Yandicoogina Gorge Mitigation Water Quality Desktop Review

Report to BHP WAIO

19 May 2023

Document Status

Revision No.	Author	Review / Approved for Issue	Approved for Issue to	
			Name	Date
1	Chris Hofmeester	Jess Delaney	Suzi Wild	12/05/23
2	Chris Hofmeester	Jess Delaney	Suzi Wild	19/05/23
3				

"IMPORTANT NOTE"

Apart from fair dealing for the purposes of private study, research, criticism, or review as permitted under the Copyright Act, no part of this report, its attachments or appendices may be reproduced by any process without the written consent of Biologic Environmental Survey Pty Ltd ("Biologic"). All enquiries should be directed to Biologic.

We have prepared this report for the sole purposes of BHP WAIO ("Client") for the specific purpose only for which it is supplied. This report is strictly limited to the Purpose and the facts and matters stated in it and does not apply directly or indirectly and will not be used for any other application, purpose, use or matter.

In preparing this report we have made certain assumptions. We have assumed that all information and documents provided to us by the Client or as a result of a specific request or enquiry were complete, accurate and up to date. Where we have obtained information from a government register or database, we have assumed that the information is accurate. Where an assumption has been made, we have not made any independent investigations with respect to the matters the subject of that assumption. We are not aware of any reason why any of the assumptions are incorrect.

This report is presented without the assumption of a duty of care to any other person (other than the Client) ("Third Party"). The report may not contain sufficient information for the purposes of a Third Party or for other uses. Without the prior written consent of Biologic:

a) This report may not be relied on by a Third Party; and

b) Biologic will not be liable to a Third Party for any loss, damage, liability or claim arising out of or incidental to a Third Party publishing, using or relying on the facts, content, opinions or subject matter contained in this report.

If a Third Party uses or relies on the facts, content, opinions or subject matter contained in this report with or without the consent of Biologic, Biologic disclaims all risk and the Third Party assumes all risk and releases and indemnifies and agrees to keep indemnified Biologic from any loss, damage, claim or liability arising directly or indirectly from the use of or reliance on this report.

In this note, a reference to loss and damage includes past and prospective economic loss, loss of profits, damage to property, injury to any person (including death) costs and expenses incurred in taking measures to prevent, mitigate or rectify any harm, loss of opportunity, legal costs, compensation, interest and any other direct, indirect, consequential or financial or other loss.

Executive Summary

Yandicoogina Gorge (YG) is adjacent to BHP Western Australian Iron Ore (WAIO)'s Ministers North tenement in the Pilbara region of Western Australia. YG supports a significant groundwater-dependent ecosystem (GDE), as well as a high richness of aquatic fauna in surface water pools, including groundwater and hyporheic invertebrate species, taxa endemic to the Pilbara and several species with short geographical ranges.

Recent declines in groundwater levels in the area have reduced the extent and persistence of permanent and semi-permanent pools within YG. BHP WAIO is proposing to ameliorate the impacts to the GDE by supplementing groundwater, through either surface discharge into an infiltration basin upstream of YG, or managed aquifer recharge (MAR). Water will be sourced from the nearby Mining Area C/South Flank mining area (MAC).

Biologic Environmental Survey (Biologic) undertook a desktop assessment, to (1) provide a comparison of water quality between MAC and YG (ground- and surface- water), and (2) assess the risk of each mitigation strategy (MAR and surface discharge) to environmental receptors within the YG. Environmental receptors include stygofauna within the YG aquifer, hyporheos fauna within the hyporheic zone, and aquatic fauna and flora within surface pools.

Monitoring data provided by BHP WAIO showed that the YG receiving environment groundwaters were circum-neutral to alkaline (pH 6.7 - 8.4), fresh to saline (430 - 5,750 µS/cm electrical conductivity; EC), and clear. Ionic composition was dominated by bicarbonate and calcium. Nutrient concentrations were low, with all nitrogen nitrate (N_NO_3) values below Australia and New Zealand guidelines (ANZG) for eutrophication. Dissolved metal concentrations were also generally low, with concentrations of most analytes below analytical limits of reporting (LORs) and/or ANZG default guideline values (DGVs). Concentrations of hydrocarbons and other contaminants were all below LORs in YG groundwater samples.

Surface waters at YG ranged from slightly acidic to alkaline (pH 6.6 - 7.9), with highly variable turbidity, DO and water temperatures. EC was classified as fresh (<1,500 µS/cm) in all samples. Ionic composition typically mirrored the ionic composition of groundwaters. Several nutrient analytes frequently exceeded DGVs, including nitrogen oxides, total nitrogen and total phosphorous. Dissolved metal concentrations were low.

Source water quality from MAC was broadly similar to the ground- and surface- waters of the YG receiving environment, on average being circum-neutral, fresh and clear, with relatively low concentrations of dissolved metals. However, several analytes of concern (AoC) were identified. These analytes exceeded YG 80th percentile values on over 25% of sampling occasions, and therefore, water supplementation is considered likely to increase their concentrations within the YG receiving environment.

For groundwater (MAR option), AoC were pH, hardness as $CaCO_3$ (hardness), magnesium (Mg), sulfate (SO_4), N_NO_3, boron (B) and EC. For surface water (discharge option), the AoC were pH, HCO_3, Mg, N_NO_3, B and zinc (Zn). In addition, the MAC groundwater was found to be supersaturated in calcium carbonate, suggesting widespread precipitation of carbonate minerals could be expected if discharged directly to the surface environment and no control measures were implemented.

For the MAR option, the risk assessment found that the majority of AoC likely pose a **negligible risk** to environmental receptors. The exception was N_NO_3, which was deemed to indirectly pose a **low eutrophication risk** to YG surface water pools. The risk of calcite precipitation was deemed to be **negligible**.

For the surface discharge option, the risk assessment also found that the majority of AoC likely posed a **negligible risk** to environmental receptors. The exception again was N_NO_3, which was deemed to pose a **moderate eutrophication risk** to YG surface water pools, although the toxicity risk was still negligible. The risk of calcite precipitation was deemed to be **moderate**.

Key mitigating factors considered during the risk assessment were:

- Environmental receptors are unlikely to be affected by slight increases in pH or HCO_3, as ground- and surface- waters of the local area (Yandicoogina/Weeli Wolli Creek catchment areas) are naturally basic (pH >7.0) and rich in bicarbonate
- Few N_NO_3 values exceeded the ANZG DGV for toxicity (2.1 mg/L), despite most values exceeding the DGV for eutrophication (0.7 mg/L)
- No boron value exceeded the ANZG DGV for toxicity (0.94 mg/L)
- High water hardness in the source groundwater and YG receiving environment is likely to ameliorate the toxic effects of Mg, SO_4, N_NO_3 and zinc
- None of the AoC appear to be increasing in MAC groundwater over time
- The increase in hydrostatic pressure associated with groundwater injection at depth increases the solubility of $CaCO_3$, reducing the potential for calcite precipitation during MAR.

The risk rankings were also based on the assumption that the following mitigation measures would be implemented:

- Potentially toxic Mg and SO_4 are monitored throughout the duration of supplementation activities, to detect any increase in concentrations

- Water hardness and Ca are monitored to ensure concentrations remain sufficiently high to ameliorate the toxic effects of Mg, SO_4, N_NO_3 and zinc, and buffer against swings in pH
- N_NO_3 concentrations are monitored to enable detection of concentrations above the ANZG DGV for toxicity
- EC is monitored to detect of increasing salinity
- To ameliorate the risk of calcite precipitation in the surface water environment (discharge option), MAC source water is stored in turkey's nest dams and infiltration ponds for a minimum of two to four days prior to discharge. Active degassing of groundwater, and optimisation precipitation (by strategies such as increased temperatures or addition of calcite seed crystals), could be used to reduce precipitation risk (although still require a controlled environment).

The risk assessment showed that the MAR option would present a lower overall risk to the YG receiving environment, owing to the lower risk of eutrophication and calcite precipitation. This option would also provide for more natural cycling of water, oxygen and nutrients, and avoid the potential impacts associated with surface discharge, such as changes to the frequency, timing and velocity of surface flows.

Given the declining groundwater levels and reduction of permanent and semi-permanent pools within YG, and the associated impacts to flora and aquatic fauna, the benefits of either supplementation option would likely outweigh any potential risks AoC pose to the receiving environment.

Table of Contents

Tables

Figures

Plates

1 Introduction

1.1 Background

Yandicoogina Gorge (YG) is located adjacent to BHP Western Australian Iron Ore (WAIO)'s Ministers North tenement, approximately 81 km north-west of Newman, in the Pilbara region of Western Australia (Figure 1.1). YG supports a groundwater-dependent ecosystem (GDE), containing several flora species which indicate a high-level of connectivity between groundwaters and the surface. Surface water pools also host a high richness of aquatic fauna, including groundwater and hyporheic invertebrate species, taxa endemic to the Pilbara and several species with narrow geographical ranges.

Recent declines in groundwater levels in the area have reduced the extent and persistence of permanent and semi-permanent pools within YG, posing a significant threat to resident flora and aquatic fauna (Biologic, 2022a, 2022b, 2023c). BHP WAIO is proposing to ameliorate the impacts to the GDE by supplementing groundwater within YG. This will involve either surface discharge into an infiltration basin located upstream of YG, or managed aquifer recharge (MAR) using bores within YG, with water sourced from the nearby Mining Area C/South Flank operations (collectively referred to as MAC), located approximately 15 km to the southwest (Figure 1.1).

As the groundwater for supplementation will be sourced from a separate aquifer, an assessment of the water quality from the source aquifer, and comparison to ground- and surface- water quality within the YG, is required. Therefore, BHP WAIO contracted Biologic Environmental Survey (Biologic) to undertake a desktop assessment, to provide a comparison of water quality between MAC and YG (ground- and surface- water), and assess the risk of each mitigation strategy (surface discharge or MAR) to environmental receptors within the YG (hereafter referred to as 'the Assessment').

1.2 Scope of Works

The scope of works (SoW) for the Assessment included:

1) Comparison of water quality between source groundwater from MAC and the water of the YG receiving environment (ground- and surface water)
2) Gap analysis if current data is not sufficient to complete the water quality comparison
3) Risk assessment to determine:
    a. the risk that analytes of concern (analytes that may increase in the receiving environment due to supplementation) may impact the aquatic ecosystems of YG

    b. the risk to YG aquatic biota, hyporheos fauna and stygofauna (environmental receptors) from potential changes in water quality
    c. the likelihood of the formation of a calcite precipitate and risk it may pose to the YG receiving environment

4) Assessment of proposed options to mitigate the potential for a calcite precipitate to form upon discharge.

Figure 1.1: Regional location of YG, including IBRA subregions, as well as the Ministers North and MAC operations

PAGE LEFT BLANK INTENTIONALLY – FIGURE TO BE INSERTED IN FINAL PDF VERSION

2 Environment

2.1 Biogeography

YG occurs within Pilbara biogeographical region as defined by the Interim Biogeographic Regionalisation of Australia (IBRA) (Thackway & Cresswell, 1995). The Pilbara bioregion is characterised by vast coastal plains and inland mountain ranges with cliffs and deep gorges (Thackway & Cresswell, 1995). Vegetation is predominantly mulga low woodlands or snappy gum over bunch and hummock grasses (Bastin, 2008).

YG is located within the Hamersley subregion (PIL03) of the Pilbara bioregion (Figure 1.1). This subregion contains the southern section of the Pilbara Craton and comprises a mountainous area of Proterozoic sedimentary ranges and plateaux, dissected by basalt, shale and dolerite gorges (Kendrick, 2001). The Hamersley contains extensive open snappy gum woodland and hummock grassland communities on ranges and plateaus, with low mulga woodlands over bunch grasses on fine textured soils in lower areas and valley floors (Kendrick, 2001).

2.2 Hydrology

YG is situated on Yandicoogina Creek, within the Weeli Wolli Creek/Marillana Creek sub-catchment of the Upper Fortescue River Catchment. Yandicoogina Creek is approximately 42 km in length and flows north-east into Marillana Creek (Figure 2.1). The upper reaches of Yandicoogina Creek comprise a relatively broad, undefined channel. However, in the mid to lower reaches, the creek flows through the gorge system (YG) and becomes well defined. It is through this section that the groundwater intercepts the surface, forming a series of seeps and pools that extend for approximately 3.5 km (Plate 2.1). Yandicoogina Creek meets Marillana Creek approximately 9 km downstream of this pool, where it flows eastwards for 7 km before draining into Weeli Wolli Creek (Figure 2.1).

Weeli Wolli Creek is approximately 70 km in length and has a catchment area of 4,100 km^2. It flows north, where it drains into the Fortescue River passing through the ecologically significant Fortescue Marsh. The two systems are only connected during flooding associated with intense cyclonic events (Kendrick, 2001).

Figure 2.1: YG surface hydrology (including Yandi Creek, Marillana Creek, Weeli Wolli Creek and Fortescue Marsh).

PAGE LEFT BLANK INTENTIONALLY – FIGURE TO BE INSERTED IN FINAL PDF VERSION

Plate 2.1: Photographs showing the groundwater-supported waterbodies of YG (Biologic ©)

2.3 Environmental Receptors

2.3.1 Yandicoogina Gorge GDE

GDEs are ecosystems that rely upon groundwater for their continued existence (BoM, 2021). As a result, the health of GDEs is subject to changes in water table levels (above and below surface soil). GDEs can be represented by many different assemblages of biota which rely on groundwater, and as a result come in many forms. For terrestrial ecosystems there are three key types of GDE:

1. Aquatic ecosystems: that rely on the surface expression of groundwater – this includes surface water ecosystems which may have a groundwater component, such as rivers, wetlands and springs.
2. Terrestrial ecosystems: that rely on the subsurface presence of groundwater–this includes all vegetation ecosystems or Groundwater Dependent Vegetation (GDV).
3. Subterranean ecosystems: this includes cave and aquifer ecosystems (BoM, 2021).

Above-ground terrestrial GDEs are typically characterised by the presence of flora species that rely on groundwater (i.e., phreatophytes). Phreatophytes may be classified as either obligate or facultative phreatophytes depending on their reliance on groundwater:

- Obligate phreatophytes are flora species confined to habitats with access to groundwater.
- Facultative phreatophytes are flora species that can utilise groundwater to satisfy a proportion of their ecological water requirement (EWR) when it is available. However, some individuals may also satisfy their EWR by relying solely on uptake from upper unsaturated soils layers where groundwater is inaccessible (Eamus *et al*., 2016).

YG is known to support both obligate phreatophytic flora, in particular *Melaleuca argentea*, and facultative phreatophytic species (e.g., *Eucalyptus camaldulensis* subsp. *obtusa* and *Eucalyptus victrix*). Other very high/high-level indicators (Rio Tinto, 2021) present at YG include *Imperata cylindrica* and *Fimbistylis sieberiana*, while moderate level indicators include *Cyperus vaginatus* and *Chara* spp. (Biologic, 2020, 2021a, 2022a, 2022b).

Although GDEs only cover a comparatively small proportion of the land surface, they provide specific ecosystem functions supporting unique and important biological diversity at both local and regional scales (Boulton & Hancock, 2006; Humphreys, 2006; Murray *et al*., 2006; Thurgate *et al*., 2001). In addition to environmental benefits, GDEs often have significant social, economic, and spiritual values (Murray *et al*., 2006). Protection of GDEs is commonly considered an important criterion in sustainable water resource management, particularly when human water management is in competition with environmental water demands.

2.3.2 Stygofauna

Stygofauna are animals that inhabit subterranean aquatic habitats (aquifers), and typically include crustaceans, beetles, annelid worms and gastropods (Guzik *et al.*, 2010). Except for three species of fish, all recorded species of stygofauna in Western Australia are invertebrates (Alpin, 1998; EPA, 2016; Larson *et al.*, 2013; Moore, 2019). The geographic ranges of stygofauna species are typically small due to the limited extent and connectivity of suitable habitat within the landscape, coupled with their poor dispersal capability (Halse, 2018; Halse *et al.*, 2014; Humphreys, 2008).

No previous stygofauna sampling has been conducted within YG specifically; however, several studies have sampled bores in Rio Tinto's Yandicoogina mine operations area, located approximately 4.5 km to the north, adjacent to Marillana Creek, revealing a rich stygofauna community. Over 10,000 stygofauna specimens from at least 88 taxa have been recorded from the Yandicoogina mine area with six classes represented, including Malacostraca (crustaceans; amphipods, syncarids and isopods), Copepoda (copepods), Ostracoda (seed shrimp), Arachnida (aquatic mites), Oligochaeta (aquatic segmented worms) and Turbellaria (flatworms) (Biota 2010, 2015). While most of the taxa collected are thought to have relatively large spatial distributions (of those that are known/documented), most stygofauna species that occur in the Pilbara are endemic to the region (Halse *et al.*, 2014).

A Pilbara-wide stygofauna survey conducted by the Department of Parks and Wildlife (now DBCA) (the Pilbara Biodiversity Survey – PBS) between 2002 and 2006 found 12 sites in the region with high richness of stygofauna, including Weeli Wolli Creek, Coondewanna Creek and Marillana Creek which are in close proximity to YG (Bennelongia, 2015). Twenty-five taxa are thought to be endemic to one of or both of the Weeli Wolli Creek and Coondewanna Creek catchments, including:

- Oligochaeta (3 taxa)
- Acarina (2 taxa)
- Ostracoda (6 taxa)
- Copepoda (3 taxa)
- Syncarida (3 taxa)
- Amphipoda (8 taxa)
- Isopoda (1 taxon).

