Deriving Surface Water Quality Closure Criteria – an Australian Uranium Mine Case Study

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Abstract

The Ranger Mine has been used as a case study to illustrate how field biological indicators of ecosystem status and results from ecotoxicological studies can be combined with a water quality record from downstream of a minesite to derive water quality guideline values that are not as conservative as would be produced by the default approach of conformance with an upstream, reference water body or historical reference condition.

It has been argued that the trigger value framework developed for performance monitoring of water quality in Magela Creek during the operational life of the mine can be applied, with some modification, to post closure performance assessment. This approach would accommodate an ongoing finite level of input of solutes from the site whilst maintaining a sufficiently conservative level of protection for the downstream aquatic environment.

Biological and water quality data have also been used to develop a technically defensible framework for deriving post closure water quality guidelines for an on site natural waterbody that has historically received low levels of inputs from the minesite.

Key words: uranium mining, mine closure, closure criteria, water quality guidelines, ecotoxicology, biological indicators, Kakadu National Park, Australia

Introduction and physical context

The Supervising Scientist Division is responsible for the supervision, monitoring and audit of uranium mines in the Alligator Rivers Region (ARR) of Australia's Northern Territory, and for carrying out research into the development of improved practices for ensuring the environment remains protected from the effects of uranium mining (see www.environment.gov.au/ssd for details). The Ranger Uranium Mine, the world's third largest producer of uranium oxide (5,500 tpa or 10% of world production) is located in the ARR, approximately 250 km to the east of Darwin (Figure 1). The Ranger Project Area lies within the World Heritage-listed Kakadu National Park (KNP), a short distance upstream of the Ramsar-listed Magela Creek wetlands. This location imposes especially stringent requirements on both operations and closure.

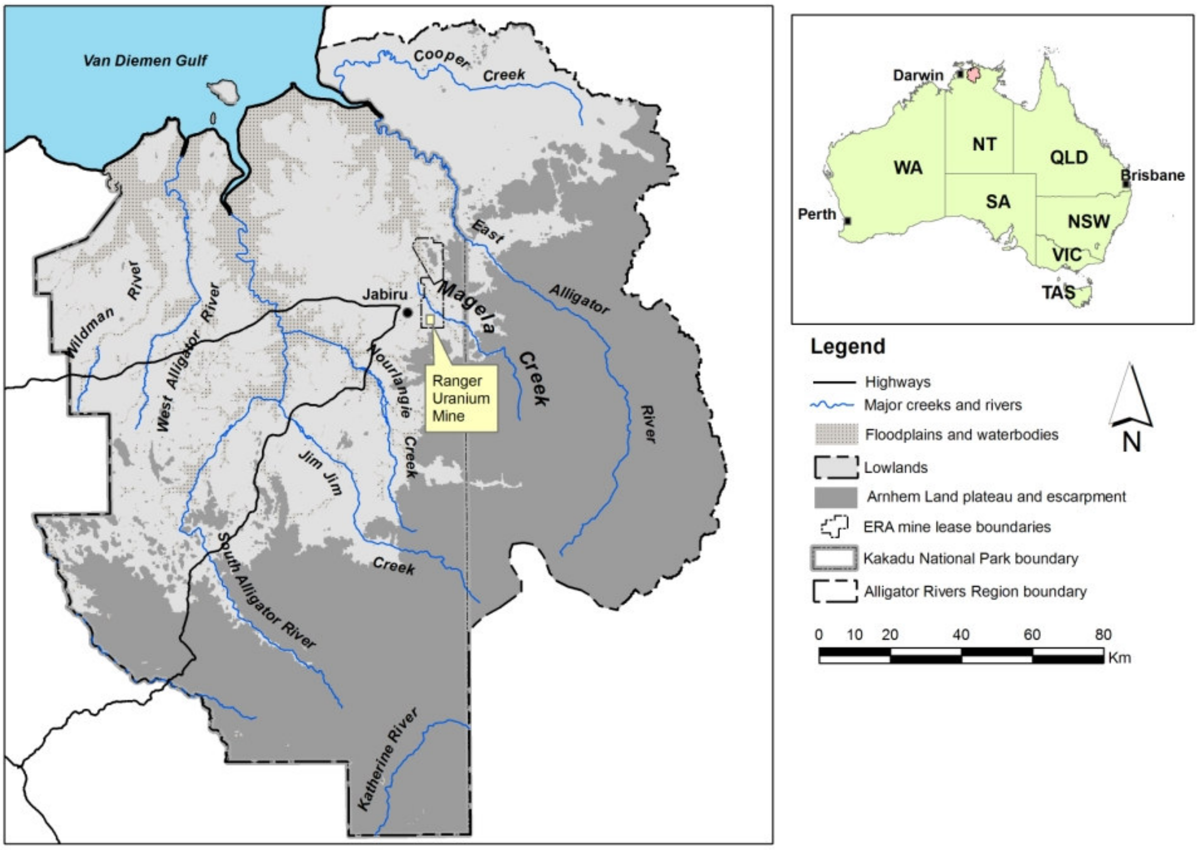
Following closure (currently planned to start in 2020) the requirement is for the mine area to be rehabilitated to a condition consistent with the values of, and to be suitable for, incorporation into the Park.

