes to the off-site environment through the groundwater pathway during decommissioning? The seepage loadings, concentrations and the fate of solutes from waste rock during decommissioning should be investigated. This may support the hypothesis that the contaminated groundwater expressed at GCT2 is from the walls of the TSF.</i>	Off-site	Essential
2.2 Radiation			
2.2.1 Risks via the atmospheric pathway			
KKN#		Spatial scale	Priority
2.2.1 a	Validation of air quality modelling from mine related emission inventory <i>What is the accuracy of the atmospheric models? This knowledge will increase confidence in predictions that mine related atmospheric emissions do not pose a significant environmental risk. This will ensure the model's value as a pre-closure monitoring tool.</i>	Off-site	Essential
2.3 Flora and Fauna			
2.3.1 Other risks			
KKN#		Spatial scale	Priority
2.3.1a	Protection of wildlife from inappropriate fire regime <i>What is the most appropriate fire management regime to adopt to protect wildlife across the Ranger lease and the buffer zone between the Ranger lease and Kakadu National Park? There is a body of existing research on fire regimes and fauna in Kakadu National Park. This research should be reviewed in the context of rehabilitation and closure of Ranger minesite to ensure wildlife is protected from inappropriate fire regimes.</i>	Landscape	Essential

3 Monitoring and assessment

3.1 Water and Sediment

3.1.1 Risks via the surface water pathway

KKN#		Spatial scale	Priority
3.1.1a	<p>Optimisation of SSB's water quality monitoring program</p> <p><i>How can the elements of SSB's routine water quality monitoring program be optimised for effectiveness in achieving their objectives and efficiency in their implementation?</i></p> <p>Ongoing review and innovation is required to ensure that the methods utilised in the water quality monitoring program are providing useful and reliable information and represent effective use of available resources. This ranges from data collection methods through to data management practices and analytical techniques. Ensuring the use of proven state-of-the-art technologies for equipment, instruments and methods is a key requirement for optimisation, while recent R&D is considering a range of remote sensing or deployed technology (including drones), videography and genomics techniques that reduce staff time and resources and improve data accuracy and field safety of workers in the measurement programs.</p>	Off-site	Essential
3.1.1b	<p>Refinement and development of laboratory methods used for surface water quality monitoring, assessment and research</p> <p><i>What method development is required to ensure that the Supervising Scientist (SSB) continues to use best or leading practice approaches to monitoring, assessment and research?</i></p> <p>SSB's programs are abreast of new technologies for increasing accuracy in data acquisition, as well as reducing staff time and resources predominately through the transition from manual operations to automation. Included amongst these new technologies are faster, cheaper and more reliable methods for radionuclide determinations, automation of algal cell counts (ecotoxicology) and sediment particle size distribution (fluvial geomorphology), while high resolution (photo) microscopy enables more accurate counts, measurements and identifications, together with image capture that can be electronically shared with colleagues anywhere in the world.</p>	Landscape	Essential

3.1.2 Risks via the groundwater pathway

KKN#		Spatial scale	Priority
3.1.2a	<p>Ongoing improvement and optimisation of groundwater monitoring and assessment methods</p> <p><i>Is the current groundwater monitoring and assessment program sufficient and adequate for achieving related research KKNs throughout all mine phases?</i> Completion of the whole of site model may provide new insights into the volume, concentration and direction of contaminants (from Pits 1 and 3) into the surface water system. These results will need to be reviewed against the current contaminant modelling to ensure the adequacy and veracity of the established monitoring program, including its timing and nature. This should include a review of all potential contaminant sources. Any updated monitoring program is to be developed to allow continual validation of the groundwater model(s).</p>	Off-site	Essential

Post decommissioning

4 Overarching knowledge needs

4.1 Cumulative risk for on-site and off-site ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
4.1a	Cumulative risks for the landscape <i>How do we quantify cumulative risk and what are the most appropriate methods for analysis and communication?</i> It is important to assess cumulative risk as examining risks individually does not address the interaction between risks and their iterative effects. An integrated conceptual model should be developed to capture the interactions between multiple risks (e.g. landform stability, revegetation and contaminant exposure) and assessment endpoints (receptors) at multiple scales for the minesite in the first instance and in the surrounding offsite environment thereafter. The foundation for this will be the conceptual models from the rehabilitation and closure risk assessment undertaken to date. The integrated model and assessment should be continually tested and improved as part of best practice. This process should also integrate outputs from all other KKNs to provide a landscape-scale context for the rehabilitation of Ranger in the context of Kakadu National Park, and should be communicated to stakeholders.	2.1 Relates to all stressors and pathways	Landscape	Essential

4.2 Understanding how the World Heritage Values for which Kakadu National Park is listed can be met by the rehabilitated Ranger Project Area

KKN#		Link to Risk Assessment	Spatial scale	Priority
4.2a	Characterising World Heritage values of the Ranger Project Area <i>What World Heritage Values are found on the Ranger Project Area and how can they be articulated to help in decision-making for incorporation of the site into Kakadu National Park?</i> There are numerous World Heritage Values for which Kakadu is listed and these can be spatially explicit (e.g. geological setting values relate to the escarpment country). There are areas within the Ranger Project Area that exhibit World Heritage Values for which Kakadu is listed, and documentation of these may assist decision-makers in incorporating the site into Kakadu National Park.	2.2 Relates to all stressors and pathways	Landscape	Essential
4.2b	Monitoring to ensure the primary environmental objectives for World Heritage Values are met <i>At what spatio-temporal scales do we need to monitor to ensure the primary environmental objectives are met?</i> The system is characterised by inherent variability which will need to be accounted for when assessing whether the Ranger Project Area has met the primary environmental objectives for world heritage values on the RPA (if required), or might compromise those objectives off the RPA. Spatial and temporal scales for each of the primary environmental objectives vary and the science underpinning this variability will be required for the Australian Government to issue closure.	2.2 Relates to all stressors and pathways	Landscape	Essential

5 The development and validation of closure criteria

5.1 Water and sediment closure criteria

5.1.1 Protection of off-site aquatic ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.1.1a	Ensuring closure criteria protect ecosystems <i>How are uncertainty and variation in field-collected data that have been used to derive single-number GVs or closure criteria for billabongs addressed? Are the current GVs suitable as closure criteria and do they address all potential ecological impacts? The measurement of community responses to solutes in the field is difficult due to the absence of high environmental concentrations of solutes, confounding and/or inherent biological variability. Laboratory-derived GVs model the concentration-responses of a limited number of organisms in the absence of confounding environmental influences, but lack environmental realism including the influence of potential modifying factors, ecological interactions relatively short exposure periods, bias against flow-dependent test organisms, and seasonal changes in water quality and biota. Combining these approaches in weight-of-evidence frameworks, additional single-species testing or semi-field studies increases the confidence in GVs and validates these models.</i>	3.1 Contaminants via multiple pathways	Landscape	Essential
5.1.1b	Understanding baseline biodiversity of the region <i>What should be the agreed reference conditions for biodiversity measurement? In order to determine appropriate closure criteria it would be desirable to gain an understanding of what spatial and temporal change in biodiversity would compromise meeting the Primary Environmental Objectives. Measuring the spatial and temporal variation in water quality and biodiversity of receiving water ecosystems (creek channels and billabongs) throughout the periods of surface water flow and inundation (wet and dry seasons) may inform this; currently biodiversity is only measured during the early dry/recessional flow period.</i>	3.1 Contaminants via multiple pathways	Landscape	Essential
5.1.1c	Characterising hyporheic and stygofauna communities <i>What is the nature and extent of hyporheic and stygofauna communities? The ancestral sands between Pit 3 and Magela Creek bed have high hydrological conductivity and will transport a higher amount of solutes. To date, hyporheic and stygofauna communities have not been researched and the significance of their contribution to ecological processes to the biodiversity of the ARR is unknown. If these communities are significant, the impact of solutes on these communities needs consideration. This will help determine if specific closure criteria are needed to protect these communities.</i>	3.1.2 Contaminants via groundwater	Off-site	Essential
5.1.1d	Effect of groundwater-derived solutes on riparian vegetation and aquatic macrophytes. <i>What is the tolerance of vegetation that will be exposed to elevated solutes for long durations? Dormant vegetation in the banks of the creeks during the dry season may be exposed to contaminated groundwater for periods of months. The GVs for Mg were derived using species that rapidly proliferate, e.g. alga, zooplankton, and are not relevant to this exposure scenario.</i>	3.1.2 Contaminants via groundwater	Off-site	Essential

5.1.1e	Deriving ammonia closure criteria for billabongs <i>What is the best method for deriving water quality closure criteria for ammonia under differing pH and temperature conditions?</i> The toxicity of ammonia is highly influenced by pH and temperature. The USEPA has published effects-based algorithms that may be used to adjust water quality guideline values for varying pH and temperatures, although local water quality conditions may be at the limits of these algorithms. A site-specific water quality GV for ammonia has been derived for conditions representative of the creek, i.e. pH 6 (KKN 1.1.1a), and this will be used to inform closure criteria. However, the pH of billabongs is significantly higher (pH 8), which increases the toxicity of ammonia. Hence, the influence of pH on ammonia toxicity needs to be considered and the suitability of closure criteria calculated from algorithms needs to be assessed. Additionally, the suitability and application of closure criteria for ammonia will need to be assessed in the context of the natural temporal variation of ammonia in billabongs.	3.1.4 Nutrients via surface and groundwater	Landscape	Essential
5.1.1f	Annual Additional Load Limits (AALL) as a management tool for nutrients <i>What is the significance of Annual Additional Load Limits (AALL) to risk of eutrophication?</i> A review of the literature supporting these limits is needed to understand their continuing relevance. Can ammonia loads be considered in the same context as the AALLs, i.e. is there data from the same body of work, or more recent work to compare predicted ammonia loads to?	3.1.4 Nutrients via surface and groundwater	Off-site	Essential
5.1.1g	Developing closure criteria for turbidity and sedimentation in off-site waterbodies <i>What are the most appropriate closure criteria for turbidity and sedimentation of off-site waterbodies?</i> There is a need for a biological based closure criterion and associated monitoring programs for turbidity and sedimentation (rates and changes in depth) in relevant off-site water bodies. A criterion is currently under development, based on late dry season and late wet season turbidity and phytoplankton or macroinvertebrate measurements. However, this criterion may need further development.	3.1.6 & 3.1.7 Bedload and suspended sediment via surface water	Off-site	Essential
5.1.1h	Impact of suspended sediment on off-site waterbodies <i>What is known about the specific impact of suspended sediment in off-site waterbodies?</i> The key off-site impacts of suspended sediment would be water quality (turbidity) and residence time, potentially leading to biodiversity/habitat changes, and also, potentially, deposition in off-site billabongs (e.g. Gulungul and Mudginberri billabongs). An assessment of this will determine if closure criteria are needed for off-site billabongs.	3.1.7 Suspended sediment via surface water	Off-site	Essential
5.1.1i	Effect of suspended sediments with different characteristics <i>Will there be differences in suspended sediment characteristics coming off the site (i.e. from different catchments)? If so, are there implications for potential impacts to aquatic biota?</i> Different sizes and shapes of particles have been found to exert different types of effects on aquatic biota. This may or may not be a significant issue at Ranger, and may require some preliminary assessment in the first instance.	3.1.7 Suspended sediment via surface water	Off-site	Desirable

5.1.2 Rehabilitation and protection of on-site aquatic ecosystems				
KKN#		Link to Risk Assessment	Spatial scale	Priority
5.1.2a	Developing closure criteria for turbidity and sedimentation in on-site waterbodies <i>What are the appropriate closure criteria for turbidity and sedimentation of on-site waterbodies?</i> There is a need for a biological based closure criterion and associated monitoring programs for turbidity and sedimentation (rates and changes in depth) in on-site billabongs. A criterion is currently under development, based on late dry season turbidity and phytoplankton measurements. However, the relevance of this dry season-based criterion to wet season turbidity values to on-site waterbodies needs to be determined.	4.1.3 & 4.1.4 Bedload and suspended sediment via surface water	On-site	Essential
5.1.2b	Impact of suspended sediment on on-site waterbodies <i>What is known about the specific impact of suspended sediment in on-site waterbodies?</i> The key on-site impacts of suspended sediment would be water quality (turbidity), potentially leading to adverse biodiversity/habitat changes, and also, potentially, deposition in on-site billabongs and backwater areas. There is a need to understand the residence time in the on-site billabongs and backwater areas (i.e. the trap efficiency), how much suspended sediment is retained, and whether this changes over time.	4.1.4 Suspended sediment via surface water	On-site	Essential
5.1.2c	Geomorphology of on-site creeks and waterbodies <i>What are the appropriate closure criteria that could be used to determine whether closure objectives have been met? How do we determine/delineate pre-mine, current and post mining geomorphic conditions of on-site creeks and waterbodies around Ranger?</i> Corridor and Coonjimba creeks and their billabongs, and drainage lines towards Gulungul Creek, are the key on-site receptors for bedload. There is a need to better understand the geomorphology of these features. This would involve mapping/characterising of existing and pre-mining geomorphic conditions.	4.1.3 & 4.1.4 Bedload and suspended sediment via surface water	On-site	Essential
5.1.2d	Physico-chemical factors that may influence the sediment Guideline Value for uranium <i>What physico-chemical factors affect U toxicity in billabong sediments (e.g. pH, DOC)?</i> The sediment quality GV for U was derived using sediments from Gulungul Billabong, which should be representative of the backflow billabongs on the minesite. However, if physico-chemical conditions of sediments are different this may affect the toxicity of U and the GV may not be protective. Knowledge of the influence of U toxicity modifying factors in sediments would help derive GVs for different sediment conditions.	4.1.1 Metals via surface and groundwater	On-site	Desirable

5.1.3 Rehabilitation and protection of on-site terrestrial ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.1.3a	Water quality Guideline Values for protection of wildlife drinking on-site water sources <i>What data, guidelines or models are suitable for assessing the potential acute risk to wildlife drinking water from on-site water bodies? A review of stock drinking guidelines shows them to be inappropriate as they are for chronic effects to cattle and sheep. Wildlife may drink raw water from on-site but their intake profile from these sources is not aligned with the models of intake on which livestock drinking water guidelines are based (e.g. infrequent, occasional use versus longer-term frequent use). The issues identified in pathways and sources also need to be considered to answer this question.</i>	6.3.4 Contaminants via surface and groundwater	On-site	Essential
5.1.3b	Acute toxicity of mine water to wildlife <i>Are there local data and information that are more relevant to determining safe drinking water concentrations of COPC for wildlife? The model of wildlife exposure to mine waters needs to be considered, i.e. how much of an animal's consumption is likely to come from water bodies on site, and what will the water quality in on-site water holes likely be? Are there any available surrogate toxicity data that can be used to predict acute toxicity to local wildlife?</i>	6.3.4 Contaminants via surface and groundwater	On-site	Essential
5.1.3c	Chronic toxicity of mine water to wildlife <i>What is the likelihood of chronic toxicity of on-site surface waters to local wildlife? The environmental requirements stipulate that mine waters should not be acutely toxic to wildlife on-site. However, this does not account for subtle long-term effects that may impact wildlife populations on the rehabilitated minesite. Chronic toxicity data for local terrestrial fauna would be desirable.</i>	6.3.4 Contaminants via surface and groundwater	On-site	Desirable

5.1.4 Protection of human health

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.1.4a	Deriving closure criteria for drinking water that protects human health <i>What guidelines or models are suitable for assessing the potential risk to humans drinking untreated water from on-site water bodies? People may drink untreated water from on-site but their intake profile from these sources is not aligned with the models of intake on which national drinking water guidelines are based (e.g. infrequent, occasional use versus longer-term frequent use). The issues identified in pathways and sources also need to be considered to answer this question. What guidance is given in the NHMRC drinking water quality guidelines about small communities, infrequently used water supplies or untreated water supplies?</i>	7.2 Contaminants via surface and groundwater	On-site	Essential
5.1.4b	Assessing the availability of drinking water guideline values for human health <i>Which of the Contaminants Of Potential Concern have guidelines for drinking water to protect health? A number of the COPCs will have water quality guidelines for human health. Those that do not have guideline value will need to be assessed for their potential to cause adverse effects.</i>	7.2 Contaminants via surface and groundwater	On-site	Essential

5.2 Radiation

5.2.1 Protection of off-site aquatic ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.2.1a	Radionuclide dose-effect relationships for aquatic biota <i>At what level of radiation dose rate does local aquatic wildlife experience radiation-induced biological effects under conditions of chronic exposure?</i> There is currently no dose-effect data for ARR wildlife to benchmark chronic radiation exposures against. The benchmarks currently used for radiation protection of aquatic ecosystems are generic and have been derived from review of the effects data pooled from international studies.	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential

5.3 Landform

5.3.1 Protection of off-site aquatic ecosystem

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.3.1a	<p>Closure criteria for bedload in off-site creek channels and water bodies</p> <p><i>What are the appropriate criteria that could be used to determine whether closure objectives have been met?</i> There is a need to understand what the acceptable rates of transport of bedload sediment offsite are by determining the natural bedload movements (non-mine-impacted) in Magela and Gulungul creeks. Bedload movement rates in the creek should not be elevated from the rehabilitated minesite.</p> <p>Landform evolution modelling should be used to predict the extent/likelihood of bedload movement off-site via specific routes, in order to inform the need for, and structure of, monitoring programs. The channel morphology monitoring program for on-site bedload risks should provide an early warning system for off-site risks. Annual visual inspections (e.g. using a photo point system) of off-site creek channels should be undertaken. Ideally, little to no sediment should be transported from the rehabilitated landform. However, if sediment movement occurs, early detection is important. Channel morphology measurement and monitoring program for on-site bedload risks should inform and provide early warning for off-site risks.</p>	<p>3.1.6 Bedload via the surface water</p>	Off-site	Essential

5.4 Flora and Fauna

5.4.1 Protection of off-site terrestrial ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.4.1a	Identification and characterisation of the source of weeds (on site) <i>What are the species and densities of weeds across the RPA (particularly in the boundary areas and disturbed areas across the site) during the decommissioning and post-decommissioning phases? Systematic surveys of weeds in the on-site environment are required during the decommissioning and post-decommissioning phases. Analysis of these surveys should be undertaken in conjunction with surveys undertaken for the adjacent offsite environment to determine sources and the magnitude of sources. It is likely the profile of sources will change over time. The information from these surveys is required to ensure environmental protection during the decommissioning phase when there will be major earthworks occurring on the lease (and hence a higher risk of weed introduction and transfer to the surrounding area) and to monitor closure criteria post-decommissioning. Hazard assessments should be undertaken for exotic weeds that pose high potential risks (e.g. gamba grass) to the success/trajectory of the rehabilitation and the meeting of closure criteria.</i>	5.1.1 Weeds via multiple pathways	Off-site	Essential

5.4.2 Rehabilitation and protection of on-site terrestrial ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
5.4.2a	Defining and refining trajectories for revegetation <i>How can we predict vegetation trajectories and determine if the rehabilitated site is an agreed stable and resilient ecosystem? There are a range of possible outcomes for the revegetation. Useful approaches for assessing minesite rehabilitation that have been identified are those that place the site in the context of successful development towards a rehabilitation objective and closure criteria. Once an appropriate trajectory (or trajectories) has been defined, suitable site-specific indicators relating to ecosystem composition, structure and function can be chosen. There is a body of research required to define a trajectory (or trajectories) that meets rehabilitation goals and/or closure criteria for the Ranger minesite. A related question in addressing the research needs is: <i>What additional information is required to develop trajectories?</i></i>	6.2 Multiple stressors via multiple pathways	On-site	Essential

5.4.2b	<p>Development and refinement of metrics to assess revegetation on rehabilitated areas</p> <p><i>What measurement endpoints (metrics) are required to assess revegetation, in the context of closure criteria, on the disturbed areas of the rehabilitated site?</i> There is a need to select suitable metrics to assess revegetation in the rehabilitated minesite environment. This knowledge needs to be acquired prior to post-decommissioning to inform both the rehabilitation strategy and the post-decommissioning monitoring of closure criteria. Knowledge for refinement of closure criteria may be acquired through use of existing analogue sites and new analogues that are representative of the waste rock substrate. New technologies (such as sensors <i>in situ</i> or on board platforms such as UAVs) may provide the ability to derive and measure new and more appropriate measurement endpoints.</p> <p>A key component in developing closure criteria for revegetation is determining the structural and functional requirements in revegetated areas that will enable them to be resilient to the fire regime in Kakadu National Park. Measurement of vegetation recovery time from fire (fire frequency, fire extent, or fire interval), fuel load, and species composition (fire-resilient species) is proposed as a measurement for the outcome of resilient vegetation in the closure criteria. In relation to determining resilience of revegetated areas to the fire regime in Kakadu National Park, previous reviews of revegetation at Ranger have identified that it is critical to establish the age class of the woody component of revegetated areas that is fire resistant to the appropriate frequency and intensity of a managed fire regime. In the first instance, the existing work undertaken at Ranger should be reviewed and knowledge gaps identified. Aside from the studies at Ranger; any available case studies from rehabilitated sites in northern Australia should be reviewed.</p>	6.2 Multiple stressors via multiple pathways	On-site	Essential
5.4.2c	<p>Importance of understorey in revegetated areas</p> <p><i>How important is it to have an understorey established in revegetated areas on waste rock for long-term ecological and habitat function?</i> There has been a previous large-scale trial to investigate the effect of non-aggressive grass species on vegetation community development under two different irrigation regimes. Due to funding limitations the trial was not monitored past the initial phase and the results were thus of limited value to an understanding of longer-term outcomes. Reviews of existing research on the importance of understorey in savannas in northern Australia and targeted research to fill specific knowledge gaps in the rehabilitated minesite context should be implemented to answer this question. Understanding the importance of understorey will help determine if a specific closure criterion is needed.</p>	6.2.1 Species diversity	On-site	Essential
5.4.2d	<p>Plant tolerance to contaminants (including magnesium sulfate) and effects of long-term exposure to plant health</p> <p><i>What is the tolerance of native plant species to contaminants (including magnesium sulfate)? Is long-term exposure to contaminants (including magnesium sulfate) detrimental to plant health?</i> Previous research at Ranger has shown that when compared with natural soils, the mine waste rock typically has a higher pH and EC, lower nitrogen and organic carbon concentrations, higher exchangeable soluble magnesium and higher phosphorus concentrations. Additionally studies have shown that the germination of some species can be affected by magnesium sulfate concentrations. The effect of Mg:Ca on the growth and physiology of native plants has proven variable. Outcomes from previous research suggest that further studies on native plant species is required to understand the effect of exposure of magnesium sulfate induced salinity, calcium and potassium deficiency, low nitrogen and moderately higher phosphorus. An understanding of plant tolerances will enable targeted species selection for revegetation and will help determine if there is a need for a specific closure criterion that protects vegetation from solute exposure via the groundwater. Areas on the rehabilitated site that may pose a risk include the area formerly occupied by the Tailings Storage Facility and the Land Application Areas. Furthermore riparian vegetation on the site may be impacted due to groundwater egress.</p>	6.2.1 Contaminants via surface and groundwater	On-site	Essential

5.4.2e	<p>Developing an appropriate closure criterion for recolonisation of fauna</p> <p><i>Will the establishment of suitable habitat on the rehabilitated site ensure recolonisation of fauna?</i> The current paradigm with respect to fauna and recolonisation at Ranger is that fauna species will return to the rehabilitated site once suitable habitat has been established. There is a lack of empirical evidence to support this (and to derive trajectories for closure criteria) from previous studies at Ranger. Such evidence is required from either similar rehabilitated landscapes in northern Australia and/or from the Ranger Project Area itself, with the trial landform area currently being the only opportunity to capture early data that would support criterion development.</p>	6.3 Multiple stressors	On-site	Essential
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6 Demonstrating closure criteria are achievable

6.1 Water and sediment

6.1.1 Protection of off-site aquatic ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
6.1.1a	Groundwater modelling of contaminant transport from the Pits <p><i>How are contaminants transported from the Pits and what is their environmental fate?</i> Continued validation and amendment (where required) of the groundwater models for the tailings containment facilities (Pit 1 and 3) is required for all COPCs. This includes further examining the transport of Mg and Ca (including through reactive transport modelling), and associated implications for the Mg:Ca ratio, which can affect Mg toxicity. Further work is needed to better understand pathways associated with the north face fault/fracture zone, the Djalkmara sands zone and deep carbonate zone of Pit 3, and the MBL zone and LMS carbonate zone of Pit 1. The most appropriate monitoring locations for calibration and verification of models need consideration. Solute transport via the Magela Creek bed alluvial groundwater system requires additional attention due to properties that may facilitate solute transport and increase the risk to the off-site ecosystems.</p>	3.1 Contaminants via surface and groundwater	Off-site	Essential
6.1.1b	Whole-of-site and regional groundwater modelling of contaminant transport <p><i>How does groundwater move on the rehabilitated site and how do hydrogeological features of the region influence this?</i> Conceptual and numerical models for the whole-of-site and regional (deeper) groundwater movement, including the role of fracturing and geological stratifications at each scale, need to be completed, validated and continually improved as necessary. There remains some ongoing concern in regards to the role the deeper groundwater system (primarily aquifer 3) may play in transporting solutes into the surface water systems. Related to this, the appropriate downstream boundaries for the models need to be reviewed, e.g. inclusion of Mudginberri Billabong or the lower floodplains. Concentrations of COPCs in natural deep groundwater need to be determined. The modelling should also be informed by a better understanding of groundwater levels and movement across the site and over time (e.g. seasonally). The times at which legacy and decommissioning issues (e.g. removal of ponds) have the potential to lead to off-site impacts should be considered and included in the models.</p>	3.1 Contaminants via surface and groundwater	Off-site	Essential
6.1.1c	Completion of a quantitative surface water model for the rehabilitated minesite. <p><i>How are contaminants transported off-site via the surface water pathway and what are predicted COPC concentrations in surface water?</i> The model needs to achieve a high spatial and temporal resolution that allows predictions of contaminant concentrations in surface waters that are appropriate for comparison with closure criteria. Ongoing review, calibration, validation and amendment (where required) of contaminant transport model(s) is required for the remaining life of mine and rehabilitation.</p>	3.1 Contaminants via surface water	Off-site	Essential
6.1.1d	Sources of contaminants and radionuclides to the groundwater <p><i>Which sources have the largest and most mobile load of contaminants?</i> A comparative assessment of each source is needed. A clear knowledge of the contribution of solute loads from each source will assist the rehabilitation and risk management of the site.</p>	3.1.5 Contaminants & radionuclides via surface and groundwater	Off-site	Essential