The highly diverse and ecologically significant stygofauna community within the Marillana and Weeli Wolli Creek catchment areas, in comparison to other similarly-sized areas in the Pilbara region, is due to the high percentage of suitable geological and hydrogeological units of the area (Bennelongia, 2015). In particular, the valley fill alluvial deposits and extensive calcretes, and shallow alluvial aquifers, associated with major drainages are highly conducive to stygofauna inhabitation. Additionally, the high and seasonally variable water table aids stygofauna dispersal throughout the area (Biota 2010, 2015).

Although targeted stygofauna sampling has not been undertaken within YG, sampling of the hyporheic zone has yielded over 20 stygal species, highlighting a high level of connection between ground- and surface- waters. See 2.4.3 below for a summary of the hyporheos fauna of YG.

2.3.3 Hyporheos Fauna

The hyporheic zone, comprising saturated interstitial spaces in alluvial sediments, represents an ecotone between the surface and groundwater, with fauna utilising this habitat (collectively referred to as the ‘hyporheos’) containing representatives of both benthic epigean (surface water) species and stygofauna. The former migrate vertically to exploit hyporheic habitats as a nursery to protect juveniles from predation (Bruno *et al.*, 2012; Jacobi & Cary, 1996), and during times of floods (Dole-Olivier & Marmonier, 1992b; Edwards, 1998; Palmer *et al.*, 1992), drought (Coe, 2001; Cooling & Boulton, 1993; Hose *et al.*, 2005), and disturbance in food supplies (Edwards, 1998).

Sampling of the hyporheos within YG between October 2019 and September 2022 has recorded over 100 invertebrate taxa residing within the hyporheic zone, 26 of which are considered true hyporheos taxa, directly dependant on groundwater for their persistence (stygobites and permanent hyporheos stygophiles) (Biologic, 2020, 2022a, 2022b). These primarily comprised water mites and crustaceans from the groups Ostracoda, Copepoda, Syncarida, Amphipoda and Isopoda, and included:

<u>Permanent stygophiles</u>

- water mites *Guineaxonopsis* `sp. Biologic-ACAR011`, *Guineaxonopsis* `sp. Biologic-ACAR013`*, Rutacarus* `sp. Biologic-ACAR007` *and Wandesia* `sp. Biologic-ACAR009`
- ostracods *Limnocythere dorsosicula*

<u>Stygobites</u>

- ostracods *Candonopsis* `sp. Biologic-OSTR025, *Notacandona boultoni*, *Gomphodella* sp., *Gomphodella alexanderi, Gomphodella* `sp. Biologic-OSTR077`, *Meridiescandona marillanae*, *Meridiescandona facies*, *Vestalenula marmonieri* and *Vestalenula matildae*
- copepods *Diacyclops* nr. *humphreysi*, *Diacyclops* nr. *cockingi, Dussartcyclops* sp., *Elaphoidella* sp., Canthocamptidae `sp. B01’, *Parastenocaris* `sp. Biologic-HARP022’ and *Pescecyclops* sp.
- syncarids Bathynellidae `sp. Biologic-BATH019` and Bathynellidae sp. BES7547

- amphipods *Chydaekata* sp. E and Paramelitidae `sp. Biologic-AMPH023`
- isopod *Pygolabis* `sp. Biologic-ISOP035’

Of these taxa, several are currently only known from YG, including the ostracod *Gomphodella* `sp. Biologic-OSTR077`and the isopod *Pygolabis* `sp. Biologic-ISOP035’ (Biologic, 2020, 2022a, 2022b). Others are known to have short geographical ranges, including *Gomphodella alexanderi, Meridiescandona marillanae*, *Meridiescandona facies*, *Chydaekata* sp. E and Paramelitidae `sp. Biologic-AMPH023, and are considered short range endemics (SREs).

2.3.4 Surface Water Biota

Sampling of aquatic biota between October 2019 and September 2022 has found YG supports a diverse and abundant surface water biota, including aquatic macrophytes, aquatic invertebrates (zooplankton and macroinvertebrates), and freshwater fish (Biologic, 2020, 2022a, 2022b). Particularly high diversity has been found within the deep, permanent pool towards the eastern end of the gorge (site YC4).

Aquatic macrophytes (aquatic plants) are important structural and biological components of lowland streams, providing aquatic fauna with habitat, breeding sites, food and cover from predators (Sainty & Jacobs, 2003). A total of nine macrophytes have been recorded from YG, including six emergent macrophytes and three submerged macrophytes. Emergent macrophytes recorded from YG included *Cyperus vaginatus, Eleocharis geniculata, Schoenoplectus subulatus, Fimbristylis sieberiana*, *Typha domingensis* and *Imperata cylindrica*. Submerged macrophytes at YG comprised *Vallisneria nana*, *Ruppia* sp., and *Chara fibrosa*. One species of conservation significant flora YG is known from the gorge. *Fimbristylis sieberiana* is a P3 priority species (DBCA, 2022) which occurs along drainage lines that support a high diversity and cover of sedge and hydrophytic/ mesophytic flora species (Biologic, 2021a).

Aquatic invertebrates, comprising zooplankton (microinvertebrates) and macroinvertebrates, form a vital component of aquatic food webs, feeding upon phytoplankton, bacteria and detritus. In turn, they provide an important food source for higher order consumers such as waterbirds and fish(Ramchandra *et al*., 2006).

Sampling within YG has recorded over 100 zooplankton taxa, with the following groups recorded:

- Protista (protists; six taxa)
- Rotifera (rotifers; 49 taxa)
- Maxillopoda (Copepoda; 18 taxa)
- Cladocera (water fleas; eight taxa)
- Ostracoda (seed shrimp; 24 taxa)

Most zooplankton taxa recorded from YG are widely distributed across northern Australia or the world (cosmopolitan species). However, one ostracod species, *Vestalenula marmonieri*, is endemic to the Pilbara region.

In addition to zooplankton, a total of 248 macroinvertebrate taxa have been recorded within YG between 2019 and 2022, consisting of:

- Nematoda (round worms; one taxon)
- Cnidaria (freshwater hydra; one taxon)
- Gastropoda (freshwater snails; three taxa)
- Oligochaeta (aquatic segmented worms; 18 taxa)
- Acarina (water mites; 26 taxa)
- Crustacea (amphipods or side swimmer; three taxa)
- Collembolla (spring tails; three taxa)
- Coleoptera (beetles; 47 taxa),
- Diptera (two winged flies; 60 taxa)
- Ephemeroptera (mayflies; seven taxa)
- Hemiptera (true bugs; 29 taxa)
- Lepidoptera (moth larvae; 1 taxon)
- Odonata (dragonflies and damselflies; 25 taxa)
- Trichoptera (caddisflies; 13 taxa)

The majority of aquatic macroinvertebrates recorded from YG are common, ubiquitous species. Taxa endemic to the Pilbara region accounted for 9% of the macroinvertebrates recorded (of those with known distributions). The Pilbara endemic fauna included three Odonata (dragonflies/damselflies) which are currently listed as Vulnerable on the IUCN Red List of Threatened Species (*Hemicordulia koomina*, *Eurysticta coolawanyah* and *Ictinogomphus dobsoni*), as well as two stygobitic SRE amphipods (*Chydaekata* `sp. E` and Paramelitidae `sp. Biologic-AMPH023`) and the potentially restricted water mite species *Austraturus* `sp. P2' (Biologic, 2020, 2022a, 2022b).

YG also supports three freshwater fish species; the western rainbowfish *Melanotaenia australis* (Melanotaeniidae), Pilbara tandan *Neosilurus* sp.[1] (Plotosidae) and spangled perch *Leiopotherapon unicolor* (Terapontidae). Western rainbowfish were the most abundant and widespread species within YG. While Pilbara tandan are a representative of a genus that is

---

[1] The *Neosilurus* catfish known from the Pilbara is genetically distinct to the described species *Neosilurus hyrtlii* (Unmack 2013). The Pilbara species is currently known as *Neosilurus* sp. until further taxonomic work has been undertaken and descriptions have been made.

wide-ranging across northern Australia, the species recorded from the Pilbara is genetically distinct to common and widespread congeners (i.e., *Neosilurus hyrtlii*) (Unmack, 2013). Regardless, all three species occur widely throughout the Pilbara and are not currently listed as being of conservation significance.

3 Water Quality Framework

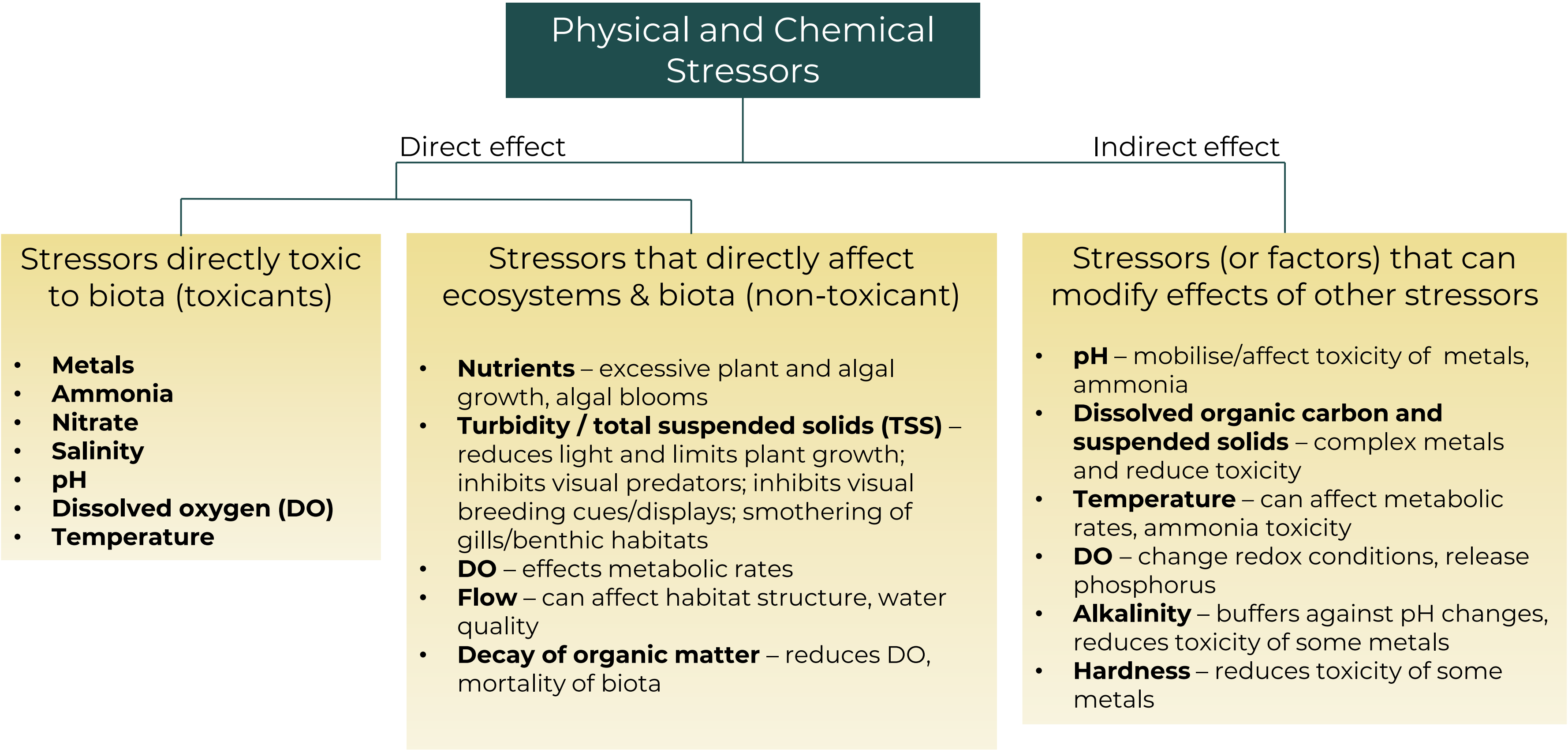
The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG, 2018) provide default guideline values (DGVs) for a range of water quality analytes, classified as physical stressors (including temperature, conductivity, turbidity, and flow) and chemical stressors (including dissolved oxygen, pH, nutrients and metals) according to whether their effects on biota are direct or indirect (Figure 3.1). The primary objective of the ANZG (2018) water quality guidelines is "to provide an authoritative guide for setting water quality objectives required to sustain current, or likely future, environmental values… for natural and semi-natural water resources in Australia and New Zealand".

Rather than acting as pass or fail compliance criteria, DGVs are designed to protect aquatic ecosystems at a low level of risk, with exceedances intended to act as prompts to alert managers and regulators of changes in water quality that may need to be investigated. In this context, a low level of risk can be inferred when water quality conditions are below (or within) relevant DGVs (ANZG, 2018).

The DGVs for surface water quality are often applied by regulators as compliance criteria under Part V of the *Environmental Protection Act 1986* (EP Act) (i.e., licence conditions), as well as occasionally as Ministerial Conditions. However, due to a combination of extreme variations in flows, climate and catchment geology, water quality parameters within Pilbara creeklines rarely meet DGVs for all analytes, which can result in immediate compliance issues once discharge commences.

Therefore, it is often crucial to accurately characterise the quality of water to be discharged (source water), as well as the water quality of receiving environment(s). ANZG (2018) recommends at least two-years of monthly monitoring data (i.e., at least 24 discrete sampling events) is required to develop an adequate characterisation of baseline water quality, and ensure seasonal and temporal variation is captured (Smith *et al.*, 2020).

Comparisons can then be made to identify the analytes in the source water which may present risk to environmental receptors by altering receiving environment water quality. Analytes in source water which record a high proportion of values outside of the 80th and 20th percentiles (80%ile and 20%ile) recorded within the receiving environment, or approximately ± one standard deviation around the median, are considered likely to present a risk of disturbance (ANZG, 2018).



Stressors directly toxic to biota (toxicants)

- **Metals**
- **Ammonia**
- **Nitrate**
- **Salinity**
- **pH**
- **Dissolved oxygen (DO)**
- **Temperature**

Stressors that directly affect ecosystems & biota (non-toxicant)

- **Nutrients** – excessive plant and algal growth, algal blooms
- **Turbidity / total suspended solids (TSS)** – reduces light and limits plant growth; inhibits visual predators; inhibits visual breeding cues/displays; smothering of gills/benthic habitats
- **DO** – effects metabolic rates
- **Flow** – can affect habitat structure, water quality
- **Decay of organic matter** – reduces DO, mortality of biota

Stressors (or factors) that can modify effects of other stressors

- **pH** – mobilise/affect toxicity of metals, ammonia
- **Dissolved organic carbon and suspended solids** – complex metals and reduce toxicity
- **Temperature** – can affect metabolic rates, ammonia toxicity
- **DO** – change redox conditions, release phosphorus
- **Alkalinity** – buffers against pH changes, reduces toxicity of some metals
- **Hardness** – reduces toxicity of some metals

Figure 3.1: Types of physical and chemical stressors and their effects on aquatic systems

4 Methods

4.1 Water Quality Characterisation

4.1.1 Receiving Environment (YG)

Groundwater quality data for YG were provided by BHP WAIO, with monitoring data collected from nine bores located to the west (upstream) of, or within, YG between May 2009 and December 2022 (Table 4.1, Figure 4.1). Surface water quality data were collated from ecosystem monitoring surveys undertaken by Biologic between 2019 and 2022. A total of four pools (YC1, YC2, YC3 and YC4) were sampled for water quality biannually (wet and dry season) during this period, although not all pools were sampled in all sampling occasions (some pools were dry at the time of sampling) (Table 4.2, Figure 4.2).

The ground- and surface- water quality analytes varied between sampling events, however typically included a range of physical and chemical stressors, such as salinity (electrical conductivity and total dissolved solids), total suspended solids and turbidity, pH, nutrients, dissolved metals and ions (e.g., sodium, potassium, magnesium, chlorine and bicarbonate) (Table 4.1, Table 4.2). Total petroleum hydrocarbons (TPH) and other potential contaminants, such as benzene, ethylbenzene, toluene and naphthalene, were also sampled within the groundwater. Data from all bores and sampling events were combined to provide an overall representation of water quality from the aquifer. Similarly, data from all pools were combined to provide an overall representation of surface water quality at YG.

For each water quality analyte, a range of summary statistics were calculated, including the minimum, median, mean, and maximum. Water quality 20th percentiles (20%iles) and 80th percentiles (80%iles) were also calculated, to be compared against groundwater quality from MAC (source groundwater). Where concentrations were below the analytical limit of reporting (LOR), values were halved to enable calculation of summary statistics.

For ecological context, parameters were compared against ANZG (2018) DGVs, with the number of exceedances recorded. For stressors and most toxicants, the DGVs for slightly disturbed lowland rivers in tropical Australia were used (95% species protection), which are applicable to northern Queensland, the Northern Territory and northwest Western Australia (ANZG, 2018). For selenium and mercury, which are known to be bioaccumulating toxicants, the 99% species protection DGVs were applied. In the case of N_NO_3, for which no DGV is provided by current Australian guidelines, groundwater data were compared to the NIWA (2013) N_NO_3 DGV for New Zealand, as recommended by ANZG (2018).