The numeric values ultimately specified for surface water quality closure criteria will strongly influence the design of the final landform, and the extent of engineering works needed to limit the total load of solutes and suspended sediments leaving the site. In the case of solute load this includes both direct surface water pathways and indirect delivery of solutes from the coupling of ground and surface water. Thus the setting of surface water quality criteria can, by default, set a limit on permissible fluxes of solutes from such features as mine pits that have been backfilled with tailings. Hence surface water criteria are a vital requirement for the closure planning process, and should be specified as early as possible.

In the case of water quality the following primary regulator-specified goals will apply through operations and closure of the Ranger Mine.

- Protect the health of traditional peoples and other members of the regional community.
- Maintain the health of the World-Heritage, Ramsar-listed Magela Creek wetlands downstream of the minesite.
- Maintain the natural biological diversity of the aquatic and terrestrial ecosystems of the Alligator Rivers Region.

Figure 1 Location of the Alligator Rivers Region (ARR) and the Ranger Uranium Mine



The mine lies adjacent to Magela Creek which feeds the high conservation value Magela Creek wetlands (Figure 1). Consequently, the water quality objectives for the operation are stringent, with the highest aquatic ecosystem protection level applied, as defined in the Australian & New Zealand Water Quality Guidelines (ANZECC and ARMCANZ, 2000); hereafter called the Guidelines).

The wet-dry tropical monsoonal climate is the key driver of catchment water supply, with the 1500 mm average annual rainfall falling during the summer months between October and May, and essentially no rainfall for the rest of the year. The annual average evaporation is 2500 mm. This cycling between “flood” and “drought” means that most of the feeder creek systems flow seasonally, introducing an additional level of complexity into defining water quality criteria. There are distinct natural annual variations in water quality between the initial flows at the start of the wet season, the peak flow period during the middle of the wet season, and the recessional flow period at the end of the wet season.

The rainfall runoff that feeds the Magela Creek system flows over an ancient weathered landscape, with the bulk of the upper catchment comprising sandstone plateaux and escarpments. As a consequence, the baseline electrical conductivity of water in Magela Creek is extremely low, typically ranging from 10 µS/cm in the middle of the wet season to around 20 µS/cm at the beginning and end of the season. This means that low level inputs of major ion solutes that elsewhere could be trivial may, in this case, have a substantial impact on receiving water quality. Management of water and associated solute loads coming from waste rock on the Ranger minesite and entering feeder catchment lines during the wet season is therefore one of the most critical operational issues. Minimising the load of solutes to Magela Creek will also be one of the greatest challenges for closure, when active water management will be replaced by passive systems comprising sedimentation basins and sentinel wetlands.