6.1.1e	The contribution of waste rock to surface water contaminants during post-decommissioning <i>What is the nature and timeframe of (hydro) geochemical reactions in the rehabilitated site?</i> The amount of contaminants leached from waste rock is expected to reduce over time. Models are needed to determine how much, and for how long, will solutes leach from the waste rock. The source terms used should be reviewed and, if required, updated with additional information from monitoring and previous geochemical studies. Geochemical modelling used in the Pit 1 and 3 contaminant transport models may have answered this question but concerns continue to be raised about the completeness of information supporting these source terms and active timeframes. Thus, the adequacy of available information and its application needs to be reviewed and/or communicated.	3.1.1 , 3.1.2 & 3.1.3 Solutes & metals via surface and groundwater	Off-site	Essential
6.1.1f	Understanding the different contributions from legacy sites <i>What is the current contamination status of the legacy sites and how will this contribute to off-site solute transport and cumulative whole-of-site impacts?</i> Remediated areas have a more contaminated soil/waste rock profile and contaminants may not have the same mobility as other areas e.g. if a high amount of clay is present. Hotspots of contaminant sources need to be considered, e.g. sulfate or metals from RP1 sediments. This information may need to be incorporated into the site-wide conceptual model and the whole-of site-solute transport model.	3.1.1 , 3.1.2 , 3.1.3 & 3.1.4 Contaminants via surface and groundwater	Off-site	Essential
6.1.1g	Predicting nutrient concentrations in the creek <i>Are concentrations and/or loads of nutrients predicted to enter the creek likely to cause eutrophication?</i> This will probably be achieved through a desktop review of the contaminant transport modelling data and comparable natural inputs.	3.1.4 Nutrients via surface and groundwater	Off-site	Essential
6.1.1h	Impact of solute plumes on ecological connectivity <i>Can a solute plume form a barrier in the creek channels that inhibits organism migration and connectivity (e.g. fish migration, invertebrate drift, gene flow)?</i> Previous studies in Magela Creek have demonstrated avoidance by fish of mine wastewater discharges, indicating potential reduced recruitment to upstream sites. Information on seasonal movement and dispersal of organisms needs to be considered and combined with groundwater contaminant modelling data, in order to assess potential for impaired movement and connectivity in streams.	3.1.1 Solutes via surface water	Off-site	Essential
6.1.1i	Assessment of acid-sulfate sediments <i>What are the current and predicted acid sulfate sediment status and nature and extent of metal contamination in the sediments of on-site water bodies?</i> The predicted SO ₄ budget for Coonjimba and Georgetown billabongs need to be assessed, which would include the SO ₄ sources (e.g. legacy of decommissioned RP1) and pathways (and their contributions).	3.1.3 Metals via surface and groundwater	Landscape	Essential
6.1.1j	Effect of billabong acidification on off-site ecosystems <i>What is the combined toxicity of low pH, increased solutes and metals on local aquatic organisms and aquatic biodiversity?</i> If acidified waters are shown to reach the off-site environment, then the impact of these waters will need to be assessed. The exposure duration should be considered and the effect of modifying factors on Mn toxicity may need assessment. It may be desirable to determine the impact of these events on the on-site billabong diversity, although this would be a lower priority. The ecological importance of the Coonjimba billabong acidic events and the potential for ecological impacts considering first flush scenarios needs to be considered. An understanding of the natural ASS processes of the analogue billabongs (lowland) in the ARR may inform this.	3.1.3 Metals via surface and groundwater	Off-site	Essential

6.1.2 Rehabilitation and protection of on-site aquatic ecosystem				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.1.2a	Predicting uranium accumulation in billabongs <i>How are U contaminated sediments transported in and out of billabongs and what are the predicted future metal budgets for billabong sediments? Prediction of the concentrations of U entering and leaving the on-site billabongs will determine if concentrations will reach a threshold at which biological impacts would be expected. If concentrations of uranium in sediments of on-site billabong are above the closure criterion, what concentrations should be considered As Low As Reasonably Acceptable (ALARA)?</i>	4.1.1 Metals via the surface and groundwater	On-site	Essential
6.1.2b	Predicting water quality of on-site surface waters <i>What is the predicted future quality of the surface water on-site? Data on metal toxicity/effects to wildlife are of little use without knowledge of actual or predicted environmental concentrations. Thus, predicted on-site water quality data will be needed as part of assessing the risk to wildlife.</i>	6.3.4 Contaminants via the surface water	On-site	Essential
6.1.3 Protection of human health				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.1.3a	Assessing the risk of drinking mine water on human health effects <i>What is the predicted future quality of the surface water on-site, and the existing and potential off-site groundwater drinking resources? Data on metal toxicity/effects to humans are of little use without knowledge of actual or predicted environmental concentrations. Thus, predicted on-site water quality data will be needed as part of assessing the risk to human health.</i>	7.2.1 Contaminants via surface and groundwater	On-site	Essential
6.1.3b	Understanding human exposure to drinking water on the minesite <i>What groundwater drinking water resources are in the region and what is the potential for these to be contaminated and made unfit for drinking by solutes transported from the closed minesite? Issues to consider include what is the quality of water in these resources compared to drinking water standards. Are solutes predicted (by modelling) to reach these supplies?</i> <i>Where, and how, should drinking water (or other) guidelines be used to assess the safety of raw surface waters on-site? Consideration should be given to issues of location and seasonality for e.g. what location in Magela Creek should be assessed, should on-site billabong water quality be assessed as a drinking water resource? How should seasonality be considered?</i> <i>What is the expected profile for people drinking water from the rehabilitated site? For example: What on-site water bodies are people likely to drink from? At what times of year and how often is it expected that people would use these sites as a drinking water supply? What are the expected intake volumes?</i>	7.2.1 Contaminants via surface and groundwater	On-site	Essential

6.2 Radiation				
6.2.1 Protection of off-site aquatic ecosystems				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.2.1a	Water radiological closure criteria <i>What maximum levels of U and Ac series radionuclides in water provide assurance that above-baseline radiation doses to aquatic wildlife will not have significant adverse impacts on off-site aquatic ecosystems? Tangible closure criteria in the form of radionuclide activity concentrations in water are essential to ensure that off-site aquatic ecosystems are adequately protected against impacts from radiation.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1b	Radionuclide loads to off-site aquatic ecosystems <i>What are the loads of U and Ac series radionuclides (dissolved and particulate) entering the aquatic environment via surface and groundwater pathways? Knowledge of U and Ac series radionuclide loads entering off-site aquatic ecosystems is an essential first step for determining activity concentrations in the ecosystem via dispersion modelling. The activity concentrations are needed to estimate radiation doses to aquatic wildlife and also to people utilising the ecosystem as a bush food resource.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1c	Radionuclide levels in off-site aquatic ecosystems <i>What is the dispersion and resulting activity concentration of U and Ac series radionuclides (especially U isotopes, ^{226}Ra, ^{210}Po, ^{227}Ac and ^{231}Pa) in off-site aquatic ecosystems? Activity concentrations of radionuclides in water are used to estimate radiation doses to aquatic wildlife and also to people utilising the aquatic ecosystem as a bush food resource. Knowledge of these activity concentrations for U and Ac series radionuclides is essential for dose assessments and the development of radiological closure criteria for water quality.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1d	Partitioning of radionuclides and leach rates from the rehabilitated landform <i>What are the leach rates and soil-water distribution coefficients (k_ds) of U and Ac series radionuclides coming from the rehabilitated landform and how might changes in soil chemistry affect these values? It is essential for surface water and groundwater transport modelling, as well as for assessments based on these model outputs, that the quantities of dissolved radionuclides coming from the landform via each waterborne pathway are known. Leaching characteristics of radionuclides from the host material may be chemistry dependent and should therefore be determined for a range of conditions.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1e	Partitioning of radionuclides in off-site aquatic ecosystems <i>What are the sediment-water distribution coefficients (k_ds) of U and Ac series radionuclides and how do they vary with differing physico-chemical conditions? Sediment-water distribution coefficients are an essential parameter in wildlife dose assessments and are used to quantify the partitioning of radionuclides between the sediment and water. Some site-specific data is available for U series radionuclides, but not for Ac series radionuclides. The data that does exist does not cover variability with differing physico-chemical conditions.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1f	Tissue to whole organism conversion factors <i>What are the tissue to whole organism conversion factors for concentration ratios for local aquatic wildlife? Much of the existing data on radionuclide concentration ratios for aquatic plants and animals are for specific tissue components consumed by Aboriginal people as bush foods. These concentration ratios need to be converted to the whole organism level in order for the data to be useful for assessing radiation doses to wildlife. While generic tissue to whole organism conversion factors are available in the literature, it is desirable to derive these from site-specific data to improve the estimate of the dose.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential

6.2.1g	Radionuclide uptake in small proliferators <i>What are the concentration ratios of U and Ac series radionuclides in phytoplanktons and zooplanktons? The focus of previous research has been on aquatic species forming part of the human food chain. No consideration has been given to radionuclide uptake in small proliferators like phyto- and zooplanktons, which are essential to ecosystem function and health.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1h	Prioritisation of U series radionuclides <i>What is the importance ranking of individual U series radionuclides in relation to radiation exposures of aquatic wildlife? Prioritisation analysis is essential to determine the most important U series radionuclide(s) and to help focus future research efforts.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1i	Uptake of Ac series radionuclides in aquatic wildlife <i>What are the concentration ratios of Ac series radionuclides (especially ^{227}Ac and ^{231}Pa) for aquatic wildlife? There is currently no data on uptake of Ac series radionuclides by aquatic wildlife. These radionuclides could make a significant contribution to radiation doses to some aquatic species. The acquisition of data on concentration ratios for Ac series radionuclides is essential to ensure that all radionuclide stressors of potential significance have been considered in the development of radiological closure criteria for off-site water quality.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.1j	Importance of Ac series radionuclides for aquatic wildlife <i>What is the importance of Ac series radionuclides (especially ^{227}Ac and ^{231}Pa) in relation to radiation exposures of aquatic wildlife? Ac series radionuclides will contribute to the radiation dose received by aquatic wildlife, but exactly how much is unknown. Knowing the contribution from Ac series radionuclides is essential to provide an accurate estimate of the radiation dose and for the development of closure criteria.</i>	3.1.5 Radionuclides via surface and groundwater	Off-site	Essential
6.2.2 Rehabilitation and protection of on-site aquatic ecosystems				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.2.2a	Radionuclide activity concentrations on the rehabilitated landform <i>What are the activity concentrations of U and Ac series radionuclides in surface waste rock and land application area soils? Doses to traditional owners via the terrestrial bush food, radon and dust inhalation and external gamma exposure pathways are proportional to the activity concentration of U and/or Ac series radionuclides in the surface substrate of the rehabilitated landform. It is highly desirable to know these activity concentrations in order to increase accuracy of the dose estimate.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential
6.2.2b	Radon dispersion <i>What is the dispersion and resulting activity concentration in air (on- and off-site) of radon coming from the rehabilitated landform? Knowledge of radon activity concentrations in air is essential to estimate doses to traditional owners via the radon inhalation exposure pathway since the dose is proportional to activity concentrations in air.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential
6.2.2c	Radon progeny equilibrium factors <i>What is the radon progeny equilibrium factor in air on- and off-site of the rehabilitated landform? This is a key constant of proportionality needed to estimate doses to traditional owners via the radon inhalation exposure pathway. Default values can be obtained from the literature, but site-specific information is highly desirable to increase accuracy of the dose estimate.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential

6.2.2d	Radon progeny activity median aerodynamic diameter <i>What is the activity median aerodynamic diameter of radon progeny in air and what are the attached and unattached fractions? Inhalation dose coefficients for radon progeny are determined from these parameters. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential
6.2.2e	Dust re-suspension factors <i>What is the re-suspension factor for dust from the surface of the rehabilitated landform? Dust radionuclide activity concentrations in air and hence radiation dose via the dust inhalation exposure pathway are proportional to the re-suspension factor. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential
6.2.2f	Dust radionuclide activity median aerodynamic diameter <i>What is the activity median aerodynamic diameter of dust-bound radionuclides in air? Inhalation dose coefficients for dust-bound radionuclides are determined from the activity median aerodynamic diameter. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.</i>	7.1.1 Radionuclides via multiple pathways	On-site	Essential
6.2.3 Protection of human health				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.2.3a	Soil and water radiological closure criteria <i>What maximum levels of U and Ac series radionuclides in soil and water provide assurance that above-baseline radiation doses to traditional owners will be below the public dose limit? Synthesis and analysis of information for each human radiation exposure pathway is essential so that soil and water activity concentrations (i.e. closure criteria) can be back-calculated from statutory dose limits.</i>	7.1 Radionuclides via surface and groundwater	On-site	Essential
6.2.3b	Uptake of Ac series radionuclides in bush foods <i>What are the concentration ratios of Ac series radionuclides (especially ²²⁷Ac and ²³¹Pa) in terrestrial and aquatic bush foods? There is little-to-no data on uptake of Ac series radionuclides in terrestrial and aquatic bush foods. Knowing the dose contribution from these radionuclides is essential to provide an accurate estimate of doses to traditional owners.</i>	7.1 Radionuclides via surface and groundwater	On-site	Essential
6.2.3c	Importance of Ac series radionuclides for human health <i>What is the importance of Ac series radionuclides (especially ²²⁷Ac and ²³¹Pa) in relation to radiation doses to traditional owners from their use of the land? Data on Ac series radionuclides is lacking for human radiation exposure pathways. Knowing the contribution from these radionuclides is essential to provide an accurate estimate of doses to traditional owners.</i>	7.1 Radionuclides via surface and groundwater	On-site	Essential

6.2.4 Rehabilitation and protection of on-site terrestrial ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
6.2.4a	Radionuclide uptake in terrestrial wildlife <i>What are the whole organism radionuclide concentration ratios for terrestrial wildlife groups likely to inhabit the rehabilitated landform?</i> Site-specific data on whole organism radionuclide concentration ratios for a number of terrestrial wildlife groups (e.g. amphibians, birds, invertebrates and vegetation) are currently lacking. While not identified as a high or critical risk, such data are needed to best estimate radiation risks to wildlife following the assessment approaches recommended under current international and national guidance.	Classified as a moderate risk – therefore, no link to Appendix A	On-site	Essential

6.3 Landform				
6.3.1 Protection of off-site aquatic ecosystems				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.3.1a	<p>Validating the use of the CAESAR-Lisflood and SIBERIA landform evolution models</p> <p><i>What is the sensitivity of CAESAR and SIBERIA parameters, and how can this knowledge be used to refine the models?</i> Applying a conservative approach, worst case scenarios should be adopted for parameters for which we have little local knowledge or there is little discriminatory ability – such as rock type placement.</p> <p>A number of input parameters for these models may be impacted by local conditions and these need to be investigated to ensure the accuracy of the model predictions, i.e.</p> <p><i>What is the appropriate sediment settling velocity parameter?</i> It may be worthwhile reviewing existing Georgetown Billabong turbidity/suspended sediment and flow (or surrogate) data to determine if this is possible.</p> <p><i>For model validation purposes, what is the proportion of measured bedload relative to measured suspended sediment from the trial landform waste rock, and how does this compare with the model outputs?</i></p> <p><i>What are the appropriate shear stress and roughness parameters for CAESAR that reflect local conditions?</i></p> <p><i>What is the appropriate rate of weathering for waste rock?</i></p> <p><i>What is the effect of vegetation succession and fire on suspended sediment transport?</i></p> <p><i>What is the impact of extreme rainfall events and scenarios over time on suspended sediment transport?</i></p> <p><i>What is the range of model outputs given worst case and best case scenarios?</i></p>	<p>3.1.6, 3.1.7, 4.1.3, 4.1.4 & 6.1</p> <p>Bedload and suspended sediment via the surface water and Landform stability</p>	Landscape	Essential
6.3.1b	<p>Identify the path, volume and timeframe for bedload sediment transport off-site</p> <p><i>In the event on-site mitigation measures are not fully effective or fail, how much bedload will be transported off-site, over what timeframe, and what is the major route(s) off-site?</i></p> <p>In particular, the drainage line around the south-east side of Pit 3 (based on the FLV-5 landform design) and the Pit 3 capping may be a direct source of bedload to Magela Creek.</p>	<p>3.1.6 & 3.1.7</p> <p>Bedload and suspended sediment via the surface water</p>	Off-site	Essential
6.3.1c	<p>Identify the particle size distribution characteristics for transported bedload</p> <p><i>What is the particle size distribution of the bedload being transported off site?</i> The particle size of the bedload being transported off the site can influence its transport and deposition and, thus, needs to be known in order to determine potential impacts.</p>	<p>3.1.6</p> <p>Bedload via the surface water</p>	Off-site	Desirable
6.3.1d	<p>Background bedload yields for Magela and Gulungul Creeks</p> <p><i>What are the estimated natural bedload rates in Magela and Gulungul Creeks?</i></p> <p>Any effects associated with minesite-derived bedload to off-site creek systems needs to be considered in the context of natural bedload yields in Magela and Gulungul creeks. However, estimated natural bedload yields for Magela and Gulungul creeks may be based on limited data, and need to be verified and/or supplemented.</p>	<p>3.1.6</p> <p>Bedload via the surface water</p>	Off-site	Essential

6.3.1e	Utilise landform modelling to predict extent of suspended sediment transport to off-site environment <i>How far, to where and how much suspended sediment will be transported by surface water?</i> This will depend on or be influenced by elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins), and can potentially be predicted using landform evolution modelling (including iteration during landform design).	3.1.7 & 4.1.4 Suspended sediment via the surface water	Off-site	Essential
6.3.1f	Improve understanding of the role of surface water in transporting suspended sediment to the off-site environment <i>How much suspended sediment will be transported to the off-site creek channels and billabongs? Will there be a temporal component to this as water quality coming off the landform changes? Related, to what extent will salinity/conductivity affect suspended sediment behaviour (e.g. flocculation/deposition v suspension/flushing)?</i>	3.1.7 Suspended sediment via the surface water	Off-site	Essential
6.3.1g	Contribution of suspended sediments from land application areas <i>How much suspended sediment may be derived from land application areas?</i> Land application areas (LAAs) represent a significant proportion of the Ranger site. The areas of LAA remediation will be determined by contaminated site assessments. This needs to be known (in addition to the area of other disturbed areas – e.g. tracks, roads) and, if the area is considered to be significant, suspended sediment loads off these surfaces may need to be determined in order to predict the impact to aquatic ecosystems.	3.1.6 , 3.1.7 , 4.1.3 , & 4.1.4 Bedload and suspended sediment via the surface water	Landscape	Essential
6.3.1h	Assess the effect of riplines on erosion <i>What effect do riplines have on erosion?</i> Riplines on the rehabilitated landform will increase surface roughness and therefore reduce water flow and, potentially, suspended sediment transport, but may also reduce the aesthetic value and traversability of the landform. There is a need to understand the impact of rip lines (including mound height, distance between rips) on erosion of the rehabilitated landform, and if or how this compromises aesthetics and traversability.	3.1.6 , 3.1.7 , 4.1.3 , 4.1.4 & 6.1 Bedload and suspended sediment via the surface water & Landform stability	Landscape	Essential
6.3.1i	Understand the impact of flood events in Magela Creek on the Pit 3 landform stability <i>How will hydrodynamics of Magela Creek during low frequency high discharge events impact the Pit 3 landform area with respect to scour and slope instability (which will deliver bedload and suspended sediment load to Magela Creek)?</i> This could be assessed using hydrodynamic modelling. Related issues include identifying what mitigation measures are proposed/required for this area and whether the access road needs to be retained as a protective structure (or some similar structure).	3.1.6 , 3.1.7 & 6.1 Bedload and suspended sediment via the surface water & Landform stability	Landscape	Essential

6.3.2 Rehabilitation and protection of on-site aquatic ecosystems		Link to Risk Assessment	Spatial scale	Priority
KKN#				
6.3.2a	Apply landform modelling to predict extent of erosion across the landform <i>How much, and where will erosion occur on the landform?</i> Although CAESAR model simulations on conceptual landform designs have been undertaken, the predicted extent of erosion for final agreed landform will need to be modelled, including the influence of extreme rainfall events and their timing/frequency.	6.1.1 Landform instability	On-site	Essential
6.3.2b	Apply landform modelling to predict gully distribution across the landform <i>Where will gullies form on the rehabilitated landform (e.g. over tailings versus elsewhere), how big will they be, and over what timeframes?</i> A specific environmental requirement is that erosion should not result in gullying which may expose contained waste material to the environment within a specified time period. Related, what are the final design criteria for the landform that will minimise gullying (this can be determined through iterative modelling)?	6.1.2 Landform instability	On-site	Essential
6.3.2c	Apply landform modelling to assess erosion characteristics of landform <i>What are the erosion characteristics of slopes other than the 2% slope of the trial landform (e.g. from Tin Camp Creek, natural site and batter slopes at Ranger)?</i> This information is needed primarily to validate CAESAR, and exists in various reports.	6.1.2 Landform instability	On-site	Essential
6.3.2d	Rates of bedload transport off the landform <i>How long do sedimentation basins need to remain functional? How long before the basins fill and what happens if the basins fail?</i> If a basin fills or fails, the stored bedload potentially becomes available to be transported. To answer this, the loss rate of bedload from the landform needs to be known.	4.1.3 Bedload via the surface water	On-site	Essential
6.3.2e	Utilise use of landform modelling to predict extent of bedload sediment transport <i>How far, where and how much bedload will be transported by surface water?</i> This will depend on elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins/other mitigations such as armouring), and can be predicted using landform evolution modelling (including iteration during landform design). Ultimately, the goal should be to design the landform so as to minimise need for sediment structures.	3.1.6 Bedload via the surface water	Off-site	Essential
6.3.2f	Improve understanding of bedload supply from Magela Creek to backflow billabongs <i>How much bedload from Magela Creek is deposited in Georgetown and Coonjimba billabongs?</i> The relative contributions of bedload sediment from the mine-site and from off-site needs to be established in order to determine how closure criteria will be met. This should be contained in the literature but, if not, the determination of natural infill rates of billabongs will also inform this knowledge need.	4.1.4 Bedload via the surface water	On-site	Desirable
6.3.2g	Improve understanding of the role of surface water in transporting suspended sediment to the on-site environment <i>How much suspended sediment will be deposited in sediment basins and the on-site creek lines and billabongs?</i> Will there be a temporal component to this as water quality coming off the landform changes? Related, to what extent will salinity/conductivity affect suspended sediment behaviour (e.g. flocculation/deposition v suspension/flushing)?	4.1.3 Suspended sediment via the surface water	On-site	Essential

6.3.2h	Utilise landform modelling to predict extent of suspended sediment transport to the on-site environment <i>How far, where and how much suspended sediment will be transported by surface water? This will depend on or be influenced by elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins, and can potentially be predicted using landform evolution modelling (including iteration during landform design)).</i>	4.1.3 Suspended sediment via the surface water	On-site	Essential
6.3.2i	Model the effects of rainfall scenarios to the final landform <i>Under what scenarios might a mass movement be expected (e.g. extreme rainfall seismic event, undermining of landform near Pit 3)?</i> Some landform design elements, such as slope, can mitigate the likelihood of mass movement. However, the optimum slopes to mitigate these risks are not known. Most mass movements of waste rock do not move materials very far. However, finer-grained materials may potentially be transported further.	6.1.1 Landform instability	On-site	Essential
6.3.3 Rehabilitation and protection of on-site terrestrial ecosystems				
KKN#		Link to Risk Assessment	Spatial scale	Priority
6.3.3a	Calibrating and collating drivers of instability for landform modelling <i>What are particle size characteristics of the proposed surfaces on the landform? Particle size can have significant effect on erosion rates. Consequently, there is a need to know the particle size distributions (PSDs) for other surfaces of relevance on the rehabilitated landform (e.g. rock armoured surfaces and also rates of particle breakdown through weathering, vehicle traffic, and animal movement).</i> <i>What is the effect of surface roughness on erosion? Surface roughness reduces flow velocities and erosion potential. It is important to understand how and the extent to which surface roughness affects runoff and erosion, and to use this knowledge to help determine the type and location of effective erosion mitigation options (e.g. ripping and surface armouring).</i> <i>What is the optimal landform shape that will reduce erosion? Slope form influences erosion and deposition. It is important to know the optimal type of slope and landform shape to minimise erosion.</i> <i>What is the effect of removing subsurface material? Theoretically, removal of finer grained sub-surface material can contribute to surface erosion. Consequently, it might be important to understand the relevance/importance of this, and whether it represents a significant risk to erosion on the rehabilitated landform.</i>	6.1 Landform stability	On-site	Essential
6.3.3b	Assessing the likelihood and extent of mass movement on the rehabilitated landform <i>Under what scenarios is mass movement likely to occur? For mass movements, the risks to vegetation are across all post-decommissioning timescales, through removal and/or burial of vegetation and substrate (in addition to those for gullyng, above). Therefore, it will be important to know the scenarios under which a mass movement might be expected (e.g. extreme rainfall seismic event, undermining of landform near pit 3). For these, which factors can be controlled through landform design?</i>	6.1 Landform stability	On-site	Essential
6.3.3c	Utilise landform modelling to assess effect of climate change <i>What effect will climate change/variable rainfall have on the landform? Erosion characteristics of the rehabilitated landform across a full range of rainfall scenarios (including climate change scenarios), and the impacts of this on vegetation community establishment, are unknown and need to be modelled.</i>	6.1 Landform stability	On-site	Essential