Table 4.1: Location, sampling period, minimum number of sampling events (for any given analyte) and analytes sampled of bores representing the YG groundwater environment

Bore Name	Latitude	Longitude	Sampling Period	Minimum No. Sampling Events	Analytes Sampled
HMN0003P	-22.813551	119.092348	Jul-20	1	• General & Ions – pH, electrical conductivity (EC), Temperature, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Turbidity, Alkalinity, Hardness, Sodium (Na), Calcium (Ca), Magnesium (Mg), Potassium (K), Bicarbonate (HCO_3), Chlorine (Cl), Sulphate (SO_4), Ionic Balance, Sulphur (S) • Nutrients –Nitrogen nitrite (N_NO_2), Nitrogen nitrate (N_NO_3), Nitrate (NO_3) • Dissolved Metals – Aluminium (Al), Arsenic (As), Antimony (Sb), Boron (B), Barium (Ba), Cadmium (Cd), Copper (Cu), Chromium (Cr), Iron (Fe), Mercury (Hg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Selenium (Se), Zinc (Zn) • Contaminants – Benzene, Ethylbenzene, Meta- and para-Xylene, Ortho-Xylene, Toluene, Total Xylenes, TPH, Gross Alpha, Gross Beta, Dibromofluoromethane, Toluene-D8, 1,2-Dichloroethane D4
HMN0013P	-22.821162	119.129858	Jul-20	1	
HMN0033P	-22.831675	119.116764	Aug-21 to Dec-21	2	
HMN0042P	-22.833818	119.136815	Dec-22	1	
HMN0043P	-22.827618	119.138627	Oct-22	1	
HMN0044P	-22.825465	119.142256	Nov-22	1	
HMN0045P	-22.831038	119.136733	Nov-22	1	
RAILGWLM322.7P	-22.824048	119.133487	May-09 to Jul-14	19	
RAILGWLM323.3P	-22.822111	119.129142	May-09 to Nov-21	27	

Figure 4.1: Location of YG and MAC groundwater monitoring sites

PAGE LEFT BLANK INTENTIONALLY – FIGURE TO BE INSERTED IN FINAL PDF VERSION

Table 4.2: Location, sampling period, number of sampling events and analytes sampled of surface water pools representing the YG receiving environment

Site Name	Latitude	Longitude	Sampling Period	No. Sampling Events	Analytes Sampled
YC1	-22.8282	119.1499	Oct-19 to Sep-22	5	• General & Ions – pH, EC, TDS, TSS, Turbidity, Temperature, Alkalinity, Hardness, Na, Ca, Mg, K, HCO_3, Cl, Carbonate (CO_3), SO_4, S • Nutrients – Total nitrogen (TN), Total phosphorous (TP), N_NO_2, N_NO_3, Nitrogen ammonia (N_NH_3), Nitrate + nitrite (N_NO_x) • Dissolved Metals – Al, As, B, Ba, Cd, Cobalt (Co), Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Uranium (U), Vanadium (V), Zn • Other – Redox
YC2	-22.8275	119.1510	Oct-19 to Sep-22	6	
YC3	-22.8246	119.1637	Oct-19 to Sep-22	7	
YC4	-22.8258	119.1628	Oct-19 to Sep-22	7	

Figure 4.2: Location of YG surface water sampling sites

PAGE LEFT BLANK INTENTIONALLY – FIGURE TO BE INSERTED IN FINAL PDF VERSION

4.1.2 Source Water Quality (MAC)

Groundwater quality data from the MAC aquifer were provided by BHP WAIO for analysis. From this dataset, groundwater quality was analysed from 10 bores, with data spanning the period September 2000 to September 2022 (Table 4.3, Figure 4.1). Eight of the 10 bores were sampled on four or more occasions, with the remaining two only sampled once: HGA0062P and HGA0065P (Table 4.3). Data from all bores and sampling events were combined to provide an overall representation of water quality from the source aquifer. A range of summary statistics were calculated for each water quality analyte, including the minimum, median, mean, and maximum. Comparisons were also made against ANZG (2018) DGVs, to provide context for values. Time series plots were created to assess which analytes were increasing or decreasing in the source groundwater over time.

4.1.3 Water Quality Comparison

Source groundwater quality from MAC was compared to surface and groundwater quality (20%ile and 80%ile values of YG), to identify analytes which may pose a risk to the receiving environment. As discussed previously, changes in water quality outside of the 20%ile and 80%ile of baseline conditions, or approximately ± one standard deviation around the median, are considered likely to cause a risk of disturbance (ANZG, 2018). Therefore, analytes which yielded a high proportion of records (over 25%), and/or median values, above YG ground or surface water 80%iles (or below the 20%iles for pH), were considered “analytes of concern” (AoC).

Table 4.3: Location, sampling period, minimum number of sampling events (for any given analyte) and analytes sampled of bores representing the MAC source groundwater

Bore Name	Latitude	Longitude	Sampling Period	Minimum No. Sampling Events	Analytes Sampled
HGA0001P	-22.925785	119.041068	Jun-10 to Nov-20	28	• General & Ions – pH, EC, Temperature, TDS, TSS, Turbidity, Alkalinity, Hardness, Na, Ca, Mg, K, HCO_3, SO_4, Ionic Balance, S • Nutrients – TN, TP, N_NO_2, Nitrite (NO_2), N_NO_3, NO_3, N_NO_x • Dissolved Metals – Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Zn • Contaminants – Benzene, Ethylbenzene, Meta- and para-Xylene, Ortho-Xylene, Toluene, Total Xylenes, TPH, Gross Alpha, Gross Beta, Dibromofluoromethane, Toluene-D8, 1,2-Dichloroethane D4
HGA0002P	-22.926125	119.043461	Sep-00 to Apr-19	28	
HGA0003P	-22.926631	119.045487	Jun-10 to Jul-20	31	
HGA0040P	-22.922998	119.038716	Jun-15 to Mar-19	18	
HGA0041P	-22.921508	119.032455	Jun-15 to Oct-19	18	
HGA0062P	-22.923060	119.035325	Jan-20	1	
HGA0065P	-22.926667	119.042066	Jan-20	1	
HGA0070P	-22.922974	119.028617	May-19 to Jan-21	7	
HGA0074P	-22.921777	119.019806	Jul-18 to Sep-22	7	
HGA0077P	-22.921849	119.023404	Jun-18 to Mar-21	4	

4.2 Calcite Precipitation

4.2.1 Precipitation Risk (LSI Calculation)

Calcite precipitation in surface water environments appears as armouring of the creekbed, filling interstitial spaces and creating a uniform stream bed. This influences sediment grain size distribution, transport rates (Parker & Sutherland, 1990) and channel hydraulics (Wilcock & DeTemple, 2005). Natural calcite precipitation is active in spring discharge areas across Australia, including Queensland (see Drysdale, 2001) and Western Australia (Reeves *et al*., 2007a; Wright, 2000). Anthropogenic induced calcite precipitation and/or increases to the rate of natural precipitation have also been reported due to the discharge of groundwaters from mining operations (AECOM, 2016; J. Delaney, Biologic, pers. comm.). In the Pilbara, artificially induced calcite precipitation has been observed in Weeli Wolli Creek, downstream of the natural, historic spring area (AECOM, 2016). In this case, the precipitate is occurring due to the degassing of carbon dioxide from the release of groundwater (from a nearby mining operation), which is supersaturated with calcium carbonate.

The Langelier Saturation Index (LSI) was used to provide an approximate estimate of the risk of calcite carbonate saturation upon discharge to surface waters (ALS, 2017). The LSI is a measure of a solution's ability to dissolve or deposit calcium carbonate, and is defined as the difference between the actual pH of the water and pH_s (pH at which water is saturated with calcium carbonate; Equation 1). The equation was later modified to include the effects of temperature and ionic strength (ALS, 2017). To calculate an LSI, pH, TDS (mg/L), calcium concentration, alkalinity, and water temperature are required.

Equation 1: Langelier Saturation Index Equation

$LSI = ph_{actual} - pH_s$

The indications for the calculations LSI are based on the following values:

- LSI < 0: Water is undersaturated with respect to calcium carbonate. Undersaturated water has a tendency to remove existing calcium carbonate protective coatings in pipelines and equipment.
- LSI = 0: Water is considered to be neutral. Neither scale-forming nor scale removing.
- LSI > 0: Water is supersaturated with respect to calcium carbonate (CaCO3) and scale forming may occur.

For this risk assessment, mean values for pH, TDS, Ca, and alkalinity (HCO_3) in groundwater were used to calculate the LSI value for the MAC source groundwater, representing the potential risk of calcite precipitation if discharged to the surface environment. As water temperature data was not available, the mean temperature for YG surface waters was used in the equation. It is noted here that LSI values do not provide a quantitative measure of calcium carbonate saturation or corrosion. The LSI was originally designed to assess the risk of scale build-up in pipes but has more recently been applied to Pilbara waters in response to calcite precipitation resulting from discharge operations. In addition, HCO_3, pH, Ca, TDS, and temperature may all affect the tendency of water to corrode or scale differently, and independently. As such, the LSI calculation should be considered indicative only for the potential for calcite precipitation to occur due to discharge.

4.3 Risk Assessment

Risk to the receiving environment was assessed based on the AoC in the source groundwater, potential for calcite precipitation, and potential application of controls/mitigation measures. Risk rankings were defined as follows:

- Negligible Risk – No impact anticipated to environmental receptors / receiving environment
- Low Risk – Impact to environmental receptors / receiving environment on a highly localised and temporary scale; no irreversible impacts expected
- Moderate Risk – Impact to environmental receptors / receiving environment expected on a short-term to medium scale (e.g. throughout the life of supplementation activities); no irreversible impacts expected
- High Risk – Potential for long term, irreversible impacts to environmental receptors / the receiving environment.

5 Results and Discussion

5.1 Receiving Environment (YG) Water Quality

5.1.1 Groundwater Quality

Groundwater of the YG receiving environment was characterised as circum-neutral (pH 6.7) to alkaline (pH 8.4), fresh to saline (430 to 5,750 µS/cm EC)[2], and clear (0.3 to 4.4 NTU turbidity) (Table 5.1). There was limited variation in EC concentrations over time, or between monitoring bores, other than higher spot measurements in November 2011 and February 2013 (Figure 5.1). Circum-neutral to alkaline pH and salinities above the ANZG (2018) DGV of 250 µS/cm are typical of Pilbara groundwaters, with higher salinities associated with the shallow alluvial aquifers (particularly during the wet season), in comparison to deeper, fractured rock aquifers (Reeves *et al.*, 2007b; Rio Tinto, 2010). It should be noted the ANZG DGV for EC is not considered appropriate for application to arid-zone inland waters, where salinity is spatially and seasonally variable, and EC often naturally exceeds the DGV.

Ionic composition was dominated by bicarbonate (HCO_3) anions, typical of groundwaters of the area (Rio Tinto, 2010), followed by Cl and SO_4 (Table 5.1). Calcium was the dominant anion, followed by Na, Mg and K (Table 5.1). Dominance by calcium can be representative of the deeper, fractured rock aquifers of the region, and/or calcrete deposits, while Na dominance is more common within shallow alluvials (Reeves *et al.*, 2007b; Rio Tinto, 2010).

Nutrient concentrations (data limited to N_NO_3 and N_NO_2), were low in the YG groundwater, with all N_NO_3 values below DGVs for eutrophication (Table 5.1). There was limited variation in N_NO_3 concentrations over time, with monitoring bore RAILGWLM322.7P recording slightly higher concentrations over the course of monitoring (Figure 5.2).

Dissolved metals were also generally low, with concentrations of most analytes falling below LORs and/or ANZG (2018) DGVs (Table 5.1). Exceptions included Cd, Cr, Cu and Zn, all of which recorded exceedances of respective ANZG (2018) DGVs (Table 5.1). However, exceedance frequency was below 50% for each of these analytes (Table 5.1).

---

[2] Salinity categories are based on the Department of Water and Regulation (DWER) classification system, where fresh/marginal < 1,000 mg/L (~1,500 µS/cm), brackish = 1,000 mg/L – 2,000 mg/L (~1,500 µS/cm to 3,100 µS/cm), saline = 2,000 mg/L – 10,000 mg/L (~ 3,100 µS/cm – 15,600 µS/cm), and hypersaline > 10,000 mg/L (> 15,600 µS/cm) (Mayer *et al.*, 2005).

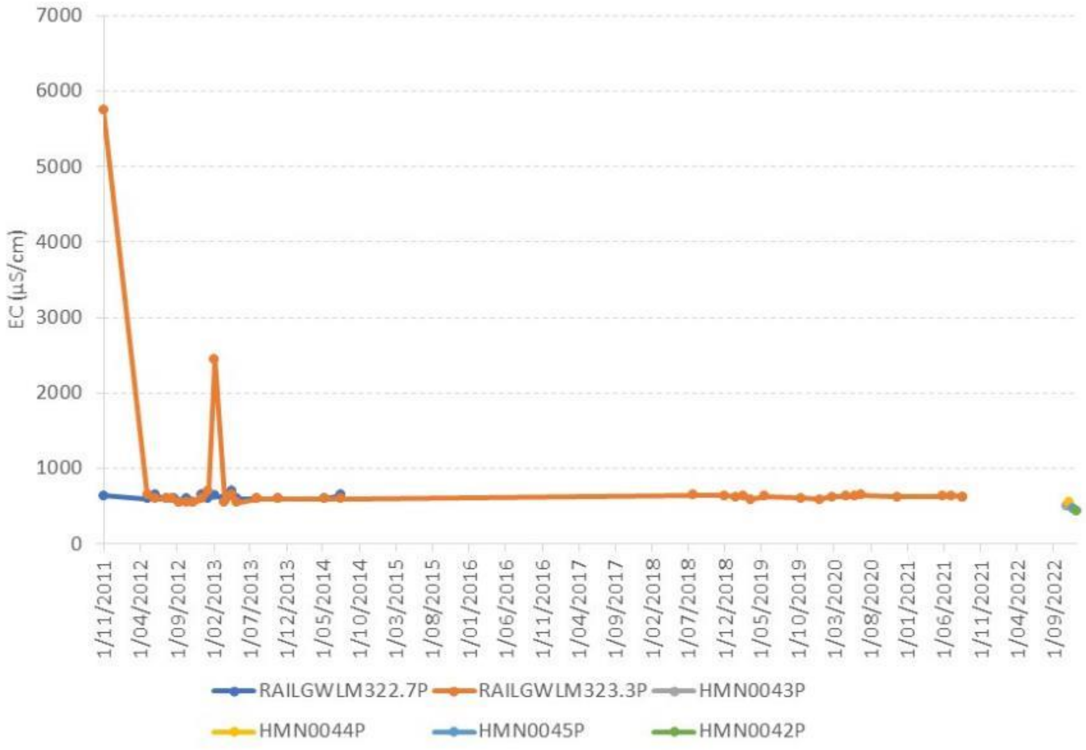


Figure 5.1: Time series plot for EC in YG groundwater

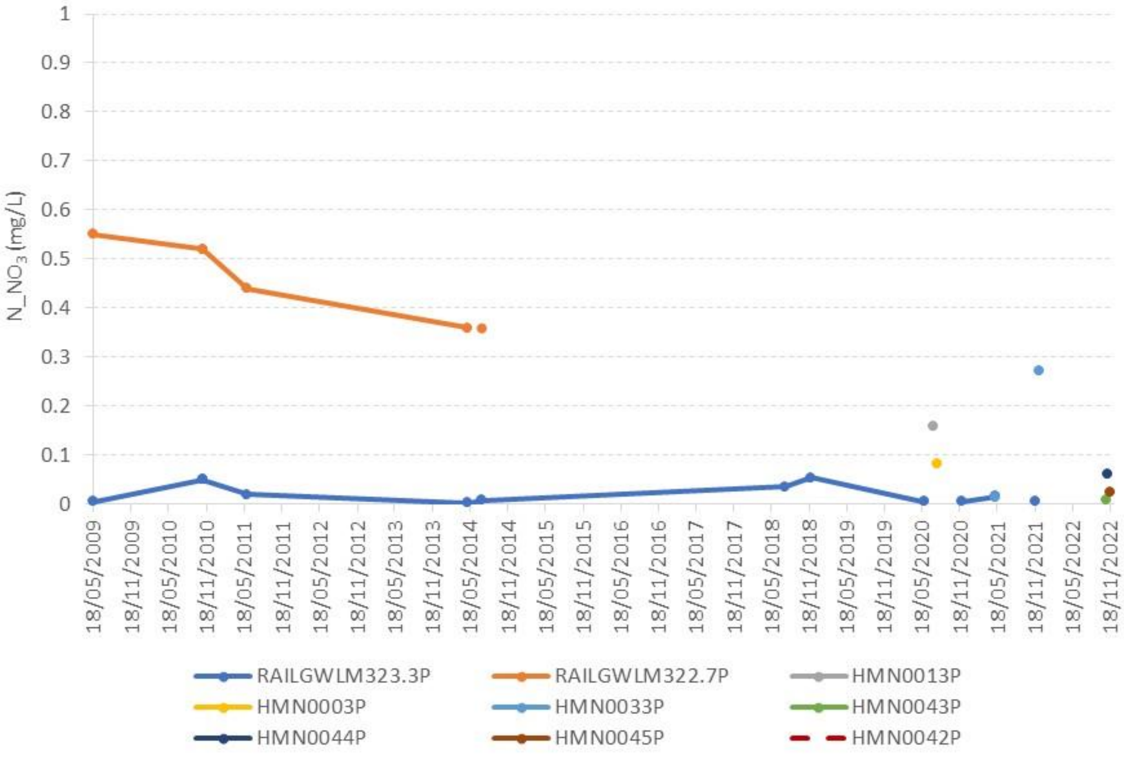


Figure 5.2: Time series plot for N_NO_3 in YG groundwater

Naturally elevated concentrations of dissolved metals (in comparison to DGVs), including Cd, Cr, Cu and Zn, are commonly reported from ground- and surface- waters of the Pilbara region (Biologic, 2021b; WRM, 2009, 2015). These likely reflect natural background concentrations within catchments, related to the weathering of sedimentary rocks enriched in metals (McLennan *et al.*, 1983).

Concentrations of hydrocarbons and other contaminants, including benzene, ethylbenzene, meta- and para-xylene, naphthalene, ortho-xylene, total xylenes, TPH and total cyanide, were all below analytical detection limits in YG groundwater samples (Table 5.1).