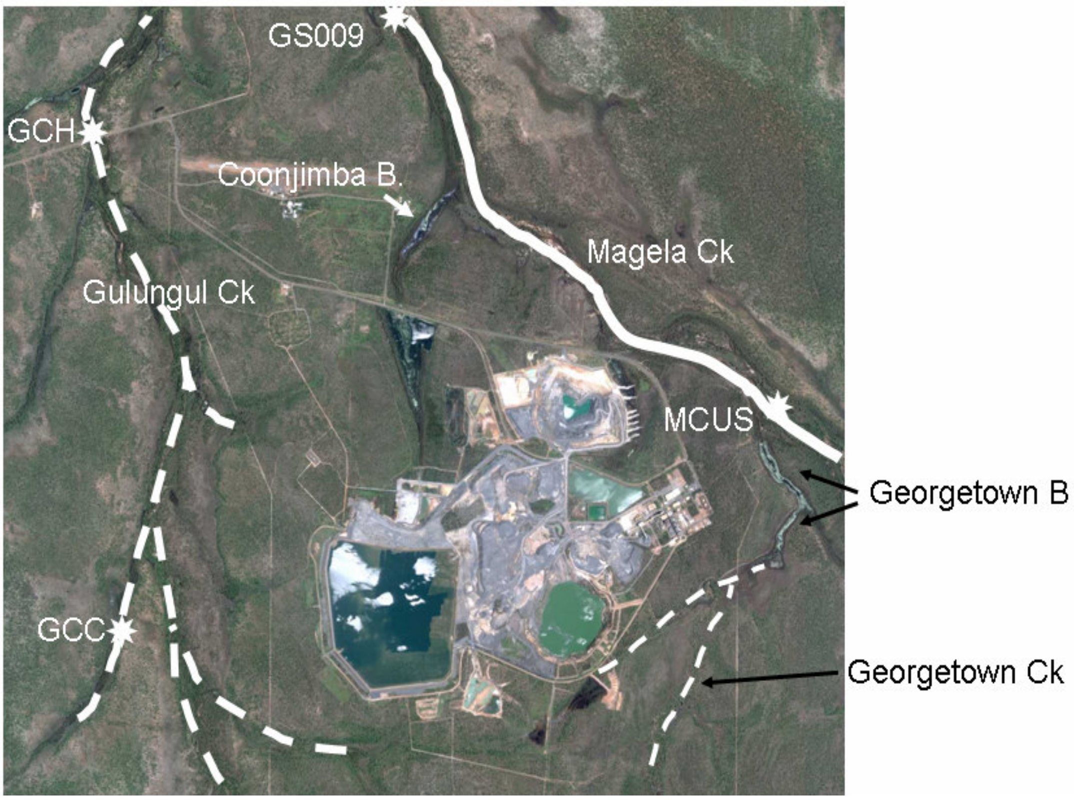
During the operational life of the mine the water quality compliance point is located at ‘GS009’ on Magela Creek downstream of the minesite (Figure 2), with the upstream reference (unimpacted by mine) located at MCUS. The Supervising Scientist Division also monitors sites in Gulungul Creek at

GCC and GCH,, upstream and downstream of minesite inputs, respectively. Whilst mine site inputs into Gulungul Creek are currently only small it is possible that as a result of expansion of the mine footprint this creek may be more impacted in the future. Gulungul Creek will also be one of the drainage lines post closure so it is important to establish its current condition.

Contingent on outcomes of discussions with regulatory and traditional owner stakeholders, a more complex regulatory framework may be necessary post closure for key feeder catchments - Gulungul and Georgetown Creeks (mine-impacted tributary catchments), and Georgetown and Coonjimba Billabongs (mine-impacted natural water bodies). Each of these aquatic systems will not only likely require different values for water quality criteria, but also different approaches to deriving criteria to protect specific attributes.

The focus of this paper will be on Magela Creek and Georgetown Billabong to illustrate the integration of chemical and biological approaches to deriving water quality closure criteria for dissolved solutes. A more wide ranging coverage of other subcatchments plus discussion of issues related to the derivation if turbidity criteria is provided in Jones et al (2006).

Figure 2 *Locations of catchment lines (creeks – Ck)and natural waterbodies (billabongs - B) in relation to the Ranger mine. Upstream and downstream water quality monitoring sites in Magela Creek are indicated by ✷ (MCUS and GS009)*



Water quality compliance framework for primary receiving waterway (Magela creek)

Operational Life of Mine

The framework described in the Guidelines has been adopted to: identify the dominant environmental values and level of protection required (a high conservation/ecological value aquatic ecosystem)[1] for waters downstream of the mine; determine background values of the important indictors (key

[1] Apart from human health values, stakeholders also recognised 'cultural and spiritual values' as an environmental value to be protected. Strategies on how to define and protect this value are being developed by others and are not discussed in this paper.

variables) in Magela Creek adjacent to the mine (Iles, 2004); and, through an integrated monitoring and assessment program identify and assess toxicity of key contaminants and the associated ecological significance of changes in in-stream water quality (Humphrey et al. 1999; van Dam et al. 2002). This best practice approach represents one of the most comprehensive implementations of the Guideline framework for deriving water quality values to protect a high conservation value aquatic ecosystem.
A key tenet of the Guidelines is use, wherever possible, of biological response data in the derivation of water quality criteria
The recommendations in the Guidelines were adapted to establish a conservative process for setting water quality guidelines for Magela Creek, using the following hierarchical approach:

- Define maximum allowable (regulatory) limits for key variables using ecotoxicological data for local aquatic species and human dietary modelling for radium.
- Produce management triggers from statistical distributions of water quality data at an appropriate (upstream) reference site.
- If triggers based on reference site data are inappropriate (for example, too conservative recognising that some level of impact on water quality is present), then findings from chemical and biological monitoring programs (if indicating that a higher than upstream baseline values can occur without significant detriment to ecosystem values) should be used to adjust the triggers.

The derived numerical objectives form a hierarchy of values that trigger increasingly stringent management responses, and are known as 'focus' action' and 'guideline' or 'limit' trigger values. The process used to derive these trigger levels is described, together with the management reporting and investigative/action responses required for each level, in Iles (2004). The greater the extent of exceedance the greater the level of management action required. The current trigger values applying at GS009 (the downstream compliance point) are summarised in Table 1.
If specific ecotoxicological data are not available then the triggers are derived from the statistical distribution of the local water quality record. The derivation of these values is based on percentiles as recommended in the Guidelines, with the focus, action and upper guideline values corresponding to the 80, 95 and 99.7th percentiles, respectively.
Limits apply when the upper guideline value is based on ecotoxicological testing and/or in-stream biological effects assessment data (e.g. uranium – 6 µg/L; Hogan et al. 2005) or human dietary pathway modelling (radium – 10 mBq/L difference between the upstream and downstream sites over the wet season). In the case of aquatic ecosystem protection the limit is derived such at least 99% of species should be protected. A species sensitivity distribution approach, using at least five test species from different trophic levels, as recommended and described in the Guidelines (Hogan et al. 2005) is followed. The lower 80th and 95th confidence limits of the ecotoxicity limit value define the 'action' and 'focus' trigger values, respectively.
In the case of U the focus (0.3 µg/L) and action (0.9 µg/L) trigger values derived from the toxicity testwork correspond to concentrations that have occasionally been measured downstream but which biological monitoring has shown do not have detrimental effects on ecosystem health. These values are thus conservatively protective of the environment, whilst being an appropriate management warning tool since they are only occasionally exceeded under normal operational circumstances.
For magnesium, two sets of criteria have been derived, depending on the ratio of magnesium to calcium in the water. The reason for this is that calcium provides a protective effect against the toxic effect of magnesium as quantified by the results of an extensive toxicity testing program (van Dam et al. 2008). Given that magnesium is a primary component of most mine drainage this finding for organisms from the ARR may have broader implications for low electrical conductivity environments elsewhere (for example, soft water lakes in Northern Europe).

Table 1 *Water quality objectives for Magela Creek*

Parameter	Method	Objective	Trigger values
pH	Upstream reference site	To retain the natural distribution of pH in Magela Creek and report and act on any trigger value exceedances.	Focus: 5.9 and 6.5 Action : 5.6 and 6.7 Guideline: 5.0 and 6.9
EC	Adaptive modified upstream site	To (i) report and act on any exceedances of the focus, action and guideline trigger values, and (ii) to sustain the improved water quality seen in the last two wet seasons[2] when practical.	Focus: 21 µS/cm Action: 30 µS/cm Guideline: 43 µS/cm
Uranium	Ecotoxicology	To (i) report and act on any trigger value exceedances, and (ii) to sustain the lower uranium concentrations measured in the last two wet seasons when practicable.	Focus: 0.3 µg/L Action: 0.9 µg/L Limit: 6. µg/L
Magnesium	Ecotoxicology		Provisional Values [a,b] Limit = 4 mg/L when Mg/Ca mass ratio is <9. Limit = 1.2 mg/L when Mg/Ca mass ratio is >9
Radium	Modelled dietary intake	The limit is based on a dose constraint of 0.3 mSv per year above natural background from the ingestion of ^{226}Ra in freshwater mussels (*Velesunio angasi*), a 10 year old child consuming 2 kg of mussels annually and a concentration factor of 19 $m^3.kg^{-1}$ for ^{226}Ra from the water column	10 mBq/L wet season median difference in ^{226}Ra activity between upstream and downstream monitoring points

[a] yet to be agreed with regulator
[b] from van Dam et al (2008)

Contrary to the third dot point above, the Aboriginal Traditional Owners of the area have indicated that they do not wish to see *any* change to the natural water quality. To reconcile these two positions, the system of having numerical values alone as water quality objectives was expanded. Narrative water quality objectives (Table 1) were developed to be used in conjunction with numerical guideline values. This approach accommodates both the scientific objectives of ecosystem protection, and the secondary management aim of minimising water quality changes downstream of the mine.

Decommissioning and closure

Developing and specifying closure guidelines

Arguably the distribution of water quality data measured at the downstream compliance point during the operational life of the mine provides a benchmark for closure, provided that no adverse effect has been measured in the waterway downstream of the compliance point. Whilst this assertion may initially appear to be controversial it does receive strong support in this present case from both the laboratory and field ecotoxicological testwork and from the long record of macroinvertebrate and fish abundance and diversity data available for Magela Creek downstream of GS009. This record has shown no detectable evidence for mine-related impact on downstream aquatic ecosystems (Johnston and Needham 1999; SSD monitoring record 1999-2007 - www.environment.gov.au/ssd).

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[2] Referring to the 2001-2 and 2002-03 wet seasons

In the context of closure it must also be recognised that return to pre-mining baseline conditions at GS009 is not likely to occur in the short to medium term given the time required for the newly created landform to come to weathering equilibrium and the continuing low, inputs from groundwater predicted to occur over the intermediate to long term. This is the situation that would prevail at most rehabilitated mine sites around the world.

The key issue here is to locate the "optimum" position between the most conservative endpoint of *nil* detectable downstream perturbation above background, and the maximum extent of perturbation above the upstream reference condition, that can occur without compromising achievement of the primary environmental protection objectives. The framework developed above for compliance assessment during the operational life of the mine provides a robust technical basis from which to argue the relative merits of various options for specifying water quality closure criteria. However, the final basis for specifying such criteria are yet to be debated and agreed upon by all stakeholders involved in the closure planning process.

Post closure monitoring and performance assessment

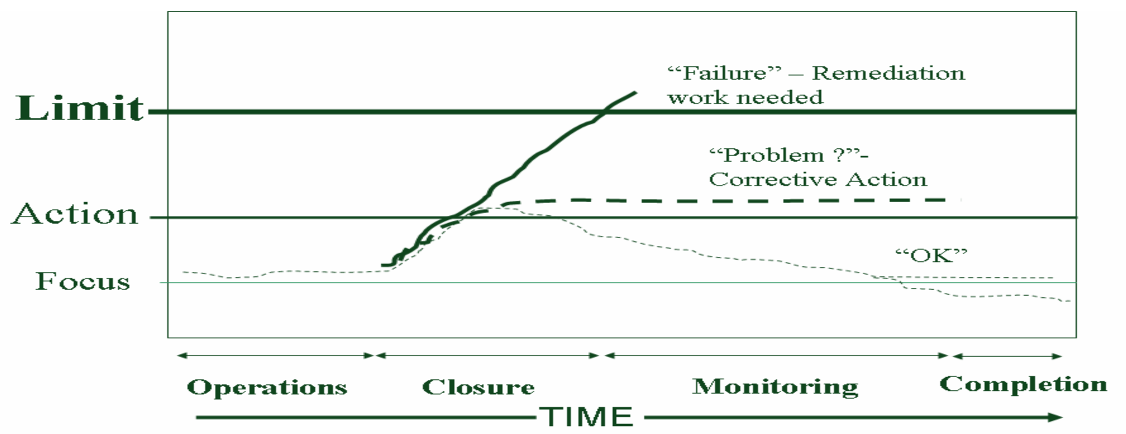
It is likely that the trigger value framework developed for monitoring and assessing water quality in Magela Creek during the operational life of the mine can be applied, with some modification, to post closure performance assessment.

