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# What do elevated background contaminant concentrations mean for AMD risk assessment and management in Western Australia?

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# WHAT DO ELEVATED BACKGROUND CONTAMINANT CONCENTRATIONS MEAN FOR AMD RISK ASSESSMENT AND MANAGEMENT IN WESTERN AUSTRALIA?

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## ABSTRACT

*Water quality contaminants include a range of naturally occurring chemicals that can cause degradation of aquatic ecosystem water values when concentration ranges exceed biological tolerances. Both acid and metalliferous drainage (AMD) and acid sulfate soil (ASS) can increase contaminant concentrations through reduced pH and increased solute concentrations especially of toxic metals and metalloids. Water quality guideline criteria are typically used to maintain existing end use value objectives when managing AMD/ASS-affected waters.*

*However, surface and ground waters of catchments comprising mining resources often show elevated solute concentrations in baseline conditions due to their unique geologies. From an AMD and ASS risk assessment perspective, regional water quality may therefore be unique and locally-relevant such that site-specific water quality guidelines may therefore be required to most reasonably manage water quality objectives.*

*We provide case study examples from iron ore and coal mining from the Western Australian regions of the Pilbara, and the South-west to show that defining water quality criteria for closure is more than just using generic national guidelines, but an explicit consideration of the baseline regional bio-physico-chemical context.*

## 1.0 INTRODUCTION

Physical and chemical stressors are naturally occurring parameters that can cause significant impacts to aquatic ecosystems when concentrations are either too high or too low. Physical and chemical stressors may also present an additive toxic risk or may modify the effects of toxicants through synergism and antagonism of other stressors, e.g. pH can alter the dissolved fraction of metals and their speciation affecting their toxicity (Neil et al. 2009). Acid and metalliferous drainage (AMD) can increase contaminant concentrations through reduced pH and increased solute concentrations, especially of toxic metals and metalloids.

### 1.1 Water Quality Guidelines

The role of water quality guideline criteria in managing waters actually or potentially affected by AMD is typically to maintain existing end use value objectives. As for much of the developed world (Jones 2012), mine closure planning in Western Australia requires development of closure objectives and commensurate criteria to demonstrate achievement of these objectives (DMP/EPA 2011). There are general acid and metalliferous drainage (AMD) monitoring protocols and standards available which can help guide mine water quality management and monitoring. The International Network for Acid Prevention (INAP) has produced a global acid rock drainage (ARD) guide (GARD Guide) which summarises the technical and management practices for industry and stakeholder use (Verburg et al. 2009). There are also many scientific and technical organisations working on AMD and heavy metal pollution from mine operations, such as the International Network for Acid Prevention (INAP), Mine Environment Neutral Drainage (MEND), the International Mine Water Association (IMWA), the Acid Drainage Technology Initiative (ADTI), the South African Water Research Commission (WRC), and the Partnership for Acid Drainage Remediation in Europe (PADRE). These organisations have all published guidelines which, together, represent an overview of strategies on monitoring water quality of surface water relevant to the extractive industries from international and national level of governments and organisations.

However, selection of related guidelines and appropriate sampling protocols still must depend on site-specific characteristics, permitting standard limits and requirements, and required data accuracy and precision. These in turn must explicitly depend upon stakeholder values such as long-term end uses for the water resource as well as accounting for regional water quality and ecological tolerances, e.g. extremely soft receiving waters (Van Dam et al. 2010) and any existing disturbances.

Across Australasia, a common default position for water quality management criteria by regulators is the use of the Australasian Water Quality Guidelines (A/A) (Batley et al. 2003a); particular those for 95% protection of aquatic ecosystems (McCullough and Van Etten 2011). The purpose of water quality guidelines is to maintain, or improve, upon current water quality values. Three broad ecosystem condition classifications are recognised by the A/A guidelines (ANZECC/ARMCANZ 2000). All ecosystem condition classifications explicitly recognise the long-term goals desired by stakeholders and implied by the selected management goals and water quality objectives for the water resource.

1. High value systems (99% biodiversity protection) — effectively unmodified or other highly-valued ecosystems that are of conservation or other ecological value with ecological integrity intact. Unlikely to occur outside of national parks or other conservation reserves, or outside of remote and undisturbed locations.
2. Slightly to moderately disturbed systems (95% biodiversity protection) — ecosystems in which aquatic biological diversity may have been slightly adversely affected by human activity. However, biological communities remain in a healthy condition and ecosystem integrity is largely retained.
3. Highly disturbed systems (80% biodiversity protection) — degraded ecosystems of low ecological value. Although this classification implies that degraded aquatic ecosystems still retain potential, or actual, ecological or conservation values, practical considerations mean it may often not be feasible to return them to a slightly–moderately disturbed condition.

## 1.2 Water Quality Guideline Development

Water quality criteria used in ecosystem protection guidelines are to protect aquatic biota (the end use value in this circumstance) and are not an end in themselves. These default values are prepared by analysis of a comprehensive set of available ecotoxicological data (Aldenberg and Slob 1993). Specifically, the default values are prepared by analysis of a comprehensive set of available ecotoxicological data from a number of regions and species; which may, or may not be, relevant to the area of interest.

Biological methods of assessing toxicity in aquatic environments have found support in developing water quality criteria because they have the capacity to integrate effects through continuous exposure, and, more specifically because they measure directly the level of change at which a particular substance becomes toxic. This approach supplants earlier efforts at indirectly estimating toxicity, using chemical and physical surrogate measurements alone (Auer et al. 1990; Karr and Chu 1997, 1999). Ecotoxicological testing with bioassays is valuable for ranking the toxicity of different chemicals and other stressors, for determining their acceptable concentrations in receiving systems, and for elucidating cause and effect relationships in the environment (Chapman 1995).

However, the data for the A/A toxicant trigger values are generally not locally-derived both in a national and almost certainly not in a regional sense; they do not include any local species in the toxicity testing array and are largely based on overseas species, e.g. rainbow trout, fathead minnow, *Daphnia magna*, etc. Hence, ecological responses such as toxicity-testing data from relevant test-species and local receiving waters are of significantly more value than broadly encompassing water chemistry guidelines such as the A/A in determining what concentrations are acceptable for protecting ecosystem values.

The A/A data for physico-chemical stressors do not incorporate toxicity-test data at all; just the 80th percentile of the amalgamation of a number of historical data sets across broad geographical regions. Therefore, there are no explicit data that these values will protect 95% of the species found in this area’s ecosystem. Indeed, in the aquatic ecosystems of most remote locations in which much mining occurs, we do not understand the assemblages well enough to know what 95% of the species (they have not yet been described) and therefore site-specific trigger values are not available.

### 1.3 Regional Differences: or one site’s ‘contaminated state’ is another site’s ‘baseline condition’

In the absence of site-specific trigger values for aquatic ecosystem protection, drainage quality and leaching test results require comparison to default guideline values. These generic values may not be appropriate for many mining regions whose catchments are expected contain enriched geological materials. Indeed, from a mining perspective, what *Contaminated Sites* practitioners may call ‘above ambient levels’, miners refer to as ‘resource indicators’ such as elevated metal concentrations in waterway sediments (Averill 2013).

This natural geochemical enrichment may lead to elevated water body solute concentrations when compared with non-site-specific assessment criteria for water bodies and aquatic ecosystems. Use of generic guidelines not accommodating this regional variability may result in over management of mine drainage not commensurate with the risk it presents (Batley et al. 2003b).

### 1.4 Water Quality Monitoring

Critically, monitoring of AMD receiving waters is not management; it is the process by which the need for management intervention is determined. In application of monitoring data to the guidelines, contaminant concentrations are usually compared with a single default trigger value, developed from a modelled protection value arising from the data generated by these tests. In the absence of local toxicity-response test data (by far the most common circumstance worldwide), the default trigger values are assumed to provide a reasonable upper limit. However, only rarely is water quality monitoring data compared with either water quality distributions from either a baseline dataset or from a reference site.

Trigger values are defined as concentrations that, if exceeded, would indicate a potential environmental problem, and consequently should ‘trigger’ a management response.

ANZECC/ARMCANZ (2000) further defines low-risk trigger values as "*concentrations (or loads) of key performance indicators below which there is a low risk that adverse biological effects will occur*". The physical and chemical trigger values are not designed to be used as 'compliance' or threshold values at which an environmental problem is inferred if exceeded, rather, they are designed to be used in conjunction with professional judgement in order to provide an initial assessment of the state of the water body (Hart et al. 1999; ANZECC/ARMCANZ 2000).

### 1.5 Trigger Values

The role of the 80th percentile at the reference site is to simply quantify the notion of a 'measurable perturbation' at the test site. These 80th percentile site-specific trigger values provide an upper limit for stressors that cause problems at high values, while the 20th percentile provides a lower limit for stressors that cause problems at low values. These site-specific trigger values set a benchmark for 'current status' against which future variation in water quality at these sites can be assessed.

Toxicant default values are based upon actual biological effects data and so by implication, exceedance of the value indicates the potential for ecological harm, rather than a percentile system which has intuitive appeal among experts but is otherwise largely arbitrary. Hence, the A/A guidelines recommend toxicity-test values take precedence over local reference conditions until more robust (e.g., local test species) toxicity-testing data can show otherwise. As a consequence, for toxicity test-derived trigger value concentrations to be increased, demonstration of no-significant ecological effect would generally have to be carried out using local species or similar site-specific data.

Trigger values are not an instrument to assess 'compliance', trigger values are an 'early warning' mechanism to alert managers of a potential problem. Compliance values will generally be set by regulators based upon national or regional water quality guidelines, or from an arbitrary deviation from regional/median expected water quality.

Trigger values are derived preferably from locally appropriate control or reference data, although the Water Quality Guidelines provide default values where such data do not exist or cannot be gathered (Barmuta et al. 2001).

In formal terms the trigger-base approach is as follows: A trigger for further investigation will be deemed to have occurred, when the median concentration of n independent samples taken at a test site exceeds the eightieth percentile of the same indicator at a suitably chosen reference site or from the relevant guideline value in the Water Quality Guidelines. This approach acknowledges natural background variation through comparison to a reference site' baseline conditions or an analogue site(s). The locally derived water quality triggers therefore accommodate site- specific anomalies.

Because the reference site is being monitored over time, the trigger criterion should be constantly updated to reflect temporal trends and the effects of extraneous effectors (e.g., climate variability, seasonality).

## 2.0 CASE STUDIES

We present two case studies for site-specific derivation of trigger values from Western Australia's South-west and Pilbara and biogeographic regions (Fig. 1).

Site-specific trigger values were derived following the derivation protocol presented in the flow chart (Fig. 2). This protocol is fundamentally based on Section 3.3.2 'Defining low-risk guideline trigger values' of the Australasian Water Quality Guidelines for Fresh and Marine Waters (ANZECC/ARMCANZ 2000). Outliers are measurements that are extremely large or small relative to the dataset distribution and, therefore, are suspected of being sampling errors that may misrepresent the population from which they were collected (USEPA 2006). Significant outliers were identified and removed from the datasets prior to analyses.

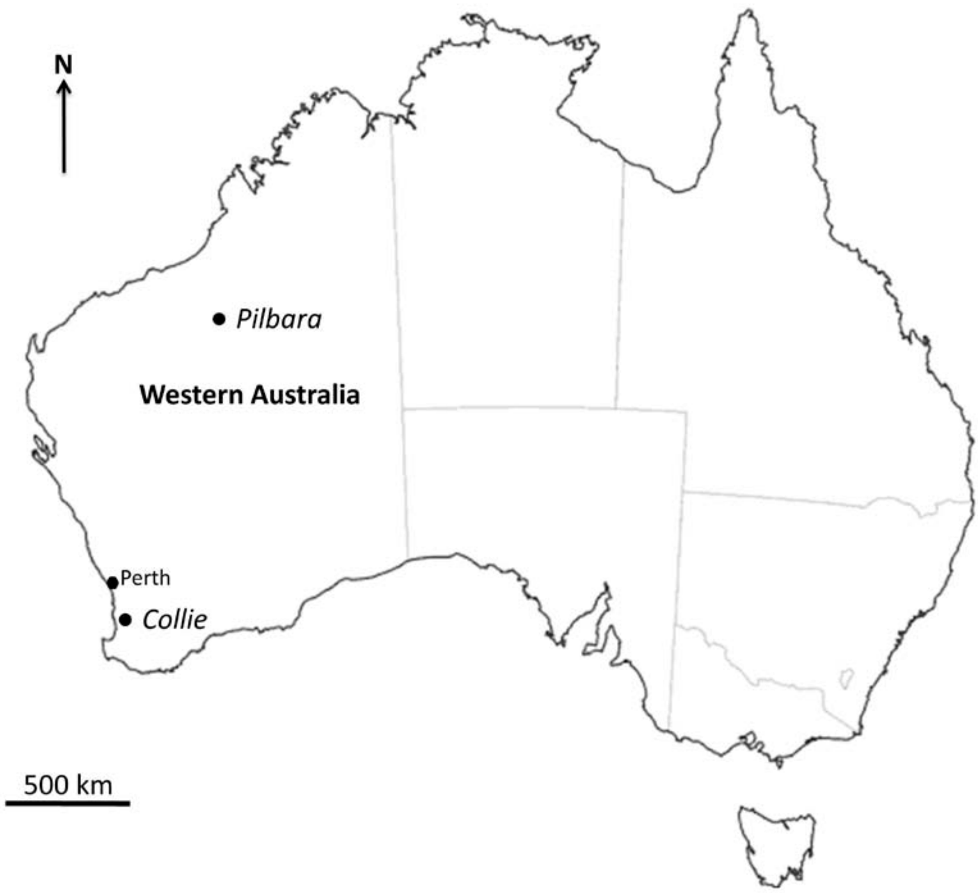


**Fig. 1. Case study locations in Western Australia**

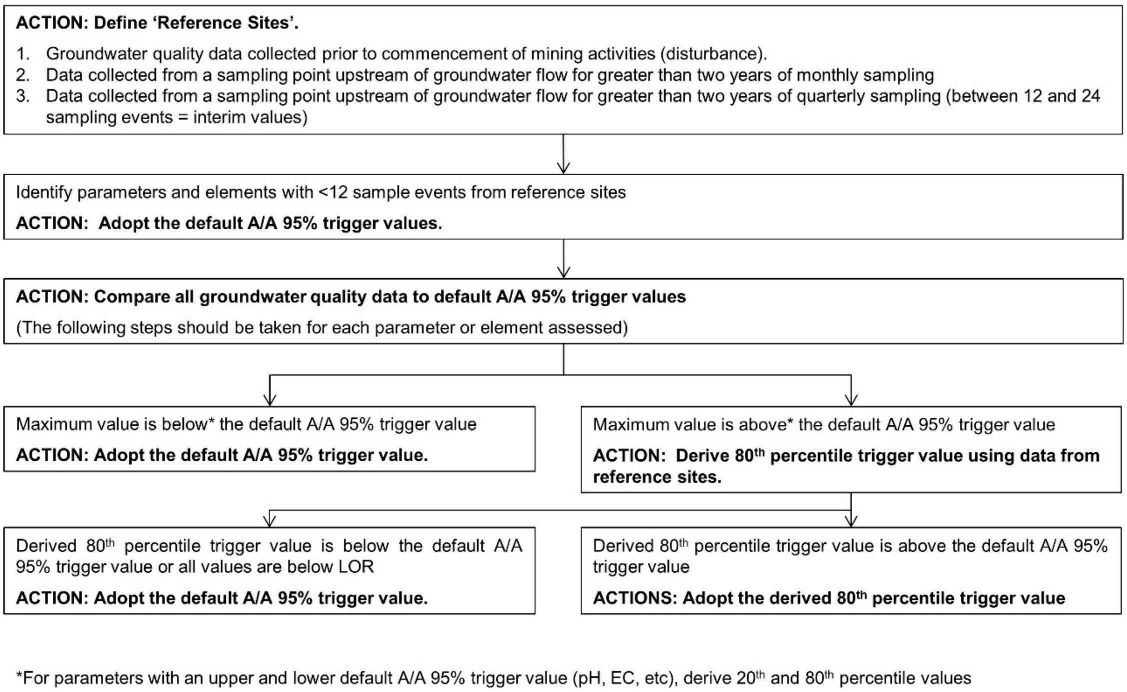


**Fig. 2. Site-specific trigger value derivation protocol used for the case studies**

## 2.1 South-West Acid and Metalliferous Discharge

Mining of the Lake Kepwari void in south-west Australia (WO5B) began with diversion of the seasonal Collie River South Branch (CRSB) away from the pit site and around the western margin, and ceased in 1997. During rehabilitation, reactive overburden dumps and exposed coal seams were covered with waste rock, battered and topsoil replaced, and revegetated with native plants. To reduce wall exposure and acid production, the lake was rapid-filled by a brackish first-flush diversion from the CRSB over three winters from 2003–2005 (Salmon et al. 2008).

Although river water initially raised water pH to above pH 5, lake pH subsequently declined to below pH 4 by 2011 and displayed elevated solute concentrations as a result of AMD inputs, most likely though in-catchment and in-lake acidity generation from PAF, and acidic groundwater inflow (Müller et al. 2011). The volume of the lake is now around $32\times10^6$ $m^3$, with a maximum depth of 65 m and surface area of 103 ha.

During the third week of August 2011, a rainfall of 85.6 mm (BOM, 25/12/2012) in Collie over 48 h led to high flows in the CRSB of a 1:8 year magnitude (DOW 2013). The water level in the CRSB rose, overtopping and then eroding the engineered northern dyke wall that separated the CRSB diversion from Lake Kepwari. As a result, water levels in Lake Kepwari rose 1.7 m adding 3 ha to the surface area of 103 ha (Premier Coal unpublished data) and increasing lake volume by around 6% (McCullough et al. 2012). Lake water then decanted through a previously designed outlet before overtopping this and then decanting back through the breach as CRSB levels dropped (McCullough et al. 2013). There is now a permanent connection to the river and lake at the breach point and through a newly designed lake outflow weir. Planned long-term flow-through of the pit lake via the weir presents a risk to downstream water quality that needed to be understood in the regional context of naturally and historically elevated CRSB solute concentrations.

Laboratory data collected through the Premier Water Quality Monitoring Program (PC-CRSWMP) were used to develop site-specific trigger values for the CRSB from a reference site above Lake Kepwari influence. Regular exceedance of water quality guidelines by a reference South Branch site above the pit lake decant indicates that Collie River background concentrations were already elevated for many of these parameters (McCullough et al. 2013). Although there are no known mine influences above this point, there are known catchment activities that have degraded water quality through eutrophication such as farming (Wetland Research & Management 2009) and salinisation through forest clearance (Tingey and Sparks 2006).

A single measurement meter (Hanna Instruments) was used to sample water quality at each CRSB site for pH and dissolved oxygen (DO). Water samples were also collected and laboratory analyses undertaken for dissolved Al, Fe, Mn, Zn and suspended sediment (SS) concentrations. Water samples were filtered and then acidified with reagent grade nitric acid (1%) until analysed for selected elements by Inductively Coupled Plasma Mass Spectrophotometry (ICP-MS, Varian). These and other water quality analyses were undertaken in a NATA-accredited laboratory and followed standard methods (APHA 1998).

PC-CRSWMP data were statistically analysed using SPSS (2011) statistical software. Prior to derivation of 80% Trigger Values, data sets were explored. Exploratory techniques include numerical summaries, data visualisation, transformations, detection of outliers, checking for censored data, trend detection and smoothing. Relative fits to normal distributions as a test of dataset skewness and median data values were calculated in addition to 80th percentile values for stressors that cause problems at high concentrations and 20th percentile values for stressors that cause problems at low concentrations.

The site-specific trigger values derived for the Collie River South Branch are shown in Table 1. Where available, derived water quality results were compared against 80% A/A Aquatic Ecosystem Protection guidelines as the CRSB is described as "highly disturbed" (Wetland Research & Management 2009). A/A 80% trigger values were used as these are based on actual environmental responses to these variables (as toxicity-test data). Where 80% Ecosystem Protection guidelines were not available, water quality results were conservatively compared against default A/A 95% Ecosystem Protection guidelines (slightly disturbed ecosystems).

Important factors influencing the interpretation of monitoring water quality data are as follows. Site-specific trigger values should be considered in context of other information relevant to individual physical and chemical variables that may serve to moderate toxicity. At this stage, site-specific triggers relate to base-flow conditions as they were only derived from ebb and base-flow conditions. Consequently, they should not be compared with monitoring during high flow events. Some site-specific trigger values, e.g. TDS also differ greatly from respective A/A (2000) default low-risk trigger values. This is due to the limitations of the regional approach adopted by A/A for developing default low-risk trigger values that, by definition, does not account for local variability and catchment geochemical differences. For example, it is also likely that the site-specific trigger value for these sites reflects the existing impact that catchment activities such as deforestation leading to increased sediment and solute loads have had on the CRSB (Mauger et al. 2001).

**Table 1. 80% Ecosystem Protection A/A (2000), derived Collie River South Branch (CRSB) and final trigger values. All values mg $L^{-1}$ unless otherwise stated.**

| Parameter | Fe | Mn[1] | pH | TDS | DO[3] | SS[3] |
|---|---|---|---|---|---|---|
| Ecosystem protection[1] | 0.31 | 3.6 | — | — | — | — |
| South-west, WA lowland river[2] | — | — | 6.5–8.0 | 77–192 | — | — |
| Livestock watering[4] | — | — | — | 2.0[4] | — | — |
| Reference[5] | 0.05–4.3 | 0.02–5.1 | 3.2–8.6 | 580–5,700 | - | 1–97 |
| Derived 20/80% | 0.83 | 1.2 | 6.5–7.3 | 1,700–3,700 | 5.7–8.4 | 17 |
| Site-specific trigger values | 0.83 | 3.6 | 6.5–8.0 | 77–3,700 | 5.7–8.4 | 17 |

[1]ANZECC (2000) 95% ecosystem protection, [2]as base river flow, [3]as diurnal range, [4]poultry no-effect limit, [5]CRSB PML09 reference monitoring site, — = no guideline available.

## 2.2 Case Study 2: Pilbara

Iron ore mining in the Pilbara has been occurring since the mid 1960's to exploit the vast mineralised banded iron formations, namely the Brockman, Marra Mamba and Nimingarra Iron Formations. Natural waters that contact these enriched geological materials may accumulate higher concentrations of solutes when compared with non-site-specific assessment criteria for water bodies and aquatic ecosystems.

Water quality databases were provided by the client for each mining operation and each operation was assessed individually. An assessment of appropriate reference sites was undertaken to identify monitoring or production wells:

- With groundwater quality data collected prior to commencement of mining activities (disturbance).
- Within undisturbed locations (i.e. from upstream of possible environmental impacts).
- Within a local but different system.

Sites required data for greater than two years of monthly sampling (≥24 sampling events) for the derivation of site-specific trigger values. Interim values were derived for datasets comprising between 12 and 24 sampling events.

Where available, water quality results were compared with default A/A 95% trigger values for aquatic ecosystem protection and default trigger values for physical and chemical stressors for tropical Australia for slightly disturbed ecosystems (ANZECC/ARMCANZ 2000). A/A 95% trigger values were used as these are based on actual environmental responses to these variables (as toxicity-test data). Where default A/A 95% trigger values were not available, water quality results were compared against interim or low-reliability values (ANZECC/ARMCANZ 2000).

Prior to the derivation of the $80^{th}$ percentile trigger values and other statistical analysis, treatment of data treatment was employed. Groundwater quality measurements reported as below the limit of reporting were considered equal to the limit of reporting (ANZECC/ARMCANZ 2000). This particular treatment of the data may influence results when a higher than usual limit of reporting was provided. Data outliers are then omitted if the raised limit of reporting is greater than any other measured concentration in the dataset.

As presented in Fig. 2, maximum values for As, Co, Mn, Sb, Se and Sn were below the default A/A 95% trigger values. Therefore, site specific trigger values were not derived for these elements and the default criteria were applied. Default A/A criteria were also applied to those parameters and elements that recorded maximum values above the default assessment criteria but lower derived 80$^{th}$ percentile values (pH, Ag, Al, B. Be, Fe, Hg, Mo and Ni).

Although the maximum values for Ag and Be were above the A/A 95% trigger values, they were not measured above the limit of reporting. Therefore, developing 80$^{th}$ percentile trigger values for Ag and Be would not be appropriate.

Derived site-specific trigger values for EC, $NO_3$, total P, Cd, Cr, Cu, Pb and Zn were above the default A/A 95% trigger values for aquatic ecosystem protection and default trigger values for physical and chemical stressors for tropical Australia for slightly disturbed ecosystems (ANZECC/ARMCANZ 2000). A subset of these parameters/elements is presented in Table 2. This exceedance of trigger values by baseline water quality may be due to intrinsic limitations of the regional approach adopted by ANZECC/ARMCANZ for developing default trigger values that, by definition, do not account for finer regional variability and catchment geochemical differences, even if they are well known, e.g. elevated Pilbara $NO_3$ concentrations (Magee 2009).

**Table 2. 95% Ecosystem Protection A/A (2000) and derived site specific trigger values. All values mg $L^{-1}$ unless otherwise stated**

| Parameter | $NO_3$ | Cd | Cr | Cu | Pb | Zn |
|---|---|---|---|---|---|---|
| Ecosystem protection | 0.7[1] | 0.0002 | 0.001[2,3] | 0.0014 | 0.0034 | 0.008[2] |
| Reference Sites | 1.5–62 | 0.0001–0.01 | 0.001–0.05 | 0.001–0.089 | 0.001–0.006 | 0.005–0.1 |
| Derived 20/80% | 12.4 | 0.001 | 0.005 | 0.006 | 0.005 | 0.013 |
| Site-specific trigger values | 12.4 | 0.001 | 0.005 | 0.006 | 0.005 | 0.013 |

[1] Figure protects against toxicity and does not relate to eutrophication issues, [2]Figure may not protect key test species from chronic toxicity, [3]as chromium VI, — = no guideline available.

Some site-specific trigger values were much higher than the respective default A/A 95% trigger values (e.g. $NO_3$). This may be due to intrinsic limitations of the regional approach adopted by ANZECC/ARMCANZ for developing default trigger values that, by definition, do not account for local variability and catchment geochemical differences.

As outlined in Case Study 1, site-specific trigger values should be considered in context of other information relevant to individual physical and chemical variables that may serve to moderate toxicity. They should also be reassessed when more data from various production and monitoring wells becomes available; this will work towards addressing any limitations identified in the dataset. The suitability of locations selected as reference sites should also be reassessed once new data becomes available.

## 3.0 CONCLUSIONS

Prior to the development by a new mining project, many sites may not have water quality conditions defined as pristine by the A/A water quality guidelines (99% biodiversity protection). An increase in contaminant concentrations is reasonably expected where the geochemistry of a site is already elevated for certain elements; characteristics that make this region of interest for mineral extraction.

Trigger values are solely intended to provide an 'early warning' mechanism to alert managers to a potential risk. The appropriate response may be further site-specific investigation, or immediate remedial action. They are not explicitly designed as compliance points in themselves; this would involve a more complete assessment of the toxicant source – pathway – receptor model (Hart et al. 2006).

In many cases 80% trigger values have values that are more sensitive than ANZECC/ARMCANZ (2000) 90% Ecosystem Protection values for the same variable. In this case we recommend that the ANZECC values be used instead of the 80% trigger values as the criteria and data quality to determine this value has been more rigorously been evaluated.

For ecosystems that can be classified as highly disturbed, the 95% protection trigger values can still apply. However, depending on the state of the ecosystem, the management goals and the approval of the appropriate state or regional authority in consultation with the community, it can be appropriate to apply a less stringent guideline trigger value, say protection of 90% of species, or perhaps even 80%. These values are provided as intermediate targets for water quality improvement. If the trigger values have been calculated using assessment factors, there is no reliable way to predict what changes in ecosystem protection are provided by an arbitrary reduction in the factor.

Comprehensive and effective assessment and management of water quality relies on integrating biological approaches with the more traditional chemical and physical-based approaches, where chemical data provide explanatory variables for trends observed for biota ("cause for consequence") (Chapman 1990). We propose that maintenance of the value of water bodies potentially impacted by AMD is best served by more explicit consideration of regional water quality norms and objectives and site-specific baseline condition than by over-simplistic application of national or regional guidance.

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