5.1.2 Gap Analysis

A total of nine discrete locations have been sampled for YG groundwater quality over a 13-year period (May 2009 and December 2022). During this period, sampling was primarily concentrated at two bores; RAILGWLM322.7P (19 sampling events) and RAILGWLM323.3P (27 sampling events). The remaining bores were sampled on two occasions or fewer.

At least 24 records exist for most water quality analytes, including EC, pH, TDS, some ions, N_NO_3, Cu, Pb and Zn, considered sufficient for accurate spatial, temporal, and seasonal characterisation. However, fewer than 24 records exist for many analytes, including most dissolved metals, ions, turbidity and N_NO_2. Additionally, there were no records for major nutrient analytes such as TN and TP, which are stressors typically included in surface water quality monitoring programs. Therefore, continuation of the current groundwater quality sampling program, with the addition of analytes such as TN and TP, and increased sampling frequency of dissolved metals, is recommended to enhance the robustness of the dataset and the accuracy of water quality characterisation and risk assessment.

There was insufficient baseline data to accurately characterise hydrocarbons and other contaminants. Concentrations of these compounds in natural surface and groundwaters are typically lower than limits of detection. Contamination with these substances is usually associated with fuel spills (surfactants), drinking water treatment plants (chlorine, fluoride) and irrigated agriculture/pest control (pesticides). Therefore, routine monitoring for these compounds would be recommended if such activities occur.

Table 5.1: Summary of water quality from YG groundwater, with comparison to ANZG (2018) DGVs (95% species protection). Red shading indicates value was outside of ANZG DGVs. All values in mg/L unless otherwise specified. "-" indicates no value.

	Analyte	ANZG DGV (95%)	No Records	Minimum	20%ile	Median	Mean	80%ile	Maximum	No. Outside of DGV	% Outside DGV
General & Ions	pH (pH Units)	6 - 8	56	6.7	7.0	7.3	7.3	7.5	8.4	**4**	**7**
	EC (µS/cm)	250	57	430	574	600	726	650	5,750	**57**	**100**
	TDS	-	47	290	328	346	392	404	1,900	-	-
	Temperature (°C)	-	23	29.2	30.0	31.0	31.3	32.2	36.6	-	-
	Turbidity (NTU)	15	7	0.3	0.3	0.5	1.2	2.8	4.4	**0**	**0**
	TSS	-	37	2.5	2.5	342.0	306.0	405.8	1900.0	-	-
	Alkalinity	-	39	170.0	203.0	220.0	217.5	230.0	252.0	-	-
	Hardness	-	24	202.0	204.0	220.0	218.4	232.0	252.0	-	-
	Na	-	50	24.0	32.0	35.0	41.2	40.0	180.0	-	-
	Ca	-	50	34.0	46.0	49.0	53.3	52.0	250.0	-	-
	Mg	-	39	20.0	25.0	26.0	25.5	26.0	31.0	-	-
	K	-	50	7.2	9.2	10.0	11.8	11.8	52.0	-	-
	HCO_3	-	17	210.0	236.0	270.0	264.7	290.0	290.0	-	-
	Cl	-	4	37	37	44.5	44	50	50	-	-
	SO_4	-	17	26.0	27.6	29.0	31.9	34.6	56.0	-	-
Nutrients	N_NO$_2$	-	1	0.0025	-	0.0025	0.0025	-	0.0025	-	-
	N_NO$_3$	0.7	27	0.003	0.007	0.050	0.140	0.360	0.550	**0**	**0**
	Al	0.055	11	0.005	0.005	0.005	0.005	0.005	0.005	**0**	**0**
Metals	As	0.024	15	0.0005	0.0005	0.0005	0.0007	0.0005	0.0030	**0**	**0**
	B	0.94	11	0.10	0.13	0.14	0.14	0.15	0.21	**0**	**0**
	Ba	-	11	0.004	0.007	0.010	0.011	0.012	0.026	-	-
	Cd	0.0002	15	0.00005	0.00005	0.00005	0.00007	0.00005	0.00030	**1**	**7**
	Cr	0.001	7	0.0005	0.0005	0.0005	0.0013	0.0024	0.0030	**3**	**43**
	Cu	0.0014	54	0.0005	0.0005	0.0005	0.0009	0.0010	0.0080	**9**	**17**
	Fe	0.7	50	0.003	0.003	0.025	0.043	0.025	0.460	**0**	**0**
	Hg	0.00006	15	0.000025	0.000025	0.000025	0.000025	0.000025	0.000025	**0**	**0**
	Mn	1.9	50	0.001	0.001	0.004	0.051	0.036	0.910	**0**	**0**
	Mo	-	11	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	-	-
	Ni	0.011	11	0.00050	0.00050	0.00050	0.00055	0.00050	0.00100	**0**	**0**
	Pb	0.0034	50	0.0005	0.0005	0.0005	0.0006	0.0005	0.0020	**0**	**0**

Analyte		ANZG DGV (95%)	No Records	Minimum	20%ile	Median	Mean	80%ile	Maximum	No. Outside of DGV	% Outside DGV
	Sb	-	3	0.0005	-	0.0005	0.0005	-	0.0005	-	-
	Se	0.011	11	0.00050	0.00050	0.00050	0.00055	0.00050	0.00100	**0**	**0**
	Zn	0.008	48	0.003	0.003	0.008	0.019	0.018	0.290	**22**	**46**
Hydrocarbons & Contaminants	Benzene (µg/L)	950	8	0.25	0.25	0.25	0.25	0.25	0.25	**0**	**0**
	Ethylbenzene (µg/L)	-	8	0.25	0.25	0.25	0.25	0.25	0.25	-	-
	meta- and para-Xylene (µg/L)	-	8	0.25	0.25	0.25	0.25	0.25	0.25	-	-
	Naphthalene (µg/L)	16	8	0.25	0.25	0.25	0.25	0.25	0.25	**0**	**0**
	Ortho-Xylene (µg/L)	350	8	0.25	0.25	0.25	0.25	0.25	0.25	**0**	**0**
	Toluene (µg/L)	-	8	0.25	0.25	0.25	0.25	0.25	0.25	-	-
	Total Xylenes (µg/L)	-	8	0.5	0.5	0.5	0.5	0.5	0.5	-	-
	TPH (µg/L)	-	3	25	-	25	25	-	25	-	-
	Total Cyanide (mg/L)	0.007	7	0.002	0.002	0.002	0.002	0.002	0.002	**0**	**0**
	Dibromofluoromethane (%)	-	6	89	92	100	100	109	114	-	-
	Gross Alpha (Bq/L)	-	8	0.014	0.017	0.043	0.086	0.229	0.259	-	-
	Gross Beta (Bq/L)	-	8	0.032	0.034	0.051	0.062	0.106	0.112	-	-
	Toluene-D8 (%)	-	6	99	100	103	103	107	108	-	-
	1,2-Dichloroethane D4 (Surrogate) (%)	-	6	84	86	99	96	104	105	-	-
	1.2-Dichloroethane-D4 (%)	-	2	98	-	109	109	-	120	-	-

5.1.3 Surface Water

Surface water pH at YG ranged from slightly acidic (6.6) to alkaline (7.9), with median pH circum-neutral (pH 7.3). All pH values were within ANZG (2018) DGVs (Table 5.2). There has been minimal change in pH within YG surface waters over time, and negligible difference between sampling locations (Figure 5.3).

Dissolved oxygen concentrations were highly variable, ranging from 7.5% to 70.3%, all below the lower ANZG (2018) DGV (80%) (Table 5.2). Water temperature was also variable, with a minimum of 18.8°C and a maximum of 28.6°C (Table 5.2). DO saturation and water temperature in small freshwater pools (such as those of YG) can vary widely across a 24-hour period (Connolly *et al.*, 2004). Typically, the lowest DO saturation and water temperatures occur in the early morning, and the highest saturation occurring in the early afternoon (Connolly *et al.*, 2004). The diel cycle for DO is usually driven by daytime photosynthesis by aquatic plants and algae, producing high oxygen concentrations during the daytime, while overnight respiration by organisms produces carbon dioxide, lowering oxygen levels in the water column (Connolly *et al.*, 2004).

Electrical conductivity was above the ANZG (2018) DGV of 250 µS/cm on all sampling occasions, although it was classified as fresh in all samples (Table 5.2). As discussed above, the DGV for EC is considered conservative and not directly applicable to arid-zone waters (Pinder *et al.*, 2010). Overall, there was limited variation in EC within YG surface waters over time, likely reflecting the influence of groundwaters and reduced evapoconcentration effects in the dry season (Figure 5.4). Ionic composition typically followed the order Ca>Na>Mg>K (cations) and HCO_3> Cl/SO_4>CO_3 (anions) (Table 5.2). These patterns are similar to those recorded within groundwaters, again reflecting the influence of groundwater on the YG surface pools.

Turbidity ranged between 0.3 and 450 NTU, and exceeded the DGV (15 NTU) on 8% of sampling occasions (Table 5.2). Turbidity is also highly variable in arid-zone river systems, mostly driven by seasonal hydrology, with high flows causing the suspension of sediments in the water column and elevated turbidity (Choy & Marshall, 2002).

Concentrations of most nutrients were low, with no or few exceedances of ANZG (2018) DGVs (Table 5.2). Exceptions included nitrogen oxides (N_NO_x), TN and TP. N_NO_x and TN exceeded respective ANZG (2018) DGVs on 24% and 16% of sampling occasions, respectively, while TP exceeded ANZG (2018) DGV on over 90% of sampling occasions (Table 5.2). Elevated N_NO_x, TN and TP concentrations can be common in Pilbara surface waters, usually associated with impacts from livestock which have unrestricted access to most waterways (Pinder & Leung, 2009). Natural or anthropogenic discharge of groundwaters, which are often nitrogen-enriched, can also lead to elevated N_NO$_x$ and TN levels in surface waters (DoW, 2010; Pinder & Leung, 2009).

Dissolved metal concentrations were low, with most parameters below LORs and/or ANZG (2018) DGVs on all, or most, sampling occasions (Table 5.2). The single exception was Fe, exceeded the DGV (0.7 mg/L) on 8% of sampling occasions (Table 5.2). Elevated Fe (in comparison to DGVs) is not unexpected, given the iron-rich geologies of the region.

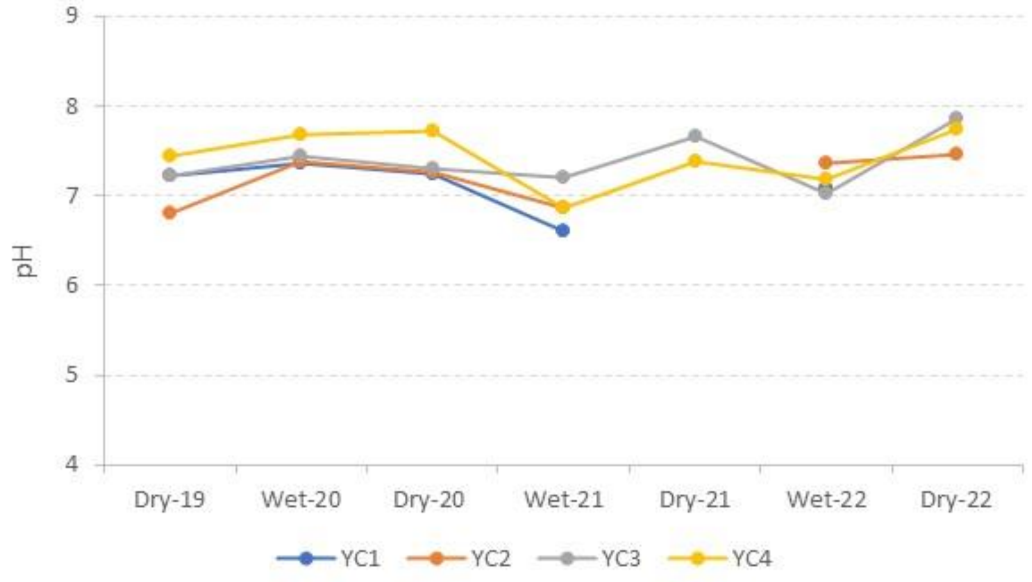


Figure 5.3: Time series plot for pH in YG surface water

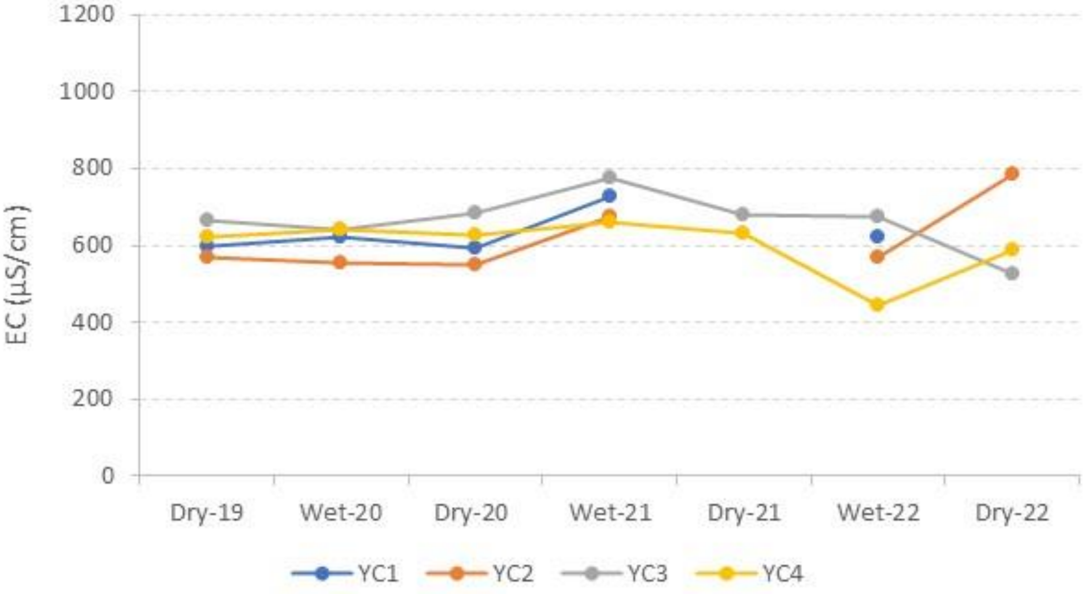


Figure 5.4: Time series plot for EC in YG surface water

5.1.4 Gap Analysis

For YG surface water quality, a total of four pools (YC1, YC2, YC3 and YC4) were sampled for water quality biannually (wet and dry season) between 2019 and 2022, although not all pools were sampled in all sampling occasions (some pools were dry at the time of sampling). This has led to least 25 discreet records existing for most water quality analytes, with biannual sampling accounting for seasonal variation. Therefore, the YG surface water data is considered sufficient for accurate baseline water quality characterisation.

Table 5.2: Summary of water quality from YG surface water, with comparison to ANZG (2018) DGVs (95% species protection). Red shading indicates value was outside of ANZG DGVs. All values in mg/L unless otherwise specified. "-" indicates no value.

Analyte		ANZG DGV (95%)	No Records	Minimum	20%ile	Median	Mean	80%ile	Maximum	No. Outside DGV	% Outside DGV
General & Ions	pH (pH Units)	6 - 8	25	6.6	7.0	7.3	7.3	7.5	7.9	**0**	**0**
	EC (µS/cm)	250	25	444	569	627	629	675	784	**25**	**100**
	TDS	-	14	142	351	435	410	476	559	-	-
	Temperature (^{o}C)	-	25	18.8	21.5	24.5	24.1	26.5	28.6	-	-
	Redox (mV)	-	15	-66.9	-46.2	39.5	29.8	82.1	224.3	-	-
	DO (%)	80 - 120	25	7.5	18.0	36.9	33.6	47.9	70.3	**25**	**100**
	Turbidity	15	25	0.3	1.1	2.1	22.1	6.1	450.0	**2**	**8**
	TSS	-	25	0.5	0.6	4.0	12.2	10.2	126.0	-	-
	Alkalinity	-	25	132	218.6	248.0	236.3	264.2	295.0	-	-
	Hardness	-	25	161	218.2	238.0	242.0	265.2	343.0	-	-
	Na	-	25	24.1	33.4	38.3	39.5	43.5	51.6	-	-
	Ca	-	25	32.9	43.3	47.2	48.7	54.6	75.1	-	-
	Mg	-	25	19.2	26.5	29.2	29.2	31.9	37.8	-	-
	K	-	25	8.7	10.1	11.0	11.0	12.0	12.7	-	-
	HCO_3	-	25	132.0	218.6	248.0	236.3	264.2	295.0	-	-
	Cl	-	25	24.0	34.4	40.0	39.4	45.0	48.0	-	-
	SO_4	-	25	24.9	27.8	52.2	77.3	86.0	306.0	-	-
	CO_3	-	25	0.5	0.5	0.5	0.5	0.5	0.5	-	-
	S	-	22	7.3	8.6	9.8	12.9	18.0	33.1	-	-
Nutrients	N_NH_3	0.9	25	0.005	0.005	0.005	0.023	0.005	0.230	**0**	**0**
	N_NO_2	-	25	0.005	0.005	0.005	0.005	0.005	0.005	-	-
	N_NO_3	0.7	25	0.005	0.005	0.005	0.013	0.020	0.070	**0**	**0**
	N_NO_x	0.01	25	0.005	0.005	0.005	0.013	0.020	0.070	**6**	**24**
	Total N	0.3	25	0.03	0.07	0.15	0.26	0.26	2.20	**4**	**16**
	Total P	0.01	25	0.003	0.018	0.030	0.038	0.060	0.092	**23**	**92**
Metals	Al	0.055	25	0.0025	0.0025	0.0025	0.0036	0.0025	0.015	**0**	**0**
	As	0.024	25	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	**0**	**0**
	B	0.94	25	0.08	0.11	0.14	0.14	0.16	0.18	**0**	**0**
	Ba	-	25	0.016	0.018	0.022	0.024	0.029	0.045	-	-
	Cd	0.0002	25	0.000025	0.000025	0.000025	0.0000	0.000025	0.000025	**0**	**0**
	Co	-	25	0.00005	0.00005	0.00005	0.00017	0.00020	0.00160	-	-
	Cr	0.001	25	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	**0**	**0**
	Cu	0.0014	25	0.00003	0.00003	0.00008	0.00010	0.00012	0.00040	**0**	**0**
	Fe	0.7	25	0.01	0.03	0.06	0.17	0.19	0.99	**2**	**8**
	Mn	1.9	25	0.001	0.003	0.010	0.021	0.036	0.086	**0**	**0**
	Mo	-	25	0.0001	0.0002	0.0002	0.0002	0.0002	0.0004	-	-
	Ni	0.011	25	0.0003	0.0003	0.0003	0.0003	0.0003	0.0027	**0**	**0**
	Pb	0.0034	25	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	**0**	**0**
	Se	0.005	25	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	**0**	**0**
	U	-	25	0.00006	0.00011	0.00016	0.00016	0.00018	0.00033	-	-
	V	-	25	0.0001	0.0002	0.0007	0.0007	0.0011	0.0019	-	-
	Zn	0.008	25	0.0005	0.0005	0.0005	0.0007	0.0005	0.0060	**0**	**0**

5.2 Source (MAC) Groundwater

5.2.1 Groundwater Quality

MAC source groundwater was acidic (pH 5.6) to alkaline (pH 8.8), fresh (70 to 1,100 µS/cm EC), warm (average temperature 29.0ºC) and relatively clear (0.25 NTU to 18 NTU turbidity; average 2.74 NTU) (Table 5.3). All EC values were above the ANZG (2018) DGV of 250 µS/cm (Table 5.3). A small percentage (12%) of pH values were in exceedance of the upper ANZG (2018) guideline (pH 8.0), while a single pH value fell below the lower guideline (pH 6.0) (Table 5.3). No DO data were available. Ionic composition was dominated by HCO_3 anions, followed by SO_4, with no Cl data available (Table 5.3). Na was dominant amongst anions, followed by Ca, Mg and K (Table 5.3).