Nevertheless, there is the question of what will represent final "success" in the context of demonstrating the level of compliance required for ultimate signoff with the regulator. While it could be argued that the frequency of exceedance of the focus and action triggers for the range of water quality parameters should ultimately be lower than during the operational life of the mine, it must be considered that during and immediately after decommissioning of the site that this frequency may well increase, before declining again, as the newly rehabilitated footprint evolves to a long-term steady state condition (Figure 3). The closure agreement reached with stakeholders will need to accommodate this possibility. Notwithstanding this short term relaxation of frequency of exceedance of management triggers, peak values of parameters should at all times remain below the upper guideline or limit values.

Three possible scenarios have been illustrated in Figure 3. In the intermediate to longer term a trend towards convergence with the downstream focus values established during the operational period of the mine might provide a reasonable indicator that closure has been successful (ie "OK") with respect to water quality parameters. As discussed above this approach would accommodate a finite level of input of solutes from the site whilst maintaining a sufficiently conservative level of protection for the downstream aquatic environment.

In the event that a water quality parameter remains around the action trigger then this would require discussion with the regulator to determine if some corrective work was required. However, for the third case where the trend is upwards and the limit value is exceeded then this would signal failure of the rehabilitation works and remedial work would definitely be required.

Figure 3 *Schematic illustrating proposed frequency of exceedance model for assessing performance against water quality closure objectives. The terms "Focus", "Action" and "Limit" have been defined in the main text*



Natural waterbodies post closure

Overview

When the Ranger mine ceases operations the requirement is for the disturbed areas to be rehabilitated to a condition consistent with the values of KNP, and to be suitable for reincorporation back into the Park. In the case of natural waterbodies this would mean that their post rehabilitation environmental values, in particular the visual aesthetic and traditional and cultural values of the waterbody, should be consistent with the expectations of the traditional owners of the land. At a minimum this would mean that the environmental attributes of these waterbodies should ultimately be consistent with similar unimpacted habitats of KNP. Georgetown Billabong (GTB) is the largest and arguably the most important such waterbody located in close proximity to the current mine operational area (Figure 2). The approach we are developing to derive closure criteria for GTB provides a model for other natural waterbodies on the lease.

The physical surrounds of GTB and its coupling with water flows from the surrounding catchment (Magela and Georgetown Creeks) has remained largely unchanged on an annual basis since mining began, and is unlikely to be changed prior to decommissioning of the site. Consequently the terrestrial landscape immediately surrounding the billabong is not of significant concern.

The key concern is the potential for delivery of solutes from the rehabilitated mine landform post closure. These solutes, if present at too high a loading, could impact on water quality and hence on the biological integrity of the waterbody. The principal objective of the closure planning process will be to produce a design for the current disturbed area such that the delivery of solutes and suspended sediment from the disturbed footprint in the catchment of Corridor and Georgetown Creeks will not compromise the post closure environmental values and objectives for the waterbody.

Use of both pre-mining baseline and upstream reference site data to derive water quality criteria for GTB is problematic because of the lack of relevant baseline and upstream sites, and because the waterbody has historically received low level discharges from the mine. However, monthly water quality data are available from GTB while intermittent water quality, fish and macroinvertebrate data are available both from GTB and from reference sites (billabongs in the region unaffected by mining) that may be used for comparison.

The situation is additionally complicated in this case by a bi-phasic seasonal regime. The billabong is well flushed during the wet season by both water from Georgetown Creek and by backflow or lateral overbank flow from Magela Creek. This flushing ceases at the end of the wet season, with the billabong contracting in surface area and undergoing substantial evaporative concentration during the six months of the subsequent dry season (Figure 4).

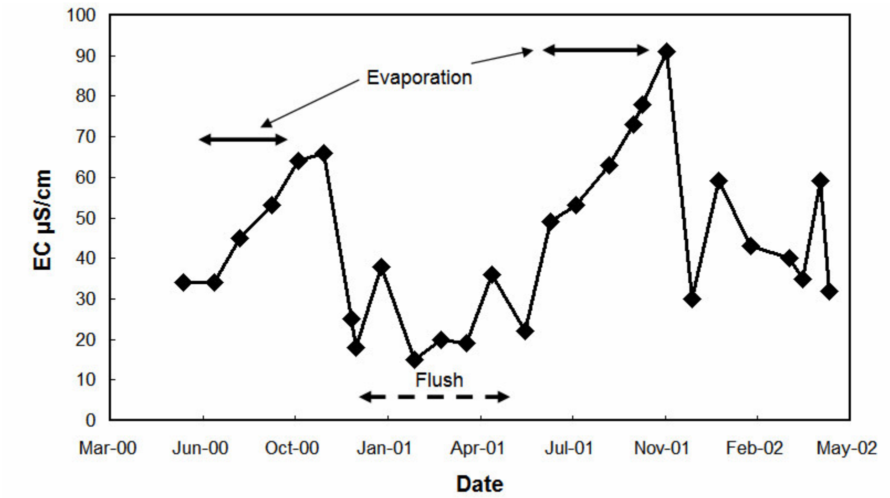
Thus two sets of water quality criteria are required – one for the wet season and one for the dry season – to avoid application of inappropriately conservative criteria during the dry season, and too lenient criteria for the wet season. An approach to deriving the wet season criteria using a combination of water quality and macroinvertebrate community structure time series data, and the derivation of dry season quality criteria from end of dry season maxima (that is, worst water quality) is described below.

Derivation of water quality criteria from biological indicators

The general philosophy and recommendation of deriving water quality criteria from local biological response data (sensu ANZECC and ARMCANZ, 2000) are being applied to the setting of water quality closure criteria for GTB. For example, if the post-closure condition in GTB is to be consistent with similar undisturbed (reference) billabong environments of KNP, then the range of water quality data from the billabong over time that supports such an ecological condition in GTB (as measured by suitable surrogate, biological indicators) may be used for this purpose.

Potential biological indicators that have been measured in GTB include fish and macroinvertebrate communities. While data for both community groups have been measured intermittently since 1979, it has only been since the mid 1990s that standardised monitoring or surveying of these communities has been in place. The fish monitoring record since 1994 is more or less uninterrupted. However, macroinvertebrate data obtained using the same sampling methodology are only available for mid-1995, mid-1996 and mid-2006. While the fish record is more complete, macroinvertebrate data are regarded as more useful for setting water quality criteria because of the enhanced sensitivity of this group of organisms to water quality generally (eg ANZECC and ARMCANZ, 2000)

__Figure 4__ Annual cycle of electrical conductivity in Georgetown Billabong. Wet season typically starts in November and ends in May



Macroinvertebrates were collected by sweep-net sampling through aquatic plants and sediments in the littoral zones of Alligator Rivers Region (ARR) billabongs or water bodies in the early dry season (May), when diversity and abundances are high after wet season flooding, from 7 (1995), 11 (1996) and 13 (2006) water bodies. Up to five of these water bodies in each year were exposed to mine-derived waters to varying extents, including GTB, while the remainder served as reference water bodies.

For the three sets of data combining aquatic plant and sediment habitat, ordination and ANOSIM[3] analysis showed that the community structure of macroinvertebrates in GTB closely resembled that of other reference water bodies. As stated above, this undisturbed condition could potentially be maintained into the future by taking as water quality criteria those physicochemical data that supported this (undisturbed) ecological condition.

Macroinvertebrate communities of shallow lowland billabongs of the ARR, such as GTB, are seasonally dynamic. Species diversity, abundance and biomass reach maxima in the early dry season, then decline dramatically, in association with reduced food availability and water quality, over the dry season to minima in December (Marchant 1982; Outridge 1988).

The consequence of the seasonal recruitment patterns and annual 're-setting' of a large number of macroinvertebrate species in lowland billabongs as described above is that populations from these species may be short-term transients in the billabong, lacking a capacity to pre-adapt to long-term changes in water quality and other environmental conditions in the billabong. Thus while a 'healthy' macroinvertebrate community present in the early dry season of a particular year would reflect the water quality of the preceding wet season, and indeed to some (unknown) extent, water quality of the antecedent dry season, it does not necessarily reflect water quality for time spans greater than this.

Thus, the conservative approach adopted in this paper is to base post-closure water quality objectives for GTB (consistent with other undisturbed environments of KNP) on the range of water quality data from the billabong over the wet season (wet season criteria) and dry season (dry season criteria) preceding each of the three macroinvertebrate sampling campaigns.

In practice, this entails for the three sampling years (1995, 1996. 2006) setting wet season criteria on the basis of water quality measured over the period January to May for the three years, and dry season criteria on the basis of the worst water quality observed in the preceding dry seasons, typically for the months September to December. Median and 80th percentile values for 3 key water quality variables

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[3] ANOSIM (ANalysis Of SIMilarity) is effectively an analogue of the univariate ANOVA and seeks to determine if assemblage groups (eg reference versus mine-exposed) are significantly different from one another in multivariate space.

relevant to Ranger, electrical conductivity (EC), magnesium and uranium, representing summary statistics from which water quality closure criteria may be derived, have been calculated from the combined water quality records from the three sampling years (Table 2). Use of the 80th percentiles from the reference data set is recommended in the Guidelines for the derivation of water quality 'trigger values' – closure criteria studying the current context, exceedance of which may elicit management action.

The statistics derived from the water quality record for the three years in which macroinvertebrates were sampled are compared in Table 2 with the statistics for GTB derived from the entire 27 y water quality record since mining commenced in the catchment.

From Table 2, it can be seen that the values for either wet season or dry season criteria derived from 1995, 1996 and 2006 data, are usually higher than equivalent values derived from all years, reflecting the gradual decline in water quality that has occurred in GTB since mining commenced, and particularly after 2000.

It is anticipated that macroinvertebrate sampling will be repeated several more times between now and projected mine closure in 2020 and the guideline values adjusted, if required, to incorporate this new information.

Table 2 *Median and 80th percentile values for major mine-related water quality indicators measured monthly in Georgetown Billabong*

Water quality variable		Wet season values – 1995, 1996 & 2006	Wet season values – All years	Dry season values – 1995, 1996 & 2006	Dry season values – All years
EC (µS/cm)	N	32	215	15	131
	Median	25.5	28.8	81.6	63.05
	80th percentile	49.8	40.8	107.6	93.2
Mg (mg/L)	N	24	162	10	86
	Median	2.0	1.8	1.4	2.1
	80th percentile	4.5	2.8	2.1	3.4
U (µg/L)	N	34	215	16	130
	Median	0.55	0.37	0.89	0.5
	80th percentile	0.93	0.91	1.24	1.23

Conclusions

The Ranger Mine has been used as a case study to illustrate how field biological indicators of ecosystem status and results from ecotoxicological studies can be combined with a water quality record from downstream of a minesite to derive water quality guideline values that are not as conservative as would be produced by the default approach of conformance with an upstream, reference water body or historical reference condition..

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References

ANZECC and ARMCANZ (2000) Australian and New Zealand guidelines for fresh and marine water quality. National Water Quality Management Strategy Paper No 4. Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Hogan, A, van Dam, RA, Markich, SJ and Camilleri, C. (2005) Chronic toxicity of uranium to a tropical green alga (*Chlorella* sp.) in natural waters and the influence of dissolved organic carbon, Aquatic Toxicology, 75, p 343-353.

Humphrey, CL, Thurtell, L, Pidgeon, R, van Dam, R and Finlayson, M (1999) A model for assessing the health of Kakadu's streams, Australian Biologist, 12, p 33-42.

Iles, M (2004) Water quality objectives for Magela Creek – revised November 2004. Internal Report 489, December, Supervising Scientist, Darwin. Unpublished paper.

Johnston A and Needham RS (1999) Protection of the environment near the Ranger uranium mine. Supervising Scientist Report 139, Supervising Scientist, Canberra.

Jones D, Humphrey CL, Iles M, and van Dam, RA (2006) An approach to deriving surface water quality criteria with implications for closure – Ranger mine case study, *In* Proceedings of the First Intl Seminar on Mine Closure, Mine Closure 2006, (A Fourie and M Tibbert, eds), September 13-15, Perth, Australia, p 635-646.

Marchant, R (1982a) The macroinvertebrates of Magela Creek, Northern Territory. Research report 1, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.

Outridge, PM (1988) Seasonal and spatial variations in benthic macroinvertebrate communities of Magela Creek, Northern Territory, Australian Journal of Marine and Freshwater Research, 39, p 211–23.

van Dam RA, Humphrey CL & Martin P (2002). Mining in the Alligator Rivers Region, northern Australia: Assessing potential and actual impacts on ecosystem and human health. *Toxicology* 181/182, 505-515

van Dam, RA., Hogan, A, McCullough, C and Humphrey, C (2008) Toxicity of magnesium sulfate in Magela Creek water to tropical freshwater species. In **eriss** Research Summary 2006–2007. eds Jones DR, Humphrey CL and van Dam RA, Supervising Scientist Report 196, Supervising Scientist, Darwin NT, in press.