6.3.3d	<p>Assessing the likelihood and extent of possible consolidation and subsidence of the rehabilitated landform</p> <p><i>Where and how much consolidation will occur on the landform?</i> The degree of subsidence over Pits 1 and 3 might influence erosional processes. An understanding of the significance of subsidence on vegetation community establishment is needed. This will require some knowledge of predicted location and extent of consolidation over the pits.</p>	6.1 Landform stability	On-site	Essential
6.3.3e	<p>Understand the effect of landform stability on development of healthy vegetation communities.</p> <p><i>How can landform stability affect vegetation community development?</i> The risk of weed (undesirable species) invasion in areas of significant erosion and vegetation disturbance/loss, and its effect on the natural vegetation community establishment, needs to be assessed. It is recognised that a potential feedback loop exists, whereby the establishment of a particular vegetation type – such as weeds – may impact on landform stability – and this may in turn impact on vegetation community development – and may need to be investigated further.</p>	6.1.2 Landform instability	On-site	Essential
6.3.3f	<p>Identify effects of sea level rise on landform stability</p> <p><i>What effect will sea level rise have on landform stability?</i> There is a need to confirm projected sea level changes over 10,000 years, how this will affect saltwater intrusion onto and hydrodynamics of the Magela floodplain, and any subsequent implications (e.g. backwater effects) on erosion and deposition at the margins of the rehabilitated landform.</p>	6.1 Landform stability	On-site	Essential
6.3.3g	<p>Understanding interactions between the final landform and groundwater movement</p> <p><i>How will groundwater movement interact with and/or be influenced by the final landform?</i> Current landform modelling focuses on erosion of the final landform surface (i.e. gully formation and sediment transport and deposition). However, the final landform will also interact with groundwater, affecting its location and movement. Related aspects that need to be considered include recharge rates, break of slope erosion at susceptible locations (e.g. at the intersection of the final landform with the natural Koolpinyah surface), perched aquifers and evapoconcentration of salts at zones of surface expression. This may have implications for both terrestrial (i.e. landform stability and revegetation) and aquatic ecosystems.</p>	6.1 Landform stability	On-site	Essential

6.4 Flora and Fauna		Link to Risk Assessment	Spatial scale	Priority
6.4.1 Rehabilitation and protection of on-site terrestrial ecosystems				
6.4.1a	Identification and characterisation of the source of weeds (off-site) <i>What weeds are present in the surrounding off-site environment (Kakadu National Park)? What are the densities of weed species in the off-site surrounding environment (Kakadu National Park)?</i> There are no systematic surveys of weeds in the adjacent off-site environment. The only dataset containing terrestrial weeds for the Magela catchment is a point dataset of 'sightings' spanning 2001-2012. The use of ultra-high resolution remote sensing should be investigated to obtain a current and quantitative dataset for the adjacent off-site area and to ascertain whether Kakadu National Park is a source for invasive weeds for the Ranger Project Area. Assessments should be undertaken in both disturbed and 'undisturbed' areas off-site. As described for the on-site source of weeds (KKN 5.4.1a) hazard assessments should be undertaken for weeds that are a risk to the rehabilitated site.	6.2.4 Weeds via multiple pathways	On-site	Essential
6.4.1b	Factors for successful recruitment and regeneration in waste rock <i>Can waste rock as the primary growth substrate maintain long-term species diversity through recruitment and regeneration? Are there other factors that need to be considered/manipulated to encourage the successful recruitment and regeneration of plants on the revegetated waste rock?</i> Some species on the 'agreed' species list might not persist on the waste rock substrate resulting in the species composition on the rehabilitated areas being different to that in the surrounding environment. Long-term monitoring of the trial landform (TLF) and exploring opportunities for further intervention with respect to testing establishment from seed, presents the opportunity to provide data towards answering this question. As the waste rock substrate is not present in the surrounding environment, the species composition on these areas of the mine footprint is unlikely to mirror that of the surrounding environment. However, there may be methods of encouraging recruitment and regeneration to increase the probability of attaining and retaining the levels of species diversity that are characteristic of the surrounds.	6.2 Multiple stressors	On-site	Essential
6.4.1c	Determining the potential for nitrogen to be a limiting factor for sustainable nutrient cycling in waste rock <i>In the waste rock substrate, is nitrogen a potential limiting factor to sustained growth in the medium- and/or long- term? What is the nitrification rate and nutrient capital of the waste rock substrate?</i> The waste rock contains less nitrogen and carbon than natural soils and represents a highly leached and leachable environment. A nitrogen maintenance regime may be required for a period of time if there is a projected deficiency as a result of the dilution of plant nitrogen concentrations due to a lag in the timing at which effective nitrogen cycling processes in the waste rock develop. Ongoing monitoring of processes that provide evidence of progression to a self-sustaining nutrient cycle will be required and the relative contributions of legumes and other nitrogen-fixing species to the nitrogen economy will support the refinement of the species composition list. The monitoring of foliar nitrogen concentrations (and those of other limiting elements) can be a predictive tool for nitrogen (and other nutrient) deficiencies from which a potential criterion could be developed.	6.2.1 Nutrient availability	On-site	Essential

6.4.1d	Plant available water limitations to substrate properties and position in the landform <i>What are the characteristics of waste rock required to maintain plant available water?</i> Plant available water (PAW) studies on the trial landform (TLF) have demonstrated a limited water holding capacity and that dry-season duration is critical for revegetation success. Despite uncertainties in measurements and modelling, the TLF studies indicate that the waste rock may support mature vegetation over short dry seasons; however PAW deficits resulting from longer dry seasons are unlikely to support vegetation communities similar to analogue sites. Research has shown that 77% of the years over a 113-year rainfall record have a longer dry season duration wherein PAW (in 4m of waste rock) may not support a vegetation community similar to that found in the analogue sites. Research is required to determine the minimum depth and characteristics of the waste rock root zone needed to provide greater certainty of sufficient PAW to support and sustain a mature vegetation community under climatic extremes. Additional knowledge needs should be focused on a temporal analysis of weathering of waste rock (type of clays), particle size distribution and pore size and how this affects the distribution of PAW temporally and spatially throughout the waste rock profiles and across the contrasting and varied positions in the reconstructed landform.	6.2.1 Water availability	On-site	Essential
6.4.1e	Establishing understorey in revegetated areas on waste rock <i>How do we successfully establish understorey species in revegetated areas? At what stage of revegetation do we introduce understorey species?</i> If the establishment of an understorey is important for long-term ecosystem and habitat function, specialist knowledge is required for understanding how to establish the right types of understorey species for overall revegetation success. Vigorous understorey vegetation can increase the carrying capacity and intensity of a fire, and so the establishment of an understorey in revegetated areas needs to be timed (and managed) so that the framework tree species are old enough to be resilient to fire.	6.2.1 Species diversity	On-site	Essential
6.4.1f	Revegetation exposure to contaminants (including magnesium sulfate) <i>What areas of the rehabilitated site are susceptible to increased contaminants (including magnesium sulfate) exposure?</i> The integrated surface and ground water modelling should identify areas that pool mine water and are potential hotspots for increased concentrations of magnesium sulfate. In addition, a model with appropriate spatial and temporal resolution will be able to provide a prediction of pulse exposure. The plant species to be grown in these areas can be assessed for tolerance and suitability. The current species planting list identifies two phases of revegetation (different species composition 'mixes') in recognition that different species will tolerate wetter areas as they emerge. This research informs the design structure of vegetation communities across the whole site.	6.2.1 Contaminants via surface and groundwater	On-site	Essential
6.4.1g	Transitioning the Ranger Project Area from asset protection to landscape management of fire <i>What is the most appropriate fire management regime to adopt to ensure the success of revegetation and protect wildlife and vegetation across the Ranger lease and the buffer zone between the Ranger lease and Kakadu National Park? How do we transition the Ranger Project Area from asset management to landscape management in the context of fire and site rehabilitation and closure?</i> In the early stages of revegetation, managing fire (exclusion) is critical to the success of revegetation. With the large spatial extent of fires in the region, management of fires is a cross-jurisdictional issue and needs to be managed for revegetation success at multiple scales. This is an important knowledge need that takes into account all the science from the above KKNs as well as reviewing existing knowledge.	6.2.2 Fire	On-site	Essential
6.4.1h	Identification and characterisation of the source of feral animals (off-site) <i>What feral animals are present in the surrounding off-site environment (Kakadu National Park)? What are the densities of feral animal species in the off-site surrounding environment (Kakadu National Park)?</i> A recent aerial survey (2015) of feral animals was undertaken for Kakadu National Park. These data have not been analysed to characterise the nature or the magnitude of the source in the off-site environment. This dataset should be reviewed and analysed to characterise the source of feral animals off-site.	6.2.3 Ferals via multiple pathways	On-site	Essential

6.4.1i	Potential for the rehabilitated site to become a refuge for feral animals <i>Can the rehabilitated site become a refuge for feral animals?</i> A review focused on case studies (if there are any existing studies) from other rehabilitated mines on feral animal utilisation and associated impacts is required. The context of the review is to determine whether the Ranger Project Area may become a refuge for feral animals compared with the surrounding landscape once active management of the site ceases during post decommissioning.	6.2.3 Ferals via multiple pathways	On-site	Essential
6.4.1j	Habitat utilisation by threatened species on the rehabilitated site <i>Could the rehabilitated site become an ecological trap for threatened species?</i> It is not known whether species may move into the rehabilitated area, into what appears to be suitable habitat, but is actually poor habitat and results in further species decline. Other knowledge needs relating to this and threatened species in particular may be: <ul style="list-style-type: none">• Which threatened and/or significant species currently use habitat surrounding the rehabilitated site?• Are these species likely to utilise the rehabilitated site, and for what purpose (i.e. nesting, foraging, and dispersal)?	6.3 Multiple stressors	On-site	Desirable

7 Monitoring to assess closure criteria

7.1 Water and Sediment

7.1.1 Protection of off-site aquatic ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
7.1.1a	Groundwater monitoring to validate groundwater models and as an early indicator tool <i>Can we use a groundwater monitoring program to validate groundwater models and as early-warning indicators of impacts on surface waters?</i> A refined surface and groundwater monitoring program needs to be developed for the primary purpose of validation of the existing models and calibration/validation of any future models. Design of the program should be informed by existing datasets, water management plans, groundwater annual reports, groundwater modelling and groundwater conceptualisations, and operational phase monitoring program designs. The final monitoring design should be fit to fulfil multiple purposes, including early warning of contaminant migration into surface waters.	3.1 Contaminants via multiple pathways	Off-site	Essential
7.1.1b	Relationship between turbidity and suspended sediment at off-site waterbodies <i>Can turbidity be successfully used as a surrogate for suspended sediment measurement at off-site waterbodies?</i> The key measurement endpoint should be turbidity as a surrogate for suspended sediment, at statutory or at other priority monitoring points in creeks and/or billabongs. Related, there is a need to establish new, and/or update existing, site-specific relationships between suspended sediment and turbidity. The specifics of an associated monitoring program will need to be considered, but initial relationships have been developed for Magela Creek.	3.1.7 Suspended sediment via surface water	Off-site	Essential
7.1.1c	Understand the morphological changes in Magela and Gulungul creeks <i>What are the channel morphological changes in Magela and Gulungul creeks?</i> Morphological changes occur naturally within Gulungul and Magela creeks. There is a need to understand the natural rates of change in the creeks to determine if change is increased/accelerated due to bedload movement off the minesite. Off-site morphological impacts of bedload movement are likely to be infilling and deposition, potentially resulting in habitat changes. Morphological change in the creek should not differ from the natural rates or pre-rehabilitation rates due to increases in bedload transport.	3.1.6 Bedload via the surface water	Off-site	Essential

7.1.2 Rehabilitation and protection of on-site aquatic ecosystems

KKN#		Link to Risk Assessment	Spatial scale	Priority
7.1.2a	Site-specific relationships between suspended sediment and turbidity <i>Can turbidity be successfully used as a surrogate for suspended sediment measurement at on-site waterbodies?</i> The key measurement endpoint should be turbidity as a surrogate for suspended sediment. Turbidity versus suspended sediment relationships need to be developed for the key water bodies (in order to be able to compare modelled suspended sediment outputs with turbidity closure criteria). A turbidity versus suspended sediment relationship exists for Georgetown Billabong, but may need to be developed for Coonjimba Billabong. Related, what should an on-site turbidity monitoring program look like? There is a need to determine if relationships are site-specific or applicable to all similar water bodies.	4.1.4 Suspended sediment via surface water	On-site	Essential

7.1.2b	Site-specific relationships between suspended sediment and turbidity <i>What is the site-specific relationship between suspended sediment and turbidity?</i> Monitoring for acceptability of erosion on-site (excluding gullies over tailings) is best done through measuring turbidity as a surrogate of suspended sediment at statutory monitoring points in billabongs and/or creeks. The specifics of an associated monitoring program will need to be considered.	4.1.4 Suspended sediment via surface water	On-site	Essential
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7.2 Landform		Link to Risk Assessment	Spatial scale	Priority
7.2.1 Rehabilitation and protection of on-site terrestrial ecosystems				
7.2.1a	Monitoring the final landform for geomorphic stability <p><i>How can we assess and measure the stability of the final landform?</i> Metrics for monitoring landform construction and assessing the evolution of the landform are required for closure criteria and ongoing monitoring. New technologies, such as UAV derived LiDAR have the capability to capture high resolution Digital Elevation Models of the landform surface at an appropriate scale for such assessments and monitoring. Additionally in-situ monitoring technologies will be investigated. The Pit 1 landform will be used to develop the monitoring methodologies which can then be applied to the whole of landform.</p> <p><i>What is the threshold of gully size for invoking quantitative analysis of gullying?</i> Annual monitoring of the rehabilitated landform for gullies (i.e. gully formation – size and distribution) will be required. Appropriate metrics are required to monitor closure criteria for gully formation and may be developed using new technologies.</p>	6.1.1 Landform stability	On-site	Essential

7.3 Flora and Fauna		Link to Risk Assessment	Spatial scale	Priority
7.3.1 Rehabilitation and protection of on-site terrestrial ecosystems				
7.3.1a	Refinement and development of metrics and monitoring methods for weeds <i>How can we measure and monitor weeds and their impact on vegetation in a robust and cost-effective manner?</i> Metrics for monitoring weeds are required for closure criteria and ongoing monitoring. There are new technologies that can be used to measure and monitor weeds at the landscape scale but require further research and development. For example, UAVs have the capability to map and identify weeds in a systematic and cost-effective manner at appropriate scales for management and assessing closure criteria. As part of the research and development it will important to identify which weed species can be monitored using remote sensing and those that will require another monitoring method. This knowledge need is also linked to KKNs 5.4.1a and 6.4.1a relating to the identification and characterisation of the source of weeds both on-site and off-site.	6.2.4 Weeds via multiple pathways	On-site	Essential
7.3.1b	Spatial and temporal scales for assessing impacts of landscape factors (e.g. fire, weather, initial conditions and feral animals) on revegetation <i>What are the most appropriate spatial and temporal scales to assess impacts of landscape factors on revegetation?</i> There are a number of landscape factors that can impact revegetation on the rehabilitated site. These landscape factors include fire, weather, feral animals and pests, and initial conditions (associated with a waste rock substrate) on the revegetated areas. The impact of these landscape factors can be measured at multiple spatial and temporal scales. Quantitative measures of the variables associated with landscape factors, along with vegetation density and composition will provide predictive ability to determine what factors affect the success of revegetation. Pit 1 will be used as a learning to inform (where possible) Pit 3 rehabilitation.	6.2 Multiple stressors	On-site	Essential
7.3.1c	Refinement of monitoring techniques for fire and its impacts in assessing vegetation trajectory during post-decommissioning <i>What are the most appropriate techniques to ensure appropriate and effective monitoring continues as required in the post-decommissioning phase?</i> Fire and its impacts will need to be monitored on the Ranger Project Area during post-decommissioning in a scientifically valid and cost-effective and time efficient way. This monitoring activity will need to occur until the vegetation communities in disturbed areas on-site have been shown to be meeting an agreed trajectory as determined through the closure criteria for flora. Fire regime (frequency, timing and severity) metrics can be derived from the existing literature for savannas in northern Australia. A multi-scaled remote sensing approach will be investigated, based on existing monitoring tools, and the use of UAV derived imagery will be included in this approach.	6.2.2 Fire via human and non-human pathways	On-site	Essential
7.3.1d	Development of monitoring techniques for revegetation closure criteria <i>How can we measure and monitor vegetation in a robust and cost-effective manner?</i> There is a requirement to assess and monitor revegetation from the outset of rehabilitation. Attributes and associated parameters to be monitored over time include: community structure (species composition, relative abundance and density); vegetation architecture (stratification, tree distribution); absence of threats (weed composition, abundance and density); and sustainability (recruitment, nutrient cycling, plant available water, and resilience to fire). This knowledge need is focused on developing an integrated ground (field) and UAV- based approach to measuring and monitoring revegetation on the rehabilitated site. Research to date has shown that UAV derived data is suited to monitoring plant mortality and volunteers (recruits) in revegetated areas at the site scale.	6.2 Multiple stressors	On-site	Essential

Other sites

Relative to research needs for the current operations and rehabilitation of Ranger, there are no imminent research or monitoring KKNs for Jabiluka, Nabarlek, the South Alligator Valley or exploration in the region. For details see Appendix 8, sections 8 - 11. However, KKNs for Nabarlek will be revisited in 2017.

Appendix A Detailed risk-based justification for the Key Knowledge Needs

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Ranger

Operations and decommissioning

1 Protection of the off-site environment

1.1 Research

Under current approvals, mining operations at Ranger must cease in January 2021. A screening level assessment of stressor pathways for the operational phase at Ranger mine was undertaken in 2013 (Bartolo et al 2013⁴). At least six significant stressor pathways were identified:

- inorganic toxicants seepage to groundwater to surface water pathway;
- inorganic toxicants via the surface water to surface water pathway;
- inorganic toxicants via the airborne emissions pathway;
- radionuclides via the surface water to surface water pathway;
- radon-222 and radon decay products pathway; and
- transported sediments via the surface water to surface water pathway.

Decommissioning of the Ranger mine began with the exhaustion of resources in Pit 3 and the commencement of its backfill. As such, the decommissioning phase is running simultaneously with operations. A screening level assessment of stressor pathways for the decommissioning phase essentially identified two high or critical risks under mitigated scenarios:

- i. solutes via the groundwater to surface water pathway impacting off-site water quality, biodiversity and terrestrial habitat function; and
- ii. weeds impacting off-site terrestrial habitat diversity & ecosystem function.

ERA and SSB undertake routine monitoring for all the above pathways and stressors, and much research has been completed to inform, improve and understand the monitoring results (probably with the exception of the inorganic toxicants via the airborne stressor pathway– see Section 1.1.3.). Thus, much of the knowledge to ensure the protection of the environment from current operations exists.

Notwithstanding the existing knowledge base for environmental issues pertinent to current mine operations and decommissioning, new knowledge is often required as new issues emerge. Such issues have been identified through routine monitoring, audit and inspection programs and sometimes follow incidents. Recent examples of known potential risks that have emerged over the past 3 years include risks associated with groundwater pathways as well as that of fire. For groundwater pathways, this includes identification of expression of high solute waters from groundwater in the vicinity of the Tailings Storage Facility (TSF), an issue that has required significant investigation,

⁴ Bartolo R, Parker S, van Dam R, Bollhöfer A, Kai-Nielsen K, Erskine W, Humphrey C & Jones D 2013. Conceptual models of stressor pathways for the operational phase of Ranger Uranium Mine. Internal Report 612, January, Supervising Scientist, Darwin.

research, monitoring and remedial effort to date to understand and manage. In addition, the need for a greater understanding of the hydrogeology and geochemistry of the groundwater system underlying the processing plant was identified following the leach tank failure incident in 2014. Fire management is a terrestrial risk that has become more apparent over the past two years, with current practices on-site having resulted in uncontrolled fires entering the off-site environment.

In performing its function, one of the key roles of the Supervising Scientist is to develop practices and procedures to ensure the impacts of uranium mining to the environment can be detected and assessed through adequate monitoring and measurement programs. Although the monitoring programs are mature, method refinement and development are important areas of research for the Supervising Scientist, and both are necessary to ensure that the research and monitoring being undertaken are in line with leading practices and principles. This includes ensuring comparability with up to date national and international standards (where applicable), as well as innovative utilisation of current technology.

It is important to note that most of the stressor pathways listed above were also identified as being critical or high risk for the post-decommissioning phases at Ranger. Accordingly, a significant number of research projects are informing knowledge needs across all mining phases. Examples of this include:

- development of site-specific water quality limits for key mine contaminants that are applicable during the operational and decommissioning phases and which will also inform final closure criteria;
- studies on water quality issues in Georgetown and Coonjimba Billabongs that are relevant to Magela Creek water quality during current operations and which will provide critical information to assist with long-term remediation of the billabongs;
- ongoing method development and improvement studies for monitoring and assessment applied during current operations and which will be required to demonstrate the achievement of closure criteria; and
- groundwater studies in the vicinity of the TSF and Gulungul Creek that are addressing current environmental issues as well as generating knowledge to understand the risks of groundwater contaminant pathways post-decommissioning.

Research-based KKNs for current operations are described below according to the key risk pathways.

1.1.1 Risks via the surface water pathway

Ecological risks via surface water pathways (e.g. point source discharge of surface waters from the minesite) have largely been assessed, and surface water discharges are actively managed in accordance with the associated knowledge. More recent knowledge needs included derivation of (i) water quality limits for ammonia and manganese, mainly because of the need for approval to discharge treated process water distillate, and (ii) a sediment quality guideline for uranium in billabongs. Work has been completed to fulfil these needs and had either been published or was in preparation for publication at the time of development of the 2016 KKNs. In addition, new knowledge on uranium and radium in the aquatic environment enabled their current water quality limits to be updated in 2015. Current KKNs for understanding and managing risks associated with the surface water pathway are listed below.

KKNs	KKN#
<p>Improving confidence in the ammonia water quality limit</p> <p><i>What is the toxicity of ammonia to local freshwater mussels, and how will this affect the ammonia water quality limit?</i></p> <p>International data indicate that freshwater mussels are particularly sensitive to ammonia. As freshwater mussels are an important component of the local aquatic ecosystem, and are a highly-valued food source for traditional owners, they should be represented in the dataset used to derive the site-specific water quality limit. This knowledge need relates also to the development of a closure criterion for ammonia (see KKN 5.1.1g).</p>	1.1.1a
<p>Validating the application of multiple single toxicant water quality limits</p> <p><i>Is the regulatory use of multiple water quality limits, each based on single contaminant toxicity, sufficiently/overly protective of an environment where multiple contaminants occur together and in varying proportions?</i></p> <p>Much effort has been invested in deriving water quality limits for individual toxicants. However, this approach does not incorporate potential interactive (e.g. additive, synergistic, antagonistic) effects of toxicant mixtures or other modifying effects occurring in the field. As additional limits for new toxicants (e.g. ammonia) are included in the regulatory framework, the continuing rigour of this approach needs to be tested in laboratory and field settings to ensure that it is appropriately protective of the aquatic environment. This knowledge need will also inform the development and application of closure criteria for toxicants.</p>	1.1.1b
<p>Source and cause of acidification events in Coonjimba Billabong</p> <p><i>What is the source and cause of acidification events in Coonjimba Billabong?</i></p> <p>Since about 2002, Coonjimba Billabong has experienced significant early wet season acidification events, with concomitant increases in dissolved metals including manganese and uranium concentrations. Although these water quality perturbations have not resulted in unacceptable water quality at the downstream monitoring point in Magela Creek, this may not be the case in the future. Thus, the source (including potential groundwater sources) and cause of these events needs to be determined in order to understand and manage any risks to the off-site aquatic environment. This knowledge need will also inform requirements for remediation of Coonjimba Billabong during rehabilitation (see section 3.1.2).</p>	2.1.1a
<p>Importance of contaminants associated with suspended sediments</p> <p><i>Are there likely to be off-site impacts associated with mobilisation of uranium and other contaminants from mine-derived sediments in downstream wetlands/deposition zones?</i></p> <p>Some work has been done to quantify concentrations of uranium and other mine-related contaminants associated with sediments in Magela and Gulungul creeks. Long-term turbidity monitoring has shown that the operational mine is not a significant source of suspended sediment to the creek systems, however suspended sediment delivery to the creeks may increase significantly during and after rehabilitation. This work will enable ongoing assessment of loads of sediment-bound contaminants transported off the minesite, giving an indication of the potential for off-site impacts related to remobilisation of these contaminants in sensitive downstream sediment deposition zones, such as wetlands.</p>	2.1.1b
<p>Temporal trends in sediment uranium concentrations in Georgetown and Coonjimba billabongs</p> <p><i>How do U concentrations change over time?</i> Uranium is the key Contaminants Of Potential Concern (COPC) in billabong sediments and readily binds to organic matter and benthic sediments. An analysis of the temporal trends in U concentrations in the sediments of the two on-site backfill billabongs will provide essential information that will determine if closure criteria for sediment quality will be met.</p>	2.1.1c

1.1.2 Risks via the groundwater pathway

Understanding the risks to the off-site environment via the groundwater pathway represents a major current focus for environmental protection from current operations and decommissioning. Groundwater monitoring and investigation across the site have occurred for many years, albeit not in the context of informing, nor being informed by, a conceptual whole-of-site model (which is currently under development). Whilst significant data and knowledge exist, the risk of contaminants reaching the off-site environment via groundwater pathways is not yet fully understood. Focus areas for investigation have included the TSF, the mine pits, the processing plant area and the

Land Application Areas (LAAs). A review of groundwater-related research needs was recently completed by SSB⁵. In addition to the whole-of-site conceptual model and more detailed analysis of hydrogeological and hydrogeochemical conditions, the review highlighted several other needs, including:

- identification of possible ameliorative approaches to prevent contaminants, including those arising from the final landform, reaching the off-site environment via the groundwater pathway;
- an understanding of existing and potential future groundwater-surface water interactions, particularly within key surface water channels around the Ranger site; and
- an understanding of the potential geochemical and dynamic behaviour of groundwater in the different layers of the final landform and its interaction with adjacent groundwater and surface water bodies.

Recently, new groundwater issues have emerged around the TSF and Corridor Creek LAAs, prompting a series of knowledge needs that will inform current operations and decommissioning as well as rehabilitation and closure. Also, investigations into the leach tank failure incident in 2014 identified deficiencies in the understanding of the nature and extent of existing contaminant plumes in the aquifers below the processing plant. A further issue is that of transport of mine solutes in the sub-surface flow of Magela Creek sand channel throughout the dry season. These and other groundwater-related KKNs for the operational phase are listed below.

KKNs	KKN#
<p>A hydrogeological conceptual whole-of-site model for current operations</p> <p><i>How does the current hydrogeological and hydrogeochemical condition of the minesite aquifers define the nature and extent of groundwater movement, groundwater/surface water interaction, existing contaminant plumes and geochemical reactivity, and as such enable identification of key groundwater pathways for mine contaminants?</i></p> <p>A significant amount of groundwater data and information has been collected throughout the mining phase at Ranger, however this data and information has not been well integrated for the purpose of assessment of key hydrogeological functions (such as groundwater/surface water interactions) nor the definition and clear delineation of existing groundwater contamination. This needs to be done in association with the current operational minesite, taking into account, amongst other things, appropriate background concentrations, the effects of open pits and rock stockpiles on groundwater head across the site. Once this model has been completed it will provide the basis for numerical modelling (e.g. solute transport modelling) and further conceptualisation throughout the decommissioning of the site and the effects that changes to surface structures may have on groundwater movement. This knowledge need will feed into similar needs for the post-decommissioning phase also (see KKNs 3.1.2b and c).</p>	<p>2.1.2a</p>

⁵ Lytton, L. & Marshall, S (2015) Critical Groundwater Research Needs For Ranger Mine and the Alligator Rivers Region. Internal Report 641, July, Supervising Scientist, Darwin.

KKNs	KKN#
<p>Dry season sub-surface water quality in the Magela Creek channel sand bed</p> <p><i>What is the source, extent (longitudinal, lateral, depth), rate of movement and residence times of current mine solute contamination in the sub-surface dry season flows in Magela sand channel downstream of Ranger, are there impacts associated with this contamination, and how might this information inform knowledge needs for closure?</i></p> <p>Mine-derived solutes have been measured at elevated concentrations in the sub-surface dry season flows in Magela sand channel downstream of Ranger. In the case of Mg, values exceeded surface water limits at MCDW in December 2015. Detailed spatial characterisation is required to determine the extent of this contamination, and to determine whether it is seasonal only, or indicative of long-term residency along the creek channel and through the sand depth profile. Characterisation of the hyporheic fauna and possible stygofauna present in the sands is also required for impact and risk assessment. Information arising from a study of current contamination should serve as important knowledge for assessing risks associated with groundwater expression of contaminants in Magela Creek predicted in the long-term (peaking 300 years after closure) from Pit 3 closure modelling.</p>	2.1.2b
<p>Source and potential off-site impacts of contaminated groundwaters in the upper Gulungul Creek catchment</p> <p><i>What is the source of groundwater contamination in the GCT2 tributary and what are the off-site impacts of expression of this water into the surface waters of Gulungul Creek?</i></p> <p>Expression of contaminated groundwater from the GCT2 tributary has recently impacted the water quality of Gulungul Creek where high electrical conductivities were measured at downstream sites throughout the 2014/15 wet season. Whilst extensive investigations have been carried out to date more work is required to ensure that the impacts of the groundwater expression are adequately assessed.</p>	2.1.2c
<p>Characterisation of groundwater changes due to irrigation of Land Application Areas</p> <p><i>What are the processes by which contamination in the Land Application Areas can be mobilised and what are the likely consequences to the off-site environment during the decommissioning phase?</i> Mine waters high in solutes have been measured near Corridor Creek LAAs, although they did not have a typical mine signal, i.e. they did not have high $MgSO_4$. An understanding of this issue would inform changes to water management practices that reduce the risks of solutes leaving site?</p>	2.1.2d
<p>Definition and delineation of current groundwater contamination plumes in minesite aquifers)</p> <p><i>What is the current state of groundwater quality in the minesite aquifers in vicinity of the key contaminant sources, including the TSF, the processing plant, ponds, waste disposal areas, etc.?</i></p> <p>Current groundwater contamination plumes in minesite aquifers need to be hydrologically and geochemically defined and spatially delineated. This information can then be used in conjunction with the conceptual whole-of-site model to determine key groundwater pathways for transport of solutes off-site.</p>	2.1.2e
<p>Characterising groundwater quality and movement during decommissioning of water management systems</p> <p><i>What will happen, and over what timeframe, once the site's through-flow water and shallow groundwater interception systems are dismantled?</i> Consideration needs to be given to the hydrological and hydrogeochemical interaction between site waters, including those currently captured by interception systems, and groundwater during decommissioning, which might lead to solutes being transported off-site during the decommissioning phase.</p>	2.1.2f
<p>Potential ameliorative effects on magnesium toxicity</p> <p><i>Will the current Mg limit be protective (or apply to) mine water quality predicted to be released from site during decommissioning, e.g. how will its Mg:Ca ratios vary? Would a better understanding of the effect of Ca on Mg toxicity help derive more accurate GVs?</i> Direct toxicity testing of expressed groundwater showed no effects at concentrations well above the GV for Mg. This was thought to be due to ameliorating factors in the groundwater, primarily Ca, as the Mg:Ca ratios were lower than those used to derive the GV. Hence, an understanding of the Mg:Ca ratio of seepage water from various sources and how this affects toxicity is required. The gathering of field (or semi-field) effects data for mine released waters (including groundwater sources) mixed with receiving waters would provide supporting evidence.</p>	1.1.2a
<p>The contribution of waste rock to groundwater solutes during decommissioning</p> <p><i>Could waste rock be a significant source of solutes to off-site environment through the groundwater pathway during decommissioning?</i> The seepage loadings, concentrations and the fate of solutes from waste rock during decommissioning should be investigated. This may support the hypothesis that the contaminated groundwater expressed at GCT2 is from the walls of the TSF.</p>	2.1.2g

1.1.3 Risks via the atmospheric pathway

The airborne emissions pathway involves the transport of stressors into the surrounding environment via airborne emissions from various point (e.g. processing plant and power station stack emissions) and diffuse sources (ego vehicles) on the mine lease. ERA implements a number of measures in order to mitigate potential risks to receptors associated with this pathway. For inorganic toxicants, emissions of sulfur dioxide and U from stacks on the minesite are monitored against statutory limits. ERA reports its total annual emissions of a range of mine-related metals and other inorganic compounds including ammonia, arsenic, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, oxides of nitrogen, sulfur dioxide and zinc on the National Pollutant Inventory, and reports its stack emissions of U in its quarterly radiation reports.

With regards to U emissions from the calciner and product packing area stacks, ERA data indicate that emissions are typically 0.03–0.3 kg/day, much lower than the emission limit of 1.5 kg/day specified in the Ranger Authorisation. Sulfur emissions, too, have been shown to not be adding to naturally elevated atmospheric levels. An air quality assessment undertaken by ERA for the Ranger 3 Deeps Environmental Impact Statement found that, apart from nitrogen dioxide (NO₂), all atmospheric contaminants of potential concern were below relevant human health guideline values (as per the National Environmental Protection Measure (NEPM) for Air Quality. Whilst there are some short-term (1-hour averaged) exceedances of modelled concentrations of NO₂ close to the minesite (Ranger mine village contractor camp), there are no exceedances of annual averaged concentrations. Ground level concentrations of selected pollutants at discrete receptors comprising public, culturally significant and ecologically significant locations were calculated. Through this air quality assessment contour plots of modelled ground-level concentrations for each identified mine related pollutant was also developed. Generally, atmospheric emissions are not considered a significant risk to the off-site environment.

One KKN related to validating the modelling predictions against monitoring data would reduce the uncertainty attached to the model results and associated impact assessment. The validated model could then be used as a basis for proactive monitoring and management of emissions if required.

KKNs	KKN#
Validation of air quality modelling from mine related emission inventory	2.2.1a
<i>What is the accuracy of the atmospheric models?</i> This knowledge will increase confidence in predictions that mine related atmospheric emissions do not pose a significant environmental risk. This will ensure the model's value as a pre-closure monitoring tool.	

1.1.4 Other risks

A key risk to the site currently is fire. The source is either Kakadu National Park (both managed and unmanaged fires) or the RPA. There is currently one KKN associated with this, however, there is a need to undertake fire monitoring and impact assessment as required.

KKNs	KKN#
Protection of wildlife from inappropriate fire regime <i>What is the most appropriate fire management regime to adopt to protect wildlife across the Ranger lease and the buffer zone between the Ranger lease and Kakadu National Park? There is a body of existing research on fire regimes and fauna in Kakadu National Park. This research should be reviewed in the context of rehabilitation and closure of Ranger minesite to ensure wildlife is protected from inappropriate fire regimes.</i>	2.3.1a

1.2 Monitoring and assessment

Routine, investigative and project-based chemical, biological and radiological monitoring and assessment programs are integral to ensuring protection of the environment during current operations. Important knowledge gained from monitoring and assessment programs will often inform or lead to KKNs. For example, the high temporal resolution of water quality data provided by continuous water quality monitoring generated new knowledge on the nature of mine discharges that led to the need for understanding of magnesium sulfate pulse exposure toxicity and the subsequent development of the novel exposure duration-based framework for setting magnesium water quality limits.

A key role of the Supervising Scientist is to develop, refine and optimise monitoring and assessment methods to improve scientific rigour, Work, Health and Safety practices and resource efficiency. The importance of maintaining leading practice in monitoring, assessment and research is critical to providing sound scientific advice as well as for assuring stakeholders that the environment is being protected. Thus enhancements and efficiencies in the monitoring and assessment programs at SSB and ERA, based on best/leading practice, are actively sought. In some instances, monitoring has ceased where sufficient evidence has indicated this would not compromise the ability of the SSB to ensure environmental protection.

The existing monitoring-based KKNs for current operations are listed below, noting that most will also have relevance to the decommissioning and post-decommissioning phases.

1.2.1 Risks via the surface water pathway

The routine integrated surface water monitoring program includes chemical, physical, radiological and biological monitoring. Laboratory-based analytical and toxicity testing methods are utilised for monitoring and assessment of surface water contaminants, particularly for the development of site-specific water quality limits for key indicators. For water chemistry monitoring, the key development over the past decade was the adoption of continuous monitoring, with research and development commencing in 2005, and the approach formally incorporated into the routine monitoring program in 2010. The biological monitoring program has also been refined over the years, with the cessation of the fish larvae toxicity monitoring and fish bioaccumulation monitoring, and move from creek-side to in situ toxicity monitoring. Analytical methods for measurement of radionuclides (Ra-226 and Ra-228) have been improved and developed, while refinement of toxicity testing methods is an ongoing need (e.g. investigating more sensitive test endpoints, increasing environmental realism), with development of new methods undertaken where the need is considered a priority (e.g. development of a freshwater mussel test and a chronic larval fish growth test). The monitoring and assessment related KKNs are listed below.

KKNs	KKN#
<p>Optimisation of SSB's stream monitoring program</p> <p><i>How can the elements of SSB's routine stream monitoring program be optimised for effectiveness in achieving their objectives and efficiency in their implementation?</i></p> <p>Ongoing review and innovation is required to ensure that the methods utilised in the stream monitoring program are providing useful and reliable information and represent effective use of available resources. This ranges from data collection methods through to data management practices and analytical techniques. Ensuring the use of proven modern technologies for equipment, instruments and methods is a key requirement for optimisation, while recent R&D is considering a range of remote sensing or deployed technology (including drones), videography and genomics techniques that reduce staff time and resources and improve data accuracy and field safety of workers in the measurement programs.</p>	3.1.1a
<p>Refinement and development of laboratory methods used for surface water quality monitoring, assessment and research</p> <p><i>What method development is required to ensure that the Supervising Scientist continues to use best or leading practice approaches to monitoring, assessment and research?</i></p> <p>SSB's programs are abreast of new technologies for increasing accuracy in data acquisition, as well as reducing staff time and resources predominately through the transition from manual operations to automation. Included amongst these new technologies are faster, cheaper and more reliable methods for radionuclide determinations, automation of algal cell counts (ecotoxicology) and sediment particle size distribution (fluvial geomorphology), while high resolution (photo) microscopy enables more accurate counts, measurements and identifications, together with image capture that can be electronically shared with colleagues anywhere in the world.</p>	3.1.1b

1.2.2 Risks via the groundwater pathway

Groundwater monitoring is undertaken by ERA, with the Northern Territory Department of Mines and Energy (NT DME) carrying out annual check monitoring. Nevertheless, the SSB has collected and analysed a significant amount of groundwater data over the past 20+ years, which has recently been compiled and reported on⁶. As noted earlier, ERA undertake their groundwater monitoring program (and analysis of monitoring data) in the absence of a conceptual whole-of-site model, often focusing on certain areas of the site where groundwater risks have been identified. This has resulted in key gaps in knowledge and understanding of whole-of-site hydrogeological processes, which is captured as a KKN (1.1.2a) under the research theme, above. Additional KKNs related to groundwater monitoring are listed below.

KKNs	KKN#
<p>Ongoing improvement and optimisation of groundwater monitoring and assessment methods</p> <p><i>Is the current groundwater monitoring and assessment program sufficient and adequate for achieving related research KKNs throughout all mine phases?</i> Completion of the whole of site model may provide new insights into the volume, concentration and direction of contaminants (from Pits 1 and 3) into the surface water system. These results will need to be reviewed against the current contaminant modelling to ensure the adequacy and veracity of the established monitoring program, including its timing and nature. This should include a review of all potential contaminant sources. Any updated monitoring program is to be developed to allow continual validation of the groundwater model(s).</p>	3.1.2a

1.2.3 Risks via the atmospheric pathway

ERA reports air quality for organic and inorganic chemicals to the National Pollution Inventory each year. The Ranger General Authorisation requires that air quality is measured at operational sites for uranium emissions and sulfur dioxide. Results for these programs and wind direction are reported along with radiation monitoring on a quarterly basis.

⁶ Bollhöfer A, Medley P & Marshall S 2014. A summary and review of eriss groundwater chemistry data at Ranger uranium mine. Internal Report 631, February, Supervising Scientist, Darwin.

Air quality dispersion modelling for the existing operations was reported as part of the Ranger 3 Deeps EIS for particulate matter, dust deposition, sulfur dioxide, nitrogen dioxide and uranium decay products. There are no exceedances of the relevant guidelines for PM_{2.5}, PM₁₀, dust deposition, annual average NO₂, or SO₂ at the sensitive receptors within and surrounding the Ranger uranium mine.

Earlier dispersion modelling of metals from the existing operations showed that levels for on-site and off-site receptors were well below the National Environment Protection Measure – Ambient Air Quality guidelines and/or Victorian environmental protection guidelines.

Comprehensive atmospheric monitoring programs are in place for radionuclides and (at the minesite only) dust. These programs are streamlined and fit for purpose and, at this stage, require no further refinement. There are currently no KKNs associated with these programs.

Post-decommissioning

2. Overarching knowledge needs

2.1 Cumulative risk for on-site and off-site ecosystems

In order to place potentially adverse on-site and off-site issues at Ranger during the decommissioning and post decommissioning phases within a risk management context, a robust risk assessment framework was developed with stakeholders. Multiple conceptual models of transport/exposure pathways for risks were developed and these models recognised the potential that some environmental stressors from the minesite could affect the park and vice versa. Implicit in this process should be consideration of the effects of extreme events and climate change.

The conceptual modelling was followed by a screening process to identify and prioritise key risks. The conceptual models are linked to closure criteria and post-decommissioning monitoring programs, and should be periodically tested and improved. Where appropriate, risk assessments should be incorporated into decision making processes for the closure plan. Outputs and all uncertainties from this risk assessment process should be effectively communicated to stakeholders.

Ecological risks associated with rehabilitation and closure of Ranger should be assessed within a landscape analysis framework to provide context in relation to more diffuse threats associated with large-scale ecological disturbances, such as invasive species, unmanaged fire, cyclones and climate change.

KKNs	KKN#
Cumulative risks for the landscape	4.1a
<i>How do we quantify cumulative risk and what are the most appropriate methods for analysis and communication?</i> It is important to assess cumulative risk as examining risks individually does not address the interaction between risks and their iterative effects. An integrated conceptual model should be developed to capture the interactions between multiple risks (e.g. landform stability, revegetation and contaminant exposure) and assessment endpoints (receptors) at multiple scales for the minesite in the first instance and in the surrounding offsite environment thereafter. The foundation for this will be the conceptual models from the rehabilitation and closure risk assessment undertaken to date (Appendix A). The integrated model and assessment should be continually tested and improved as part of best practice. This process should also integrate outputs from all other KKNs to provide a landscape-scale context for the rehabilitation of Ranger in the context of Kakadu National Park, and should be communicated to stakeholders.	

2.2 Understanding how the World Heritage Values for which Kakadu National Park is listed can be met by the rehabilitated Ranger Project Area

The primary environmental objectives in the Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine state that

“the company must rehabilitate the Ranger project area to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park”.

The primary ERs also direct that the World Heritage Values of the park and Ramsar status of the wetlands are to be protected, but that impacts on the RPA can be as low as reasonably achievable. The World Heritage Values of Kakadu are well documented and

known. However, in order for these objectives to be achieved it is necessary to understand which World Heritage Values apply and how these can be met, or jeopardised, by the rehabilitated Ranger Project Area.

KKNs	KKN#
Characterising World Heritage values of the Ranger Project Area <i>What World Heritage Values are found on the Ranger Project Area and how can they be articulated to help in decision-making for incorporation of the site into Kakadu National Park? There are numerous World Heritage Values for which Kakadu is listed and these can be spatially explicit (e.g. geological setting values relate to the escarpment country). There are areas within the Ranger Project Area that exhibit World Heritage Values for which Kakadu is listed, and documentation of these may assist decision-makers in incorporating the site into Kakadu National Park.</i>	4.2a
Monitoring to ensure the primary environmental objectives for World Heritage Values are met <i>At what spatio-temporal scales do we need to monitor to ensure the primary environmental objectives are met? The system is characterised by inherent variability which will need to be accounted for when assessing whether the Ranger Project Area has met the primary environmental objectives for world heritage values on the RPA (if required), or might compromise those objectives off the RPA. Spatial and temporal scales for each of the primary environmental objectives vary and the science underpinning this variability will be required for the Australian Government to issue closure.</i>	4.2b

3 Protection of off-site aquatic ecosystems

3.1 Water and sediment quality and/or biodiversity of off-site aquatic ecosystems are protected and for, post-decommissioning, are on a trajectory towards meeting agreed closure criteria.

The knowledge needs address both the Ranger ERs and closure criteria relating to water quality. The primary environmental objectives for rehabilitation that this group of knowledge needs (aside from the ERs associated with environmental protection) informs are:

- 1.2 *In particular, the company must ensure that operations at Ranger do not result in: change to biodiversity, or impairment of ecosystem health, outside of the Ranger Project Area. Such change is to be different and detrimental from that expected from natural biophysical or biological processes operating in the Alligator Rivers Region.*
- 3.1 *The company must not allow either surface or ground waters arising or discharged from the Ranger Project Area during its operation, or during or following rehabilitation to compromise the achievement of the primary environmental objectives:*
 - (a) *maintain the attributes for which Kakadu National Park was inscribed on the World Heritage list;*
 - (b) *maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park);*
 - (c) *maintain the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region, including ecological processes.*

3.1.1 The risk of solutes impacting off site ecosystems via the surface water during post-decommissioning

Sources of solutes to surface water

The conceptual model concerning the risk of solutes to off-site ecosystems identified 5 potential primary sources of solutes for the post-decommissioning phase: 1) waste rock in pits; 2) exposed and buried waste rock in the landform; 3) buried tailings and brine contained in the Pits; 4) soils in the Land Application Areas and roads; and 5) (other) legacy sites (e.g. the Tailings Storage Facility (TSF), decommissioned ponds, dump sites and the plant area). Three secondary sources were also identified but they are also considered to be legacy sites: 1) contaminated on-site surface waters; 2) contaminated on-site sediments; and 3) contaminated groundwater. All these sources contain and leach MgSO_4 but they differ in the concentration and mobility of the solutes present and also spatially. Such factors determine the pathway of the solutes and the rate of transport off-site.

Waste rock (in pits and landform) as a source of solutes

Waste rock as a source of solutes has been well characterised through seepage and runoff data collected during the operational phase of the mine. This information has been enhanced with some leaching test work and geochemical modelling. Additional knowledge needs include:

KKNs	KKN#
<p>The contribution of waste rock to surface water solutes during post-decommissioning</p> <p><i>What is the nature and timeframe of (hydro) geochemical reactions in the rehabilitated site? The amount of solutes leached from waste rock is expected to reduce over time. Models are needed to determine how much, and for how long, will solutes leach from the waste rock. The source terms used should be reviewed and, if required, updated with additional information from monitoring and previous geochemical studies. Geochemical modelling used in the Pit 1 and 3 solute transport models may have answered this question but concerns continue to be raised about the completeness of information supporting these source terms and active timeframes. Thus, the adequacy of available information and its application needs to be reviewed and/or communicated.</i></p>	6.1.1e

Land Application Areas and soils as a source of solutes

The Land Application Areas will be remediated during decommissioning and are unlikely to be a significant source of solutes during post-decommissioning.

Buried tailings and brine as a source of solutes

The tailings and brine sources have been well characterised, and solutes from these sources in the pits have been extensively modelled. These sources are not expected to be significant contributors to surface water solutes and no knowledge needs were identified.

Legacy sites as a source of solutes, including secondary sources (contaminated groundwater, surface water and sediments)

Legacy sites will be a significant focus of rehabilitation and the aim will be to reduce their potential to be sources of stressors during the post-decommissioning phase. In order to achieve this, a knowledge need was identified:

KKNs	KKN#
Understanding the different contributions from legacy sites <i>What is the current contamination status of the legacy sites and how will this contribute to off-site solute transport and cumulative whole-of-site impacts?</i> Remediated areas have a more contaminated soil/waste rock profile and contaminants may not have the same mobility as other areas e.g. if a high amount of clay is present. Hotspots of contaminant sources need to be considered, e.g. sulfate or metals from RP1 sediments. This information may need to be incorporated into the site wide conceptual model and the whole-of site-solute transport model.	6.1.1f

Contaminated groundwater and surface waters are significant secondary sources of solutes. The knowledge needs surrounding these sources are covered in the pathways sections.

Solutes as a stressor

The only solute stressor identified as a high risk during the post-decommissioning phase was the solute, MgSO_4 . All the knowledge needs identified for MgSO_4 in the decommissioning phase are relevant. No additional KKNs were identified.

Surface water as a pathway for solutes

Surface water modelling has been conducted for the operational phase of the mine and closure of Pits 1 and 3 but this has not yet been extended to the whole site in the post-decommissioning phase, which will need to account for the final landform and its evolution. The knowledge needs required are:

KKNs	KKN#
Completion of a quantitative surface water model for the rehabilitated minesite. <i>How are contaminants transported off-site via the surface water pathway and what are predicted COPC concentrations in surface water?</i> The model needs to achieve a high spatial and temporal resolution that allows predictions of contaminant concentrations in surface waters that are appropriate for comparison with closure criteria. Ongoing review, calibration, validation and amendment (where required) of contaminant transport model(s) is required for the remaining life of mine and rehabilitation.	6.1.1c

Measurement endpoints

The health of aquatic ecosystems for the operational phase is currently monitored in surface waters through numerous measurement endpoints including; water and sediment quality, macroinvertebrate biodiversity surveys, *in situ* toxicity tests and the bioaccumulation of contaminants in organisms. Water and sediment quality Guideline Values (GVs) for metals and solutes have been derived using laboratory ecotoxicological modelling. Biodiversity indicators are measured in the field at reference and mine-exposed sites during the recession flow periods in order to determine any impact of the mine. Biodiversity field data are also used to validate the accuracy of the ecotoxicologically-derived GV's. *In situ* toxicity is monitored in Magela and Gulungul creeks using the reproduction of an aquatic snail. This endpoint is sensitive to exposure to the contaminants of potential concern (COPC) and the test serves as an early-warning indicator of biological effects occurring in the field. The bioaccumulation of solutes does not occur and this measurement endpoint is not used for solutes. These measurement endpoints continue through the decommissioning phase but the knowledge listed in 1.2.1a and b (continued development of monitoring and laboratory assessment tools) are directly relevant.

As the mine enters into the post-decommissioning phases these measurement endpoints used in the operational and decommissioning phases are likely to form the basis of

closure criteria for the mine. In order to derive appropriate and tangible closure criteria and number of knowledge needs were identified.

KKNs	KKN#
Ensuring closure criteria protect ecosystems	5.1.1a
<i>How are uncertainty and variation in field collected data that have been used to derive single-number GVs or closure criteria for billabongs addressed? Are the current GVs suitable as closure criteria and do they address all potential ecological impacts?</i> The measurement of community responses to solutes in the field is difficult due to the absence of high environmental concentrations of solutes, confounding and/or inherent biological variability. Laboratory-derived GVs model the concentration-responses of a limited number of organisms in the absence of confounding environmental influences, but lack environmental realism including the influence of potential modifying factors, ecological interactions relatively short exposure periods, bias against flow-dependant test organisms, and seasonal changes in water quality and biota. Combining these approaches in weight-of-evidence frameworks, additional single-species testing or semi-field studies increases the confidence in GVs and validates these models.	
Impact of solute plumes on ecological connectivity	6.1.1h
<i>Can a solute plume form a barrier in the creek channels that inhibits organism migration and connectivity (e.g. fish migration, invertebrate drift, gene flow)?</i> Previous studies in Magela Creek have demonstrated avoidance by fish of mine wastewater discharges, indicating potential reduced recruitment to upstream sites. Information on seasonal movement and dispersal of organisms needs to be considered and combined with groundwater contaminant modelling data, in order to assess potential for impaired movement and connectivity in streams.	
Understanding baseline biodiversity of the region	5.1.1b
<i>What should be the agreed reference conditions for biodiversity measurement?</i> In order to determine appropriate closure criteria it would be desirable to gain an understanding of what spatial and temporal change in biodiversity would compromise meeting the Primary Environmental Objectives. Measuring the spatial and temporal variation in water quality and biodiversity of receiving water ecosystems (creek channels and billabongs) throughout the periods of surface water flow and inundation (wet and dry seasons) may inform this; currently biodiversity is only measured during the early dry/recessional flow period.	

3.1.2 The risk of solutes impacting off site ecosystems via the groundwater during post-decommissioning

Sources of solutes to groundwater

Although all the contaminant sources leach the primary COPC, they differ in the spatial distribution, concentration and mobility of the contaminants present. Such factors determine the rate of transport off-site and the pathway of the contaminants, i.e. surface water or groundwater. The following knowledge need was identified.

KKNs	KKN#
Sources of solutes to the groundwater	6.1.1d
<i>Which sources have the largest and most mobile load of contaminants?</i> A comparative assessment of each source is needed. A clear knowledge of the contribution of solute loads from each source will assist the rehabilitation and risk management of the site.	

Solutes as a stressor

The context and knowledge needs for solutes as a stressor are described in 3.1.1.

Groundwater as a pathway for solutes

The movement of contaminants via the groundwater pathway has received increasing attention in recent years. Groundwater modelling of contaminant movement from Pits 1 and 3 has been completed and these will be validated using field data as it becomes available. These models are planned to evolve into whole-of-site and regional scale groundwater conceptual models. A whole-of-site groundwater model will also be integrated with surface water modelling. This will allow an assessment of the cumulative

impact of the whole landform and the tailings containment facilities (Pit 1 and 3). In order to increase confidence in the accuracy of the models' predictions to an appropriate level, the specific knowledge needs include:

KKNs	KKN#
Groundwater modelling of contaminant transport from the Pits <i>How are contaminants transported from the Pits and what is their environmental fate?</i> Continued validation and amendment (where required) of the groundwater models for the tailings containment facilities (Pit 1 and 3) is required for all COPCs. This includes examining the transport of Mg and Ca, and associated implications for the Mg:Ca ratio, which can affect Mg toxicity. Further work is needed to better understand pathways associated with the north face fault/fracture zone, the Djalkmara sands zone and deep carbonate zone of Pit 3, and the MBL zone and LMS carbonate zone of Pit 1. The most appropriate monitoring locations for calibration and verification of models need consideration. Solute transport via the Magela Creek bed alluvial groundwater system requires additional attention due to properties that may facilitate solute transport and increase the risk to the off-site ecosystems.	6.1.1a
Whole-of-site and regional groundwater modelling of contaminant transport <i>How does groundwater move on the rehabilitated site and how do hydrogeological features of the region influence this?</i> Conceptual and numerical models for the whole-of-site and regional (deeper) groundwater movement, including the role of fracturing and geological stratifications at each scale, need to be completed, validated and continually improved as necessary. There remains some ongoing concern in regards to the role the deeper groundwater system (primarily aquifer 3) may play in transporting solutes into the surface water systems. Related to this, the appropriate downstream boundaries for the models need to be reviewed, e.g. inclusion of Mudginberri Billabong or the lower floodplains. The modelling should also be informed by a better understanding of groundwater levels and movement across the site and over time (e.g. seasonally). The times at which legacy and decommissioning issues (e.g. removal of ponds) have the potential to lead to off-site impacts should be considered and included in the models.	6.1.1b

Measurement endpoints

The impact of groundwater transported solutes is likely to be measured primarily using surface water measurement endpoints, i.e. those listed in 3.1.1, and these are likely to provide the basis for the closure criteria. Three groundwater-specific measurement endpoints were identified as potential knowledge needs:

KKNs	KKN#
Groundwater monitoring to validate groundwater models and as an early indicator tool <i>Can we use a groundwater monitoring program to validate groundwater models and as early-warning indicators of impacts on surface waters?</i> A refined surface and groundwater monitoring program needs to be developed for the primary purpose of validation of the existing models and calibration/validation of any future models. Design of the program should be informed by existing datasets, water management plans, groundwater annual reports, groundwater modelling and groundwater conceptualisations, and operational phase monitoring program designs. The final monitoring design should be fit to fulfil multiple purposes, including early warning of contaminant migration into surface waters.	7.1.1a
Characterising hyporheic and stygofauna communities <i>What is the nature and extent of hyporheic and stygofauna communities?</i> The ancestral sands between Pit 3 and Magela Creek bed have high hydrological conductivity and will transport a higher amount of solutes. To date, hyporheic and stygofauna communities have not been researched and the significance of their ecological processes to the biodiversity of the ARR is unknown. If these communities are significant, the impacts of solutes on these communities need consideration. This will help determine if specific closure criteria are needed to protect these communities.	5.1.1c
Effect of groundwater-derived solutes on riparian vegetation and aquatic macrophytes. <i>What is the tolerance of vegetation that will be exposed to elevated solutes for long durations?</i> Dormant vegetation in the banks of the creeks during the dry season may be exposed to contaminated groundwater for periods of months. The GVs for Mg were derived using species that rapidly proliferate, e.g. alga, zooplankton, and are not relevant to this exposure scenario.	5.1.1d

3.1.3 The risk of metals impacting off-site ecosystems via the surface water and groundwater during post-decommissioning

Sources of metals

The sources of metals are the same as those listed for solutes in 3.1.2. and the load of metals in each source has been well-characterised. Hence, the knowledge needs are the same.

Secondary sources of metals

Observations of sulfate-driven acidification events in Coonjimba billabong during the early-wet season have highlighted on-site sediments as a significant potential secondary source of metals, solutes and acidic mine-waters. Due to the nature of flow in Magela Creek, these observations in Coonjimba have not translated to exceedances of water quality GVs at downstream monitoring sites. The management of this issue has received attention for the operational phase, but there are also relevant knowledge needs in order to assess the risks to the off-site environment during post-decommissioning.

KKNs	KKN#
Assessment of acid-sulfate sediments	6.1.1i
<i>What are the current and predicted acid sulfate sediment status and nature and extent of metal contamination in the sediments of on-site water bodies?</i> The predicted SO ₄ budget for Coonjimba and Georgetown billabongs need to be assessed, which would include the SO ₄ sources (e.g. legacy of decommissioned RP1) and pathways (and their contributions).	

Metals as a stressor

The key metals of concern from the mine are uranium (U) and manganese (Mn). An extensive body of knowledge exists regarding the toxicity of these metals to local freshwater species. This includes the effect of Dissolved Organic Carbon (DOC) on U toxicity. However, acidification events in billabongs result in high metal concentrations (especially Mn) and low pH, the effects of which have not been researched to date. The knowledge needs that are required for metal stressors are:

KKNs	KKN#
Effect of billabong acidification on off-site ecosystems	6.1.1j
<i>What is the combined toxicity of low pH, increased solutes and metals on local aquatic organisms and aquatic biodiversity?</i> If acidified waters are shown to reach the off-site environment, then the impact of these waters will need to be assessed. The exposure duration should be considered and the effect of modifying factors of Mn toxicity may need assessment. It may be desirable to determine the impact of these events on the on-site billabong diversity, although this would be a lower priority. The ecological importance of the Coonjimba billabong acidic events and the potential for ecological impacts considering first flush scenarios needs to be considered. An understanding of the natural ASS processes of the analogue billabongs (lowland) in the ARR may inform this.	

Pathways for metals

Metals can be transported off-site via the surface water and groundwater pathways. Dissolved metals are readily transported via the groundwater, although small particulate-bound U (colloidal) may also be transported depending on the porosity of the aquifer. Both dissolved and particulate-bound metals are transported via the surface water. The knowledge needs for the transport of metals off-site are the same as those listed for solutes in 3.1.1 and 3.1.2.

Measurement endpoints

All measurement endpoints listed in 3.1.1 are relevant for metals but some metals may also bioaccumulate in organisms. Although this measurement endpoint is not particularly

useful for ecosystem health, it is useful in assessing human health issues. These measurement endpoints will provide the basis for the closure criteria for metals. No additional knowledge needs were identified.

3.1.4 The risk of nutrients impacting off site ecosystems via the surface water or groundwater during post-decommissioning

Nutrients as a stressor

There is a large body of knowledge concerning the effect of pH on ammonia speciation, and to some extent toxicity, but not for local species. The toxicity of ammonia to local species, and the finalisation of a site-specific GV, was under investigation at the time of this review but not yet complete. The GV will be derived for conditions representative of the creeks but will also include research into the effect of pH on toxicity. This is needed to adapt the GV to billabongs, where pH can be higher.

KKNs	KKN#
Effect of ammonia on local species <i>What is the toxicity of ammonia to local freshwater species (site-specific GV for NH₃) and what is the effect of pH? A water quality GV for ammonia will be derived for conditions representative of the creek, i.e. pH 6 and this will be used to inform closure criteria. However, the pH of billabongs is significantly higher (pH 8), which increases the toxicity of ammonia. Hence, the influence of pH on ammonia toxicity needs to be considered.</i>	5.1.1e

Pathways for nutrients

Nutrients will primarily be transported via the groundwater pathway during the post-decommissioning phase. The Pit 1 and 3 groundwater model used a conservative reaction estimate for ammonia, nitrate and total phosphorous i.e. assumed that all nutrients would reach the creek without attenuation. The potential for these nutrients to cause eutrophication needs to be assessed. The knowledge need identified is:

KKNs	KKN#
Predicting nutrient concentrations in the creek <i>Are concentrations and/or loads of nutrients predicted to enter the creek likely to cause eutrophication? This will probably be achieved through a desktop review of the contaminant transport modelling data and comparable natural inputs.</i>	6.1.1g

Measurement endpoints

The measurement endpoints for nutrients impacting the environment are the same as 3.1.1. The water quality GV for ammonia may be the primary closure criterion for nutrients although this is based on its toxicity and not the risk of eutrophication. The Annual Additional Load Limits (AALL) is a tool used to minimise the risk of eutrophication in the creeks, but is based on natural background loads for nitrate and total phosphorous only. The knowledge need identified was:

KKNs	KKN#
Assessment of Annual Additional Load Limits (AALL) as a management tool for nutrients <i>What is the significance of Annual Additional Load Limits (AALL) to risk of eutrophication? A review of the literature supporting these limits is needed to understand their continuing relevance. Can ammonia loads be considered in the same context as the AALLs, i.e. is there data from the same body of work, or more recent work to compare predicted ammonia loads to?</i>	5.1.1f

3.1.5 The risk of radionuclides impacting off-site aquatic ecosystems during post-decommissioning

Radionuclides from the rehabilitated landform entering off-site aquatic ecosystems may give rise to elevated radiation exposures of aquatic wildlife. Best international practice is

to assess these exposures in order to provide assurance that the ecosystem will not suffer significant adverse radiological impacts.

Sources of radionuclides

The rehabilitated landform is the broad source of radionuclides to off-site aquatic ecosystems. The compartments within the landform from where radionuclides may come are: (i) surface waste rock; (ii) land application area soils; (iii) buried waste rock; and (iv) buried tailings and brines. Radionuclides can be liberated from the host material within each compartment by leaching to infiltrating groundwater and surface water. They may then be transported with the water and enter the aquatic ecosystem. Knowledge is needed of the partitioning characteristics of radionuclides between the host material and infiltrating water in order to quantify environmental availability.

KKNs	KKN#
Partitioning of radionuclides and leach rates <i>What are the leach rates and soil-water distribution coefficients (k_ds) of U and Ac series radionuclides coming from the rehabilitated landform (including land application areas) and how might changes in soil chemistry affect these values?</i> It is essential for surface water and groundwater transport modelling, as well as for assessments based on these model outputs, that the quantities of dissolved radionuclides coming from the landform via each waterborne pathway are known. Leaching characteristics of radionuclides from the host material may be chemistry dependent and should therefore be determined for a range of conditions.	6.2.1d

Radionuclides as stressors

The radionuclides of concern to off-site aquatic ecosystems from the rehabilitated landform are those of the U and Ac series. Radionuclides of the U series have been extensively studied in a human dose context, but not in the context of doses to aquatic wildlife. Radionuclides of the Ac series have received effectively no attention in both the human and non-human biota dose context. The knowledge needs for U and Ac series radionuclides as stressors to aquatic wildlife are to establish the importance of each series and individual radionuclides therein.

KKNs	KKN#
Prioritisation of U series radionuclides <i>What is the importance ranking of individual U series radionuclides in relation to radiation exposures of aquatic wildlife?</i> Prioritisation analysis is essential to determine the most important U series radionuclide(s) and to help focus future research efforts.	6.2.1h

KKNs	KKN#
Importance of Ac series radionuclides for aquatic wildlife <i>What is the importance of Ac series radionuclides (especially ^{227}Ac and ^{231}Pa) in relation to radiation exposures of aquatic wildlife?</i> Ac series radionuclides will contribute to the radiation dose received by aquatic wildlife, but exactly how much is unknown. Knowing the contribution from Ac series radionuclides is essential to provide an accurate estimate of the radiation dose and for the development of closure criteria.	6.2.1j

Pathways for radionuclides

Radionuclides can be transported to off-site aquatic ecosystems via the surface water and groundwater pathways. They can also be transported via the atmospheric pathway in fugitive dusts, but transport via this pathway is considered insignificant based on atmospheric monitoring results. Radionuclide activity concentrations in off-site aquatic ecosystems will depend on loads delivered via the surface water and groundwater pathways, as well as on dispersion and partitioning within the ecosystem. Current surface

water radiological monitoring focuses on ^{226}Ra because of its potential dose importance to traditional owners from the consumption of freshwater mussels. Consequently, operational baseline activity concentrations are available for ^{226}Ra in off-site aquatic ecosystems, but not for other radionuclides (e.g. ^{210}Po , ^{227}Ac , ^{231}Pa) of potential importance to doses to aquatic wildlife. Limited data is also available for deriving sediment-water distribution coefficients of radionuclides in off-site aquatic ecosystems.

KKNs	KKN#
Radionuclide loads to off-site aquatic ecosystems <i>What are the loads of U and Ac series radionuclides (dissolved and particulate) entering the aquatic environment via surface and groundwater pathways? Knowledge of U and Ac series radionuclide loads entering off-site aquatic ecosystems is an essential first step for determining activity concentrations in the ecosystem via dispersion modelling. The activity concentrations are needed to estimate radiation doses to aquatic wildlife and also to people utilising the ecosystem as a bush food resource.</i>	6.2.1b
Radionuclide levels in off-site aquatic ecosystems <i>What is the dispersion and resulting activity concentration of U and Ac series radionuclides (especially U isotopes, ^{226}Ra, ^{210}Po, ^{227}Ac and ^{231}Pa) in off-site aquatic ecosystems? Activity concentrations of radionuclides in water are used to estimate radiation doses to aquatic wildlife and also to people utilising the aquatic ecosystem as a bush food resource. Knowledge of these activity concentrations for U and Ac series radionuclides is essential for dose assessments and the development of radiological closure criteria for water quality.</i>	6.2.1c
Partitioning of radionuclides in off-site aquatic ecosystems <i>What are the sediment-water distribution coefficients (K_ds) of U and Ac series radionuclides and how do they vary with differing physico-chemical conditions? Sediment-water distribution coefficients are an essential parameter in wildlife dose assessments and are used to quantify the partitioning of radionuclides between the sediment and water. Some site-specific data is available for U series radionuclides, but not for Ac series radionuclides. The data that does exist does not cover variability with differing physico-chemical conditions.</i>	6.2.1e

Measurement endpoints

Radiological closure criteria are required for off-site water quality in order to provide adequate protection of off-site aquatic ecosystems against radiation risks. The criteria should ideally be expressed as radionuclide activity concentrations in water so that they are measurable through standard radiometric techniques. The development of such criteria require knowledge of: (i) radionuclide uptake by aquatic wildlife, since this is a key radiation exposure route; and (ii) dose rate benchmarks for aquatic wildlife, since water quality closure criteria for radionuclides are back-calculated from these. Radionuclide uptake in plants and animals has been primarily studied in the context of Aboriginal bush foods. This has resulted in knowledge of radionuclide concentration ratios for specific tissue components consumed by traditional owners. The data are potentially useful for assessing radiation exposures to some aquatic wildlife after conversion to the whole organism level. For wildlife types not consumed as bush foods (e.g. small proliferators such as phytoplanktons and zooplanktons), there is currently no data available for assessments. There is also no data available on uptake of Ac series radionuclides, which recent international evidence suggests could potentially make a significant dose contribution to some aquatic species.

KKNs	KKN#
Water radiological closure criteria <i>What maximum levels of U and Ac series radionuclides in water provide assurance that above-baseline radiation doses to aquatic wildlife will not have significant adverse impacts on off-site aquatic ecosystems? Tangible closure criteria in the form of radionuclide activity concentrations in water are essential to ensure that off-site aquatic ecosystems are adequately protected against impacts from radiation.</i>	6.2.1a

KKNs	KKN#
Radionuclide uptake in small proliferators <i>What are the concentration ratios of U and Ac series radionuclides in phytoplanktons and zooplanktons?</i> The focus of previous research has been on aquatic species forming part of the human food chain. No consideration has been given to radionuclide uptake in small proliferators like phyto- and zooplanktons, which are essential to ecosystem function and health.	6.2.1g
Uptake of Ac series radionuclides in aquatic wildlife <i>What are the concentration ratios of Ac series radionuclides (especially ²²⁷Ac and ²³¹Pa) for aquatic wildlife?</i> There is currently no data on uptake of Ac series radionuclides by aquatic wildlife. These radionuclides could make a significant contribution to radiation doses to some aquatic species. The acquisition of data on concentration ratios for Ac series radionuclides is essential to ensure that all radionuclide stressors of potential significance have been considered in the development of radiological closure criteria for off-site water quality.	6.2.1i
Tissue to whole organism conversion factors <i>What are the tissue to whole organism conversion factors for concentration ratios for local aquatic wildlife?</i> Much of the existing data on radionuclide concentration ratios for aquatic plants and animals are for specific tissue components consumed by Aboriginal people as bush foods. These concentration ratios need to be converted to the whole organism level in order for the data to be useful for assessing radiation doses to wildlife. While generic tissue to whole organism conversion factors are available in the literature, it is desirable to derive these from site-specific data to improve the estimate of the dose.	6.2.1f
Dose-effects relationships <i>At what level of radiation dose rate does local aquatic wildlife experience radiation-induced biological effects under conditions of chronic exposure?</i> There is currently no dose-effect data for ARR wildlife to benchmark chronic radiation exposures against. The benchmarks currently used for radiation protection of aquatic ecosystems are generic and have been derived from review of the effects data pooled from international studies.	5.2.1a

3.1.6 The risk of increased bedload sediment to off-site habitat diversity and water quality during post decommissioning

Increased bedload has the potential to infill waterbodies off-site, potentially resulting in habitat change.

Sources of bedload sediments

Potential sources of bedload include: waste rock from the rehabilitated landform; other disturbed areas not composed of waste rock on the minesite; areas representing the undisturbed Koolpinyah surface on the minesite; and material transported from the reaches of Magela Creek above the minesite. Landform modelling of the Ranger FLV5-02 conceptual landform and earlier erosion plot studies indicates that up to 70 % of total sediment load is composed of bedload. Studies indicate that bedload will decrease significantly over time. Also refer to KKN 4.1.3 for risks of bedload to on-site aquatic ecosystems (specifically for waste rock and LAA sources).

KKNs	KKN#
Background bedload yields for Magela and Gulungul Creeks <i>What are the estimated natural bedload rates in Magela and Gulungul Creeks?</i> Any effects associated with minesite-derived bedload to off-site creek systems needs to be considered in the context of natural bedload yields in Magela and Gulungul creeks. However, estimated natural bedload yields for Magela and Gulungul creeks may be based on limited data, and need to be verified and/or supplemented.	6.3.1d

Bedload sediment stressors

Bedload broadly encompasses all surface materials transported by water with a grain size larger than 63 micrometers.

KKNs	KKN#
Identify the particle size distribution characteristics for transported bedload	6.3.1c
<i>What is the particle size distribution of the bedload being transported off site? The particle size of the bedload being transported off the site can influence its transport and deposition and, thus, needs to be known in order to determine potential impacts.</i>	

Pathways of bedload sediments

Surface water movement is the mechanism by which bedload is transported off-site. However, not all bedload reaches the drainage lines, as it can deposit on low slopes and where there is a significant change of slope (grade). Corridor and Coonjimba creeks are likely to be lower sources of bedload to the off-site environment due to the drainage lines and downstream billabongs acting as sinks. Bedload movement rates (field investigation) for the nearby Ngarradj catchment are reasonably well known and there has been some limited work done on bedload movement rate on Gulungul and Magela creeks. The bedload movement rates in Gulungul and Magela need to be reviewed and where necessary additional measurements made to determine the natural transport rates (non-mine-impacted) This is particularly important in the decades following construction of the final landform and post-decommissioning when there is potentially more material available to be transported. Long-term bedload movement (decades – millennia) can be modelled using landform evolution models such as CAESAR-Lisflood.

KKNs	KKN#
Identify the path, volume and timeframe for sediment transport off-site	6.3.1b
<i>In the event on-site mitigation measures are not fully effective or fail, how much bedload will be transported off-site, over what timeframe, and what is the major route(s) off-site?</i>	
In particular, the drainage line around the south-east side of Pit 3 (based on the FLV-5 landform design) and the Pit 3 capping may be a direct source of bedload to Magela Creek.	
Understand the impact of flood events in Magela Creek on the Pit 3 landform	6.3.1i
<i>How will hydrodynamics of Magela Creek during low frequency high discharge events impact the Pit 3 landform area with respect to scour and slope instability (which will deliver bedload and suspended sediment load to Magela Creek)? This could be assessed using hydrodynamic modelling. Related issues include identifying what mitigation measures are proposed/required for this area and whether the access road needs to be retained as a protective structure (or some similar structure).</i>	

Measurement endpoints

Closure criteria are required for measurement endpoints deemed essential for achieving the relevant closure objectives.

The key off-site impacts of bedload would be morphological changes such as infilling and deposition, potentially resulting in habitat changes. In order to be able to detect such effects, there is a need to consolidate and synthesise existing knowledge on temporal channel morphological changes in Magela and Gulungul creeks. Associated with this, there may be a need to acquire higher resolution elevation data of channels in Magela and Gulungul creeks.

KKNs	KKN#
<p>Closure criteria for bedload in off-site creek channels and water bodies</p> <p><i>What are the appropriate criteria that could be used to determine whether closure objectives have been met?</i> There is a need to understand what the acceptable rates of transport of bedload sediment offsite are by determining the natural bedload movements (non-mine-impacted) in Magela and Gulungul creeks. Bedload movement rates in the creek should not be elevated from the rehabilitated minesite.</p> <p>Landform evolution modelling should be used to predict the extent/likelihood of bedload movement off-site via specific routes, in order to inform the need for, and structure of, monitoring programs. The channel morphology monitoring program for on-site bedload risks should provide an early warning system for off-site risks. Annual visual inspections (e.g. using a photo point system) of off-site creek channels should be undertaken. Ideally, little to no sediment should be transported from the rehabilitated landform. However, if sediment movement occurs, early detection is important. Channel morphology measurement and monitoring program for on-site bedload risks should inform and provide early warning for off-site risks.</p>	5.3.1a
<p>Understand the morphological changes in Magela and Gulungul creeks</p> <p><i>What are the channel morphological changes in Magela and Gulungul creeks?</i> Morphological changes occur naturally within Gulungul and Magela creeks. There is a need to understand the natural rates of change in the creeks to determine if change is increased/accelerated due to bedload movement off the minesite. Off-site morphological impacts of bedload movement are likely to be infilling and deposition, potentially resulting in habitat changes. Morphological change in the creek should not differ from the natural rates or pre-rehabilitation rates due to increases in bedload transport.</p>	7.1.1c

3.1.7 The risk of increased suspended sediment to off-site habitat diversity and water quality during post-decommissioning

Suspended sediment movement off the Ranger rehabilitated minesite is likely to increase during the post-decommissioning phase. It is envisaged that over a period of time (which needs to be determined) that the rates of suspended sediment from the rehabilitated minesite will decrease down towards the natural rates (non-mine-impacted) of suspended sediment movement in the creeks. The rate of suspended sediment movement off the rehabilitated landform can be predicted using the LEM models, validated with parameters obtained from studies including the waste rock dump and the trial landform.

Closure criteria are required for measurement endpoints deemed essential for achieving the relevant closure objectives and criteria.

Sources of suspended sediment

Waste rock is considered to be the major source of suspended sediment load (<63 micrometers) from the rehabilitated landform. Other potential sources include soils in the land application areas, roads, areas of the undisturbed Koolpinyah surface on the minesite; and areas of the Magela catchment upstream of the minesite. Although further developmental work is required, the transport of suspended sediment should be predicted via landform evolution modelling (using CAESAR-Lisflood and SIBERIA). Model validation is important to ensure that the model input parameters appropriately reflect local conditions and, therefore, the modelling outputs are robust. Specific knowledge needs include:

KKNs	KKN#
<p>Validating the use of the CAESAR-Lisflood and SIBERIA landform evolution models</p> <p><i>What is the sensitivity of CAESAR and SIBERIA parameters, and how can this knowledge be used to refine the models?</i> Applying a conservative approach, worst case scenarios should be adopted for parameters for which we have little local knowledge or there is little discriminatory ability – such as rock type placement.</p> <p>A number of input parameters for these models may be impacted by local conditions and these need to be investigated to ensure the accuracy of the model predictions, i.e.</p> <p><i>What is the appropriate sediment settling velocity parameter?</i> It may be worthwhile reviewing existing Georgetown Billabong turbidity/suspended sediment and flow (or surrogate) data to determine if this is possible.</p> <p><i>For model validation purposes, what is the proportion of measured bedload relative to measured suspended sediment from the trial landform waste rock, and how does this compare with the model outputs?</i></p> <p><i>What are the appropriate shear stress and roughness parameters for CAESAR that reflect local conditions?</i></p> <p><i>What is the appropriate rate of weathering for waste rock?</i></p> <p><i>What is the effect of vegetation succession and fire on suspended sediment transport?</i></p> <p><i>What is the impact of extreme rainfall events and scenarios over time on suspended sediment transport?</i></p> <p><i>What is the range of model outputs given worst case and best case scenarios?</i></p>	<p>6.3.1a</p>
<p>Assess the effect of ripples on erosion</p> <p><i>What effect do ripples have on erosion?</i> Rip lines on the rehabilitated landform will increase surface roughness and therefore reduce water flow and, potentially, suspended sediment transport, but may also reduce the aesthetic value and traversability of the landform. There is a need to understand the impact of rip lines (including mound height, distance between rips) on erosion of the rehabilitated landform, and if or how this compromises aesthetics and traversability.</p>	<p>6.3.1h</p>
<p>Contribution of suspended sediments from land application areas</p> <p><i>How much suspended sediment may be derived from land application areas?</i> Land application areas (LAAs) represent a significant proportion of the Ranger site. The areas of LAA remediation will be determined by contaminated site assessments. This needs to be known (in addition to the area of other disturbed areas – e.g. tracks, roads) and, if the area is considered to be significant, suspended sediment loads off these surfaces may need to be determined in order to predict the impact to aquatic ecosystems.</p>	<p>6.3.1g</p>

Suspended sediments as stressors

Suspended sediment broadly encompasses all surface sediment materials transported by water with a grain size equal to, or less than 63 micrometers. Similar to on-site suspended sediment risks, the key factor with off-site suspended sediment is the contaminant transport, turbidity and potentially habitat changes resulting from deposition or smothering. Specifically, large increases in suspended sediment or turbidity over long durations can impact on aquatic biota and if present in sufficient quantities could increase sedimentation rates. Some work on the impact of turbidity has been undertaken in the late dry season in Georgetown Billabong and in the late wet season on Jim Jim Creek. Suspended sediment is one of the particle size classes able to be modelled by the CAESAR-Lisflood landform evolution model.

KKNs	KKN#
<p>Effect of suspended sediments with different characteristics</p> <p><i>Will there be differences in suspended sediment characteristics coming off the site (i.e. from different catchments)? If so, are there implications for potential impacts to aquatic biota?</i> Different sizes and shapes of particles have been found to exert different types of effects on aquatic biota. This may or may not be a significant issue at Ranger, and may require some preliminary assessment in the first instance.</p>	<p>5.1.1i</p>

Pathways of suspended sediments

The movement of surface water is the mechanism by which suspended sediment is transported off-site. Site-specific turbidity suspended sediment relationships have been determined for Ngarradj Creek and some initial relationships for Magela Creek. Suspended sediment turbidity relationships need to be reviewed and updated for Magela Creek and developed for Gulungul Creek. Landform evolution models such as CAESAR-Lisflood should be able to determine how far the suspended sediment will move in the longer term.

KKNs	KKN#
Utilise landform modelling to predict extent of suspended sediment transport to the off-site environment <i>How far, to where and how much suspended sediment will be transported by surface water? This will depend on or be influenced by elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins), and can potentially be predicted using landform evolution modelling (including iteration during landform design).</i>	6.3.1e
Improve understanding of the role of surface water in transporting suspended sediment <i>How much suspended sediment will be transported to the off-site creek channels and billabongs? Will there be a temporal component to this as water quality coming off the landform changes? Related, to what extent will salinity/conductivity affects suspended sediment behaviour (e.g. flocculation/deposition v suspension/flushing)?</i>	6.3.1f

Measurement endpoints

There are two practical means which may be used as measurement endpoints when assessing the off-site impacts of suspended sediment: water quality (as measured by turbidity); and biodiversity of the off-site water bodies.

KKNs	KKN#
Developing closure criteria for turbidity and sedimentation in off-site waterbodies <i>What are the most appropriate closure criteria for turbidity and sedimentation of off-site waterbodies? There is a need for a biological based closure criterion and associated monitoring programs for turbidity and sedimentation (rates and changes in depth) in relevant off-site water bodies. A criterion is currently under development, based on late dry season and late wet season turbidity and phytoplankton or macroinvertebrate measurements. However, this criterion may need further development.</i>	5.1.1g
Relationship between turbidity and suspended sediment at off-site water bodies <i>Can turbidity be successfully used as a surrogate for suspended sediment measurement at off-site waterbodies? The key measurement endpoint should be turbidity as a surrogate for suspended sediment, at statutory or at other priority monitoring points in creeks and/or billabongs. Related, there is a need to establish new, and/or update existing, site-specific relationships between suspended sediment and turbidity. The specifics of an associated monitoring program will need to be considered, but initial relationships have been developed for Magela Creek.</i>	7.1.1b
Impact of suspended sediment on off-site waterbodies <i>What is known about the specific impact of suspended sediment in off-site waterbodies? The key off-site impacts of suspended sediment would be water quality (turbidity) and residence time, potentially leading to biodiversity/habitat changes, and also, potentially, deposition in off-site billabongs (e.g. Gulungul and Mudginberri billabongs).</i>	5.1.1h

4 Rehabilitation and protection of on-site aquatic ecosystems

4.1 Water and sediment quality and/or biodiversity of on-site ecosystems are on a trajectory towards meeting agreed closure criteria.

This set of knowledge needs address both the Ranger ERs and closure criteria relating to water quality on-site. The primary environmental objectives for rehabilitation that this group of knowledge needs (aside from the ERs associated with environmental protection) informs are:

- 1.2 *In particular the company must ensure that operations at Ranger do not result in: environmental impacts within the Ranger Project Area which are not as low as reasonably achievable, during mining excavation, mineral processing, and subsequently during and after rehabilitation.*
- 3.1 *The company must not allow either surface or ground waters arising or discharged from the Ranger project Area during its operation, or during or following rehabilitation to compromise the achievement of the primary environmental objectives.*

4.1.1 The risk of metals (uranium) contaminating on-site billabongs via the groundwater or surface water during post-decommissioning Measurement endpoints

The most relevant measurement endpoint for this risk and, therefore, one for which a closure criterion is required, is the sediment quality GV for U, but biodiversity closure criteria might also be needed to assess the impact of sediment-bound U (and, potentially, other metals) on aquatic organisms, e.g. environmental genomics or traditional methods. The GV for U in sediments has been established using results from field-based recolonisation of laboratory-spiked sediments. Impacts on-site are to be as low as reasonably achievable and if closure criteria cannot be met, an assessment of potential remediation measures would be undertaken, possibly within a Best Practicable Technology (BPT) process. There are no other metals of potential concern from the mine and, therefore no other closure criteria knowledge needs were identified at this stage.

Sources of metals

The sources listed in the off-site risks are all relevant for the on-site spatial scale.

Metals (U) as stressors

The only metal of potential concern in billabong sediments is U, and an extensive body of work has been completed regarding the toxicity of U in billabong sediments.

KKNs	KKN#
Physico-chemical factors that may influence the sediment Guideline Value for uranium <i>What physico-chemical factors affect U toxicity in billabong sediments (e.g. pH, DOC)?</i> The sediment quality GV for U was derived using sediments from Gulungul Billabong, which should be representative of the backflow billabongs on the minesite. However, if physico-chemical conditions of sediments are different this may affect the toxicity of U and the GV may not be protective. Knowledge of the influence of U toxicity modifying factors in sediments would help derive GVs for different sediment conditions.	5.1.2d

Groundwater and surface water as a pathway for metals (U)

On-site billabongs may become contaminated by U via the groundwater or surface water pathway. Dissolved and particulate-bound U can be transported via the surface water.

Only dissolved and colloidal-bound U can be transported via the groundwater, and once it is expressed in the surface waters the dissolved U and colloidal U will bind to suspended and bedded sediments, ultimately accumulating in depositional zones, e.g. the backflow billabongs. The knowledge needs are:

KKNs	KKN#
Predicting uranium accumulation in billabongs <i>How are U contaminated sediments transported in and out of billabongs and what are the predicted future metal budgets for billabong sediments?</i> Prediction of the concentrations of U entering and leaving the on-site billabongs will determine if concentrations will reach a threshold at which biological impacts would be expected. If concentrations of uranium in sediments of on-site billabong are above the closure criterion, what concentrations should be considered As Low As Reasonably Acceptable (ALARA)?	6.1.2a

4.1.2 The risk of weeds becoming established in on-site billabongs during post-decommissioning

Measurement endpoints

The aquatic on-site habitats will be susceptible to weed invasion in a similar way to the terrestrial environment. The weeds of primary concern are salvinia and para grass. Hence the knowledge needs are the same as those for the terrestrial environment (refer to Section 6.2.4).

4.1.3 The risk of increased bedload sediment to on-site habitat diversity during post decommissioning

Source of sediment bedload

Refer to key knowledge needs for sources in section 3.1.6.

Bedload sediment as a stressor

Bedload broadly encompasses all surface materials transported by water with a grain size larger than 63 micrometers. The CAESAR-Lisflood landform evolution model is able to model up to 9 different grain sizes representing bedload in its simulations. Increases in bedload in the creek beds can cause aggradation/sedimentation and change the morphodynamics of the creek potentially smothering aquatic biota. Similarly increases in bedload into the billabongs could infill the billabongs potentially impacting on habitat diversity.

KKNs	KKN#
Rates of bedload transport off the landform <i>How long do sedimentation basins need to remain functional? How long before the basins fill and what happens if the basins fail?</i> If a basin fills or fails, the stored bedload potentially becomes available to be transported. To answer this, the loss rate of bedload from the landform needs to be known.	6.3.2d

Pathways of bedload sediment

Surface water movement is the mechanism by which bedload is transported on-site. Key on-site drainage lines are Corridor and Coonjimba creeks, and the channels feeding into Gulungul. Various studies have been undertaken to determine bedload sediment that is coming off parts of the Ranger minesite. Not all bedload reaches the drainage lines – it may deposit on low slopes and where there is a significant change in grade. Low slope areas are unlikely to be major sources of bedload. Bedload that has been transported off erosion plots (2% slope) on the trial landform has been measured for 6 wet seasons (2009-10 to 2014-15). Some studies were undertaken in the 1990's and the results of this

work need to be reviewed and updated. Landform evolution models such as CAESAR-Lisflood are able to model the movement of surface water.

KKNs	KKN#
Utilise the landform modelling to predict extent of bedload sediment transport <i>How far, where and how much bedload will be transported by surface water?</i> This will depend on elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins/other mitigations such as armouring), and can be predicted using landform evolution modelling (including iteration during landform design). Ultimately, the goal should be to design the landform so as to minimise need for sediment structures.	6.3.2e
Improve understanding of bedload supply from Magela Creek <i>How much bedload from Magela Creek is deposited in Georgetown and Coonjimba billabongs?</i> The relative contributions of bedload sediment from the mine-site and from off-site needs to be established in order to determine how closure criteria will be met. This should be contained in the literature but, if not, the determination of natural infill rates of billabongs will also inform this knowledge need.	6.3.2f

Measurement endpoints

Key measurement endpoints should include channel morphology (i.e. deposition, scouring of channel at important locations, including cross sections – e.g. at change of grade, upstream of sedimentation basins) and annual visual inspections of natural creek channels (e.g. using a photo point system). Appropriate monitoring locations and requirements can be determined once the final landform and design/location of sediment mitigation structures are known. Closure criteria are required for measurement endpoints deemed essential for achieving the relevant closure objectives.

KKNs	KKN#
Geomorphology of on-site creeks and waterbodies <i>What are the appropriate criteria that could be used to determine whether closure objectives have been met? How do we determine/delineate pre-mine, current and post mining geomorphic conditions of on-site creeks and waterbodies around Ranger?</i> Corridor and Coonjimba creeks and their billabongs, and drainage lines towards Gulungul Creek, are the key on-site receptors for bedload. There is a need to better understand the geomorphology of these features. This would involve mapping/characterising of existing and pre-mining geomorphic conditions.	5.1.2c

4.1.4 The risk of increased suspended sediment to on-site water quality during post-decommissioning

Historical erosion plot studies on the Ranger site indicate significant mobile suspended sediment loads in erosion from waste rock. Landform modelling indicates that 20 % of total sediment load from the current conceptual landform composed of waste rock is suspended sediment.

Sources of suspended sediment

Refer to key knowledge needs for sources in section 3.1.7.

Suspended sediment as a stressor

Suspended sediment broadly encompasses all surface sediment materials transported by water with a grain size equal to, or less than 63 micrometers. Suspended sediment is one of the particle size classes able to be modelled by the CAESAR-Lisflood landform evolution model. The key factor for suspended sediment risk is the contaminant transport, turbidity, and potentially deposition/smothering changes.

KKNs	KKN#
Improve understanding of the role of surface water in transporting suspended sediment <i>How much suspended sediment will be deposited in sediment basins and the on-site creek lines and billabongs? Will there be a temporal component to this as water quality coming off the landform changes? Related, to what extent will salinity/conductivity affects suspended sediment behaviour (e.g. flocculation/deposition v suspension/flushing)?</i>	6.3.2g

Pathways for suspended sediments

The movement of surface water is the mechanism by which suspended sediment is transported on site. The key natural drainage lines pathways impacting on-site are Gulungul, Corridor and Coonjimba creeks. Drainage line development in constructed flow paths on a conceptual landform has been done using the CAESAR-Lisflood LEM.

Turbidity-suspended sediment relationships are usually site-specific and are currently being developed for the erosion studies on the trial landform at Ranger. Landform evolution models such as CAESAR-Lisflood should be able to determine how far the suspended sediment will move in the longer term, over temporal periods of decades to millennia.

KKNs	KKN#
Utilise landform modelling to predict extent of suspended sediment transport <i>How far, where and how much suspended sediment will be transported by surface water? This will depend on or be influenced by elements of the landform design (e.g. slope curvature, length and angle, construction and location of sediment basins, and can potentially be predicted using landform evolution modelling (including iteration during landform design)).</i>	6.3.2h

Measurement endpoints

There are two practical means which may be used as measurement endpoints when assessing the on-site impacts of suspended sediment: water quality (as measured by turbidity); and the health or biodiversity of the off-site waterbodies.

Closure criteria are required for measurement endpoints deemed essential for achieving the relevant closure objectives and criteria.

KKNs	KKN#
Developing closure criteria for turbidity and sedimentation in on-site waterbodies <i>What are the appropriate closure criteria for turbidity and sedimentation of on-site waterbodies? There is a need for a biological based closure criterion and associated monitoring programs for turbidity and sedimentation (rates and changes in depth) in on-site billabongs. A criterion is currently under development, based on late dry season turbidity and phytoplankton measurements. However, the relevance of this dry season-based criterion to wet season turbidity values to on-site waterbodies needs to be determined.</i>	5.1.2a
Site-specific relationships between suspended sediment and turbidity? <i>Can turbidity be successfully used as a surrogate for suspended sediment measurement at on-site waterbodies? The key measurement endpoint should be turbidity as a surrogate for suspended sediment. Turbidity versus suspended sediment relationships need to be developed for the key water bodies (in order to be able to compare modelled suspended sediment outputs with turbidity closure criteria). A turbidity versus suspended sediment relationship exists for Georgetown Billabong, but may need to be developed for Coonjimba Billabong. Related, what should an on-site turbidity monitoring program look like? There is a need to determine if relationships are site-specific or applicable to all similar water bodies.</i>	7.1.2a

KKNs	KKN#
<p>Impact of suspended sediment on on-site waterbodies</p> <p><i>What is known about the specific impact of suspended sediment in on-site waterbodies?</i> The key on-site impacts of suspended sediment would be water quality (turbidity), potentially leading to adverse biodiversity/habitat changes, and also, potentially, deposition in on-site billabongs and backwater areas. There is a need to understand the residence time in the on-site billabongs and backwater areas (i.e. the trap efficiency), how much suspended sediment is retained, and whether this changes over time.</p>	5.1.2b

5 Protection of off-site terrestrial ecosystems

There is one assessment endpoint associated with those risks that are ranked critical or high in terms of protecting off-site terrestrial ecosystems. The key risk is weeds sourced from the Ranger Project Area becoming established in the off-site environment.

5.1 Habitat diversity and ecosystem function within the landscape of the Magela Creek sub-catchment and broader Kakadu National Park is similar to an agreed reference condition.

The primary environmental objectives these knowledge needs inform are:

1.2 In particular, the company must ensure that operations at Ranger do not result in:

change to biodiversity, or impairment of ecosystem health, outside of the Ranger Project Area. Such change is to be different and detrimental from that expected from natural biophysical or biological processes operating in the Alligator Rivers Region.

3.1 The company must not allow either surface or ground waters arising or discharged from the Ranger Project Area during its operation, or during or following rehabilitation to compromise the achievement of the primary environmental objectives:

(a) maintain the attributes for which Kakadu National Park was inscribed on the World Heritage list;

(b) maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park);

(c) maintain the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region, including ecological processes.

The KKNs for the stressors (fire, feral animals and weeds) articulated in Section 6 apply to this assessment endpoint, except that the focus here is on off-site habitat diversity and ecosystem function rather than on-site vegetation and fauna.

5.1.1 The risk of weeds from the Ranger Project Area becoming established in the off-site environment

This risk is relevant for both the decommissioning and post-decommissioning phases. The KKN is framed around whether the Ranger Project Area is a source of weeds for the surrounding landscape and whether this potential source may have a detrimental impact on habitat diversity and ecosystem function, now and in the future. The risk is ranked critical during the decommissioning phase as earthworks and other disturbances occur during the construction of landforms and revegetation activities.

Sources of weeds

The sources during the decommissioning phase are the disturbed areas of the lease. This includes the disturbed footprint (rehabilitated areas), land application areas, exploration tracks and drill pads, Ranger mine village and Jabiru East.

KKNs	KKN#
Identification and characterisation of the source of weeds (on site) <i>What are the species and densities of weeds across the RPA (particularly in the boundary areas and disturbed areas across the site) during the decommissioning and post-decommissioning phases?</i> Systematic surveys of weeds in the on-site environment are required during the decommissioning and post-decommissioning phases. Analysis of these surveys should be undertaken in conjunction with surveys undertaken for the adjacent offsite environment to determine sources and the magnitude of sources. It is likely the profile of sources will change over time. The information from these surveys is required to ensure environmental protection during the decommissioning phase when there will be major earthworks occurring on the lease (and hence a higher risk of weed introduction and transfer to the surrounding area) and to monitor closure criteria post-decommissioning. Hazard assessments should be undertaken for exotic weeds that pose high potential risks (e.g. gamba grass) to the success/trajectory of the rehabilitation and the meeting of closure criteria.	5.4.1a

6 Rehabilitation and protection of on-site terrestrial ecosystems

6.1 Erosion characteristics of the rehabilitated landform meet agreed closure criteria

The ERs for closure of the Ranger mine specify that the final landform should possess *“erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas”*.

It is therefore crucial that rehabilitation planning and landform design incorporate landform shape and surface treatments that reduce erosion and minimise release of contaminants.

A digital elevation model (DEM) of the proposed final landform is required. This would be based upon the optimum mine plan from the operational point of view and it would take into account the broad closure criteria, engineering considerations and the specific criteria developed for guidance in the design of the landform. The final landform would need to be optimised using the information obtained in detailed water quality, geomorphic, hydrological and radiological studies arising from the KKNs identified in this document.

6.1.1 Monitoring the final landform for geomorphic stability Sources of landform instability

Localised surface material processes (LSMPs)

Five potential drivers have been classified as localised surface material processes, which may influence landform stability. These are vegetation, particle size distribution of surface materials, sub-surface materials, surface roughness, and the form and shape of the landform slope. Earlier studies on the Ranger site provide some information on particles size characteristics of surface materials. Studies at Tin Camp Creek have shown that particle size distribution can have significant effect on erosion rate. Ripping of uniform slopes is known to reduce erosion and increase infiltration, whilst concavity and convexity are known to affect erosion and deposition rates. Studies have also shown that the presence of vegetation can reduce erosion.

KKNs	KKN#
<p>Calibrating and collating drivers of instability for landform modelling</p> <p><i>What are particle size characteristics of the proposed surfaces on the landform?</i> Particle size can have significant effect on erosion rates. Consequently, there is a need to know the particle size distributions (PSDs) for other surfaces of relevance on the rehabilitated landform (e.g. rock armoured surfaces and also rates of particle breakdown through weathering, vehicle traffic, and animal movement).</p> <p><i>What is the effect of surface roughness on erosion?</i> Surface roughness reduces flow velocities and erosion potential. It is important to understand how and the extent to which surface roughness affects runoff and erosion, and to use this knowledge to help determine the type and location of effective erosion mitigation options (e.g. ripping and surface armouring).</p> <p><i>What is the optimal landform shape that will reduce erosion?</i> Slope form influences erosion and deposition. It is important to know the optimal type of slope and landform shape to minimise erosion.</p> <p><i>What is the effect of removing subsurface material?</i> Theoretically, removal of finer grained subsurface material can contribute to surface erosion. Consequently, it might be important to understand the relevance/importance of this, and whether it represents a significant risk to erosion on the rehabilitated landform.</p>	6.3.3a

External drivers (EDs) of landform instability

Additional drivers potentially impacting on landform stability include: rainfall; seismic events; sea level rise; local groundwater dynamics (movement and location) and subsidence of the pit caps on the landform. A long-term rainfall dataset has been developed, based on analysis of local/regional rainfall records, which will be used to simulate periods of up to 10,000 years.

KKNs	KKN#
<p>Utilise landform modelling to assess effect of climate change</p> <p><i>What effect will climate change/variable rainfall have on the landform?</i> Erosion characteristics of the rehabilitated landform across a full range of rainfall scenarios (including climate change scenarios) are unknown and needs to be modelled.</p>	6.3.3c
<p>Utilise landform modelling to identify location and extent of possible consolidation</p> <p><i>Where and how much consolidation will occur on the landform?</i> The degree of subsidence over pits 1 and 3 might influence erosional processes. An understanding of the significance of subsidence on erosion is needed. This will require some knowledge of predicted location and extent of consolidation over the pits.</p>	6.3.3d
<p>Identify effects of sea level rise on landform stability</p> <p><i>What effect will sea level rise have on landform stability?</i> There is a need to confirm projected sea level changes over 10,000 years, how this will affect saltwater intrusion and hydrodynamics of the Magela floodplain, and any subsequent implications (e.g. backwater effects) on erosion and deposition at the margins of the rehabilitated landform.</p>	6.3.3f
<p>Understanding interactions between the final landform and groundwater movement</p> <p><i>How will groundwater movement interact with and/or be influenced by the final landform?</i> Current landform modelling focuses on erosion of the final landform surface (i.e. gully formation and sediment transport and deposition). However, the final landform will also interact with groundwater, affecting its location and movement. Related aspects that need to be considered include recharge rates, break of slope erosion at susceptible locations (e.g. at the intersection of the final landform with the natural Koolpinyah surface), perched aquifers and evapoconcentration of salts at zones of surface expression. This may have implications for both terrestrial (i.e. landform stability and revegetation) and aquatic ecosystems.</p>	6.3.3g

Stressors of landform instability

Landform instability has been categorised into three sub-stressors.

Gullying as a stressor

Gullies, or channels, are the result of fluvial erosion in the landscape. A channel which is more than 0.3 metres deep is considered a gully. Gully formation is a fundamental measure of landform stability. Gullies could potentially become conduits for rapidly

exporting large volumes of sediment. In the context of landform stability, the concern is to ensure that gullies do not develop which could expose buried contaminants in the landform over a period of up to 10,000 years. Predictions on the location of gully formation by landform modelling can inform landform design.

KKNs	KKN#
Apply landform modelling to predict gully distribution across the landform <i>Where will gullies form on the rehabilitated landform (e.g. over tailings versus elsewhere), how big will they be, and over what timeframes? A specific environmental requirement is that erosion should not result in gullying which may expose contained waste material to the environment within a specified time period. Related, what are the final design criteria for the landform that will minimise gullying (this can be determined through iterative modelling)?</i>	6.3.2b

Sheet-flow as a stressor

Sheet-flow is another form of fluvial erosion, typically expressing itself as the flow of a shallow unchannelled sheet of water across the landscape surface. The extent and velocity of the flow may be affected by a range of factors including slope and surface roughness. Some historical data exists for the Ranger site on erosion rates resulting from sheet flow.

KKNs	KKN#
Apply landform modelling to assess erosion characteristics of landform <i>What are the erosion characteristics of slopes other than the 2% slope of the trial landform (e.g. from Tin Camp Creek, natural site and batter slopes at Ranger)? This information is needed primarily to validate CAESAR, and exists in various reports.</i>	6.3.2c

Mass movement as a stressor

Mass movement is broadly defined as the movement of surface material under the influence of gravity, often combined with the presence of rainfall. In the context of landform stability, this may be potentially exhibited through either slumping of the ground surface, or landslides. The extreme rainfall event recorded in March 2007 is not known to have caused any mass movement of materials on site.

KKNs	KKN#
Model the effects of rainfall scenarios to the final landform <i>Under what scenarios might a mass movement be expected (e.g. extreme rainfall seismic event, undermining of landform near Pit 3)?</i> Some landform design elements, such as slope, can mitigate the likelihood of mass movement. However, the optimum slopes to mitigate these risks are not known. Most mass movements of waste rock do not move materials very far. However, finer-grained materials may potentially be transported further.	6.3.2i

Measurement endpoints

Various erosion studies have been undertaken during the life of the Ranger mine, including early studies looking at the erosion on waste rock dumps and more recently the trial landform. Some erosion studies have also been undertaken on natural sites near to the minesite at Tin Camp Creek (analogous to the mine material at Ranger).

It is known that erosion will predominate on the upper slopes, while deposition will occur on the lower slopes. Landform modelling is able to predict the extent (distribution and depth) of erosion.

KKNs	KKN#
Site-specific relationships between suspended sediment and turbidity <i>What is the site-specific relationship between suspended sediment and turbidity?</i> Monitoring for acceptability of erosion on-site (excluding gullies over tailings) is best done through measuring turbidity as a surrogate of suspended sediment at statutory monitoring points in billabongs and/or creeks. The specifics of an associated monitoring program will need to be considered.	7.1.2b
Identify gully classes and risks for the landform <i>What is the threshold of gully size for invoking quantitative analysis of gullying?</i> Annual monitoring of the rehabilitated landform for gullies (i.e. gully formation – size and distribution) will be required. This can be measured visually (possibly remotely). The specifics of such a monitoring program will need to be developed.	7.2.1a
Apply landform modelling to predict extent of erosion across the landform <i>How much, and where will erosion occur on the landform?</i> Although CAESAR model simulations on conceptual landform designs have been undertaken, the predicted extent of erosion for final agreed landform will need to be modelled, including the influence of extreme rainfall events and their timing/frequency.	6.3.2a

6.1.2 The risk of landform instability to vegetation on site during post-decommissioning

Landform instability has the potential to lead to less desirable plant communities - such as invasive weed species – dominating the landform, which may prevent the establishment of healthy native vegetation communities. These undesirable species may in turn lead to further erosion and further instability on the landform.

Sources of landform instability

Refer to KKNs for sources in Section 6.1.1.

External drivers (EDs) of landform instability

Additional drivers potentially impacting on landform instability to vegetation includes: rainfall; seismic events; sea level rise; and subsidence of the pit caps on the landform.

KKNs	KKN#
Utilise landform modelling to assess effect of climate change <i>What effect will climate change/variable rainfall have on the landform?</i> Erosion characteristics of the rehabilitated landform across a full range of rainfall scenarios (including climate change scenarios), and the impacts of this on vegetation community establishment, are unknown and need to be modelled.	6.3.3c
Utilise landform modelling to identify location and extent of possible consolidation <i>Where and how much consolidation will occur on the landform?</i> The degree of subsidence over Pits 1 and 3 might influence erosional processes. An understanding of the significance of subsidence on vegetation community establishment is needed. This will require some knowledge of predicted location and extent of consolidation over the pits.	6.3.3d
Identify effects of sea level rise <i>What effect will sea level rise have on landform stability?</i> There is a need to confirm projected sea level changes over 10,000 years, how this will affect saltwater intrusion onto and hydrodynamics of the Magela floodplain, and any subsequent implications (e.g. backwater effects) on erosion and deposition at the margins of the rehabilitated landform.	6.3.3e

Stressors of landform instability

Gullying as a stressor

See section 6.1.1.

KNs	KN#
<p>Apply landform modelling to predict gully distribution across the landform</p> <p><i>Where will gullies form on the rehabilitated landform (e.g. over tailings versus elsewhere), how big will they be, and over what timeframes? For gullying, the risks to vegetation are across all post-decommissioning timescales, through removal and/or burial of vegetation and substrate and removal of seedbank. Moreover, gullying can potentially result in depressurisation of aquifers and loss of soil water holding capacity, and nutrient and carbon loss. Therefore, it will be important to know where gullies will form on the rehabilitated landform (e.g. over tailings versus elsewhere), how big will they be, and over what timeframes. Related, what are the final design criteria for the landform that will minimise gullying (this can be determined through iterative modelling)?</i></p>	6.3.2b

Sheet-flow as a stressor

See section 6.1.1.

KNs	KN#
<p>Apply landform modelling to assess erosion characteristics of landform</p> <p><i>What are the erosion characteristics of slopes other than the 2% slope of the trial landform (e.g. from Tin Camp Creek, natural site and batter slopes at Ranger)? Sheet-flow represents more of a short-term risk, through removal of seedlings, seeds, fertiliser, substrate, etc. Therefore, it will be important to know the erosion/runoff characteristics of slopes other than the 2% slope of the trial landform (e.g. from Tin Camp Creek, natural site and batter slopes at Ranger). This information is needed primarily to validate CAESAR, and exists in various reports.</i></p>	6.3.2c

Mass movement as a stressor

See KKN 6.1.1.

KNs	KN#
<p>Utilise landform modelling to assess effect likelihood of mass movement</p> <p><i>Under what scenarios is mass movement likely to occur? For mass movements, the risks to vegetation are across all post-decommissioning timescales, through removal and/or burial of vegetation and substrate (in addition to those for gullying, above). Therefore, it will be important to know the scenarios under which a mass movement might be expected (e.g. extreme rainfall seismic event, undermining of landform near Pit 3). For these, which factors can be controlled through landform design?</i></p>	6.3.3b

Measurement endpoints

This risk shares the same measurement endpoint and, therefore, closure criteria, as the revegetation measurement endpoints (Section 6.2).

KNs	KN#
<p>Understand the effect of landform stability on development of healthy vegetation communities.</p> <p><i>How can landform stability affect vegetation community development? The risk of weed (undesirable species) invasion in areas of significant erosion and vegetation disturbance/loss, and its effect on the natural vegetation community establishment, needs to be assessed. It is recognised that a potential feedback loop exists, whereby the establishment of a particular vegetation type – such as weeds – may impact on landform stability – and this may in turn impact on vegetation community development – and may need to be investigated further.</i></p>	6.3.3e

6.2 Vegetation on the disturbed sites of the Ranger Project Area is on a trajectory towards meeting agreed closure criteria

The key risks to this assessment endpoint are: waste rock as a substrate for revegetation and a source of contaminants; fire frequency and intensity; and establishment of feral animals and weeds on the rehabilitated site. These risks are relevant to the post-decommissioning phase.

The knowledge needs address both the Ranger ERs and closure criteria relating to vegetation. The primary environmental objective for rehabilitation that this group of knowledge needs informs is:

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

KKNs	KKN#
Defining and refining trajectories for revegetation <i>How can we predict vegetation trajectories and determine if the rehabilitated site is an agreed stable and resilient ecosystem?</i> There are a range of possible outcomes for the revegetation. Useful approaches for assessing minesite rehabilitation that have been identified are those that place the site in the context of successful development towards a rehabilitation objective and closure criteria. Once an appropriate trajectory (or trajectories) has been defined, suitable site-specific indicators relating to ecosystem composition, structure and function can be chosen. There is a body of research required to define a trajectory (or trajectories) that meets rehabilitation goals and/or closure criteria for the Ranger minesite. A related question in addressing the research needs is: <i>What additional information is required to develop trajectories?</i>	5.4.2a
Development and refinement of metrics to assess revegetation on rehabilitated areas <i>What measurement endpoints (metrics) are required to assess revegetation, in the context of closure criteria, on the disturbed areas of the rehabilitated site?</i> There is a need to select suitable metrics to assess revegetation in the rehabilitated minesite environment. This knowledge needs to be acquired prior to post-decommissioning to inform both the rehabilitation strategy and the post-decommissioning monitoring of closure criteria. Knowledge for refinement of closure criteria may be acquired through use of existing analogue sites and new analogues that are representative of the waste rock substrate. New technologies (such as sensors <i>in situ</i> or on board platforms such as UAVs) may provide the ability to derive and measure new and more appropriate measurement endpoints. A key component in developing closure criteria for revegetation is determining the structural and functional requirements in revegetated areas that will enable them to be resilient to the fire regime in Kakadu National Park. Measurement of vegetation recovery time from fire (fire frequency, fire extent, or fire interval), fuel load, and species composition (fire-resilient species) is proposed as a measurement for the outcome of resilient vegetation in the closure criteria. In relation to determining resilience of revegetated areas to the fire regime in Kakadu National Park, previous reviews of revegetation at Ranger have identified that it is critical to establish the age class of the woody component of revegetated areas that is fire resistant to the appropriate frequency and intensity of a managed fire regime. In the first instance, the existing work undertaken at Ranger should be reviewed and knowledge gaps identified. Aside from the studies at Ranger; any available case studies from rehabilitated sites in northern Australia should be reviewed.	5.4.2b
Development of monitoring techniques for revegetation closure criteria <i>How can we measure and monitor vegetation in a robust and cost-effective manner?</i> There is a requirement to assess and monitor revegetation from the outset of rehabilitation. Attributes and associated parameters to be monitored over time include: community structure (species composition, relative abundance and density); vegetation architecture (stratification, tree distribution); absence of threats (weed composition, abundance and density); and sustainability (recruitment, nutrient cycling, plant available water, and resilience to fire). This knowledge need is focused on developing an integrated ground (field) and UAV- based approach to measuring and monitoring revegetation on the rehabilitated site. Research to date has shown that UAV derived data is suited to monitoring plant mortality and volunteers (recruits) in revegetated areas at the site scale.	7.3.1d

6.2.1 The risk of waste rock substrate on the rehabilitated site, resulting in poor vegetation diversity and abundance of plant species

Waste rock processes as a source

The landform design contains areas where the surface for revegetation will be waste rock capping with no soil covering. Such a surface will likely present challenges for revegetation and maintaining species diversity.

KKNs	KKN#
<p>Factors for successful recruitment and regeneration in waste rock</p> <p><i>Can waste rock as the primary growth substrate maintain long-term species diversity through recruitment and regeneration? Are there other factors that need to be considered/manipulated to encourage the successful recruitment and regeneration of plants on the revegetated waste rock? Some species on the 'agreed' species list might not persist on the waste rock substrate resulting in the species composition on the rehabilitated areas being different to that in the surrounding environment. Long-term monitoring of the trial landform (TLF) and exploring opportunities for further intervention with respect to testing establishment from seed, presents the opportunity to provide data towards answering this question. As the waste rock substrate is not present in the surrounding environment, the species composition on these areas of the mine footprint is unlikely to mirror that of the surrounding environment. However, there may be methods of encouraging recruitment and regeneration to increase the probability of attaining and retaining the levels of species diversity that are characteristic of the surrounds.</i></p>	6.4.1b

Waste rock as a stressor

Nutrient availability for revegetation on waste rock

Reports have stated that waste rock from Ranger is deficient in nitrogen compared to natural soils. One of the risks to successful persistence of healthy vegetation in a non-soil environment is nitrogen deficiency as a result of effective nitrogen cycling processes not becoming established prior to nitrogen deficiencies and nitrogen imbalances occurring and, thus, limiting the progress of key framework species. Understorey species, including legumes, may be required to ensure nitrogen deficiency does not impact revegetation success long-term. Previous revegetation trials at Ranger should be reviewed to inform and refine the KKNs associated with this stressor.

KKNs	KKN#
<p>Determining the potential for nitrogen to be a limiting factor for sustainable nutrient cycling in waste rock</p> <p><i>In the waste rock substrate, is nitrogen a potential limiting factor to sustained growth in the medium- and/or long-term? What is the nitrification rate and nutrient capital of the waste rock substrate? The waste rock contains less nitrogen and carbon than natural soils and represents a highly leached and leachable environment. A nitrogen maintenance regime may be required for a period of time if there is a projected deficiency as a result of the dilution of plant nitrogen concentrations due to a lag in the timing at which effective nitrogen cycling processes in the waste rock develop. Ongoing monitoring of processes that provide evidence of progression to a self-sustaining nutrient cycle will be required and the relative contributions of legumes and other nitrogen-fixing species to the nitrogen economy will support the refinement of the species composition list. The monitoring of foliar nitrogen concentrations (and those of other limiting elements) can be a predictive tool for nitrogen (and other nutrient) deficiencies from which a potential criterion could be developed.</i></p>	6.4.1c

Importance of understorey in revegetated areas

[5.4.2c](#)

How important is it to have an understorey established in revegetated areas on waste rock for long-term ecological and habitat function? There has been a previous large-scale trial to investigate the effect of non-aggressive grass species on vegetation community development under two different irrigation regimes. Due to funding limitations the trial was not monitored past the initial phase and the results were thus of limited value to an understanding of longer-term outcomes. Reviews of existing research on the importance of understorey in savannas in northern Australia and targeted research to fill specific knowledge gaps in the rehabilitated minesite context should be implemented to answer this question. Understanding the importance of understorey will help determine if a specific closure criterion is needed.

KKNs	KKN#
<p>Establishing understorey in revegetated areas on waste rock</p> <p><i>How do we successfully establish understorey species in revegetated areas? At what stage of revegetation do we introduce understorey species?</i> If the establishment of an understorey is important for long-term ecosystem and habitat function, specialist knowledge is required for understanding how to establish the right types of understorey species for overall revegetation success. Vigorous understorey vegetation can increase the carrying capacity and intensity of a fire, and so the establishment of an understorey in revegetated areas needs to be timed (and managed) so that the framework tree species are old enough to be resilient to fire.</p>	6.4.1e

Lack of species diversity in revegetated areas on waste rock

There are reasonably large areas of the rehabilitated site where there will be no soil cover, with waste rock being the primary substrate available for plant growth. Results from the waste rock direct-seeding plots on the current trial landform and the limited timeframe for assessments of secondary recruitment in the tube stock-planted plots indicate that achieving species diversity the same as that in undisturbed areas off-lease may be unrealistic. From a self-sustaining and resilience perspective, however, it is necessary to ensure that the species that are required through agreement to be present in these landscapes show evidence of a natural recruitment strategy.

KKNs	KKN#
<p>Plant available water limitations to substrate properties and position in the landform</p> <p><i>What are the characteristics of waste rock required to maintain plant available water?</i> Plant Available Water (PAW) studies on the trial landform (TLF) have demonstrated a limited water holding capacity and that dry-season duration is critical for revegetation success. Despite uncertainties in measurements and modelling, the TLF studies indicate that the waste rock may support mature vegetation over short dry seasons; however PAW deficits resulting from longer dry seasons are unlikely to support vegetation communities similar to analogue sites. Research has shown that 77% of the years over a 113-year rainfall record have a longer dry season duration wherein PAW (in 4m of waste rock) may not support a vegetation community similar to that found in the analogue sites. Research is required to determine the minimum depth and characteristics of the waste rock root zone needed to provide greater certainty of sufficient PAW to support and sustain a mature vegetation community under climatic extremes. Additional knowledge needs should be focused on a temporal analysis of weathering of waste rock (type of clays), particle size distribution and pore size and how this affects the distribution of PAW temporally and spatially throughout the waste rock profiles and across the contrasting and varied positions in the reconstructed landform.</p>	6.4.1d

Contaminants from waste rock

Magnesium sulfate is produced from the weathering of waste rock. Revegetated areas down slope of the landform will be exposed to higher concentrations of magnesium sulfate/salinity that are potentially toxic to plants. It is not known how chronic exposure to magnesium sulfate/salinity affects the long-term growth and health of plants in revegetated areas at Ranger, although some preliminary studies were undertaken previously focused on germination of seeds of selected native plant species. The results showed that responses to increased concentrations of MgSO₄ were variable between species.

KKNs	KKN#
<p>Revegetation exposure to contaminants (including magnesium sulfate)</p> <p><i>What areas of the rehabilitated site are susceptible to increased contaminants (including magnesium sulfate) exposure?</i> The integrated surface and ground water modelling should identify areas that pool mine water and are potential hotspots for increased concentrations of magnesium sulfate. In addition, a model with appropriate spatial and temporal resolution will be able to provide a prediction of pulse exposure. The plant species to be grown in these areas can be assessed for tolerance and suitability. The current species planting list identifies two phases of revegetation (different species composition 'mixes') in recognition that different species will tolerate wetter areas as they emerge. This research informs the design structure of vegetation communities across the whole site.</p>	6.4.1f

KKNs	KKN#
<p>Plant tolerance to contaminants (including magnesium sulfate) and effects of long-term exposure to plant health</p> <p><i>What is the tolerance of native plant species to contaminants (including magnesium sulfate)? Is long-term exposure to contaminants (including magnesium sulfate) detrimental to plant health?</i> Previous research at Ranger has shown that when compared with natural soils, the mine waste rock typically has a higher pH and EC, lower nitrogen and organic carbon concentrations, higher exchangeable soluble magnesium and higher phosphorus concentrations. Additionally studies have shown that the germination of some species can be affected by magnesium sulfate concentrations. The effect of Mg:Ca on the growth and physiology of native plants has proven variable. Outcomes from previous research suggest that further studies on native plant species is required to understand the effect of exposure of magnesium sulfate induced salinity, calcium and potassium deficiency, low nitrogen and moderately higher phosphorus. An understanding of plant tolerances will enable targeted species selection for revegetation and will help determine if there is a need for a specific closure criterion that protects vegetation from solute exposure via the groundwater. Areas on the rehabilitated site that may pose a risk include the area formerly occupied by the Tailings Storage Facility and the Land Application Areas. Furthermore riparian vegetation on the site may be impacted due to groundwater egress.</p>	5.4.2d

Measurement endpoints

There is a lack of literature on the long-term successional development (trajectory) of revegetated areas in northern Australia. The acceptable end-point for the rehabilitated site is that the nature and type of vegetation assemblages that have established and persisted on site are such that future management of these areas will require a management regime not significantly different from that required on the surrounding off-lease region (e.g. resilient to fire and weeds). A trajectory approach is preferred, as it does not require decades of monitoring to meet rehabilitation goals. Previous revegetation trials and associated research, including the more recent trial landform revegetation, have showed that establishment of vegetation is possible. However prediction of how these areas develop and the acceptability of rehabilitated vegetation communities in relation to the ERs needs further investigation and consideration.

KKNs	KKN#
<p>Defining and refining trajectories for revegetation</p> <p><i>How can we predict vegetation trajectories and determine if the rehabilitated site is an agreed stable and resilient ecosystem?</i> There is a range of possible outcomes for the revegetation. Useful approaches for assessing mine-site rehabilitation that have been identified are those that place the site in the context of successful development towards a rehabilitation objective and/or closure criteria. Once an appropriate trajectory (or trajectories) has been defined, suitable site-specific indicators relating to ecosystem composition, structure and function can be chosen. There is a body of research required to define a trajectory (or trajectories) that meets rehabilitation goals and/or closure criteria for the Ranger minesite. A related question in addressing the research needs is: <i>What additional information is required to develop trajectories?</i></p>	5.4.2a

6.2.2 The risk of fire being at a frequency and/or intensity that impacts vegetation on the rehabilitated site

Fire as a stressor

Fire in itself is a stressor and the conceptual models for this risk have specified the stressor to be early and late dry season fire. The timing of fire and subsequent patterns of this timing characterise fire regime and impact vegetation accordingly. There is a large body of research on fire in Kakadu National Park, but this has not been reviewed or applied to rehabilitation and closure of Ranger. The following knowledge needs will address this:

KKNs	KKN#
<p>Transitioning the Ranger Project Area from asset protection to landscape management of fire</p> <p><i>What is the most appropriate fire management regime to adopt to ensure the success of revegetation and protect wildlife and vegetation across the Ranger lease and the buffer zone between the Ranger lease and Kakadu National Park? How do we transition the Ranger Project Area from asset management to landscape management in the context of fire and site rehabilitation and closure?</i> In the early stages of revegetation, managing fire (exclusion) is critical to the success of revegetation. With the large spatial extent of fires in the region, management of fires is a cross-jurisdictional issue and needs to be managed for revegetation success at multiple scales. This is an important knowledge need that takes into account all the science from the above KKNs as well as reviewing existing knowledge.</p>	6.4.1g

Measurement endpoints

Fire is one of the most important landscape drivers affecting the development of young rehabilitated areas towards self-sustaining vegetation communities. There is a sound knowledge base for management of fire (e.g. exclusion of fire during the early stages of revegetation is recommended). Currently, there is no active monitoring of the effects of fire to vegetation onsite as the current fire management regime is exclusion of fire (asset protection). There is a requirement to develop suitable monitoring methods to assess closure criteria in relation to fire and to ensure the revegetation is developing on an acceptable trajectory. A component of this requirement is technology transfer to the people responsible for ongoing monitoring during post-decommissioning.

KKNs	KKN#
<p>Development and refinement of metrics to assess revegetation on rehabilitated areas</p> <p><i>What measurement endpoints (metrics) are required to assess revegetation, in the context of closure criteria, on the disturbed areas of the rehabilitated site?</i> There is a need to select suitable metrics to assess revegetation in the rehabilitated minesite environment. This knowledge needs to be acquired prior to post-decommissioning to inform both the rehabilitation strategy and the post-decommissioning monitoring of closure criteria. Knowledge for refinement of closure criteria may be acquired through use of existing analogue sites and new analogues that are representative of the waste rock substrate. New technologies (such as sensors <i>in situ</i> or on board platforms such as UAVs) may provide the ability to derive and measure new and more appropriate measurement endpoints.</p> <p>A key component in developing closure criteria for revegetation is determining the structural and functional requirements in revegetated areas that will enable them to be resilient to the fire regime in Kakadu National Park. Measurement of vegetation recovery time from fire (fire frequency, fire extent, or fire interval), fuel load, and species composition (fire-resilient species) is proposed as a measurement for the outcome of resilient vegetation in the closure criteria. In relation to determining resilience of revegetated areas to the fire regime in Kakadu National Park, previous reviews of revegetation at Ranger have identified that it is critical to establish the age class of the woody component of revegetated areas that is fire resistant to the appropriate frequency and intensity of a managed fire regime. In the first instance, the existing work undertaken at Ranger should be reviewed and knowledge gaps identified. Aside from the studies at Ranger; any available case studies from rehabilitated sites in northern Australia should be reviewed.</p>	5.4.2b
<p>Spatial and temporal scales for assessing impacts of landscape factors (e.g. fire, weather, initial conditions and feral animals) on revegetation</p> <p><i>What are the most appropriate spatial and temporal scales to assess impacts of landscape factors on revegetation?</i></p> <p>There are a number of landscape factors that can impact revegetation on the rehabilitated site. These landscape factors include fire, weather, feral animals and pests, and initial conditions (associated with a waste rock substrate) on the revegetated areas. The impact of these landscape factors can be measured at multiple spatial and temporal scales. Quantitative measures of the variables associated with landscape factors, along with vegetation density and composition will provide predictive ability to determine what factors affect the success of revegetation. Pit 1 will be used as a learning to inform (where possible) Pit 3 rehabilitation.</p>	7.3.1b

KKNs	KKN#
Refinement of monitoring techniques for fire and its impacts in assessing vegetation trajectory during post-decommissioning	7.3.1c
<i>What are the most appropriate techniques to ensure appropriate and effective monitoring continues as required in the post-decommissioning phase? Fire and its impacts will need to be monitored on the Ranger Project Area during post-decommissioning in a scientifically valid and cost-effective and time efficient way. This monitoring activity will need to occur until the vegetation communities in disturbed areas on-site have been shown to be meeting an agreed trajectory as determined through the closure criteria for flora. Fire regime (frequency, timing and severity) metrics can be derived from the existing literature for savannas in northern Australia. A multi-scaled remote sensing approach will be investigated, based on existing monitoring tools, and the use of UAV derived imagery will be included in this approach.</i>	

6.2.3 The risk of feral animals becoming established and impacting on vegetation on the rehabilitated site

Sources of feral animals

It is necessary to understand feral animal distribution (species and densities) in surrounding areas to frame discussions on closure criteria, management challenges and best practice approaches. During decommissioning and for an initial period post-decommissioning, the Ranger Project Area will likely be managed for feral animals. Once the minesite is not being actively managed for feral animals there will be a need to understand and monitor sources of feral animals in the landscape to ensure the ongoing development of ecosystems on the agreed trajectory. KKNs relating to the magnitude of the source when comparing the off-site (Kakadu National Park) and the Ranger Project Area environments are:

KKNs	KKN#
Identification and characterisation of the source of feral animals (off-site)	6.4.1h
<i>What feral animals are present in the surrounding off-site environment (Kakadu National Park)? What are the densities of feral animal species in the off-site surrounding environment (Kakadu National Park)? A recent aerial survey (2015) of feral animals was undertaken for Kakadu National Park. These data have not been analysed to characterise the nature or the magnitude of the source in the off-site environment. This dataset should be reviewed and analysed to characterise the source of feral animals off-site.</i>	
Potential for the rehabilitated site to become a source of feral animals	6.4.1i
<i>Can the rehabilitated site become a refuge for feral animals? A review focused on case studies (if there are any existing studies) from other rehabilitated mines on feral animal utilisation and associated impacts is required. The context of the review is to determine whether the Ranger Project Area may become a refuge for feral animals compared with the surrounding landscape once active management of the site ceases during post decommissioning.</i>	

Measurement endpoints

The presence of feral animals has been measured in the off-site environment in 2015, through an observational dataset collected by helicopter survey. Current survey methods use 'spotters' in a helicopter and are not cost-effective. A systematic and cost-effective method needs to be developed and implemented to target management of feral animals and assess closure criteria specific to vegetation and weeds.

KKNs	KKN#
Development of monitoring techniques for revegetation closure criteria	7.3.1c
<i>How can we measure and monitor vegetation in a robust and cost-effective manner? There is a requirement to assess and monitor revegetation from the outset of rehabilitation. Attributes and associated parameters to be monitored over time include: community structure (species composition, relative abundance and density); vegetation architecture (stratification, tree distribution); absence of threats (weed composition, abundance and density); and sustainability (recruitment, nutrient cycling, plant available water, and resilience to fire). This knowledge need is focused on developing an integrated ground (field) and UAV- based approach to measuring and monitoring revegetation on the rehabilitated site. Research to date has shown that UAV derived data is suited to monitoring plant mortality and volunteers (recruits) in revegetated areas at the site scale.</i>	

6.2.4 The risk of weeds becoming established and impacting on vegetation on the rehabilitated site

Rehabilitated areas will initially be susceptible to weed invasion, and as time progresses the risk of weeds may increase due to the activity of other landscape disturbances such as erosion, fire and feral animals. Addressing knowledge needs on the risk of weeds to revegetation and the Ranger Project Area during post decommissioning are key to develop suitable closure criteria for revegetation and to successful ecosystem rehabilitation.

Sources of weeds

It is necessary to understand weed distribution (species and densities) in surrounding areas to frame discussions on closure criteria, management challenges and best practice approaches. Questions relating to the magnitude of the source when comparing the offsite (Kakadu National Park) and the Ranger Project Area environments are:

KKNs	KKN#
Identification and characterisation of the source of weeds (off-site)	6.4.1a
<i>What weeds are present in the surrounding off-site environment (Kakadu National Park)? What are the densities of weed species in the off-site surrounding environment (Kakadu National Park)?</i> There are no systematic surveys of weeds in the adjacent off-site environment. The only dataset containing terrestrial weeds for the Magela catchment is a point dataset of 'sightings' spanning 2001-2012. The use of ultra-high resolution remote sensing should be investigated to obtain a current and quantitative dataset for the adjacent off-site area and to ascertain whether Kakadu National Park is a source for invasive weeds for the Ranger Project Area. Assessments should be undertaken in both disturbed and 'undisturbed' areas off-site. As described for the on-site source of weeds (KKN 5.4.1a) hazard assessments should be undertaken for weeds that are a risk to the rehabilitated site.	

Measurement endpoints

Weeds are currently not being measured or monitored in a systematic manner either in the on-site or off-site environment. A systematic and cost-effective method needs to be developed and implemented to target management of weeds and assess closure criteria specific to vegetation and weeds.

KKNs	KKN#
Refinement and development of metrics and monitoring methods for weeds	7.3.1a
<i>How can we measure and monitor weeds and their impact on vegetation in a robust and cost-effective manner?</i> Metrics for monitoring weeds are required for closure criteria and ongoing monitoring. There are new technologies that can be used to measure and monitor weeds at the landscape scale but require further research and development. For example, UAVs have the capability to map and identify weeds in a systematic and cost-effective manner at appropriate scales for management and assessing closure criteria. As part of the research and development it will be important to identify which weed species can be monitored using remote sensing and those that will require another monitoring method. This knowledge need is also linked to KKNs 5.4.1a and 6.4.1a relating to the identification and characterisation of the source of weeds both on-site and off-site.	

6.3 Recolonisation of fauna on the rehabilitated site meets agreed closure criteria

The knowledge needs for the risks associated with fire, feral animal and weeds and the vegetation assessment (see Section 6.2) are also relevant for the fauna assessment endpoint and are stated further below in this section. The questions related to sources are the same as in Sections 6.2.3. and 6.2.4. Additionally, there is a specific knowledge need for contaminants. There is, however, three broader knowledge needs required to address development of closure criteria for wildlife, if it is agreed they are needed. These knowledge needs must be based on best practice for fauna management in the tropical savanna environment and minesite rehabilitation.

The primary environmental objectives these knowledge needs inform are:

3.1 The company must not allow either surface or ground waters arising or discharged from the Ranger Project Area during its operation, or during or following rehabilitation to compromise the achievement of the primary environmental objectives:

- (a) maintain the attributes for which Kakadu National Park was inscribed on the World Heritage list;*
- (b) maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park);*
- (c) maintain the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region, including ecological processes.*

10.1 All operations should be managed to minimise, to the maximum extent practicable, and to the satisfaction of the Supervising Authority or the Minister with the advice of the Supervising Scientist:

- (a) the disturbance of soil, vegetation and fauna within the Ranger Project Area; and*
- (b) the risk to fauna as a result of drinking contaminated water.*

10.2 The company must ensure that the operations at Ranger will not result in any adverse impact on Kakadu National Park through the introduction of exotic fauna or flora.

KKNs	KKN#
<p>Developing an appropriate closure criterion for recolonisation of fauna</p> <p><i>Will the establishment of suitable habitat on the rehabilitated site ensure recolonisation of fauna? The current paradigm with respect to fauna and recolonisation at Ranger is that fauna species will return to the rehabilitated site once suitable habitat has been established. There is a lack of empirical evidence to support this (and to derive trajectories for closure criteria) from previous studies at Ranger. Such evidence is required from either similar landscapes in northern Australia or from the Ranger Project Area.</i></p>	5.4.2e
<p>Habitat utilisation by threatened species on the rehabilitated site</p> <p><i>Could the rehabilitated site become an ecological trap for threatened species? It is not known whether species may move into the rehabilitated area, into what appears to be suitable habitat, but is actually poor habitat and results in further species decline. Other knowledge needs relating to this and threatened species in particular may be:</i></p> <ul style="list-style-type: none"> • Which threatened and/or significant species currently use habitat surrounding the rehabilitated site? • Are these species likely to utilise the rehabilitated site, and what for (i.e. nesting, foraging, and dispersal)? 	6.4.1j

6.3.1 The risk of fire being at a frequency and/or intensity that impacts wildlife on the rehabilitated site

Fire as a Stressor

With the large spatial extent of fires in the region, management of fires is a cross-jurisdictional issue and needs to be managed for protection of wildlife at multiple scales (and particularly for threatened species).

Measurement endpoints

There is a need to select suitable metrics to assess impacts of fire on vegetation and wildlife in the rehabilitated minesite environment. Knowledge on this exists through other research conducted in the broader Kakadu region. There is good experimental data on fire frequency and biodiversity from the Kapalga fire experiment. The Kapalga experiment showed that not all habitat and fauna have a general resilience to fire. There are also new technologies (such as sensors *in situ* or on board platforms such as UAVs)

that may provide the ability to derive and measure new and more appropriate measurement endpoints. Refer to section 6.2.2 (d) (KKN 5.4.2b).

6.3.2 The risk of feral animals becoming established and impacting on wildlife on the rehabilitated site

Measurement endpoints

Refer to section 6.2.3 (KKN 7.3.1d)

6.3.3 The risk of weeds becoming established and impacting on wildlife on the rehabilitated site

Measurement endpoints

Refer to section 6.2.4 (KKN 7.3.1a)

6.3.4 The risk of surface water chemical contaminants in on-site water bodies is acutely toxic to wildlife

The ERs for Ranger state that:

“all operations should be managed to minimise, to the maximum extent practicable...the risk to fauna as a result of drinking contaminated water.”

Reflecting this an objective has been set, by the closure criteria working group that *“water on the rehabilitated minesite will not be acutely toxic to terrestrial and avi-fauna”*.

The conceptual model for risks to terrestrial ecosystems at the RPA scale identifies surface water as a pathway and contaminants as a stressor for wildlife. Refer to the aquatic ecosystems conceptual models and KKNs for information on surface-waters as a (secondary) source of contaminants and on COPC.

Sources

The aquatic ecosystems conceptual models show that on-site surface waters are a (secondary) source of contaminants. One knowledge need was raised:

KKNs	KKN#
Predicting water quality of on-site surface waters	6.1.2b
<i>What is the predicted future quality of the surface water on-site?</i> Data on metal toxicity/effects to wildlife are of little use without knowledge of actual or predicted environmental concentrations. Thus, predicted on-site water quality data will be needed as part of assessing the risk to wildlife.	

Surface water contaminants as a stressor

The key stressors to be considered would be the mine-derived COPC for which guidelines exist. Two knowledge needs were identified:

KKNs	KKN#
Acute toxicity of mine water to wildlife	5.1.3b
<i>Are there local data and information that are more relevant to determining safe drinking water concentrations of COPC for wildlife?</i> The model of wildlife exposure to mine waters needs to be considered, i.e. how much of an animal's consumption is likely to come from water bodies on site, and what will the water quality in on-site water holes likely be? Are there any available surrogate toxicity data that can be used to predict acute toxicity to local wildlife?	
Chronic toxicity of mine water to wildlife	5.1.3c
<i>What is the likelihood of chronic toxicity of on-site surface waters to local wildlife?</i> The environmental requirements stipulate that mine waters should not be acutely toxic to wildlife on-site. However, this does not account for subtle long-term effects that may impact wildlife populations on the rehabilitated minesite. Chronic toxicity data for local terrestrial fauna would be desirable.	

Pathways of surface water contaminants

The conceptual model for risks to identifies surface water as a pathway and source for wildlife drinking water on-site. No knowledge needs were identified for the pathways.

Measurement endpoints

The Closure Criteria Working Group identified stock drinking water guidelines as appropriate to avoid acute toxicity to wildlife drinking from on-site water bodies. A review of stock drinking guidelines shows them to be inappropriate as they are for chronic effects to cattle and sheep. An alternative approach that has been suggested to support closure criteria for this goal is to review water quality in on-site water bodies that wildlife have been known to drink from, without any reports of wildlife deaths on-site, during the operational life of the mine. Issues to consider in deciding if this is the best approach to develop closure criteria for this risk are:

KKNs	KKN#
Water quality Guideline Values for protection of wildlife drinking on-site water sources <i>What data, guidelines or models are suitable for assessing the potential acute risk to wildlife drinking water from on-site water bodies? A review of stock drinking guidelines shows them to be inappropriate as they are for chronic effects to cattle and sheep. Wildlife may drink raw water from on-site but their intake profile from these sources is not aligned with the models of intake on which livestock drinking water guidelines are based (e.g. infrequent, occasional use versus longer-term frequent use). The issues identified in pathways and sources also need to be considered to answer this question.</i>	5.1.3a

7 Protection of human health

This group of knowledge needs address both the Ranger ERs and closure criteria relating to human health. The primary environmental objectives for rehabilitation that this group of knowledge needs informs are:

2.2 (b) stable radiological conditions on areas impacted by mining so that, the health risk to members of the public, including traditional owners, is as low as reasonably achievable; members of the public do not receive a radiation dose which exceeds applicable limits recommended by the most recently published and relevant Australian standards, codes of practice, and guidelines.

3.1 The company must not allow either surface or ground waters arising or discharged from the Ranger Project Area during its operation, or during or following rehabilitation, to compromise the achievement of the primary environmental objectives:

- *protect the health of Aboriginals and other members of the regional community.*

7.1 Radiation doses to people are below acceptable limits

7.1.1 The risk that radiation dose will inhibit people's use of the land

Traditional owners may receive an above-baseline radiation dose from their use of the land (on- and off-site) post-decommissioning of Ranger mine. The ERs for the mine require that this dose must be as low as reasonably achievable and must not exceed the public dose limit prescribed in national radiation protection standards. The radiation exposure pathways of concern for traditional owners are: (i) external gamma; (ii) inhalation of radon progeny; (iii) inhalation of radionuclides in dust; (iv) ingestion of terrestrial bush foods; (v) ingestion of aquatic bush foods; and (vi) ingestion of drinking water. The above-baseline radiation dose via each exposure pathway is determined by both radiological aspects (e.g. radionuclide activity concentrations in soil, water, air, bush

food, etc.) and human aspects (e.g. land use and diet). The anticipated land use of the rehabilitated landform by traditional owners has been established through a consultation process. Also established are the baseline radiological conditions of the site. Current knowledge needs are to do with characterising the outstanding radiological aspects of each exposure pathway in order to assess doses to traditional owners and develop radiological closure criteria for human health protection.

Sources of radionuclides

The rehabilitated landform is the broad source of radionuclides to the human environment at on- and off-site locations. The compartments within the landform from where radionuclides may come are: (i) surface waste rock; (ii) land application area soils; (iii) buried waste rock; and (iv) buried tailings and brines. Current knowledge needs in regards to sources of radionuclides and the aquatic ecosystem have been articulated in section 3.1.6. Knowledge needs for the terrestrial ecosystem relate to the activity concentrations of U and Ac series radionuclides in surface waste rock and land application area soils, as these compartments of the rehabilitated landform are the source of radionuclides important to the external gamma, radon and dust inhalation and terrestrial bush food ingestion exposure pathways.

KKNs	KKN#
Radionuclide activity concentrations on the rehabilitated landform	6.2.2a
<i>What are the activity concentrations of U and Ac series radionuclides in surface waste rock and land application area soils? Doses to traditional owners via the terrestrial bush food, radon and dust inhalation and external gamma exposure pathways are proportional to the activity concentration of U and/or Ac series radionuclides in the surface substrate of the rehabilitated landform. It is highly desirable to know these activity concentrations in order to increase accuracy of the dose estimate.</i>	

Radionuclides as stressors

The radionuclides of concern in relation to radiation doses to traditional owners are those of the U and Ac series. Radionuclides of the U series have been extensively studied in a human dose context, but those of the Ac series have not. The current knowledge need for radionuclides as stressors to human health is to determine the importance of Ac series radionuclides.

KKNs	KKN#
Importance of Ac series radionuclides for human health	6.2.3c
<i>What is the importance of Ac series radionuclides (especially ²²⁷Ac and ²³¹Pa) in relation to radiation doses to traditional owners from their use of the land? Data on Ac series radionuclides is lacking for human radiation exposure pathways. Knowing the contribution from these radionuclides is essential to provide an accurate estimate of doses to traditional owners.</i>	

Pathways for radionuclides

Radionuclides can be transported into the human environment via the atmospheric, surface water and groundwater pathways. Another pathway of potential exposure is external gamma radiation, but this only occurs on-site of the rehabilitated landform due to elevated radionuclide levels in surface waste rock. Relationships to determine gamma dose rates from waste rock have been established and so too have those between radon exhalation flux to the atmosphere and radionuclide levels in waste rock. Current knowledge needs for the atmospheric pathway are to do with the dispersion and activity concentration of exhaled radon and resuspended dust in air at on-site and off-site locations. Knowledge needs for waterborne pathways are to determine radionuclide loads

entering the aquatic ecosystem and activity concentrations following dispersion and partitioning within the ecosystem as articulated in section 3.1.6.

KKNs	KKN#
Radon dispersion	6.2.2b
<i>What is the dispersion and resulting activity concentration in air (on- and off-site) of radon coming from the rehabilitated landform?</i> Knowledge of radon activity concentrations in air is essential to estimate doses to traditional owners via the radon inhalation exposure pathway since the dose is proportional to activity concentrations in air.	
Radon progeny equilibrium factors	6.2.2c
<i>What is the radon progeny equilibrium factor in air on- and off-site of the rehabilitated landform?</i> This is a key constant of proportionality needed to estimate doses to traditional owners via the radon inhalation exposure pathway. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.	
Radon progeny activity median aerodynamic diameter	6.2.2d
<i>What is the activity median aerodynamic diameter of radon progeny in air and what are the attached and unattached fractions?</i> Inhalation dose coefficients for radon progeny are determined from these parameters. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.	
Dust re-suspension factors	6.2.2e
<i>What is the re-suspension factor for dust from the surface of the rehabilitated landform?</i> Dust radionuclide activity concentrations in air and hence radiation dose via the dust inhalation exposure pathway are proportional to the re-suspension factor. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.	
Dust radionuclide activity median aerodynamic diameter	6.2.2f
<i>What is the activity median aerodynamic diameter of dust-bound radionuclides in air?</i> Inhalation dose coefficients for dust-bound radionuclides are determined from the activity median aerodynamic diameter. Default values can be obtained from the literature, but site-specific information is desirable to increase accuracy of the dose estimate.	

Measurement endpoints

Closure criteria are required for soil and water radiological quality in order to provide assurance that radiation doses to traditional owners from their use of the land will be below the public dose limit. It is anticipated that these closure criteria will be back-calculated from statutory dose limits and expressed as radionuclide activity concentrations in soil and water so that are measurable through standard radiometric techniques. The derivation of closure criteria will need to consider dose contributions from both U and Ac series radionuclides. U series radionuclides have been extensively studied in a human dose context, but knowledge on Ac series radionuclides is generally lacking, especially with regard to bush foods where they may bioaccumulate and contribute to radiation doses via the ingestion pathway.

KKNs	KKN#
Uptake of Ac series radionuclides in bush foods	6.2.3b
<i>What are the concentration ratios of Ac series radionuclides (especially ²²⁷Ac and ²³¹Pa) in terrestrial and aquatic bush foods?</i> There is little-to-no data on uptake of Ac series radionuclides in terrestrial and aquatic bush foods. Knowing the dose contribution from these radionuclides is essential to provide an accurate estimate of doses to traditional owners.	

7.2 Water resources used for drinking continue to meet drinking water limits for mine-derived contaminants (post decommissioning)

The ERs for Ranger state that there will be no “*adverse effect on the health of Aboriginals and other members of the regional community by ensuring that exposure to radiation and chemical pollutants is as low as reasonably achievable and conforms with relevant Australian law*”.

7.2.1 The risk of contamination of people’s drinking water resource

Sources of contaminants

The aquatic ecosystems conceptual models show that on-site surface waters are a (secondary) source of contaminants. One knowledge need was raised:

KKNs	KKN#
Assessing the risk of drinking mine waters on human health effects	6.1.3a
<i>What is the predicted future quality of the surface water on-site, and the existing and potential off-site groundwater drinking resources? Data on metal toxicity/effects to humans are of little use without knowledge of actual or predicted environmental concentrations. Thus, predicted on-site water quality data will be needed as part of assessing the risk to human health.</i>	

Contaminants as stressors

The key stressors to be considered would be the mine-derived COPC for which guidelines exist. One knowledge need was identified:

KKNs	KKN#
Assessing the availability of drinking water guideline values for human health	5.1.4b
<i>Which of the Contaminants Of Potential Concern have guidelines for drinking water to protect health? A number of the COPCs will have water quality guidelines for human health. Those that do not have guideline value will need to be assessed for their potential to cause adverse effects.</i>	

Pathways of contaminants

The conceptual model for risks to people identifies surface water as a pathway for drinking water on-site. The on-site groundwater is not to be considered as a drinking resource but questions have been raised about the potential for existing drinking water resources in the region to be contaminated over the long-term. The knowledge needs identified were:

KKNs	KKN#
Understanding human exposure to drinking water on the minesite	6.1.3b
<i>What groundwater drinking water resources are in the region and what is the potential for these to be contaminated and made unfit for drinking by solutes transported from the closed minesite? Issues to consider include what is the quality of water in these resources compared to drinking water standards. Are solutes predicted (by modelling) to reach these supplies?</i>	
<i>Where, and how, should drinking water (or other) guidelines be used to assess the safety of raw surface waters on-site? Consideration should be given to issues of location and seasonality for e.g. what location in Magela Creek should be assessed, should on-site billabong water quality be assessed as a drinking water resource? How should seasonality be considered?</i>	
<i>What is the expected profile for people drinking water from the rehabilitated site? For example: What on-site water bodies are people likely to drink from? At what times of year and how often is it expected that people would use these sites as a drinking water supply? What are the expected intake volumes?</i>	

Measurement endpoints

The Closure Criteria Working Group set the objective that mine-derived analytes will not cause human drinking water resources to exceed National Health and Medical Research

Council (NHMRC) drinking water guidelines for consumption. Closure Criteria Working Group currently views that groundwater on-site is not to be considered a drinking resource but that surface water on-site should be. The Drinking Water Guidelines have guiding principles and specific advice on where, when and how drinking water guidelines should be applied. The guiding principles state that the guidelines are not directly relevant to raw water. Given these opposing expectations the KKN to identify a suitable measurement endpoint for closure criteria for this risk is:

KKNs	KKN#
Deriving closure criteria for drinking water that protects human health <i>What guidelines or models are suitable for assessing the potential risk to humans drinking raw water from on-site water bodies?</i> People may drink raw water from on-site but their intake profile from these sources is not aligned with the models of intake on which national drinking water guidelines are based (e.g. infrequent, occasional use versus longer-term frequent use). The issues identified in pathways and sources also need to be considered to answer this question. What guidance is given in the NHMRC drinking water quality guidelines about small communities, infrequently used water supplies or untreated water supplies?	5.1.4a

Other sites

8 Jabiluka

8.1 Protection of the off-site environment

8.1.1 Research

Given its care and maintenance status, there is currently little research activity in relation to Jabiluka. However, in the event development at Jabiluka is proposed, a review of knowledge needs will be required to assess minimum requirements. This review should include radiological data, the groundwater regime (permeabilities, aquifer connectivity etc.), hydrometeorological data, waste rock erosion, site-specific ecotoxicological issues and additional baseline for flora and fauna surveys.

8.1.2 Monitoring

Surface water quality in Ngarradj (Swift Creek) at Jabiluka is still monitored by ERA and, up until the 2015-16 wet season, was also monitored by SSB. The site typically results in no water quality impacts in Ngarradj. ERA also conducts groundwater monitoring at the site. The monitoring programs have been refined to be commensurate with the status and associated environmental risks posed by the site. Current and historical monitoring data are considered to represent a sound baseline, although further baseline data are likely to be required in advance of any development. SSB is currently undertaking annual inspections of erosion on, and associated sediment and bedload transport off, the revegetated site. Whilst there has been some sediment movement, it has not reached the off-site environment.

There are no imminent research or monitoring KKNs for Jabiluka at the moment.

8.2 Rehabilitation of the on-site environment

8.2.1 Research

The Jabiluka site was revegetated by ERA in 2013 and 2014, following decommissioning and rehabilitation of the Interim Water Management Pond. The only research project underway on the site is a project by SSB that is developing remote monitoring methods for revegetation for potential employment at Ranger post-decommissioning.

8.2.2 Monitoring

Revegetation monitoring has been underway by ERA since the revegetation of the rehabilitated site in 2013 and 2014. The revegetation is also being monitored through the acquisition of time series data as part of SSB's remote revegetation monitoring methods project.

There are no imminent research or monitoring KKNs for Jabiluka at the moment.

9 Nabarlek

A process to identify KKNs for Nabarlek is required which would include reviewing what research and monitoring has been previously undertaken and given the site's status, what still needs to be done. This process is dependent on time and resources. The sections below outline the current status of research and monitoring for the site.

9.1 Protection of the off-site environment

9.1.1 Research

Given the current status of Nabarlek there is currently little research in relation to the site for the protection of the off-site environment. An ecological risk assessment of the site and surrounding landscape may be useful to help understand landscape risks for Ranger during rehabilitation. This would need to be considered in the process for identifying KKNs for the site.

9.1.2 Monitoring

Statutory monitoring of the site is conducted by the Northern Territory Department of Mines and Energy (DME) and the operator, UEL. DME carries out surface and groundwater monitoring on and off-site, including surface water monitoring downstream of the mine in Kadjirrikamarnda and Cooper creeks, and reports the results of this monitoring in the six monthly Northern Territory Supervising Authorities Environmental Monitoring in the Alligator Rivers Region reports.

There are no imminent research or monitoring KKNs for Nabarlek at the moment, although it is anticipated that a project to review and analyse the groundwater data will be undertaken, resources permitting.

9.2 Rehabilitation of the on-site environment

9.2.1 Research

Rehabilitation of the Nabarlek site commenced with earthworks in mid-1995 and revegetation via seeding in late 1995. As it was the first contemporary uranium mine to be rehabilitated in Australia, it illustrates many issues that are highly relevant to the rehabilitation of Ranger uranium mine. SSB has previously completed research on a preliminary characterisation of vegetation on the Nabarlek site and on adjacent natural landscapes, including a seasonal comparison of the groundcover vegetation on the minesite and adjacent natural reference areas. SSB has also conducted research into characterising the Radiologically Anomalous Area (RAA) and erosion and containment transport.

9.2.2 Monitoring

Statutory monitoring of the site is conducted by DME and UEL. DME carries out surface and groundwater monitoring on and off-site. Preliminary investigations into the use of high resolution satellite data for minesite rehabilitation assessment and monitoring was undertaken by SSB in conjunction with the vegetation assessments referred to in section 9.2.1.

During 2016, historical groundwater data for Nabarlek were compiled and reviewed. Groundwater quality issues continue to occur in the former forested irrigation area adjacent to Kadjirrikarmada Creek, while a contaminated groundwater plume is slowly moving towards Cooper Creek. The outcomes of this review will feed into a review in 2017 of the KKNs for Nabarlek. This will, undoubtedly, identify knowledge gaps and needs for Nabarlek. However, at this point, and in the context of the current operations and imminent rehabilitation of Ranger, there are no urgent research or monitoring KKNs for Nabarlek.

10 South Alligator Valley

Like Nabarlek, there is no formal research program being undertaken at the El Sherana containment or at other former mining sites in the SAV. Similarly, a process to identify any KKNs should be undertaken.

10.1 Protection of the off-site environment

10.1.1 Research

Research and development of monitoring methods for erosion using UAV ultra-high resolution data can be further investigated through data collection at the El Sherana radiological containment as part of the opportunistic monitoring referred to in the following section.

10.1.2 Monitoring

There is no formal off-site environmental monitoring around the El Sherana containment. However, opportunistic monitoring of erosion and gulying occurring to the west of the containment is being conducted through ultra-high resolution captures via UAV.

There are no imminent research or monitoring KKNs for the South Alligator at the moment.

10.2 Rehabilitation of the on-site environment

10.2.1 Research

Research and development of monitoring methods for revegetation and erosion using UAV ultra-high resolution data can be further investigated through data collection at the El Sherana containment as part of the opportunistic monitoring referred to in the following section.

10.2.2 Monitoring

SSB currently assists Parks Australia by conducting biennial monitoring to assess the radiological conditions on-site at the El Sherana containment. Opportunistic monitoring of revegetation and erosion has also been undertaken, with pre- and post- wet season ultra-high resolution image captures via UAV.

There are no imminent research or monitoring KKNs for the South Alligator at the moment.

11 Uranium exploration

The exploration sites in western Arnhem Land are: Cameco King River Camp and Arnhem Project; Alligator Energy Myra Camp and Arnhem Project; and Uranium Equities Limited West Arnhem Joint Venture. Like Nabarlek and the South Alligator Valley a process to identify KKNs should be undertaken.

11.1.1 Research

Myra Camp is viewed as being an analogue for the long-term post-mining landscape for Ranger. Previous research undertaken by or in collaboration with SSB at Myra Camp includes the use of SIBERIA for landform evolution monitoring, long-term erosion transects, and assessing the impacts of pigs on the landscape with particular reference to erosion. However, there is no formal research program for Myra Camp or the other sites in West Arnhem Land.

11.1.2 Monitoring

There are no formal environmental monitoring programs being conducted at the West Arnhem Land sites.

There are no imminent research or monitoring KKNs for uranium exploration sites in West Arnhem Land at the moment.