Nitrate concentrations were relatively high in the MAC groundwater, with N_NO_3 exceeding DGVs for eutrophication on 69% of sampling occasions (Table 5.3). For total P, 31% of values exceeded the eutrophication guideline (0.01 mg/L), although the dataset was limited to 13 records. Only two records for N_NO_x and total N were provided, with all values being above DGVs (Table 5.3).

Concentrations of most dissolved metals were below LORs and/or ANZG (2018) DGVs (Table 5.3). Exceptions included Cd, Cu Ni and Zn, however, ANZG (2018) DGV exceedance frequency was 26% or lower for each of these analytes (Table 5.3). The LOR for Cr (0.004 mg/L) was not sufficiently low to allow for comparison against the ANZG (2018) DGV (0.001 mg/L) (Table 5.3).

Concentrations of hydrocarbons and other contaminants were mostly below analytical detection limits (Table 5.3).

5.2.2 Gap Analysis

Groundwater data were available from 10 bores within the MAC area, with data spanning the period September 2000 to September 2022. Eight of the 10 bores were sampled on four or more occasions, with the remaining two only sampled once: HGA0062P and HGA0065P.

A comprehensive dataset exists for most analytes, with at least 100 records for EC, pH, TDS, major ions, N_NO_3, and the majority of dissolved metals, considered sufficient for accurate spatial, temporal, and seasonal characterisation. Analytes with less than 24 records included hardness, nutrients including $N\_NO_{2,}$ $N\_NO_{x,}$ TN and TP, and the metals Co and Cr. It is recommended that further sampling of these analytes be undertaken to enable more accurate characterisation.

A major gap for this assessment is the fact that the analytical limits of reporting for many dissolved metals within the MAC groundwater dataset were not sufficiently low to enable comparison against YG surface water data (i.e., LORs were higher than concentrations recorded during YG surface water monitoring). It is recommended that in future, LORs are reduced for MAC groundwater data.

There was insufficient baseline data to accurately characterise hydrocarbons and other contaminants, except TPH. As mentioned in 5.1.2., contamination with these substances is usually associated with fuel spills, drinking water treatment plants and use of pesticides. Therefore, routine monitoring for these compounds would be recommended if such activities occur.

Table 5.3: Summary of MAC groundwater quality, with comparison to ANZG (2018) DGVs (95% species protection) and YG groundwater (GW) 80%ile values (20%ile value also included for pH). Red shading indicates value was outside of YG GW 20%ile/80%iles. Bold red text indicates value was outside of ANZG (2018) DGVs. All values in mg/L unless otherwise specified. "-" indicates no value.

	Analyte	ANZG DGV	YG GW 20%ile (pH) / 80%ile	No. Records	Minimum	Median	Mean	Maximum	No. Outside DGV	% Outside DGV	No. Outside GW 20%ile/80%ile	% Outside GW 20%ile/80%ile
General & Ions	pH (pH units)	6 - 8	7 / 7.5	455	**5.6**	7.7	7.6	**8.8**	58	13	**316**	**69**
	EC (µS/cm)	250	650	453	70	**612**	**611**	**1,100**	453	100	**146**	**32**
	TDS	-	404	137	240	340	344	700	-	-	**7**	**5**
	Temperature (°C)	-	32.2	200	20.6	29.7	29.0	38.6	-	-	**17**	**9**
	Turbidity (NTU)	15	2.84	25	0.25	1.00	2.74	**18.00**	1	4	**5**	**20**
	TSS	-	405.8	133	0.5	2.5	3.6	38.0	-	-	**0**	**0**
	Alkalinity	-	230	138	160	200	204	260	-	-	**19**	**14**
	Hardness	-	232	4	228	251	247	258	-	-	**3**	**75**
	Na	-	40	136	21	30	30	96	-	-	**2**	**1**
	Ca	-	52	136	11	44	43	68	-	-	**10**	**7**
	Mg	-	26	136	24	30	30	67	-	-	**112**	**82**
	K	-	11.8	136	4.9	6.9	7.1	19.0	-	-	**1**	**1**
	HCO_3	-	290	123	190	250	245	320	-	-	**11**	**9**
	SO_4	-	34.6	135	20.0	40.0	40.0	100.0	-	-	**115**	**85**
Nutrients	N_NO_2	-	-	6	0.0025	0.0025	0.003	0.005	0	0	**-**	**-**
	N_NO_3	0.7	0.36	134	0.003	**1.010**	**1.470**	**22.000**	92	69	**127**	**95**
	N_NO_x	0.01	-	3	**0.58**	**0.63**	**0.620**	**0.65**	2	100	**-**	**-**
	Total N	0.3	-	2	**0.8**	**0.85**	**0.850**	**0.9**	2	100	**-**	**-**
	Total P	0.01	-	13	0.01	0.01	**0.030**	**0.03**	4	31	**-**	**-**
Metals	Al	0.055	0.005	132	0.005	0.005	0.006	0.037	0	0	**12**	**9**
	As	0.024	0.0005	132	0.001	0.001	0.001	0.001	0	0	**0**	**0**
	B	0.94	0.146	135	0.027	0.24	0.246	0.61	0	0	**134**	**99**
	Ba	-	0.0116	136	0.0005	0.0075	0.0090	0.0610	-	-	**19**	**14**
	Cd	0.0002	0.00005	132	0.00005	0.00005	0.00006	**0.001**	2	2	**2**	**2**
	Co	-	-	21	0.001	0.001	0.001	0.005	-	-	**-**	**-**
	Cr	0.001	0.0024	18	**0.002****	0.002	0.002	0.002	LOR Not Sufficient	LOR Not Sufficient	**0**	**0**
	Cu	0.0014	0.001	132	0.001	0.001	**0.003**	**0.360**	8	6	**8**	**6**
	Fe	0.7	0.025	136	0.0025	0.0025	0.017	0.34	0	0	**28**	**21**
	Hg	0.00006	0.000025	130	0.000025	0.000025	0.000027	0.000050	0	0	**11**	**8**
	Mn	1.9	0.036	136	0.0005	0.0005	0.004	0.043	0	0	**4**	**3**
	Mo	-	0.0005	136	0.0005	0.0005	0.001	0.003	-	-	**1**	**1**
	Ni	0.011	0.0005	136	0.0005	0.0005	0.008	**0.097**	24	18	**25**	**18**
	Pb	0.0034	0.0005	136	0.0005	0.0005	0.001	0.002	0	0	**2**	**1**

	Analyte	ANZG DGV	YG GW 20%ile (pH) / 80%ile	No. Records	Minimum	Median	Mean	Maximum	No. Outside DGV	% Outside DGV	No. Outside GW 20%ile/80%ile	% Outside GW 20%ile/80%ile
	Sb	-	-	27	0.001	0.001	0.003	0.025	-	-	**0**	**0**
	Se	0.011	0.0005	136	0.0005	0.0005	0.001	0.005	0	0	**32**	**24**
	Zn	0.008	0.0176	136	0.0025	0.0025	0.0080	**0.0940**	36	26	**14**	**10**
Hydrocarbons & Contaminants	Benzene (μg/L)	950	0.25	6	0.25	0.25	0.25	0.25	0	0		
	Ethylbenzene (μg/L)	-	0.25	6	0.25	0.25	0.25	0.25	-	-	**-**	**-**
	meta- and para-Xylene (μg/L)	-	0.25	6	0.5	0.5	0.5	0.5	-	-	**-**	**-**
	Naphthalene (μg/L)	16	0.25	6	0.25	0.25	0.25	0.25	0	0	**-**	**-**
	Ortho-Xylene (μg/L)	350	0.25	6	0.25	0.25	0.25	0.25	0	0	**-**	**-**
	Toluene (μg/L)	-	0.25	6	0.25	0.25	0.25	0.25	-	-	**-**	**-**
	Total Xylenes (μg/L)	-	0.5	3	0.5	0.5	0.5	0.5	-	-	**-**	**-**
	TPH (μg/L)	-	-	29	25	225	145	225	-	-	**-**	**-**
	Total Cyanide (mg/L)	0.007	0.002	6	0.002	0.002	0.004	**0.011**	1	17	**1**	**17**
	Dibromofluoromethane (%)	-	109	3	49	53	52	53	-	-	**-**	**-**
	Gross Alpha (Bq/L)	-	0.229	8	0.015	0.035	0.043	0.121	-	-	**-**	**-**
	Gross Beta (Bq/L)	-	0.106	8	0.026	0.031	0.040	0.076	-	-	**-**	**-**
	Toluene-D8 (%)	-	107	3	50	52	51	52	-	-	**-**	**-**
	1.2-Dichloroethane-D4 (%)	-	104	3	52	52	52	53	-	-	**-**	**-**
	1,2-Dichloroethane D4 (Surrogate) (%)	-	-	-	-	-	-	-	-	-	**-**	**-**
	4-Bromofluorobenzene (%)	-	-	3	45	47	47	47	-	-	**-**	**-**

Table 5.4: Summary of MAC groundwater quality, with comparison to ANZG (2018) DGVs (95% species protection) and YG surface water (SW) 80%ile values (20%ile value also provided for pH). Red shading indicates value was outside of YG SW 20%ile/80%iles. Bold red text indicates value was outside of ANZG (2018) DGV. All values in mg/L unless otherwise specified. "-" indicates no value.

	Analyte	ANZG DGV	YG SW 20%ile (pH) / 80%ile	No Records	Minimum	Median	Mean	Maximum	No. Outside DGV	% Outside DGV	No. Outside GW 20%ile/80%ile	% Outside GW 20%ile/80%ile
General & Ions	pH (pH units)	6 - 8	7 / 7.5	455	**5.6**	7.7	7.6	**8.8**	27	5	**324**	**66**
	EC (µS/cm)	250	675	453	70	**612**	**610**	**1,100**	453	99.6	**99**	**22**
	TDS	-	476	137	240	340	344	700	-	-	**3**	**2**
	Temperature (ºC)	-	32.2	200	20.6	29.7	29.0	38.6	-	-	**17**	**9**
	Turbidity (NTU)	15	6.0	25	0.3	1.0	2.7	**18.0**	1	4	**3**	**12**
	TSS	-	10.2	133	0.5	2.5	3.6	38.0	-	-	**7**	**5**
	Alkalinity	-	264	138	160	200	204	260	-	-	**0**	**0**
	Hardness	-	265	4	228	251	247	258	-	-	**0**	**0**
	Na	-	43	136	21	30	30	96	-	-	**2**	**1**
	Ca	-	54	136	11	44	43	68	-	-	**7**	**5**
	Mg	-	32	136	24	30	30	67	-	-	**44**	**32**
	K	-	12.0	136	4.9	6.9	7.1	19.0	-	-	**1**	**1**
	HCO$_3$	-	264	123	190	250	245	320	-	-	**36**	**29**
	SO$_4$	-	86	135	20	40	40	100	-	-	**1**	**1**
Nutrients	N_NO$_2$	-	0.005	6	0.003	0.003	0.003	0.005	-	-	**0**	**0**
	N_NO$_3$	0.7	0.020	134	0.003	**1.010**	**1.470**	**22.000**	92	69	**133**	**99**
	N_NO$_x$	0.01	0.02	3	**0.58**	**0.63**	**0.62**	**0.65**	3	100	**3**	**100**
	Total N	0.3	0.26	2	**0.80**	**0.85**	**0.85**	**0.90**	2	100	**2**	**100**
	Total P	0.01	0.06	13	0.01	0.01	**0.03**	**0.03**	4	31	**0**	**0**
Metals	Al	0.055	0.0025	132	0.005**	0.005	0.006	0.037	0	0	LOR Not Sufficient	LOR Not Sufficient
	As	0.024	0.0002	132	0.001**	0.001	0.001	0.001	0	0	LOR Not Sufficient	LOR Not Sufficient
	B	0.94	0.158	135	0.027	0.240	0.246	0.610	0	0	**133**	**99**
	Ba	-	0.0288	136	0.0005	0.0075	0.009	0.061	-	-	**5**	**4**
	Cd	0.0002	0.000025	132	0.00005**	0.00005	**0.0005**	**0.001**	2	2	LOR Not Sufficient	LOR Not Sufficient
	Co	-	0.0002	21	0.001**	0.001	0.001	0.005	0	0	LOR Not Sufficient	LOR Not Sufficient
	Cr	0.001	0.0001	18	**0.002*****	0.002	0.002	0.002	LOR Not Sufficient	LOR Not Sufficient	LOR Not Sufficient	LOR Not Sufficient
	Cu	0.0014	0.00012	132	0.001**	0.001	**0.003**	**0.360**	8	6	LOR Not Sufficient	LOR Not Sufficient
	Fe	0.7	0.194	136	0.003	0.003	0.017	0.340	0	0	**1**	**1**
	Mn	1.9	0.0357	136	0.0005	0.0005	0.0040	0.0430	0	0	**4**	**3**
	Mo	-	0.0002	136	0.0005**	0.0005	0.001	0.003	-	-	LOR Not Sufficient	LOR Not Sufficient
	Ni	0.011	0.00025	136	0.0005**	0.0005	0.008	**0.097**	24	18	LOR Not Sufficient	LOR Not Sufficient
	Pb	0.0034	0.00005	136	0.0005**	0.0005	0.001	0.002	0	0	LOR Not Sufficient	LOR Not Sufficient
	Se	0.011	0.0001	136	0.0005**	0.0005	0.001	0.005	0	0	LOR Not Sufficient	LOR Not Sufficient
	Zn	0.008	0.0005	136	0.0025**	0.0025	0.008	**0.094**	36	26	LOR Not Sufficient	LOR Not Sufficient

5.3 Water Quality Comparison and Analytes of Concern

5.3.1 Groundwater

Source groundwater quality from MAC was broadly similar to that of YG receiving environment groundwaters, on average being circum-neutral (albeit slightly higher at MAC), fresh and clear, with relatively low concentrations of dissolved metals (in comparison to ANZG DGVs) (Table 5.3). The most notable difference in groundwater quality was the markedly higher concentrations of nitrates (N_NO_3) in MAC groundwaters (Table 5.3).

Among the ions, HCO_3 was the dominant cation, as was the case within YG groundwaters. However, Na was the dominant anion, contrasting with YG groundwaters, where Ca was predominant (although it was interchangeable with Na in some instances) (Table 5.3). Overall, hardness and concentrations of Mg and SO_4 were higher within MAC groundwaters. Relatively high $CaCO_3$ and Mg is likely due to production bores at MAC intercepting groundwater from dolomite-bearing carbonate lithologies, where groundwater is likely saturated with several carbonate minerals, such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and/or magnesite ($MgCO_3$) (Earth Systems, 2022). Elevated SO_4 is likely related to early-stage sulfide oxidation due to groundwater drawdown in the MAC area (Earth Systems, 2022).

Analytes in MAC groundwater considered AoC for YG groundwater (i.e., exceeding the YG groundwater 80%ile on over 25% of sampling occasions) were:

- pH – exceeded the 80%ile on 66% of sampling occasions
- Hardness– exceeded the 80%ile on 75% of sampling occasions
- Mg – exceeded the 80%ile on 82% of sampling occasions
- SO_4 – exceeded the 80%ile on 85% of sampling occasions
- N_NO_3 – exceeded the 80%ile on 95% of sampling occasions
- B – exceeded the 80%ile on 99% of sampling occasions
- EC – exceeded the 80%ile on 32% of sampling occasions (Table 5.3).

5.3.2 Surface Water

Groundwater quality from MAC was also generally comparable to YG surface waters, which had predominantly circum-neutral pH, warm water temperatures, and low salinity and turbidity (Table 5.4). Composition of anions in MAC groundwater was slightly different to YG surface waters, with Na being dominant over Ca, and Mg being notably higher in the MAC groundwaters (Table 5.4).

Concentrations of N_NO_3 were also notably greater in MAC groundwaters, with N_NO_x and total N also being higher, although the latter two analytes were limited to three and two records, respectively (Table 5.4). Dissolved metals concentrations were generally low in comparison to ANZG (2018) DGVs, analytical detection limits for most analytes were not sufficiently sensitive to enable comparison against YG surface water 80%ile values (i.e., LORs were higher than the 80%ile values in most cases) (Table 5.4). As such, ANZG (2018) DGVs were used to determine AoC for metals.

Analytes in MAC groundwater considered AoC for YG surface water (i.e., exceeding the YG surface water 80%ile on over 25% of sampling occasions; 10 or more records) were:

- pH – exceeded the 80%ile on 66% of sampling occasions
- N_NO_3 – exceeded the 80%ile on 99% of sampling occasions
- B – exceeded the 80%ile on 99% of sampling occasions
- Mg – exceeded the 80%ile on 32% of sampling occasions
- HCO_3 - exceeded the 80%ile on 29% of sampling occasions
- Zn – exceeded the ANZG (2018) DGV on 26% of sampling occasions (Table 5.4).

5.3.3 Change Over Time

The main temporal trends in the AoC within MAC groundwaterwere:

- pH was variable between bores and sampling events, with most values recorded at bores HGA0001P, HGA0002P, HGA0003P, HGA0040P and HGA0041P above the YG groundwater and surface water 80%ile of 7.5, and values at HGA0070P, HGA0074P and HGA0077P below the 80%ile. However, there were no clear increasing or decreasing trends over time (Figure 5.5).
- The EC at bores HGA0001P, HGA0002P, HGA0003P, HGA0040P and HGA0041P was mostly below the YG groundwater 80%ile (650 µS/cm). Concentrations at HGA0040P and HGA0041P appeared to increase over time before records ceased in 2019 (Figure 5.5). EC at monitoring bores with more recent data (HGA0070P, HGA0074P and HGA0077P) was mostly above the YG surface water 80%ile (675 µS/cm), although there was no clear increasing or decreasing trend at these bores (Figure 5.5).
- There were no clear temporal trends in major ions including Mg, SO_4 or HCO_3, although the highest concentrations were typically recorded at HGA0070P, HGA0074P and HGA0077P (Figure 5.5, Figure 5.6).
- Although the majority of N_NO_3 values exceeded the YG groundwater and surface water 80%iles, concentrations were highly variable at most monitoring bores over time, with no clear temporal trends (Figure 5.6).
- There was a relatively high degree of variability in dissolved boron and zinc concentrations over time, and no clear temporal trends in either analytes (Figure 5.6).

5.4 Calcite Precipitation Risk (LSI Calculation)

Based on mean pH, TDS, Ca, HCO_3 and temperature values, the mean LSI for the MAC source groundwater is 0.33 (Table 5.5). This suggests that the groundwater is supersaturated in calcium carbonate and is potentially scale forming.

Table 5.5: LSI calculation for the MAC source groundwater and indication of scale-forming (precipitation) potential.

Mean pH	Mean TDS (mg/L)	Mean Ca (mg/L)	Mean HCO_3 (mg/L)	Mean Temp. (°C)	pH_s	LSI	Indication
7.6	700	68	320	29.0	7.3	0.33	Water is supersaturated with respect to calcium carbonate ($CaCO_3$) and scale forming may occur.

A recent assessment by Earth Systems (2022) also indicated that the majority of production bores at MAC host carbonate-saturated groundwater, suggesting widespread precipitation of carbonate minerals could be expected if discharged directly to the surface environment (potentially 40 kg of calcium carbonate for each megalitre (ML) of water discharged under optimum conditions). Additionally, Earth Systems (2022) found groundwaters from certain deposits within the MAC area (A and C deposits) are becoming increasingly carbonate saturated over time. The carbonate saturated groundwater reflects the dolomitic geologies in the area where the majority of groundwater is drawn from (Earth Systems, 2022).

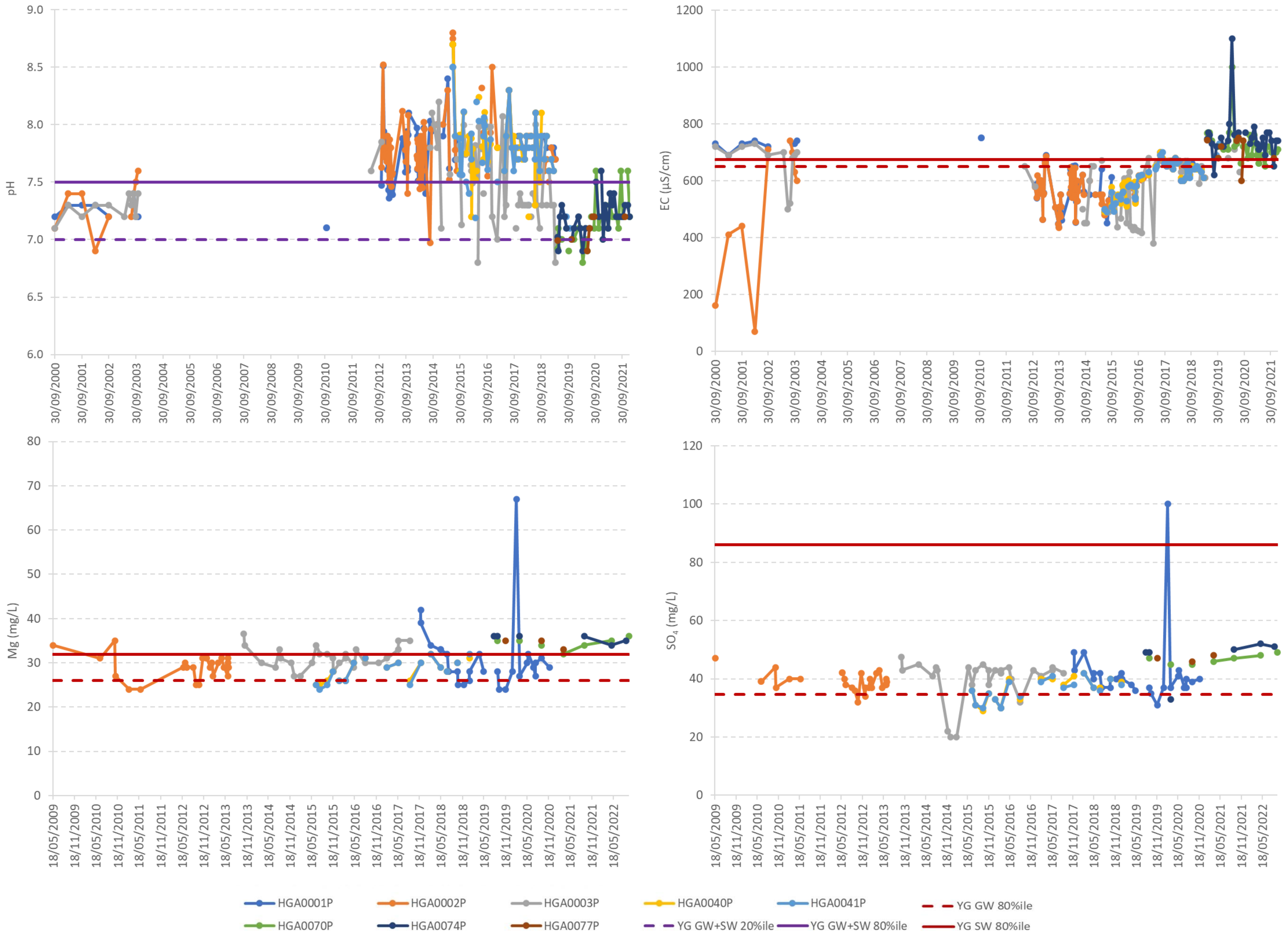


Figure 5.5: Time series plots of pH, EC, Mg and SO_4 from MAC groundwater monitoring bores, compared to YG 20%iles (pH)/80%iles

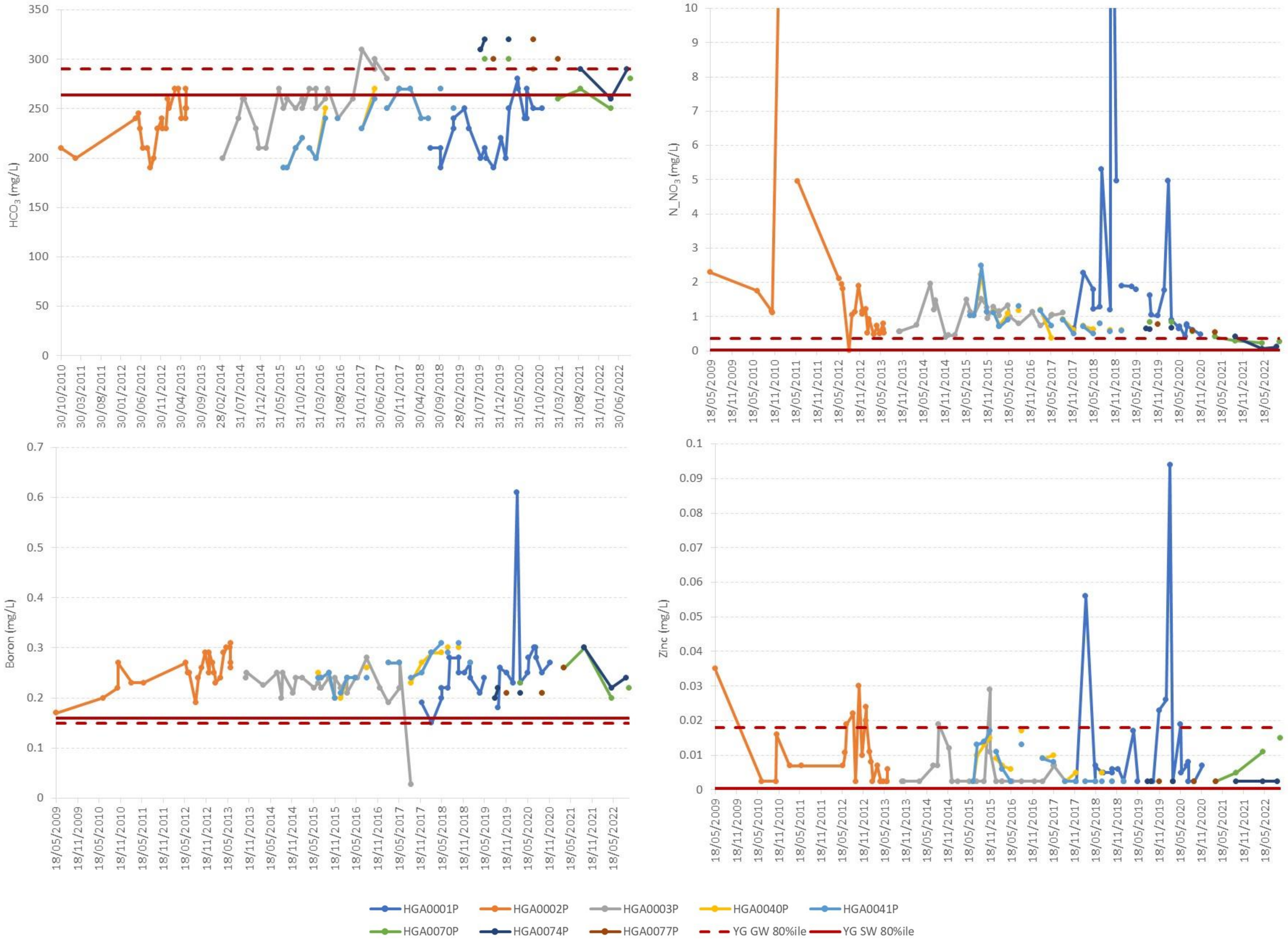


Figure 5.6: Time series plots of HCO$_3$, N_NO$_3$, dissolved boron and dissolved zinc from MAC groundwater monitoring bores, compared to YG 20%iles (pH)/80%iles

5.5 Risk Assessment

5.5.1 MAR Option (Groundwater)

5.5.1.1 Description and Receptors

MAR involves direct injection of groundwater into the receiving aquifer through injection bores. Its benefits for groundwater recharge, in comparison to instalment of infrastructure such as infiltration ponds or discharge outlets, would include, but not be limited to, a smaller surface footprint, reduced evaporation losses, and avoidance of alterations to natural surface hydrology. This strategy would also provide for a more natural hydrological regime, and avoid potential impacts associated with surficial discharge, such as increased flow velocity, creekbed scouring, and alterations to the frequency and timing of surface water flows.

Environmental receptors of YG that would be directly affected by changes to water quality from MAR are stygofauna. Hyporheic fauna, GDVs/phreatophytes, and surface water biota, may also be affected as groundwater levels rise and intercept the hyporheic and surface ecotones.

5.5.1.2 Water Quality

Analytes in MAC groundwater considered AoC for YG groundwater were:

- pH
- Hardness
- Mg
- SO_4
- N_NO_3
- B
- EC.

Although injection of MAC groundwater may lead to an increase in YG groundwater pH, median pH (7.7) was only marginally above the YG groundwater median (pH 7.3), and was well below the YG groundwater maxima (pH 8.4) (Table 5.3). Additionally, groundwaters of the local area, including of the Marillana and Weeli Wolli Creek catchment areas, are typically circum-neutral to alkaline, with pH not known to strongly influence stygofauna richness or composition (Halse *et al.*, 2014). Therefore, receptors are unlikely to be affected by a slight increase in groundwater pH within the YG receiving environment, with the risk considered negligible (Table 5.6).

An increase of hardness, Mg and SO_4, which all exceeded YG 80%iles on most occasions (>80% of sampling occasions;Table 5.3), is likely to occur in YG groundwaters if MAC groundwater is injected. Recent studies suggest that $MgSO_4$ can be highly toxic to aquatic biota in soft water environments (i.e. environments with low concentrations of ions), with Mg being more toxic than SO_4 (van Dam *et al.*, 2008). However, hardness, and in particular Ca, has an ameliorating effect on Mg toxicity, with toxic affects reduced or eliminated at a Mg:Ca ratio of around 10:1 (van Dam *et al.*, 2008). Therefore, given that Ca and hardness were greater than Mg concentrations in MAC groundwaters, increased $MgSO_4$ concentrations are unlikely to be toxic, posing negligible risk to environmental receptors (Table 5.6).

Increases to Mg and SO_4 may represent an early indication of sulfide oxidation as MAC groundwaters are drawn down (Earth Systems, 2022). Sulphide oxidisation, caused by the exposure sulfur-bearing minerals to the atmosphere and oxidising bacteria, can produce acidic pH solution, defined as acid-metalliferous drainage (AMD), if discharged to the environment. AMD is considered a primary pollutant of surface and groundwater with well-documented effects on the environment (Akcil & Koldas, 2006; Simate & Ndlovu, 2014; van Dam *et al.*, 2008). It is recommended that ongoing monitoring of pH, Mg, SO_4, Ca and $CaCO_3$ continue in the YG receiving environment, to provide a means to detect AMD and the potential toxic effects of Mg (in relation to concentrations of ameliorating Ca/$CaCO_3$).

Shifts in ionic composition are known to have little influence on stygofauna richness or abundance (Halse *et al.*, 2014). More important is the influence of salinity, with TDS above 1,500 mg/L expected to reduce stygofauna richness and abundance (Halse *et al.*, 2014). Despite potential increases to some ions (e.g. Mg and SO_4), there is no indication that injection of MAC groundwater would cause an increase in TDS in the YG receiving environment, with an 80%ile exceedance frequency of less than 10% (Table 5.3). Additionally, although EC was flagged as an AoC, mean and median EC were below the YG groundwater 80%ile (Table 5.3). Thus, potential increases to hardness, Mg and SO_4, as well as EC, are expected to have a negligible impact on stygofauna (Table 5.6).

Elevated nitrate is considered likely to occur in the receiving environment, as 99% of nitrate (N_NO_3) values exceeded the YG groundwater 80%ile (Table 5.3). Nitrate is both a stressor, leading the eutrophication at lower concentrations, and a toxicant, at higher concentrations leading to direct toxicity (ANZG, 2018). A recent review conducted by Becher *et al.* (2022) suggested nitrates have minimal effect on stygofauna at concentrations below 50 mg/L (all values in MAC groundwater were well below this level) (Table 5.3). Furthermore, less than 1% of N_NO_3 values in MAC groundwater exceeded the ANZG (2018) DGV for toxicity (2.1 mg/L) (Table 5.3). High water hardness also ameliorates nitrate toxicity in Pilbara waters (Van Dam *et al.*, 2022). Therefore, the nitrate concentrations recorded in MAC source water are unlikely to cause direct toxic effects to environmental receptors within the YG aquifer (Table 5.6).

Eutrophication, characterised by an excess of algal and plant growth due to an increased availability of nutrients, would not occur in the YG groundwater environment, as absence of light would be a limiting factor. Increased nitrates in groundwater may indirectly trigger eutrophic conditions in pools, where nitrate-enriched groundwater is expressed at the surface (Table 5.6). It is possible that some attenuation of nitrate in saturated sediments, as well as some assimilation/uptake by microbes and phreatophytes, may occur following groundwater injection (Rivett *et al.*, 2008). However, research into the attenuation of nitrate in Australian creeks is limited, making it difficult to predict how much nitrate could potentially be removed in this way.

Dissolved metals levels in MAC groundwater were low (Table 5.3), presenting negligible risk to environmental receptors. The exception was dissolved boron, which was elevated compared to YG groundwaters, with 99% of records exceeding the YG groundwater 80%ile (Table 5.3). Toxic effects to biota are considered highly unlikely, as no value exceeded the ANZG (2018) DGV for toxicity of 0.94 mg/L (Table 5.6).). In general, stygobitic and hypogean species have been found to be have a greater tolerance to metals than surface water fauna, likely due to the former having lower metabolic, assimilation, growth and reproduction rates (Becher *et al.*, 2022).

5.5.1.3 Calcite Precipitation

Risk of carbonate precipitation to groundwaters from MAR groundwater injection is likely to be negligible (Table 5.6), as the increase in hydrostatic pressure associated with groundwater injection at depth increases the solubility of $CaCO_3$, reducing the capacity for calcite precipitation (Earth Systems, 2022).

Table 5.6: Summary of risk to environmental receptors from MAR / groundwater injection

Analyte of Concern	Exceedance Summary & Potential Risk	Mitigating Factors / Potential Management	Residual Risk to Environmental Receptors
MAR / Groundwater Injection			
pH	• Exceeded YG GW 80%ile on 66% of sampling occasions • Potential for slight increase in pH in YG GW	• MAC median pH (7.7) only marginally above the YG GW median (pH 7.3) • Median pH well below the YG GW maxima (pH 8.4) • pH does not appear to be increasing over time in MAC GW • Groundwater pH of the local area (Yandicoogina/Weeli Wolli Creek catchment areas) typically circum-neutral to basic (>7.5) • Stygofauna unlikely to be affected by slight increase in pH	Negligible
Salinity (EC)	• Exceeded YG GW 80%ile on 32% of sampling occasions • Potential for slight increase in salinity in YG GW	• Relatively low exceedance percentage (32%); significant shifts in EC therefore unlikely • MAC median (612 µS/cm) and mean (611 µS/cm) below YG GW 80%ile (650 µS/cm) • TDS (analogue for salinity) not flagged as an AoC; all values well below 1,500 mg/L (concentration at which impacts to stygofauna are expected) • Ongoing monitoring of EC should continue for early detection of salinity increases	Negligible
Ions ($CaCO_3$, Mg, SO_4)	• $CaCO_3$ exceeded the YG GW 80%ile on 75% of sampling occasions • Mg exceeded the YG GW 80%ile on 82% of sampling occasions • SO_4 exceeded the YG GW 80%ile on 85% of sampling occasions • Potential for marked increases to all three analytes in YG groundwaters • Mg can be highly toxic to aquatic biota (soft water environments)	• None of these analytes appear to be increasing significantly over time in MAC GW • Toxic effects of Mg likely to be ameliorated due to high water hardness and high Ca in MAC and YG GW • The above could be confirmed by ecotoxicity testing • Ongoing monitoring of ions and hardness should continue for early detection of changes in composition • Stygofauna community unlikely to be impacted by shifts in ionic composition; salinity a more important factor	Negligible
Nutrients (N_NO_3)	• Exceeded YG GW 80%ile on 95% of sampling occasions • Likely marked increase in N_NO_3 in YG GW • Nitrate both a toxicant and stressor (eutrophication) in high concentrations • Eutrophication may occur in surface water pools if nitrate enriched groundwaters	• Eutrophication will not occur in GW; absence of light a limiting factor for eutrophication • Some nitrate may be taken up / assimilated in the GW environment before surface expression • Direct toxicity unlikely; less than 1% of N_NO_3 values exceed the ANZG toxicity DGV (2.1 mg/L) • N_NO_3 does not appear to be increasing over time in MAC GW • Ongoing monitoring of N_NO_3 should continue for early detection of increases above toxicity levels	Negligible Toxicity Risk Low Eutrophication Risk (Surface Water Pools)

Analyte of Concern	Exceedance Summary & Potential Risk	Mitigating Factors / Potential Management	Residual Risk to Environmental Receptors
Metals (Dissolved Boron)	• Only dissolved boron exceeded the YG GW 80%ile on >25% of sampling occasions • 99% of dissolved boron values exceeded the 80%ile; increase in boron in the receiving environment likely	• Toxicity unlikely as no dissolved boron values exceeded the 95% ANZG toxicity DGV (0.94 mg/L) • Boron does not appear to be increasing over time in MAC GW • Stygofauna typically less sensitive to metals toxicity due to slow metabolic rates	Negligible
Calcite	• MAC GW supersaturated with calcium carbonate	• Precipitation unlikely to occur during groundwater injection due to pressure differential	Negligible

5.5.2 Discharge Option (Surface water)

5.5.2.1 Description and Receptors

Supplementation using surface discharge will likely involve construction of and discharge into infiltration ponds/basins within the YG ecosystem, or direct discharge to the YG surface water environment through a discharge outfall or spur system. Although this may provide a means of supplementing pool water levels, discharge would likely alter natural hydrological regimes, with increased and aseasonal flows.

Environmental receptors of YG that would be directly affected by changes to water quality from surface discharge are surface water biota (zooplankton, macroinvertebrates, macrophytes and fish). Hyporheos fauna, GDV phreatophytes and stygofauna may be indirectly affected as discharge water infiltrates the hyporheic and subsurface ecotones.

5.5.2.2 Water Quality

Analytes in MAC groundwater considered AoC for YG surface waters were:

- pH
- N_NO_3
- B
- Mg
- HCO_3
- Zn (Table 5.4).

Discharge of MAC groundwaters may lead to an increase in surface water pH within YG. However, the increase would likely be minimal. Median MAC groundwater pH (7.7) was only slightly above the YG surface water median (pH 7.3), and was within the surface water historical range (pH 6.6 to 7.9) (Table 5.4). Like groundwaters, surface waters of the Weeli Wolli Creek catchment, and Pilbara riverine systems more broadly, are typically basic (above pH 7.0), influenced by carbonate rich geologies (Pinder *et al.*, 2010). Therefore, the risk to aquatic biota from a slight increase in surface water pH within the YG receiving environment is likely negligible (Table 5.7).

It is also possible that increases of Mg may occur, although exceedance frequency was relatively low (32%), compared to the groundwater comparison (Table 5.4). As discussed previously, Mg can be highly toxic to aquatic biota in soft water environments (van Dam *et al.*, 2008). Therefore, high concentrations of Ca and $CaCO_3$ in MAC groundwaters are likely to nullify Mg toxicity (van Dam *et al.*, 2008), with negligible toxicity risk to receptors (Table 5.7).

HCO_3 was also highlighted as an AoC, with 29% of records from MAC groundwater exceeding the YG surface water 80%ile of 264 mg/L (Table 5.4).However, it is likely that increases to HCO_3 in the YG receiving environment would be minor, as median HCO_3 (250 mg/L) was below the surface water 80%ile, and within the historic range recorded in surface waters (132 mg/L to 295 mg/L). Riverine systems of the Pilbara are commonly rich in bicarbonate, particularly those in the Weeli Wolli/Marillana Creek sub-catchment areas (Biologic, 2023a, 2023b; Halse *et al.*, 2014; Pinder *et al.*, 2010). As such, the environmental receptors of YG surface waters would likely be unaffected by a slight increase in HCO_3 concentrations (Table 5.7).

Nitrate (N_NO_3) is likely to increase markedly in YG surface waters if MAC groundwaters are discharged directly. YG surface waters are naturally low in nitrate (median 0.005 mg/L, maximum 0.07 mg/L), while MAC groundwaters are nitrate-enriched, with concentrations several orders of magnitude higher than YG surface waters (median 1.01 mg/L; maximum 22.0 mg/L). In addition, 69% of values exceeded the eutrophication DGV of 0.7 mg/L (Table 5.4). However, less than 1% of N_NO_3 values in MAC groundwater exceeded the ANZG (2018) DGV for toxicity (2.1 mg/L). Therefore, discharge of MAC groundwaters presents a moderate eutrophication risk to the YG receiving environment, however, direct toxic effects to environmental receptors are unlikely (Table 5.7).

Eutrophication typically presents as increased algal and macrophyte growth, which can physically smother aquatic invertebrates, as well as deplete oxygen in the water, due to increased biological oxygen demand as plants decay and are decomposed by bacteria. The relationship between nitrate-enrichment and enhanced algal growth in freshwaters is well documented, often resulting in very high density/abundance but low species richness (Camargo & Alonso, 2006; Wagenhoff *et al.*, 2011).

The risk of metals toxicity to YG surface water biota is negligible (Table 5.7), as concentrations of the majority of analytes in MAC groundwater did not exceed LORs, DGVs or YG surface water 80%iles. The exceptions were dissolved boron and zinc. Almost all dissolved boron values were elevated compared to YG surface waters, with 99% of records exceeding the YG 80%ile (Table 5.4). Regardless, toxic effects to biota are considered highly unlikely, as no value exceeded the ANZG (2018) DGV for toxicity of 0.94 mg/L (Table 5.4). Direct toxic effects to aquatic biota from elevated dissolved zinc are also considered unlikely (Table 5.7), despite 26% of values exceeding the toxicity DGV (0.008 mg/L) in MAC groundwaters. This is due to the source groundwater being rich in $CaCO_3$, with hardness known to ameliorate zinc toxicity.

5.5.2.3 Calcite Precipitation

The LSI calculations undertaken for this assessment, as well as a recent assessment by Earth Systems (2022), indicated that widespread precipitation of carbonate minerals is expected if

MAC groundwater is discharged directly to the surface environment, as the water is supersaturated with $CaCO_3$.

Calcite precipitation smothers sediments, infilling interstices, and effectively 'cementing' cobbles and pebbles together which results in armouring of the creek bed (Casas *et al.*, 1994). This leads to a loss of habitat for interstitial and burrowing species, as well as a loss of habitat heterogeneity, which ultimately results in an overall loss of biodiversity (Bis *et al.*, 2000; Brasil *et al.*, 2014; Miserendino, 2001). Over time, armouring of the creek bed can lead to alteration of channel geomorphology such as decreased channel dynamics, changes to channel dimension, channel slope and floodplain characteristics, halted lateral migration, and altered sediment deposition (Kimbal & Kondolf, 2002).

Calcite precipitate can influence a range of habitat-forming processes, including reduction of riparian vegetation and in-stream cover, alteration of riffle-pool sequences, and changes to substrate composition. Increased flow velocities tend to result from creek bed armouring, as natural scouring processes which assist in dissipating stream velocity can no longer occur when banks have been hardened (Kimbal & Kondolf, 2002; Schmetterling *et al.*, 2001). Calcite precipitation can also lead to reduced connectivity between ground and surface waters. This causes inhibition of gas and nutrient exchange between the hyporheic zone and surface waters, resulting in a reduction in redox potential, dissolved oxygen, organic matter, food resources and nutrient flow (Boulton, 2001; Dole-Olivier & Marmonier, 1992a; Edwards, 1998).

Currently, MAC groundwater used for production is stored in a series of turkey's nest dams and infiltration ponds prior to use, with water residing in this system for a period of two to four days. This, along with the inherent drop in pressure between the groundwater and surface environment, enables passive degassing of CO_2, which in turn leads to precipitation of carbonate prior to processing use (Earth Systems, 2022). The exception is groundwater sourced from A Deposit, which resides in the turkey's nest dam for three to five hours prior to use, due to the configuration of inflow and outflow pipework (infiltration ponds are not used). This residence time is considered insufficient for CO_2 degassing and carbonate precipitation, resulting in scale build-up on processing infrastructure (Earth Systems, 2022).

As such, the combination of the turkey's nest dams and downstream infiltration ponds likely provides adequate conditions for optimising carbonate precipitation and deposition in a controlled environment prior to discharge (assuming residence time would be more than two days) (Earth Systems, 2022). No further intervention would likely be necessary for lowering the risk of carbonate precipitation to the surface water environment.

If the use of dams and ponds is not viable, or the residence time cannot be met, intervention is likely to be required in the form of active degassing of groundwater, and optimisation precipitation (using strategies such as increased temperatures or addition of calcite seed crystals). However, these methods would still be required to be undertaken in a controlled environment prior to environmental discharge. Regardless, the risk of calcite precipitation to the YG surface water environment was still classified as moderate, due to the high saturation of $CaCO_3$ in the source water (Table 5.7).

Table 5.7: Summary of risk to environmental receptors from surface discharge

Analyte of Concern	Exceedance Summary & Potential Risk	Mitigating Factors / Potential Management	Residual Risk to Environmental Receptors
Surface Discharge			
pH	• Exceeded YG SW 80%ile on 66% of sampling occasions • Potential for slight increase in pH in YG SW	• MAC median pH (7.7) only marginally above the YG SW median (pH 7.3) • Median pH below the YG SW maxima (pH 7.9) • pH does not appear to be increasing over time in MAC GW • Groundwater pH of the Yandicoogina/Weeli Wolli Creek catchment areas typically circum-neutral to basic (>7.5) • Aquatic biota unlikely to be affected by slight increase in pH	Negligible
Ions (HCO_3, Mg)	• HCO_3 exceeded the YG SW 80%ile on 29% of sampling occasions • Mg exceeded the YG SW 80%ile on 32% of sampling occasions • Potential for slight increases to HCO_3 and Mg • Mg can be highly toxic to aquatic biota (soft water environments)	• Neither analyte appears to be increasing significantly over time in MAC GW • Toxic effects of Mg likely to be ameliorated due to high water hardness and high Ca in MAC GW and YG receiving environment • Aquatic biota unlikely to be impacted by slight increases to HCO_3 as the Weeli Wolli Creek and Marillana Creek catchments are typically bicarbonate rich • Ongoing monitoring of ions and hardness should continue for early detection of changes in composition	Negligible
Nutrients (N_NO_3)	• Exceeded YG SW 80%ile on 99% of sampling occasions • Likely marked increase in N_NO_3 in YG SW • Nitrate is both a toxicant and stressor (eutrophication) in high concentrations • Eutrophication likely to occur, expressed as excessive algal and macrophyte growth; can lead to reduced water quality and aquatic biota diversity	• Direct toxicity unlikely; less than 1% of N_NO_3 values exceed the ANZG toxicity DGV (2.1 mg/L) • High hardness ameliorates toxicity • N_NO_3 does not appear to be increasing over time in MAC GW • Ongoing monitoring of N_NO_3 should continue for early detection of increases above toxicity levels	Negligible Toxicity Risk Moderate Eutrophication Risk
Metals (Dissolved Zinc, Dissolved Boron)	• Only dissolved boron and zinc exceeded the YG SW 80%ile on >25% of sampling occasions • 99% of dissolved boron values exceeded the 80%ile; increase in boron in the receiving environment likely • 26% of dissolved zinc values exceeded the SW 80%ile; slight increase in dissolved zinc may occur	• Toxicity unlikely as no dissolved boron values exceeded the 95% ANZG toxicity DGV (0.94 mg/L) • Boron or zinc do not appear to be increasing over time in MAC GW • No dissolved boron value exceeded the ANZG (2018) 95% toxicity DGV (0.94 mg/L); toxic effects unlikely • Hard water of MAC groundwater likely to ameliorate any potential toxic effects	Negligible
Calcite	• MAC GW supersaturated with calcium carbonate • Up to 40 kg of calcium carbonate may be deposited within the receiving environment for each ML of water discharged under optimum conditions	• Storage of water in turkey's nest dams and infiltration ponds prior to discharge (minimum 2 – 4 days) will reduce precipitation risk • Active degassing of groundwater, and optimisation precipitation using strategies such as increased	Moderate Precipitation Risk

Analyte of Concern	Exceedance Summary & Potential Risk	Mitigating Factors / Potential Management	Residual Risk to Environmental Receptors
	• Calcite precipitation leads to armouring of the creekbed and associated reductions in biodiversity	temperatures or addition of calcite seed crystals, (although still require a controlled environment)	🟨

6 Summary and Conclusion

Groundwaters of the YG receiving environment were circum-neutral to alkaline (pH 6.7 - 8.4), fresh to saline (430 - 5,750 µS/cm EC), and clear. Ionic composition was dominated by bicarbonate and calcium. Nutrient concentrations were low, with all N_NO_3 values below the ANZG DGV for eutrophication. Dissolved metal concentrations were also generally low, with concentrations of most analytes below LORs and/or ANZG DGVs. Concentrations of hydrocarbons and other contaminants were all below LORs in YG groundwater samples.

Surface waters at YG ranged from slightly acidic to alkaline (pH 6.6 - 7.9), with highly variable turbidity, DO and water temperatures. EC was classified as fresh (<1,500 µS/cm) in all samples. Ionic composition typically mirrored the ionic composition of groundwaters. Several nutrient analytes recorded relatively frequent exceedances of DGVs, including N_NOx, TN and TP. Dissolved metal concentrations were low.

Although source groundwater quality from MAC was considered broadly similar to the ground- and surface- waters of the YG receiving environment, on average being circum-neutral, fresh and clear, several AoC were identified. For groundwater (MAR option) these were pH, hardness Mg, SO_4, N_NO_3, B and EC. For surface water (discharge option), the AoC were pH, HCO_3, Mg, N_NO_3, B and Zn. In addition, the MAC groundwater was found to be supersaturated in calcium carbonate, suggesting widespread precipitation of carbonate minerals could be expected if discharged directly to the surface environment and no control measures were implemented.

For the MAR option, the risk assessment found that the majority of AoC likely pose a **negligible risk** to environmental receptors. The exception was N_NO_3, which was deemed to indirectly pose a **low eutrophication risk** to YG surface water pools. The risk of calcite precipitation was deemed to be **negligible**.

For the surface discharge option, the risk assessment also found that the majority of AoC likely posed a **negligible risk** to environmental receptors. The exception again was N_NO_3, which was deemed to pose a **moderate eutrophication risk** to YG surface water pools, although the toxicity risk was still negligible. The risk of calcite precipitation was deemed to be **moderate**.

Key mitigating factors considered during the risk assessment were:

- Environmental receptors are unlikely to be affected by slight increases in pH or HCO_3, as ground- and surface- waters of the local area (Yandicoogina/Weeli Wolli Creek catchment areas) are naturally basic (pH >7.0) and rich in bicarbonate

- No N_NO_3 value exceeded the ANZG DGV for toxicity (2.1 mg/L), despite most values exceeding the DGV for eutrophication (0.7 mg/L)
- No boron value exceeded the ANZG DGV for toxicity (0.94 mg/L)
- High water hardness in the source groundwater and YG receiving environment is likely to ameliorate the toxic effects of Mg, SO_4, N_NO_3 and zinc
- None of the AoC appear to be increasing in MAC groundwater over time
- The increase in hydrostatic pressure associated with groundwater injection at depth increases the solubility of $CaCO_3$, reducing the potential for calcite precipitation during MAR.

The risk rankings were also based on the assumption that the following management measures would be implemented:

- Potentially toxic Mg and SO_4 are monitored throughout the duration of supplementation activities, to detect any increase in concentrations
- Water hardness and Ca are monitored to ensure concentrations remain sufficiently high to ameliorate the toxic effects of Mg, SO_4, N_NO_3 and zinc, and buffer against swings in pH
- N_NO_3 concentrations are monitored to enable detection of concentrations above the ANZG DGV for toxicity
- EC is monitored to detect of increasing salinity
- To ameliorate the risk of calcite precipitation in the surface water environment (discharge option), MAC source water is stored in turkey's nest dams and infiltration ponds for a minimum of two to four days prior to discharge. Active degassing of groundwater, and optimisation precipitation (by strategies such as increased temperatures or addition of calcite seed crystals), could be used to reduce precipitation risk (although still require a controlled environment).

The risk assessment showed that the MAR option would present a lower overall risk to the YG receiving environment, owing to the lower risk of eutrophication and calcite precipitation. This option would also maintain upwelling of groundwater to surface pools, and natural movement of nutrients, resources (such as organic carbon), and oxygen, between the surface and subsurface ecotones, while avoiding changes to the frequency, timing and velocity of surface flows. The MAR option would also have a lower physical disturbance footprint, as the construction of infiltration ponds and discharge infrastructure would not be required.

Given the declining groundwater levels and reduction of permanent and semi-permanent pools within YG, and the associated impacts to flora and aquatic fauna, the benefits of either supplementation option would likely outweigh any potential risks AoC pose to the receiving environment.

7 References

AECOM. (2016). *Iron Valley below water table assessment on proponent information – ERD. Appendix D fauna studies*. Unpublished report prepared for Iron Valley.

Akcil, A., & Koldas, S. (2006). Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production, 14*(12), 1139-1145. doi:https://doi.org/10.1016/j.jclepro.2004.09.006

Alpin, K. P. (1998). Three new blindsnakes (Squamata: Typhlopidae) from northwestern Australia. *Records of the Western Australia Museum, 19*, 1-12.

ALS. (2017). Technical Datasheet: Langelier Index. Retrieved from https://www.alsenvironmental.co.uk/media-uk/pdf/datasheets/drinking-water/langelier-index_td_uk.pdf

ANZG. (2018). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Retrieved from www.waterquality.gov.au/anz-guidelines

Bastin, G. (2008). *Rangelands 2008 - Taking the pulse*. Canberra, Australian Capital Territory: National Land & Water Resources Audit.

Becher, J., Englisch, C., Grieber, C., & Bayer, P. (2022). Groundwater fauna downtown – Drivers, impacts and implications for subsurface ecosystems in urban areas. *Journal of Contaminant Hydrology, 248*, 16.

Bennelongia. (2015). *Strategic environmental assessment: Description of regional subterranean fauna*. Jolimont, WA:

Biologic. (2020). *Ministers North: Yandicoogina Creek Aquatic Ecosystem Surveys*. East Perth, WA:

Biologic. (2021a). *Ministers North Miscellaneous Licence Area Amendment Surveys and Yandicoogina Creek Detailed Flora and Vegetation Assessment*. Unpublished report prepared for BHP Western Australia Iron Ore.

Biologic. (2021b). *WPIOP Stage 1: Red Hill Creek and Cane River Aquatic Ecosystem Survey Interim Report*. East Perth, W.A.:

Biologic. (2022a). *Ministers North: Yandicoogina Creek Aquatic Ecosystem Surveys Dry 2020 and Wet 2021*. East Perth, WA:

Biologic. (2022b). *Ministers North: Yandicoogina Creek Aquatic Ecosystem Surveys Dry 2021 and Wet 2022*. East Perth, WA:

Biologic. (2023a). *MAC Phase 4: Marillana Creek Baseline Aquatic Ecosystem Survey Dry 2021 and Wet 2022. Draft v2*. East Perth:

Biologic. (2023b). *Weeli Wolli Spring: Aquatic Monitoring 2021*. East Perth, WA:

Biologic. (2023c). *Yandicoogina Gorge Riparian Vegetation Monitoring 2020–2022. DRAFT v2 Report*.

Bis, B., Zdanowicz, A., & Zalewski, M. (2000). Effects of catchment properties on hydrochemistry, habitat complexity and invertebrate community structure in a lowland river. *Hydrobiologia, 422/423*, 369-387.

BoM, Bureau of Meteorology. (2021). Groundwater dependent ecosystems atlas.

Boulton, A. J. (2001). Twixt two worlds: taxonomic and functional biodiversity at the surface water/groundwater interface. *Records of the Western Australian Museum Supplement, 64*, 1-13.

Boulton, A. J., & Hancock, P. J. (2006). Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. *Australian Journal of Botany, 54*(2), 133-144.

Brasil, L. S., Juen, L., & Cabette, S. R. (2014). The effects of environmental integrity on the diversity of mayflies, Leptophlebiidae (Ephemeroptera), in tropical streams of the Brazilian Cerrado. *Annales de Limnologie – International Journal of Limnology, 50*, 325-334.

Bruno, M. C., Bottazzi, E., & Rossetti, G. (2012). Downward, upstream or downstream? Assessment of meio- and macrofaunal colonization patterns in a gravel-bed stream using artificial substrates. *Annales de Limnologie - International Journal of Limnology, 48*, 371-381.

Camargo, J., & Alonso, A. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assesssment. *Environment International, 32*, 831-849.

Casas, J. J., Picazo, J., & Carceleân, M. L. (1994). Leaf litter breakdown in a karstic Mediterranean stream. *Verhandlungen der Internationalen Vereinigung für Limnologie, 25*, 1739-1744.

Choy, S., & Marshall, J. C. (2002). Ecological condition of central Australian arid-zone rivers. *Water Science & Technology, 45*(11), 225-232.

Coe, H. J. (2001). *Distribution patterns of hyporheic fauna in a riparian floodplain terrace, Queets River, Washington.* (MSc thesis), University of Washington,

Connolly, N. M., Crossland, M. R., & Pearson, R. G. (2004). Effect of low dissolved oxygen on survival, emergence, and drift of tropical stream macroinvertebrates. *Journal of the North American Benthological Society, 23*, 251-270.

Cooling, M. P., & Boulton, A. J. (1993). Aspects of the hyporheic zone below the terminus of a south Australian arid-zone stream. *Australian Journal of Marine and Freshwater Research, 44*, 411-426.

DBCA, Department of Biodiversity, Conservation and Attractions. (2022). Threatened and Priority Flora List. Retrieved 22/07/2022 https://www.dpaw.wa.gov.au/plants-and-animals/threatened-species-and-communities/threatened-plants

Dole-Olivier, M.-J., & Marmonier, P. (1992a). Effects of spates on the vertical distribution of the interstitial community. *Hydrobiologia, 230*, 49-61.

Dole-Olivier, M.-J., & Marmonier, P. (1992b). Patch distribution of interstitial communities: prevailing factors. *Freshwater Biology, 27*, 177-191.

DoW, Department of Water. (2010). *Pilbara Regional water plan 2010-2030: Supporting detail.*

Drysdale, R. N. (2001). Factors controlling the hydrochemistry of Louie Creek, a travertine-depositing stream in the seasonally wet tropics of northern Australia. *Marine and Freshwater Research, 52*, 793-804.

Eamus, D., Fu, B., Springer, A. E., & Stevens, L. E. (2016). Groundwater dependent ecosystems: Classification, identification techniques and threats. In A. J. Jakeman, O. Barreteau, R. J. Hunt, J. D. Rinaudo, & A. Ross (Eds.), *Integrated Groundwater Management: Concepts, Approaches and Challenges* (pp. 313-346). Cham: Springer International Publishing.

Earth Systems. (2022). *MAC and South Flank: Carbonate Precipitation from Groundwater - Source, Controls and Management*. Hawthorne, Victoria:

Edwards, R. T. (1998). The hyporheic zone. In R. J. Naiman, R. E. Bilby, & S. Kantor (Eds.), *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. New York, United States of America: Springer-Verlag.

EPA, Environmental Protection Authority. (2016). *Environmental Factor Guideline: Subterranean Fauna*. Perth, Western Australia: Environmental Protection Authority.

Guzik, M. T., Austin, A. D., Cooper, S. J. B., Harvey, M. S., Humphreys, W. F., Bradford, T., . . . Tomlinson, M. (2010). Is the Australian subterranean fauna uniquely diverse? *Invertebrate Systematics, 24*, 1-12.

Halse, S. A. (2018). Subterranean fauna of the arid zone. In *On the Ecology of Australia's Arid Zone* (pp. 215-241).

Halse, S. A., Scanlon, M. D., Cocking, J. S., Barron, H. J., Richardson, J. B., & Eberhard, S. (2014). Pilbara stygofauna: deep groundwater of an arid landscape contains globally significant radiation of biodiversity. *Records of the Western Australian Museum, Supplement, 78*, 443-483.

Hose, G. C., Jones, P., & Lim, R. P. (2005). Hyporheic macroinvertebrates in riffle and pool areas of temporary streams in south-eastern Australia. *Hydrobiologia, 532*, 81-90.

Humphreys, W. F. (2006). Aquifers: the ultimate ground-water dependent ecosystems. *Australian Journal of Botany, 54*, 115-132.

Humphreys, W. F. (2008). Rising from Down Under: developments in subterranean biodiversity in Australia from a groundwater fauna perspective. *Invertebrate Systematics, 22*, 85-101.

Jacobi, G. Z., & Cary, S. J. (1996). Winter stoneflies (Plecoptera) in seasonal habitats in New Mexico, USA. *Journal of the North American Benthological Society, 15*(4), 690-699.

Kendrick, P. (2001). Pilbara 3 (PIL3 - Hamersley subregion). In J. May & N. McKenzie (Eds.), *A biodiversity audit of Western Australia's 53 biogeographical subregions in 2002* (pp. 568-580). Kensington, Western Australia: Department of Conservation and Land Management.

Kimbal, L. C., & Kondolf, G. M. (2002). *Analysis of channel geomorphology and habitat forming processes for feasibility assessment of rip-rap removal, Muir Woods National Monument Mill Valley, California*. Berkeley:

Larson, H. K., Foster, R., Humphreys, W. F., & Stevens, M. I. (2013). A new species of the blind cave gudgeon *Milyeringa* (Pisces: Gobioidei, Eleotridae) from Barrow Islan, Western Australia, with a redescription of *M. veritas* Whitley. *Zootaxa, 3616*(2), 135-150.

Mayer, X. M., Ruprecht, J. K., & Bari, M. A. (2005). *Stream salinity status and trends in south-west Western Australia. Report No. SLUI38*.

McLennan, S. M., Taylor, S. R., & Eriksson, K. A. (1983). Geochemistry of Archean Shales from the Pilbara Supergroup, Western Australia. *Geochemica n Cosmochimica Acta, 47*(7), 1211-1222.

Miserendino, M. L. (2001). Macroinvertebrate assemblages in Andean Patagonian rivers and streams: environmental relationships. *Hydrobiologia, 444*, 147-158.

Moore, G. I. (2019). New morphological data and live photographs of the rare subterranean blind cave eel *Ophisternon candidum* (Synbranchidae) from north-western Australia. *Ichthyological Research, 66*(1), 160-165. doi:10.1007/s10228-018-0647-2

Murray, B. R., Hose, G. C., Eamus, D., & Licari, D. (2006). Valuation of groundwater-dependent ecosystems: a functional methodology incorporating ecosystem services. *Australian Journal of Botany, 54*(2), 221-229. doi:https://doi.org/10.1071/BT05018

NIWA. (2013). *Updating nitrate toxicity effects on freshwater aquatic species*. Hamilton, New Zealand:

Palmer, M. A., Bely, A. E., & Berg, K. E. (1992). Response of invertebrates to lotic disturbance: a test of the hyporheic refuge hypothesis. *Oecologia, 89*, 182-194.

Parker, G., & Sutherland, A. J. (1990). Fluvial armor. *Journal of Hydraulic Research, 28*, 529-544.

Pinder, A. M., Halse, S. A., Shiel, R. J., & McRae, J. M. (2010). An arid zone awash with diversity: Patterns in the distribution of aquatic invertebrates in the Pilbara region of Western Australia. *Records of the Western Australian Museum*, 205-246.

Pinder, A. M., & Leung, A. (2009). *Conservation Status and Habitat Associations of Aquatic Invertebrates in Pilbara Coastal River Pools*. Perth, Western Australia:

Ramchandra, T. V., Rishiram, R., & Karthik, B. (2006). *Zooplankton as bioindicators: hydrobiological investigations in selected Bangalore lakes*. Bangalore:

Reeves, J. M., De Deckker, P., & Halse, S. (2007a). Groundwater ostracods from the arid Pilbara region of northwestern Australia: Distribution and water chemistry. *Hydrobiologia, 585*, 99-118.

Reeves, J. M., De Deckker, P., & Halse, S. A. (2007b). Groundwater ostracods from the arid Pilbara region of northwestern Australia: Distribution and water chemistry. *Hydrobiologia, 585*(1), 99-118. doi:10.1007/s10750-007-0632-7

Rio Tinto. (2010). *Yandicoogina Water Balance; Pre and Post Mining Hydraulics and Hydrochemistry*. https://www.epa.wa.gov.au/sites/default/files/PER_documentation/Appendix%20A13%20-%20Yandicoogina%20Water%20Balance_Pre%20and%20Post%20Mining%20Hydraulics%20%26%20Hydrochemistry.pdf

Rio Tinto. (2021). *Riparian Ecohydrological Assessment Framework. Draft version 7.* Perth, Western Australia:

Rivett, M. O., Buss, S. R., Morgan, P., Smith, J. W. N., & Bemment, C. D. (2008). Nitrate attenuation in groundwater: A review of biogeochemical controlling processes. *Water Research, 42*, 4215-4232.

Sainty, G., R., & Jacobs, S., W., L. (2003). *Waterplants in Australia* (4th ed.). Griffith, NSW: Sainty and Associates Pty Ltd.

Schmetterling, D. A., Clancy, C. G., & Brandt, T. M. (2001). Effects of riprap bank reinforcement on stream salmonids in the western United States. *Fisheries, 26*, 6-13.

Simate, G. S., & Ndlovu, S. (2014). Acid mine drainage: Challenges and opportunities. *Journal of Environmental Chemical Engineering, 2*(3), 1785-1803. doi:https://doi.org/10.1016/j.jece.2014.07.021

Smith, R. E. W., Boulton, A. J., Baldwin, D. S., Humphrey, C. L., Butler, B., & Halse, S. A. (2020). *Assessing and Managing Water Quality in Temporary Waters*. Canberra, ACT, Australia:

Thackway, R., & Cresswell, I. D. (1995). *An Interim Biogeographical Regionalisation for Australia*. Canberra, ACT: Australian Nature Conservation Agency.

Thurgate, M. E., Gough, J. S., Clarke, A. K., Serov, P., & Spate, A. (2001). Stygofauna diversity and distribution in Eastern Australian cave and karst areas. *Records of the Western Australian Museum, 64*(Supplement), 49-62.

Unmack, P. J. (2013). Biogeography. In P. Humphries & K. Walker (Eds.), *Ecology of Australian Freshwater Fishes* (pp. 25-48). Collingwood: CSIRO Publishing.

van Dam, R., Hogan, A., McCullough, C., & Humphrey, C. (2008). *Toxicity of magnesium sulfate in Magela Creek water to tropical freshwater species*.

Van Dam, R. A., Bankin, K., & Parry, D. (2022). Derivation of site-specific guideline values for nitrate toxicity in Pilbara receiving waters with high hardness. *Integrated Environmental Assessment & Management, 18*(4), 1035-1046.

Wagenhoff, A., Townsend, C. R., Phillips, N., & Matthaei, C. D. (2011). Subsidy-stress and multiple-stressor effects along gradients of deposited fine sediment and dissolved nutrients in a regional set of streams and rivers. *Freshwater Biology, 56*, 1916-1936.

Wilcock, P. R., & DeTemple, B. T. (2005). Persistence of armor layers in gravel-bed streams. *Geophysical Research Letters, 32*, 1-4.

Wright, J. S. (2000). Tufa accumulations in ephemeral streams: Observations from the Kimberley, north-west Australia. *Australian Geographer, 31*, 333-347.

WRM. (2009). *API Aquila: Baseline Aquatic Ecosystem Surveys*. Nedlands, WA: https://library.dbca.wa.gov.au/static/FullTextFiles/071225.pdf

WRM. (2015). *Red Hill Creek Project: Potential Impacts to Aquatic Systems Literature Review & Site Reconnaissance*. Burswood, WA: