SCHOOL OF NATURAL SCIENCES

Faculty of Science and Engineering

MACQUARIE University

APPLICATION OF THE GROUNDWATER HEALTH INDEX (GHI) AS A WATER MONITORING TOOL

Benchmarking and assessing groundwater ecosystems within the lower Darling-Baaka River catchment

Citation:

Hose GC, Dabovic J and Korbel K (2025) Application of the Groundwater Health Index (GHI) as Water Monitoring Tool: Benchmarking and assessing groundwater ecosystems within the Darling-Baaka River catchment. Report to NSW DCCEEW. Macquarie University, Sydney.

Cover Photo: Lower Darling Baaka River upstream of Wilcannia. Credit: K Korbel 2024

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Executive summary

The NSW Chief Scientist and Engineer's report on the 2023 fish kills at Menindee, published on 29 September 2023 (OCSE 2023), provided an in-depth analysis of the factors contributing to the mass fish deaths in the Darling Baaka River and offered recommendations for river management.

The Darling Baaka River Health Project ('the Project') was established as a long-term river health monitoring program as part of the recovery response to the 2023 flooding disaster. It transitions the NSW Government's initial emergency response, led through NSW Environmental Services Functional Area (EnvSFA), into an ongoing program focused on river health and recovery. The project is being delivered from August 2023 until June 2025 by DCCEEW Science and Insights Division.

Groundwater contributes to river flows and is thus an important contributor to the water quality of the Darling Baaka River. The quality of groundwater depends on healthy groundwater ecosystems that contain microbes and invertebrates (stygofauna). These organisms improve water quality and aid the flow of water through an aquifer. Without healthy groundwater ecosystems, the quality and quantity of groundwater entering the Darling Baaka River may decline, particularly in dry periods when groundwater inputs may be most critical.

The Groundwater Health Index (GHI) (Korbel and Hose 2011; 2017) was used in this project to assess groundwater health using a combination of environmental, biological and water chemistry variables. Additionally, water levels were monitored and provided to DCCEEW to inform monitoring outcomes (DCCEEW 2025; Chapter 8).

This GHI project aimed to 1) fill critical gaps in the knowledge of groundwater ecosystems in the shallow alluvial aquifers of the Darling Baaka River floodplain and 2) establish baseline conditions to support ongoing monitoring of groundwater health in the region. It has successfully provided:

- Documentation of the extent and condition of subterranean GDEs in the region
- A first ever assessment of the groundwater microbial and invertebrate biodiversity in the region
- Baseline data on groundwater chemistry and groundwater water levels
- Improved groundwater ecosystem sampling methodologies
- Application of the GHI to assess overall groundwater health within the Darling Baaka River catchment

The study has provided the first ever records of stygofauna and has highlighted the significant biodiversity contained within aquifers in the Darling Baaka River region. The groundwater health index identified sites in good, fair and poor condition, but without a clear trend in index values that could be explained by geography or river management. Shallow groundwater in the region ranged from fresh to highly saline, and nitrate and reactive phosphorus concentrations were generally lower than reported elsewhere in groundwater in the MDB. Water levels changed little at most sites over the study period, likely reflecting the high rainfall during the study period. The GHI method provides a valuable addition, shifting groundwater management from the current focus on monitoring water levels and occasional sampling of physico-chemical parameters to a holistic approach that considers groundwater biodiversity and the maintenance of ecosystem function and services. The baseline data from this study will allow for future assessment of change in groundwater health and inform ecological sustainability and natural resource stewardship, while concurrently improving the capacity for the future management of this resource.

Introduction

The Darling Baaka River and its catchment have been subjected to landscape changes, vegetation clearing and the construction of weirs and dams. Combined with extensive extraction of water for agricultural, industrial and domestic uses, this has altered river flow dynamics, resulting in a decline in water quality in many parts of the river. This decline in water quality has caused immense concern for local communities. These complexities and concerns were amplified by significant flooding in January 2023 and a subsequent mass fish death event in the vicinity of Menindee in March 2023.

The NSW Government's response to the mass fish death event in 2023 was undertaken through its emergency management arrangements, activated due to the declared flooding disaster (Special Disaster Grant, Australian Government Reference Number 1034). The NSW Chief Scientist and Engineer's report on the 2023 fish kills at Menindee, published on 29 September 2023 (OCSE 2023), provided an in-depth analysis of the factors contributing to the mass fish deaths in the Darling Baaka River and offered recommendations for improving river management. The Darling Baaka River Health Project ('the project') was established as a long-term river health monitoring program as part of the recovery response to the 2023 flooding disaster. The project is being delivered from August 2023 until June 2025 by DCCEEW Science and Insights Division.

Due to the known connections between groundwater and surface waters across the Murray Darling Basin and the potential impacts that groundwater may have on river water quality and quantity, DCCEEW engaged Macquarie university to investigate the groundwater quality, water levels and ecosystem health of shallow aquifers potentially connected to the river. Groundwater level data were used in the main Darling Baaka project for modelling (see DCCEEW 2025, Chapter 8). This report provides an assessment of groundwater dependent ecosystems (GDEs), specifically the subterranean GDEs, and assesses the overall health of the shallow alluvial aquifers in the lower Darling Baaka River.

GROUNDWATER DEPENDENT ECOSYSTEMS

The mapping, monitoring and protection of Groundwater Dependent Ecosystems (GDEs) has come to the forefront of both Federal and State government policies, with GDEs incorporated in the National Water Initiative (2004), and many water management plans requiring monitoring and protection of these ecosystems. There are several types of GDEs that can be grouped into three broad categories:

- Terrestrial GDEs
- Surface-aquatic GDEs (e.g. rivers, wetlands)
- Subterranean GDEs

Within groundwater, exists unique ecosystems, commonly known as *subterranean GDEs* or *groundwater ecosystems,* which are 100% reliant on groundwater for their existence. The need to understand and sustainably manage these ecosystems is important for their biodiversity value and to maintain the ecosystem services they provide, such as maintaining aquifer flow, water quality and contributions to river flow and health (Griebler et al. 2019). These ecosystems are the focus of this report.

Groundwater ecosystems harbour highly specialised, diverse and complex communities typically consisting of small invertebrates (known as stygofauna), protozoa and microorganisms. These organisms have adapted to the dark, low energy conditions in subterranean environments where concentrations of oxygen and nutrients are typically low. Photosynthesis is absent in the dark environment, so the ecosystem depends on external (surface) sources of carbon and oxygen.

A diverse group of Archaea, Bacteria and Fungi (known generically as microbes) inhabit the groundwater environment. These microbes are fundamental to water chemistry and biogeochemical processes, as they are able to degrade pesticides, organic compounds and nitrates within groundwater. Previous studies in the Murray Darling Basin (MDB) have highlighted the presence of microorganisms with the capacity to degrade nitrates and reduce methane, hydrocarbons, iron and sulfur within groundwater (Korbel et al. 2022). These microbes have the important ecosystem service of maintaining groundwater quality in agricultural areas as well as providing the basis for the food web in these ecosystems.

Most of the larger animals found in alluvial aquifers are highly evolved, obligate groundwater dwelling invertebrates (stygofauna) that are not found in surface environments. They are predominantly crustaceans (Fig 1), however also include oligochaetes (worms), mites and occasionally beetles.

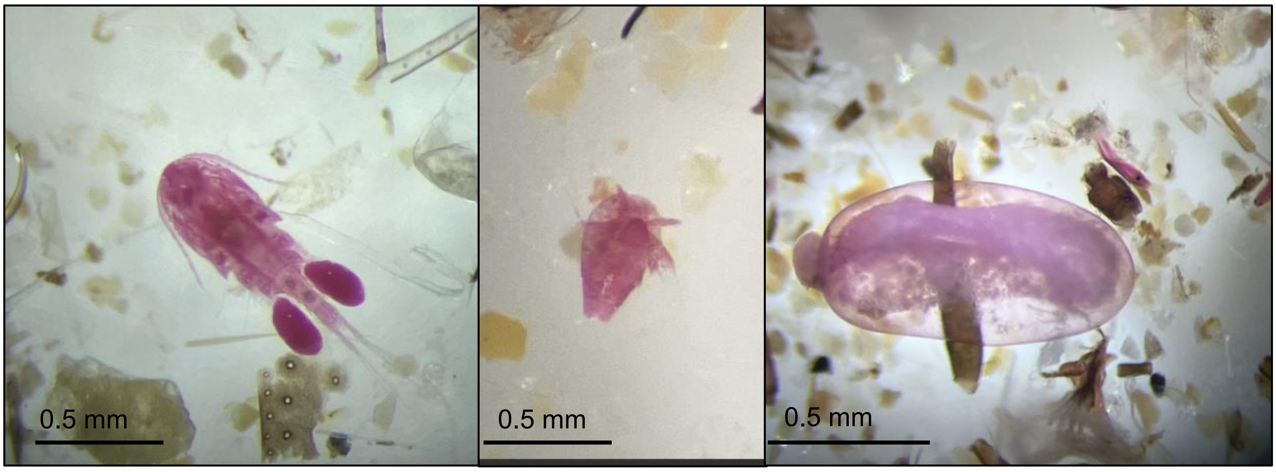

Figure 1: Groundwater copepod, nauplii and ostracod: Photos: J Dabovic, DCCEEW.

The biota of groundwater ecosystems are particularly important for maintaining the quality and quantity of groundwater available for agricultural and potable use. They are able to tolerate and mitigate small changes in environmental conditions (such as water quality), but large changes in conditions will cause changes in biological assemblages, potentially creating communities that are less able to provide ecosystem services. Maintaining the health of groundwater ecosystems and the delivery of ecosystem services is thus critical to meeting the water needs of NSW.

Shallow aquifers are often intimately connected to rivers. Research in the northern Murray Darling Basin provides evidence that these connections result in the exchange of water and biota between the two ecosystems (Korbel et al. 2019). Groundwaters contribute to base flows in rivers, maintaining water holes and providing refugia that can sustain river biota in times of drought (see Shanafield et al. 2024). There is emerging evidence linking groundwater to surface water biogeochemical processes. For example, an influx of nutrients and organic carbon from groundwater may contribute to surface water productivity and stimulate algal growth (Burrows et al. 2020; Brookfield et al. 2021; McDonough et al. 2022).

Abstraction of groundwater can result in lowering the water table, consequently establishing a disconnect between these two ecosystems. This impacts of disrupting connectivity on the biota and water quality in both ecosystems has rarely been studied, however studies have shown that groundwater drawdown has impacted river base-flows within the upper Darling River catchment (Giambastiani et al. 2012; McCallum et al. 2013). Alternatively, floods are also known to impact groundwater ecosystems.

As groundwaters are typically low in nutrients, oxygen and organic matter (Marmonier et al. 2023), large flood events can result in huge influxes of these resources (Dao et al. 2024). The magnitude of hydraulic exchange between surface and groundwaters in times of heavy rains and floods is enhanced (Lasagna et al. 2020), as groundwaters are replenished by infiltrating rainwater from the surface through the vadose zone, or from swollen or over-flowing surface water bodies. Water levels in the aquifer rise and, as a result, there can be an increase in stygoxenes (accidental inhabitants of aquifers) from surface waters. The influx of enriched surface waters can also drastically increase microbial activity and create a 'boom' in the ecosystem. Thus, floods can create a state of 'flux' and disruption to usual biotic diversity and water chemistry within shallow alluvial aquifers.

GROUNDWATER HEALTH INDEX

Groundwater health is the ability of an ecosystem to sustain its ecological function and structure, whilst maintaining ecosystem services (Korbel and Hose 2011). The Groundwater Heath index (GHI) provides a tiered framework to measure groundwater health. The GHI was initially developed for the northern MDB and has since been applied across the southern and central MDB, and has recently been applied in Germany, Italy (Di Lorenzo et al. 2020) and the Philippines (Velasco et al. submitted).

The GHI framework incorporates s indicators reflecting biological diversity, ecosystem structure and function, as well as indicators measuring human-induced stressors. When combined, a holistic view of the system can be provided, which enables changes in health to be monitored through time (Korbel and Hose 2011). The values recorded for each indicator at a site are compared to those expected if the site were in an undisturbed condition. In this way, the framework is conceptually similar to those used for monitoring surface waters (such as AUSRIVAS), which are based on comparing site metrics to a reference condition. Additionally, the framework allows for the incorporation of new indicators as scientific knowledge improves or management priorities require a specific focus (e.g., Di Lorenzo et al. 2020).

APPLICATION OF THE WEIGHTED GHI IN THE MURRAY DARLING BASIN

The weighted GHI framework (Korbel and Hose 2017) builds on the original GHI framework (Korbel and Hose 2011). The framework provide two levels (or Tiers) of assessment based primarily on detail of investigation required and associated cost. Tier 1 is a generic assessment whereas Tier 2 is a catchment-based assessment with MDB specific thresholds and is weighted to take into account the natural variation in groundwater biota due to environmental factors. The framework was extensively trialled in over 80 sites within four catchments of the upper MDB between 2014 and 2018 (Hose and Korbel unpub. data).

This project applies the GHI framework to assess baseline groundwater health in the lower Darling Baaka River. Sites were sampled on two occasions. We acknowledge that this level of sampling may not be sufficient to fully characterise the groundwater biota at a site, and that a minimum of four sampling events is recommended assess stygofauna richness and diversity (Hancock and Boulton 2008) due to high heterogeneity which is typical of shallow aquifers in the Murray Darling Basin and around the world (Marmonier et al. 2023; Boulton et al. 2023). It is also acknowledged that, at the time of sampling, groundwater levels in the region were high and likely reflecting recent flood events.

PROJECT AIMS

The aims of this project were to monitor groundwater quality and ecosystem health in the lower Darling Baaka River, and the Great Darling Anabranch, between Wilcannia and Wentworth. This was achieved by:

- Documenting the microbial activity, invertebrate diversity and condition of subterranean GDEs
- Documenting groundwater quality and groundwater levels in the lower Darling Baaka catchment
- Providing an assessment of groundwater health for sites across the region.

REPORT STRUCTURE

This report is divided into four sections:

1. Methods used to sample groundwater quality and biota within bore sites in the Darling Baaka River system and the application of the GHI framework
2. Results and discussion – an assessment of health of subterranean GDEs in the Darling Baaka River system using the Groundwater Health Index (GHI) (Korbel and Hose 2011, 2017). This includes assessing water quality and groundwater stressors, stygofauna diversity as well as an investigation into environmental variables which may be influencing biota.
3. Future outlook
4. Conclusions.

Methods

PROJECT STUDY AREA

The project was undertaken in the Darling Baaka River system between Wilcannia and Wentworth (Figure 2). The region is semi-arid region. and hosts the rural townships Wilcannia, Menindee and Pooncarie. Grazing is the dominant landuse. The sediments on the lower Darling Baaka River and floodplains are from the quaternary period and consist of sands, silts and clays. The alluvium is the Menindee formation and overlying Coonambidgal formation (DPIE 2019).

Surface water quality and flow in the lower Darling Baaka River system is heavily influenced by river regulation. The alluvial aquifers and their connections to surface waters in the region are not well known by western science, and the impacts of river regulation on these systems is even less well understood. However, the local Aboriginal Barkandji People, have a deep connection to the Darling Baaka River over tens of thousands of years. This intimate knowledge of the system and its dynamics has indicated areas of likely groundwater surface water connectivity, knowledge which has been shared with Macquarie University scientists for the purpose of the Project. Additionally, modelling undertaken as part of the broader DCCEEW project indicates that the areas of the lower Darling Baaka River and its alluvium below Weir 32 and on the Great Darling Anabranch, gains water from the connected shallow aquifers (DCCEEW 2025). Thus, the Darling Baaka alluvium is thought to be highly connected, hydrologically, to the lower Darling Baaka River.

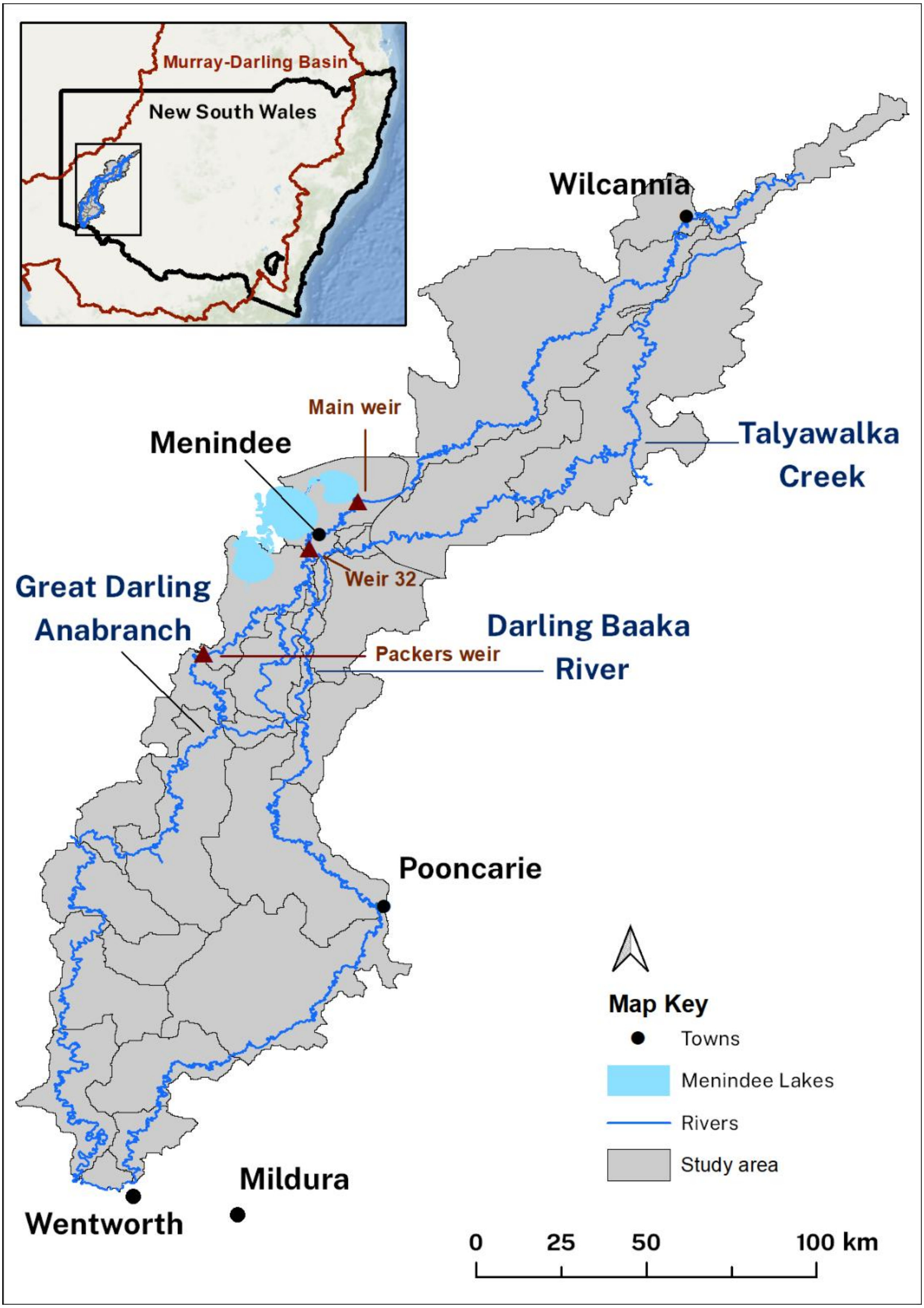

Figure 2: Study area of the Darling Baaka River Health Project (source: DCCEEW 2025)

STUDY SITES

The program was the first to survey groundwater ecosystems in the lower Darling Baaka River system. Samples were collected from 18 sites across 11 RCI sub catchment (Figure 3). Each site was sampled twice, first in June 2024 and again in November 2024. Site numbers refer to WaterNSW groundwater bore numbers and all bores were accessed under agreement with WaterNSW.

All bores were constructed from PVC pipe and were limited to those <40 m deep. A desktop analysis identified a suite of bores potentially suitable for sampling. There was relatively few suitable monitoring bores located within 'natural' areas such as National Parks, or other areas dominated by native vegetation that could serve as reference sites. Therefore, reference conditions and GHI thresholds were the same as those used elsewhere in the MDB (Korbel and Hose 2017).

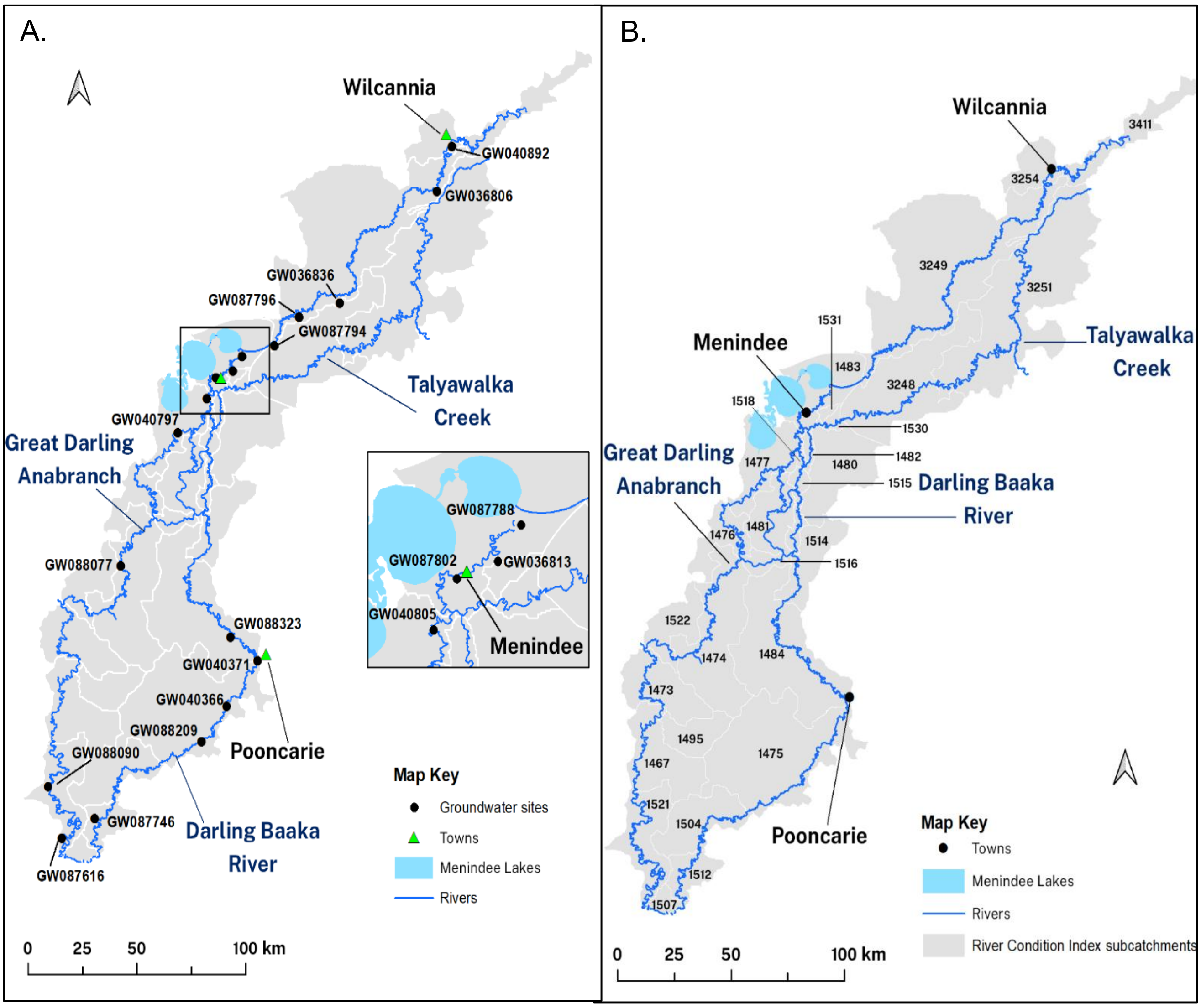

Figure 3: Location of A) sampling sites B) RCI subcatchments in the lower Darling-Baaka River catchment. (Source: DCCEEW 2025).

SAMPLING METHODS

BORE PURGING

Prior to sampling, the standing water level (SWL) was measured using an electronic dip meter. Pump tubing, was sterilised internally with sodium hypochlorite and rinsed with distilled water to eliminate cross-contamination between sites (Dickie et al. 2018). The pump tubing was sterilised externally using ethanol wipes as it was inserted into the groundwater bore. Bores were purged by pumping a minimum of three bore volumes of water or until the bore went dry using a motorised high-flow inertia pump (Waterra Power pump II, Waterra, Ontario, Canada) (Korbel et al. 2017). The purging process ensured water quality and microbial samples were representative of the surrounding alluvial aquifer and not the stagnant water residing in the bore (Korbel et al. 2017).

Figure 4: Typical groundwater sampling setup. Site 28 on the Great Darling Anabrach (Source: G Hose 2025)

GROUNDWATER CHEMICAL, PHYSICAL AND SITE PARAMETERS

Site characteristics were recorded at each site. The metrics recorded were sediment type (Wentworth 1923), canopy tree cover (%), dominant land use in the surrounding 5 km and evidence of irrigation. Other factors including distance to river and vegetation types were noted.

Water quality parameters were measured before and after purging. Electrical conductivity (EC), pH, temperature (°C) and dissolved oxygen (DO) in the groundwater were measured using a hand-held water quality probe (YSI, Yellow Springs, USA). Groundwater samples were collected and stored in accordance with NATA, and Australian and US standards. Water samples for chemical analysis were collected in clean, sterile containers and stored on ice/fridge.

Samples were analysed for total nitrogen (TN), total phosphorus (TP), nitrate (NO_3), ammonia (NH_4), sulphate (SO_4), dissolved organic carbon (DOC), total and dissolved ferrous iron (Fe^{2+}) and metals were analysed by Australian Laboratory Services (NATA accredited laboratory). Pesticides were analysed by Environment Protection Science Branch in the Department of Climate Change, Energy, the Environment and Water.

Groundwater levels were monitored continuously in study bores using Aquaread Leveline® loggers that were deployed on the first site visit and data were retrieved on the second site visit. Water level data were standardised using atmospheric pressure following the manufacturer's instructions. Water level data were supplemented with spot measurements made on each site visit using a level meter. The water level change over time was determined as the maximum and minimum values recorded by the logger over the study period. Where logger data were not available, the difference between spot measurements was used to determine the water level change over time.

STYGOFAUNA SAMPLING AND ANALYSIS

Stygofauna were collected by sieving the water extracted from the bore through a 63-µm mesh sieve. Samples were collected in two stages. In the first stage, the water pumped to purge the bore (10- 60L depending on bore depth) was sieved, and the contents of the sieve preserved in 100% ethanol. Following purging, an additional 90-L of groundwater was pumped, sieved and preserved separately in 100% ethanol. In some cases, the full 90-L post purge volume could not be collected because of the extremely slow recharge rate of the aquifer being sampled.

Prior to identification, rose bengal was added to all samples to aid the identification process. The removal of stygofauna from sediment-rich samples was assisted by flotation using colloidal silica (Ludox® HS 40 solution)(see Korbel et al. 2024). Stygofauna samples were identified at Macquarie University using appropriate taxonomic keys (e.g., Serov 2002).

MICROBIAL ACTIVITY

The cotton strip assay method was used to measure of microbial activity in the groundwater. A sterile 4 cm x 20 cm cotton strip was deployed in each bore after sampling was completed (Lategan et al. 2010). The cotton strip was enclosed in a plastic mesh and left suspended in the water column of a bore for six-weeks. Three cotton strips were sealed in sterile 18°C water for the same six-week period to serve as controls.

Cotton strips were air dried and treated by removing 3 mm of threads from each side (to remove edge effect). The cotton strips (including controls) were then cut into three section, each 5 cm long by 2.5 cm wide. Tensile strength of each section (top, middle and bottom) was measured with a pneumatic tensiometer Universal Testing Machine (UTM Instron 6022 10-kN load 18 frame) with 2.5 cm^2 flat plate grips (Lategan et al., 2010). Maximum load (N) at breaking was recorded for each triplicate of the cotton strip. Triplicate measurements are taken as groundwater depth fluctuations may result in the top of the cotton strip not being submerged for the entire 6-week period, resulting in biased microbial activity measurements.

The loss of strength was determined as difference in the measured strength of the cotton strip after deployment compared to the controls, expressed as a proportion of the control strength.

TIER 1 GHI ASSESSMENT

Tier 1 of the GHI assessment assesses groundwater ecosystem health using generic indicators (i.e., indicators based on expected, general attributes of an undisturbed aquifer, Korbel and Hose 2011), allowing the discrimination of 'impacted' from 'non-impacted' sites. However, it does not provide any mechanisms to distinguish between levels of health, nor incorporate factors that may influence biotic distribution, and thus perceived 'health' of the site. Tier 1 is intentionally conservative, meaning that sites that fail this Tier should progress to Tier 2 assessment which may indicate a lower level of impact than the Tier 1 assessment.

The assessment in this study uses Tier 1 indicators as shown in Table 1. These indicators do not vary from previously published work (Korbel and Hose 2017). GHI Tier 1 assessments were determined separately for each site in June 2024 and November 2024. The overall site assessment was determined as the worst-case assessment for the site on the two sampling occasions.

Table 1: Tier 1 indicators (adapted from Korbel and Hose 2011;2017)

Indicator Type	Indicator	Tier 1 'Pass' threshold
Functional	Dissolved Organic Carbon	< 4 mg/L
Organisational	Total abundance of crustaceans	>0%
	Total abundance of oligochaetes	<10%
	Stygoxene* abundance	Absent (0)
Stressor	Pesticides	Absent (detection at 2 μg/L)
	Nitrate	<2 mg/L
	Total phosphorus	<0.5 mg/L

*Stygoxene = non-groundwater specialist taxa.

TIER 2 GHI ASSESSMENT

Tier 2 of the GHI assessment provides a breakdown of the level of deviation from 'reference-like' groundwater health conditions. Originally, health benchmarks for the GHI were calculated using data from reference sites in shallow alluvial aquifers of the Gwydir River catchment in the northern MDB (Korbel and Hose 2011, 2017). These indicators were then slightly modified for the southern Murray Darling Basin catchments (Hose and Korbel unpubl.). The Tier 2 indicators used for this project are presented in Table 2, with modifications presented below.

the Tier 2 indicators used in the southern MDB (Table 2) and were considered mostly applicable for the assessment of the lower Darling Baaka River system. However, due to the unique conditions of this region slight modifications were made. Given the overall low abundance of stygofauna collected in all samples, there was a strong correlation between stygofauna abundance and stygofauna richness, particularly because many samples had only 1 or 2 individuals. Accordingly, the indicator based on stygofauna abundance was not included while stygofauna richness was retained.

Additional indicators that were applied in this study include (see Table 2):

- Water level decline between sampling events to indicate stress on the ecosystem (based data from the small number of reference sites in this study)
- Habitat suitability: the following characteristics were considered not suitable for stygofauna (Hancock and Boulton 2008):
    1. Dominance of clays, due to the small pore sizes associated with clay sediments,

2. Electrical conductivity (>5000 µS/cm),
3. Absence or low abundance of trees within 5 km of the bore site
4. Dissolved oxygen (DO) (<3 mg/L)
5. Total organic carbon (TOC) (>2%) concentrations.

The number of attributes that failed these conditions was summed and informed the degree of weighting applied to organisational and functional indicators as per Korbel and Hose 2017). GHI Tier 2 assessments were determined separately for each site in June 2024 and November 2024. As this was the first study of groundwater ecosystems in the lower Darling Baaka, baseline conditions for this catchment are not established. We have taken the most conservative approach to assessing groundwater health, being that the overall site assessment was determined as the worst-case assessment for the site on the two sampling occasions.

Table 2: GHI benchmarks indicating reference conditions for Tier 2 assessment

Indicator type	Indices	Reference Benchmark	
		GHI*	New
Functional	Stygofauna total abundance	25 ± 8	Not included in this study.
	Cotton strip assay	<25% loss in tensile strength	<30% loss
	Dissolved organic carbon	<3.5 mg/L	
Organisational	Stygofauna richness	0-5	
	Stygoxene abundance	Presence (<10%)	
	Crustacean abundance	>50%	>0%
	Oligochaete abundance	<10%	
Stressors	Nitrate	<2 mg/L	
	Reactive phosphorus	<0.5 mg/L	
	Presence of irrigation infrastructure	Present	
	Water level decline between sampling events		Change <0.5 m
Habitat suitability	Clay soils, high EC, low tree abundance, TOC and low DO		Weighting to those sites that did not have suitable habitat

*Existing published benchmarks as per Korbel and Hose (2011, 2017)

Results and discussion

WATER QUALITY

Total nitrogen concentrations in groundwater ranged from below detection limit (0.1 mg/L) to 3.8 mg/L (Figure 5). A number of sites exceeded the water quality guideline value for total nitrogen (1 mg/L) for the protection of aquatic ecosystems (lowland rivers of southern central Australia, ANZG 2018) and this was more frequent in sites at the lower end of the catchment and anabranch.

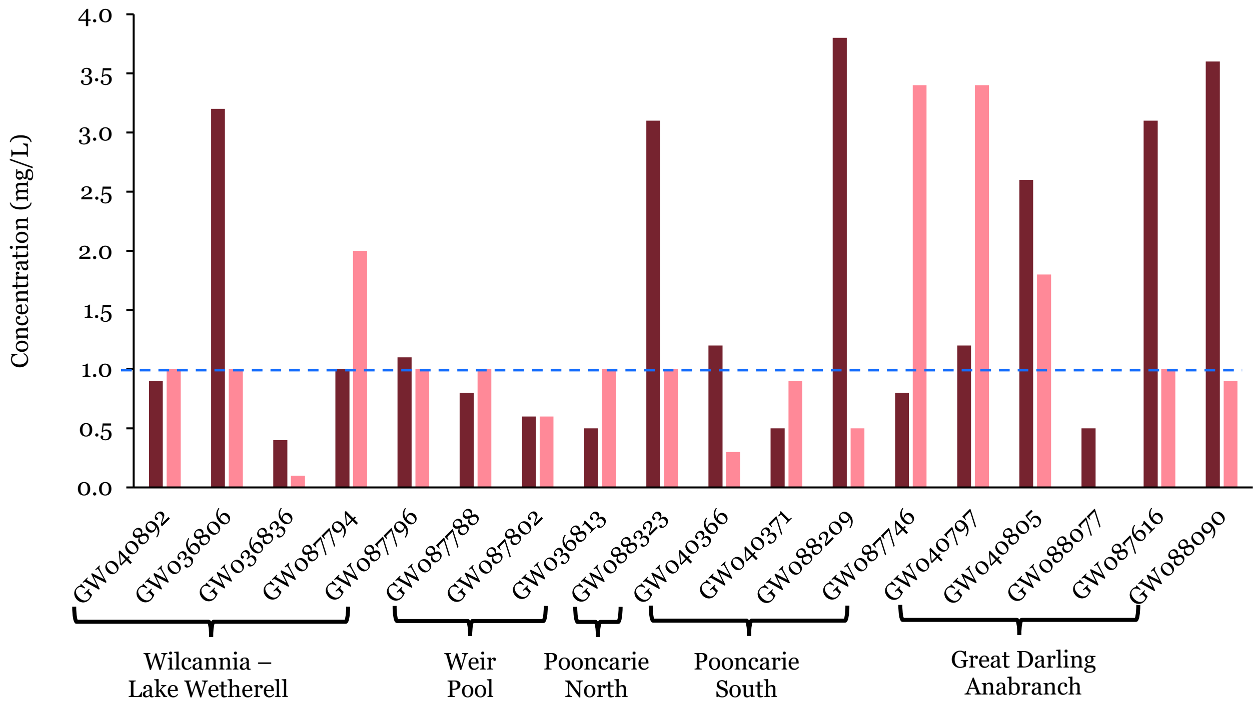

Figure 5: Total nitrogen (as nitrogen) concentration in groundwater bores on each sampling occasion, per site. Dark shaded bars= June 2024, light shaded bars = November 2024. Dotted line represents ANZG (2018) surface water upper limit guideline value (1 mg/L total nitrogen (as Nitrogen)).

Concentrations of nitrate were relatively low, ranging from below detection limit (0.01 mg/L) to 0.6 mg/L (Figure 6) and mostly below the relevant ANZG (2018) surface water quality guideline value (0.1 mg NOx-N/L) (here using the value for inland rivers in South central Australia — low rainfall area). The low nitrate concentrations may be attributed to the land use type in the Darling Baaka River system. The majority of sites were under dryland grazing and dominated by saltbush and bluebush understory with no pasture improvement. There were however some sites that exceeded guideline values, with the highest recorded concentration of nitrate (0.6 mg/L) noted in the Wilcannia to Wetherell zone.

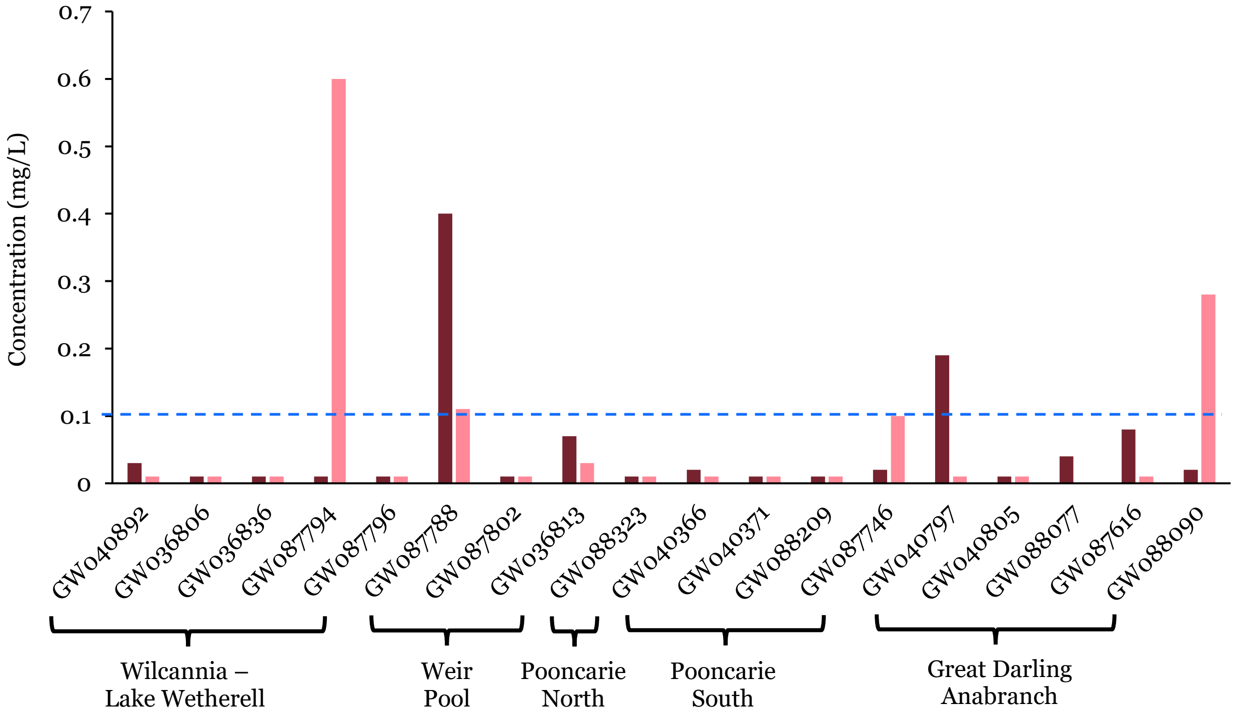

Figure 6: Nitrate (as nitrogen) concentration in groundwater bores on each sampling occasion, per site. Dark shaded bars= June 2024, light shaded bars = November 2024. ANZG (2018) surface water upper limit guideline values (0.1 mg/L N as NOx).

Total phosphorus concentrations ranged from 0.14 to 5.89 mg/L (Figure 7). Most samples exceeded the guideline values for protection of aquatic ecosystems (lowland rivers of southern central Australia, ANZG 2018) for total phosphorus (Figure 7). While these guidelines do not apply to groundwaters, it is evident that groundwaters in the region had high nutrient concentrations. The median total phosphorus concentration across the study area was 0.2 mg/L, with very high concentrations (>5 mg/L) present near Lake Wetherell (site GW036813) and in the lower Darling Baaka River downstream of Pooncarie (site GW0088209).

Reactive phosphorus concentrations ranged from below detection limit to 1.13 mg/L, many of which exceeded the surface water quality guideline value (Figure 8). Sites GW040797 in the upper Great Darling Anabranch, and GW088209 and GW087746 at Pooncarie South were all above the GHI threshold concentration of 0.5 mg/L (Figure 8). The generally low reactive phosphorus concentrations are most likely due to the dryland grazing land use, and the limited use of agricultural fertilisers in the area.

High levels of phosphorus and nitrogen in groundwater are in many places higher than concentrations recorded in nearby River sites (see DCCEEW 2025). This is of particular concern in those areas where groundwater modelling (see DCCEEW 2025) indicates that the groundwater is contributing to river flows.

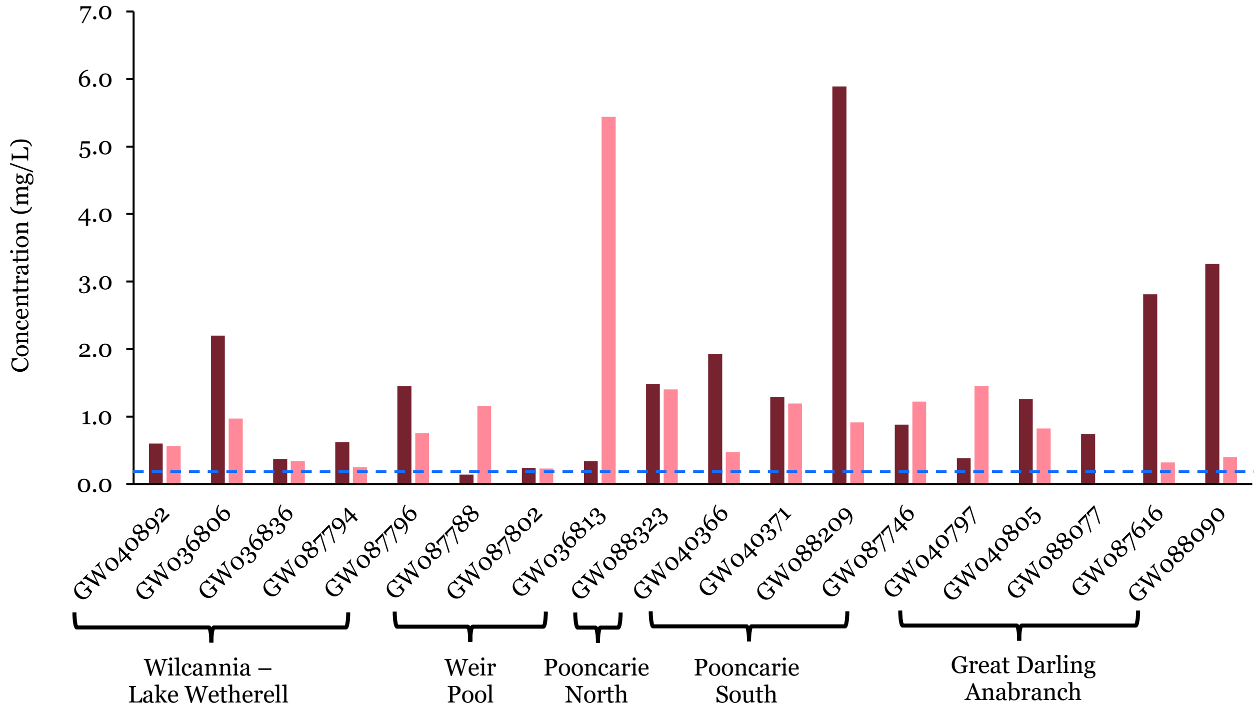

Figure 7: Total phosphorus concentration in groundwater bores on each sampling occasion, per site. Dark shaded bars= June 2024, light shaded bars = November 2024. Dotted line represents ANZG (2018) surface water upper limit guideline values (0.1 mg/L total phosphorus).

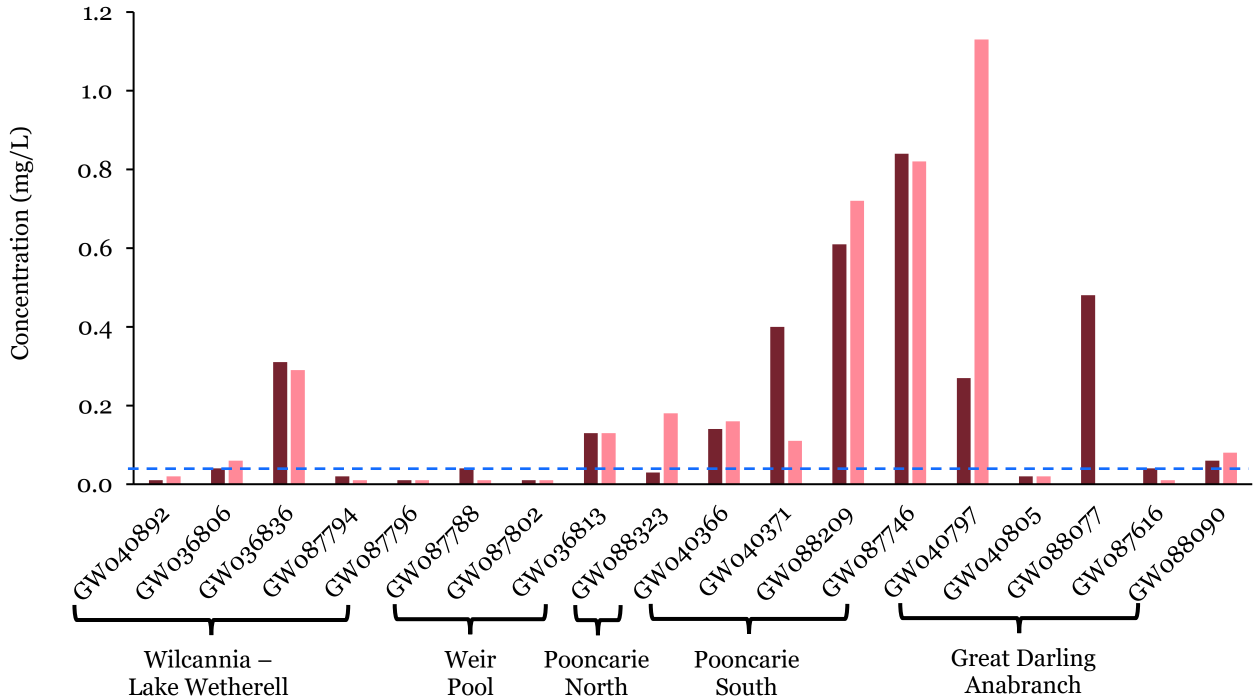

Figure 8: Reactive phosphorus concentration in groundwater bores on each sampling occasion, per site. Dark shaded bars = June 2024, light shaded bars = November 2024. Dotted line represents ANZG (2018) surface water upper limit guideline values (0.04 mg/L reactive phosphorus). Values below detection limit are presented as detection limit (0.01 mg/L).

Groundwater ecosystems typically have low carbon, nutrient and oxygen concentrations due to their relative isolation from the surface, and lack of light means there are no photosynthetic primary producers (Marmonier et al. 2023). The groundwater in the region had generally high concentrations of dissolved organic carbon, ranging from below detection limit (1 mg/L) to 53 mg/L (Figure 9), which may reflect the effects of aquifer recharge following the floods in the region prior to sampling (e.g.., Reiss et al. 2019). Flood events recharge aquifers, resulting in inputs of water that transports nutrients, carbon and oxygen into the shallow aquifer ecosystems. Due to the low biomass of fauna within these ecosystems, it is likely that these nutrients and carbon would take some time (potentially years) to be depleted after major flooding events. Values above 4 mg/L are considered high for alluvial aquifers in the Murray Darling Basin (Korbel and Hose 2017).

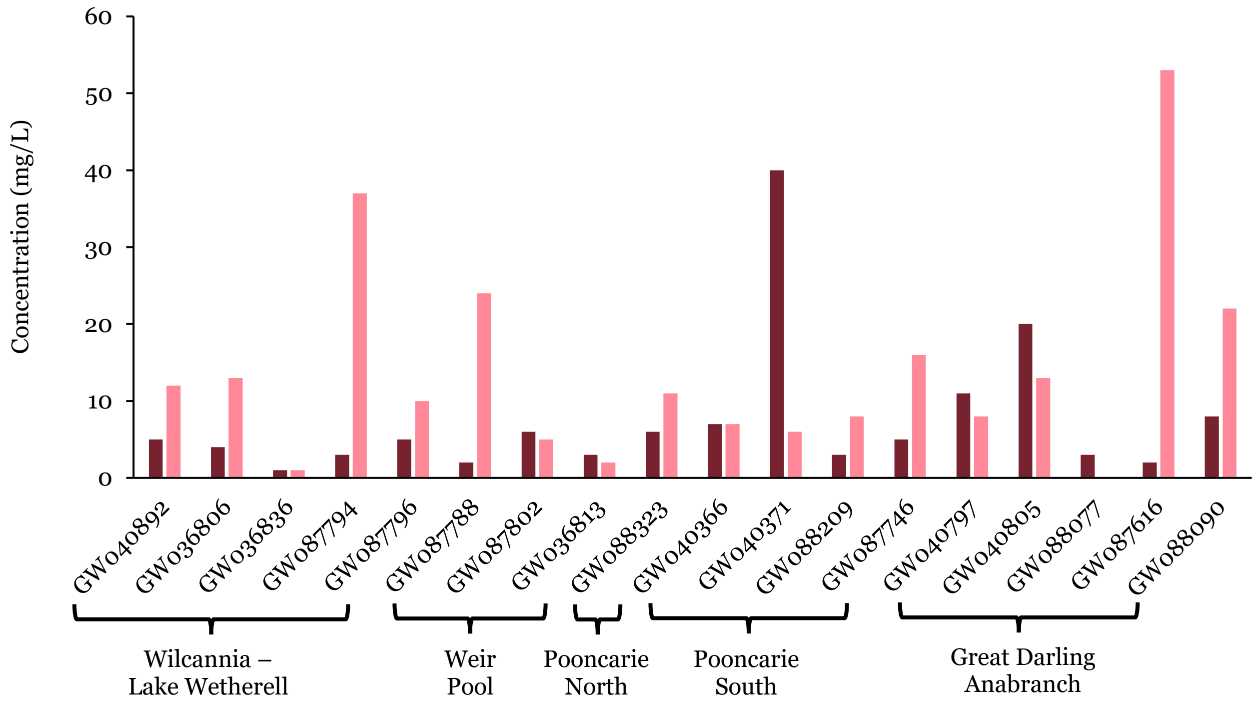

Figure 9: Dissolved organic carbon concentration recorded in groundwater bores on each sampling occasion, per site. Dark shaded bars = June 2024, light shaded bars = November 2024.

Electrical conductivity through the study area ranged from 625 – 55,484 µS/cm (Figure 10). This represents fresh to highly saline waters. The highest salinity was recorded on the lower Great Darling Anabranch and may be due to a naturally high salinity region of the aquifer. Similar high salinities have been reported elsewhere in the MDB (Korbel and Hose 2017) and may reflect the natural increasing salinity gradient from east to west across the MDB (Nelson et al. 2024).

The concentrations of nutrients, metals, pesticides and physico-chemical variables measured in groundwater are presented in Appendix 1. For the GHI, nutrients, pesticides and change in groundwater level are the most useful indicators of stress.

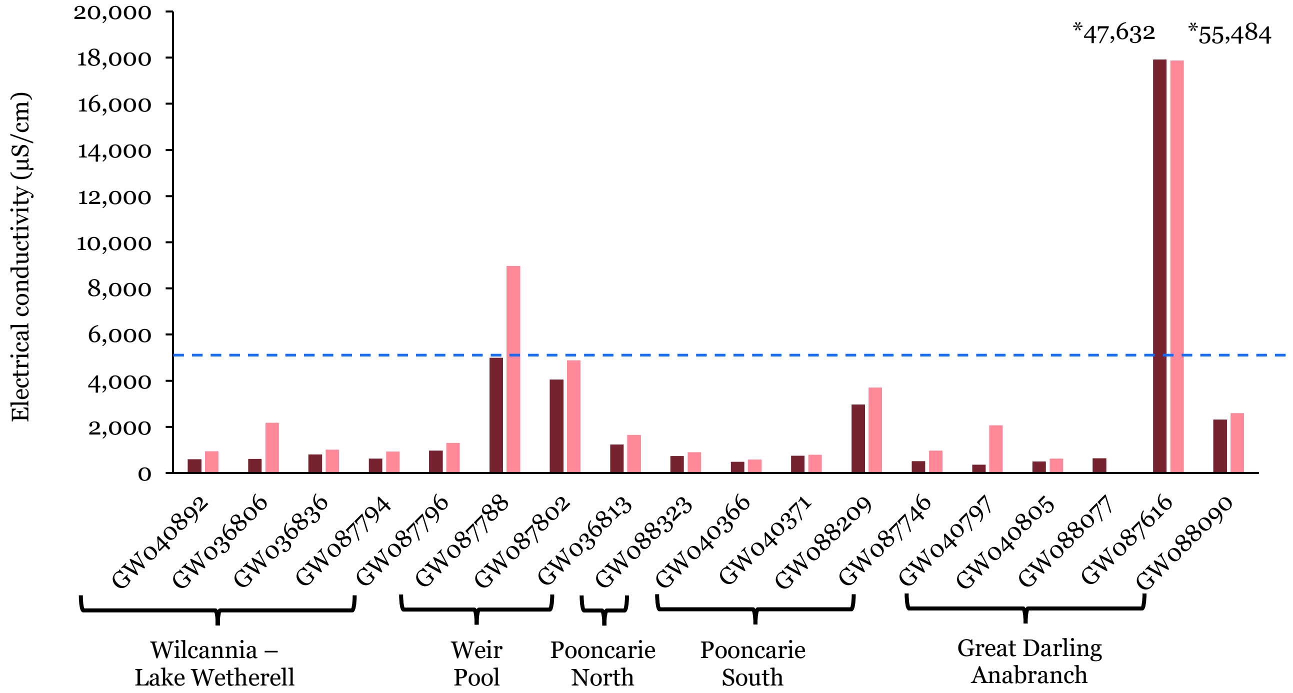

Figure 10: Electrical conductivity concentration in groundwater bores on each sampling occasion, per site Dark shaded bars = June 2024, light shaded bars = November 2024. Dotted line represents ANZG (2018) surface water upper limit guideline values (upper limit 5000 µS/cm). *Bars truncated and actual values shown.

GROUNDWATER LEVELS

Groundwater loggers were deployed in all bores (either Macquarie University or WaterNSW owned loggers) to understand the variability of groundwater levels during the project timeframe (See Figure 2 for site locations). These data were used to inform the groundwater model undertaken by the DCCEEW Darling Baaka River project modelling team and was also used to determine changes in the groundwater level as an impact stressor for the GHI tier 2 assessment.

Water levels were relatively stable across the GHI sites, and changes were less than 0.5 m from the June to November sampling (Figures 11,12). The exception was bore GW04805 in which the groundwater water level change was above the stress indicator with a 0.69 m change.

In the lower Darling Baaka River sites (Figure 11), groundwater levels ranged between 5 and 15.5 m below ground level (BGL). Groundwater levels generally decreased going down river. However, GW087796 (located in the Wilcannia to Lake Wetherell zone) was 3 m shallower than the other sites in this region, which may warrant further investigation.

The groundwater levels on the Great Darling Anabranch ranged from 3 to 8 m (BGL) (Figure 4). These groundwater levels were similar to those downstream of Weir 32. This shallower groundwater is located in the region where DCCEEW modellers indicate groundwater is discharging into the river. Groundwater levels were relatively stable over time (Figure 4).

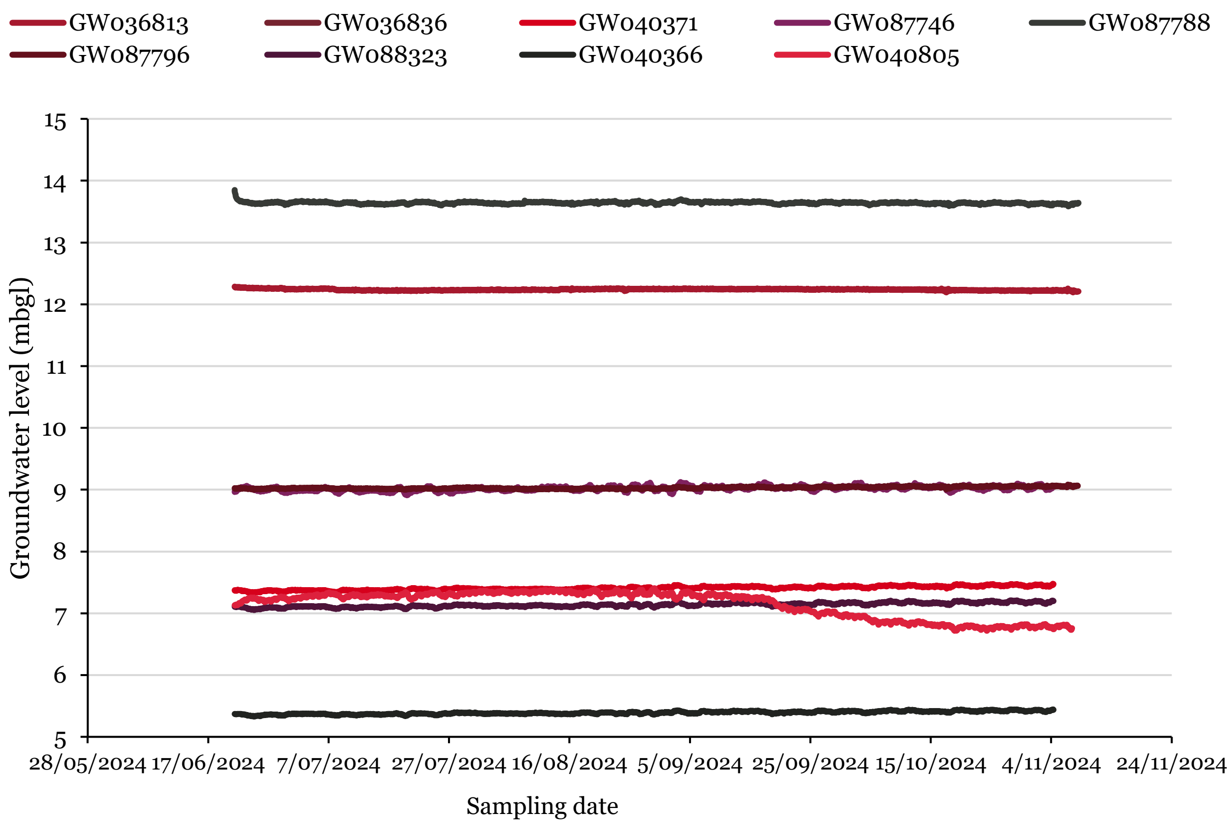

Figure 11. Groundwater levels at the lower Darling Baaka River sites. Sites ordered north to south along the river.

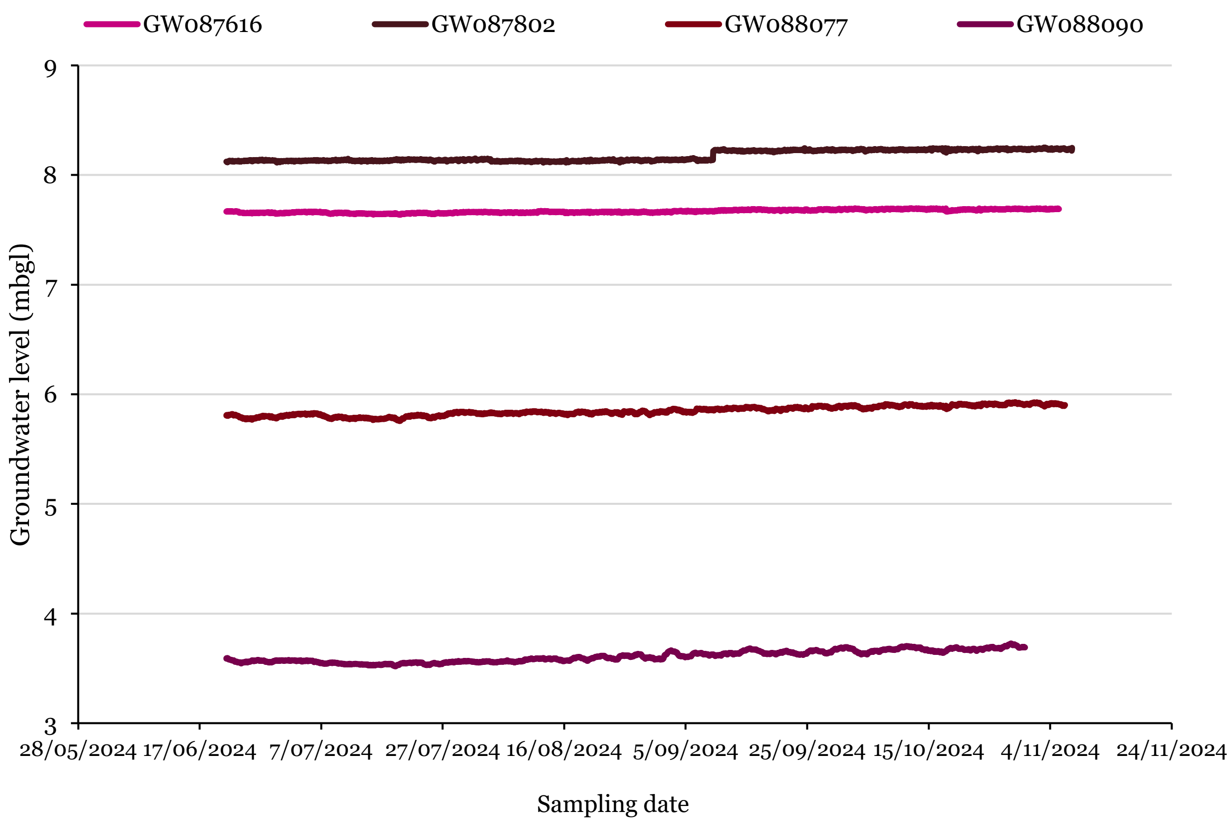

Figure 4. Groundwater levels at the Great Darling Anabranch River sites. Sites ordered north to south along the river.

ENVIRONMENTAL HABITAT INDICATORS

Electrical conductivity (EC, µS/cm), tree cover, sediment type, dissolved oxygen (DO, mg/L) and total organic carbon (%TOC) concentration are considered important for stygofauna habitat requirements. Dissolved organic carbon was used as a functional indicator in the GHI with a benchmark of 4 mg/L.

All sites except GW088323 had EC concentrations below 10,000 µS/cm (Appendix 1). Several sites had very low EC concentrations (<2200 µS/cm, ANZG, 2018). Other sites (GW087802, GW087788, GW088209 and GW088090) had electrical conductivity between 2,200 and 7,000 µS/cm, which may not be suitable habitat for stygofauna diversity. It is likely that GW08823 that had EC >55, 000 µS/cm is not suitable for most stygofauna taxa.

Tree abundance within a 5 km radius of each sampling bore was assigned a category (0 = no trees, 1 = 25 trees, 2 = 50 trees, 3 = 75 trees, 4 = >100 trees). A site with > 50 trees was considered good habitat. Four sites (GW040797, GW040892, GW087616 and GW088323) had less than 50 trees present within the 5 km radius. Two of the sites also had high EC (GW088323 and GW040371) and one site had clay sediments (GW040892), which are both may be limiting for stygofauna.

Dissolved oxygen was low with the exception of GW040371, GW040892, GW087746, GW087788 and GW087794 (Figure 13). Total organic carbon content of the sediments extracted from the bores was variable across the lower Darling Baaka River system, with some sites containing highly organic sediments (Figure 14) containing up to around 80% organic matter. The organic content of the sediments was typically higher in June 2024 than November 2024, which may reflect inputs of organic matter to groundwaters from the floods preceding the June 2024 sampling. There did not appear to be a strong correlation between sediment organic matter content (Figure 14) and dissolved organic carbon concentrations in the groundwater (Figure 9). The dissolved organic carbon of the groundwater was very high across all sites except GW036836 (Appendix 1). This high DOC concentrations were likely due to flooding across the lower Darling Baaka floodplain that resulted in inputs of carbon to bores and the groundwater, which may have been subsequently broken down by microbial communities giving rise to high DOC concentrations.

The sediment type also impacts the presence of stygofauna at each site. The movement of stygofauna as well as water within aquifers depends on size of the interstitial spaces. Substrates consisting mostly of clays are known to contain minimal stygofauna (Korbel and Hose 2017). All bores in the regions contained a mixture of clays and fine sands. There were numerous bores which had very high clay content. These bores were considered as less likely to contain stygofauna and were weighted accordingly within the Tier 2 GHI assessment.

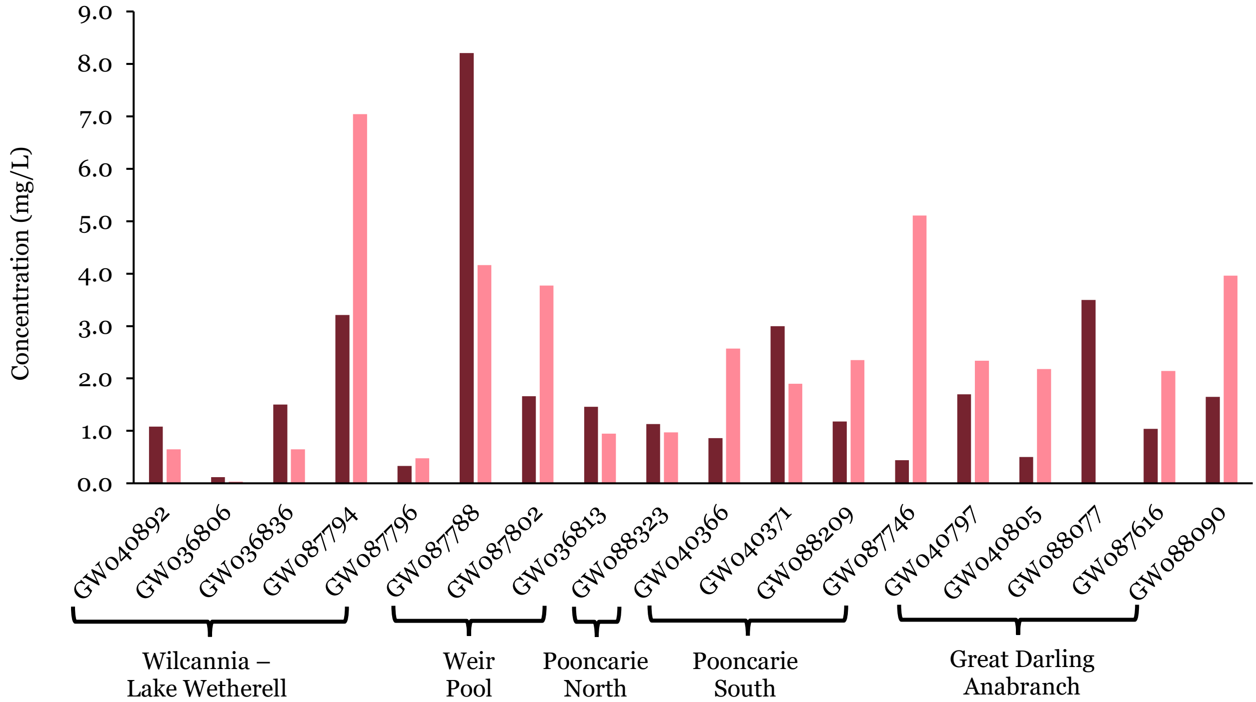

Figure 5 Dissolved oxygen concentration in groundwater bores on each sampling occasion, per site. Dark shaded bars = June 2024, light shaded bars = November 2024.

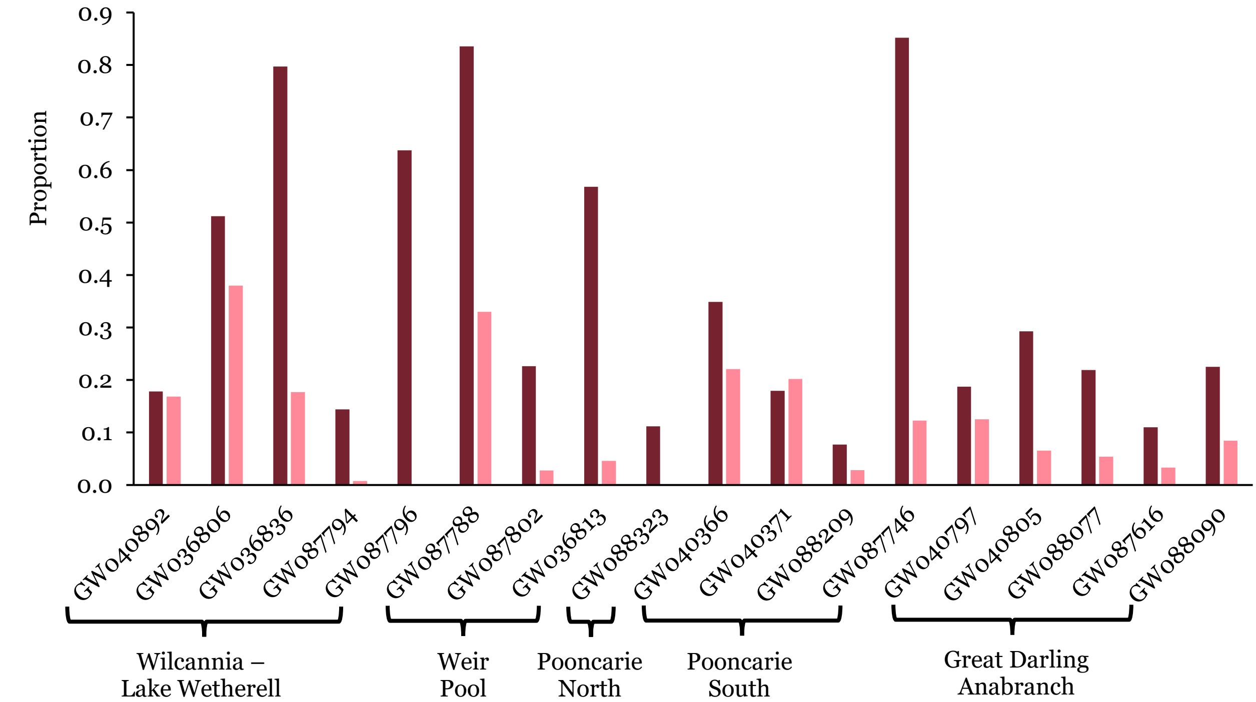

Figure 6 Proportion of total organic carbon (TOC) in sediment determined by loss on ignition. Dark shaded bars= June 2024, light shaded bars = November 2024.

STYGOFAUNA RICHNESS AND ABUNDANCE

Stygofauna were sampled on two occasions in this study area. These bores had never been sampled for stygofauna before. It was evident during sampling that the bores may not have been developed (previously pumped) at the time of drilling due to the large amount of sediment that was removed during purge and post purge sampling in the bores.

All bores sampled in the June 2024 sampling had stygofauna present except for Bore GW087746 (Table 3). Stygofauna taxa recorded were Ostracoda, Copepoda (Harpacticoida and Cyclopoida), Syncarida (Bathynellidae), Rotifera, Tardigrada (water bears), Nematoda (round worms), Acarina (mites), and Oligochaeta (segmented worms).

Unlike the June 2024 sampling, the majority of samples collected in November 2024 did not contain stygofauna (Table 3) and those that did only had a small number of mites and oligochaetes. The lack of individuals present in the November sampling does not mean that they are not present in the surrounding aquifer. The high abundances recorded from the June sampling are likely to be indicative of the accumulation of individuals breeding and living within the bores over a long period, as the bores had not been sampled or purged previously. Low abundances of taxa within this region may also be related to the dominance of clays within the aquifer.

GW088077 (on the Great Darling Anabranch) had the highest taxa richness (12 taxa) and the second highest abundance (260 individuals -combined purge and post purge samples) among all bores samples. GW036836, on the Lower Darling River, located between Wilcannia and Menindee, had the highest total abundance with 653 individuals (combined purge and post purge samples) however these taxa were oligochaetes (Table 3). This site also had mites and oligochaetes present in the November 2024 sampling.

The most significant sites in the lower Darling Baaka in terms of stygofauna were: GW088077 and GW040797 (Great Darling Anabranch zone), GW040892, GW036836, GW036806 (Wilcannia to Lake Wetherell zone) and GW087802 (the Menindee weir pool zone). All of these sites had ostracods, copepods and syncarids present. These taxa are common in groundwater ecosystems in Australia (Hose et al. 2015a,b). The site GW088077, on the Great Darling Anabranch, recorded the highest richness of 12, and had relatively high abundances of stygofauna present.

Several samples contained a relatively large number of taxa commonly found in surface waters, such as cladocerans and Chironomidae. Interestingly, a riffle beetle (Coleoptera: Psephenidae) was found in bore GW08077. These taxa were mostly present in the June samples. They are unlikely to be permanent inhabitants of groundwater, and likely reflect taxa that have entered the bores, during flooding when bores were inundated prior to sampling.

The crustacean specimens collected exhibited attributes expected of groundwater-adapted fauna (lack of eyes and pigment). These taxa are likely to be new, undescribed species given that there have been no previous stygofauna collections being sampled in this area of the Murray Darling Basin. These taxa were not present in the November sampling. Environmental DNA (eDNA) samples are yet to be analysed and when done will provide further evidence of the diversity and distribution of stygofauna.

MICROBIAL ACTIVITY

Microbial activity, as indicated by cotton strip strength loss, was relatively high throughout the region which is indicated by the very high strength loss on most strips. In many cases the strips were largely decayed and could be easily torn by hand. In such cases, a nominal score of 100% strength loss was applied. The relative strength loss of the cotton strips is shown in Figure 15. Both cotton strips deployed in well GW087616 had tensile strength greater than the control, indicating cementation had occurred. A number of cotton strips could not be retrieved, particularly in November because of flooding and site inaccessibility.

The threshold for cotton strip strength loss for the GHI assessment was set at 30%. The period of sampling was preceded by floods and high rainfall. These factors are known to increase microbial activity within groundwaters (Gowrisankar et al. 2017, Reiss et al. 2019). Microbes play important biogeochemical processes in aquatic ecosystems, and in groundwaters are known to play roles in carbon, nutrient and oxygen cycling. Thus, understanding the impacts of wet-weather events on these communities is necessary to improve our knowledge of groundwater quality.

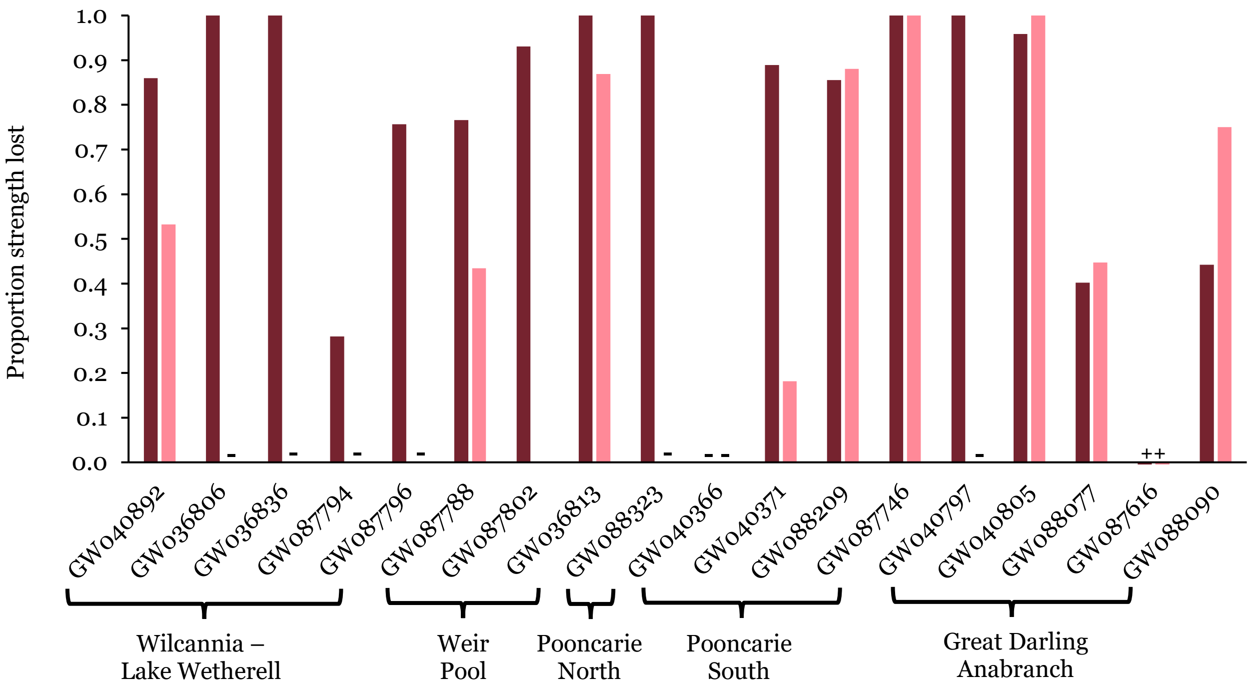

Figure 7. Proportion of tensile strength of cotton strips lost following deployment in groundwater in the Darling Baaka R catchment. + indicates strength of test strips >100% of controls reflecting cementation. - indicates sample unable to be retrieved. Dark shaded bars= June 2024, light shaded bars = November 2024.

Table 3 Stygofauna species richness and abundance for the June and November sampling dates.

Sample and site info			Jun-24		Nov-24	
Site	Litres Pumped	Purge/post	Taxa richness	Abundance	Taxa richness	Abundance
40892	40	Purge	5	7	0	0
40892	90	Post	4	4	0	0
36806	40	Purge	2	4	1	1
36806	90	Post	0	0	0	0
36836	90	Purge	1	378	1	83
36836	90	Post	4	275	4	31
87796	30	Purge	3	6	0	0
87796	55	Post	2	9	0	0
87794	35	Purge	2	4	2	4
87794	10	Post	1	5	0	0
87788	25	Purge	1	7	2	2
87788	20	Post	0	0	2	4
36813	90	Purge	1	1	2	3
36813	80	Post	0	0	0	0
40805	60	Purge	1	2	0	0
40805	90	Post	4	9	0	0
88323	50	Purge	1	5	0	0
88323	30	Post	0	0	0	0
40371	30	Purge	1	1	0	0
40371	150	Post	3	6	0	0
40366	40	Purge	0	0	1	1
40366	90	Post	1	1	0	0
88209	60	Purge	3	5	0	0
88209	150	Post	0	0	0	0
87746	30	Purge	0	0	0	0
87746	180	Post	0	0	0	0
87802	30	Purge	5	40	1	4
87802	90	Post	3	5	0	0
40797	30	Purge	7	18	0	0
40797	5	Post	0	0	2	3
88077	40	Purge	12	139	0	0
88077	150	Post	11	131	0	0
88090	30	Purge	4	10	0	0
88090	10	Post	1	2	0	0
87616	20	Purge	1	4	0	0
87616	20	Post	1	7	0	0

GROUNDWATER HEALTH INDEX ASSESSMENT

TIER 1 ASSESSMENT RESULTS

Our results indicated that groundwaters in the lower Darling-Baaka catchment have, to varying degrees, impaired ecosystem health (Table 4, Figure 16). Five sites passed the Tier 1 assessment on at least one occasion (Appendix 2). However, using our conservative approach, in which the worst-case of the June and November assessments were used to indicate health, only bore GW036813 (Menindee weir pool zone) passed the Tier 1 assessment (Table 4). All sites except two had evidence of agricultural activities in the vicinity, including cropping and grazing (Table 4).

The groundwater bores were only sampled on two occasions, which is less than the recommended four sampling events to adequately characterise biota and ecology within a site (Hancock and Boulton 2008). Due to the small number of samples collected at each site, a precautionary approach was taken, with each site recorded as 'failing' Tier 1 if two or more indicators failed benchmark values on any sampling occasion. Additionally, Tier 1 does not take into account habitat suitability and natural distribution factors that contribute to the presence/absence of stygofauna. These factors are more than likely contributing to the Tier 1 results in this study and indicate that a Tier 2 assessment is warranted.

Tier 1 assessment allowed for the discrimination of 'nominally impacted' from 'nominally unimpacted' sites. However, due to the use of generic indicators (applicable world-wide), it does not distinguish between levels of health or consider factors that may influence biotic distribution and thus the perceived 'health' of the site. Thus, the more comprehensive Tier 2 assessment was completed on all samples collected for this project.

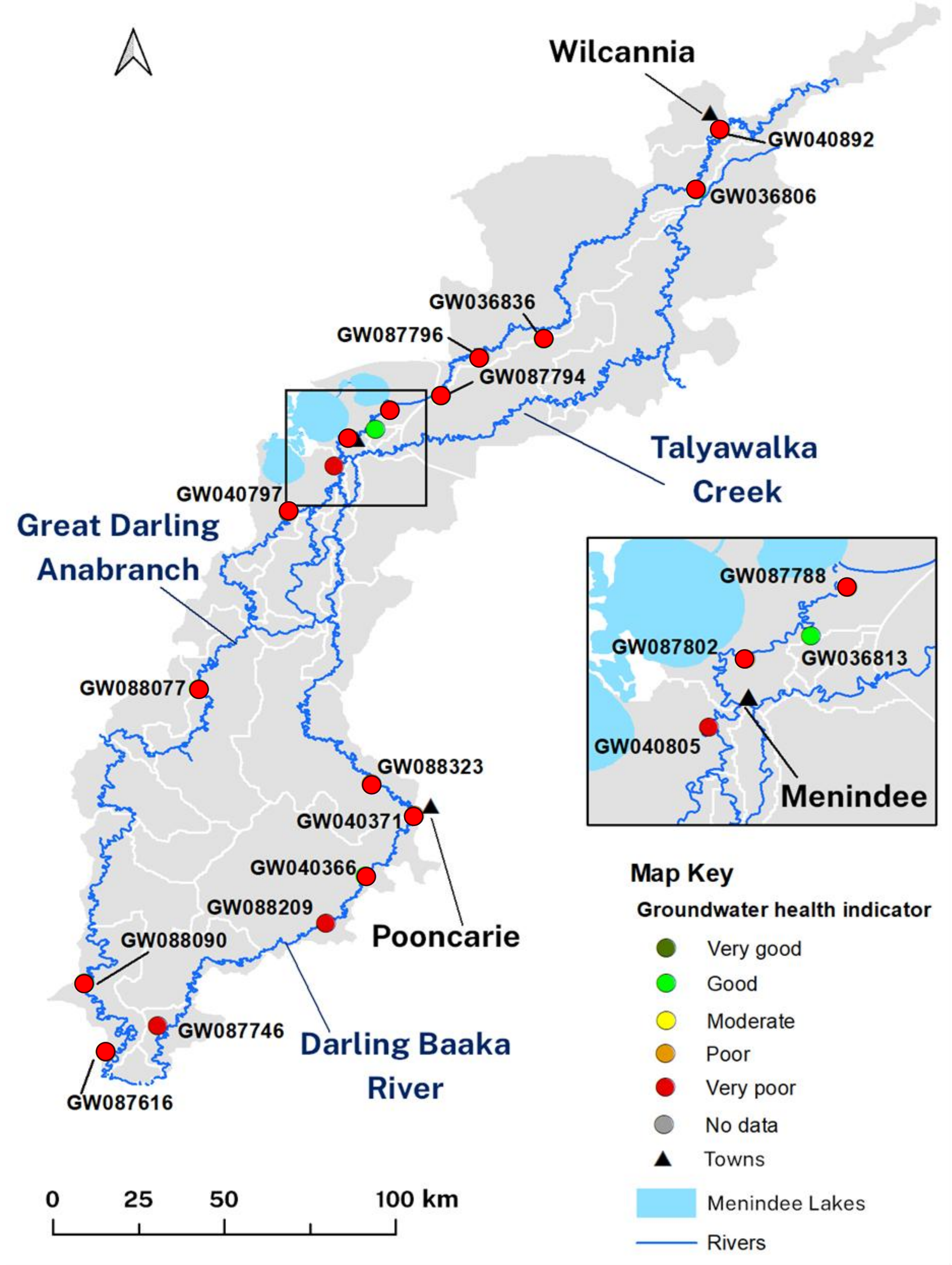

Figure 8. Tier 1 groundwater health assessments across the lower Darling Baaka catchment. Values reflect the combined assessment over June and November 2024, in which the worst-case assessment of the two assessments is presented as a conservative summary.

Table 4: Results of Tier 1 and Tier 2 assessment of sites within the lower Darling Baaka River system. For Tier 2 assessments, Green (scores <2.0) = similar to reference health, Orange (scores 2-3.9) = mild deviation from reference health, Red (scores ≥4) = major deviation from reference health. Tier 2 assessment scores are derived as per Korbel and Hose (2017). For breakdown of Tier 1 and 2 results for each sampling period see Appendix 2.

Site	Land use	Tier 1	Tier 2
GW040892	Native vegetation (no grazing)	Fail	2.00
GW036806	Grazing	Fail	1.50
GW036836	Grazing	Fail	2.25
GW087796	Grazing	Fail	3.00
GW087794	Grazing	Fail	2.25
GW087788	Grazing	Fail	2.00
GW036813	Grazing	Pass	1.00
GW040805	Grazing	Fail	4.00
GW088323	Grazing	Fail	1.50
GW040371	Grazing	Fail	1.50
GW040366	Cropping	Fail	1.50
GW088209	Grazing	Fail	4.00
GW087746	Grazing	Fail	5.50
GW087802	Grazing	Fail	2.25
GW040797	National Park	Fail	5.50
GW088077	Grazing	Fail	2.63
GW088090	Grazing	Fail	1.50
GW087616	Cropping	Fail	1.50

TIER 2 ASSESSMENT RESULTS

Most sites in the study area, were assessed as being in good or moderate health in the Tier 2 assessment (Table 4). Sites assessed with good health were found in all areas of the study region (Figure 17). Two south of Pooncarie (GW088209 and GW087746) and two sites on the Darling Anabranch (GW040805 and GW040797) south of Menindee were assessed as having poor groundwater health (Table 4, Figure 17). Sites GW040805 and GW040797 (in the northern region of the Great Darling Anabranch) had relatively large changes in groundwater levels over the study period, as well as a relatively large proportion of stygoxenes and high dissolved organic carbon concentrations that influenced the poor health rating. The sites south of Pooncarie (GW088209 and GW087746) had high reactive phosphorus concentrations that contributed to the poor rating at those sites.

Tier 2 allows for stygofauna habitat suitability to be considered in the analysis. The presence of clay soils, high EC, low DO and/or the absence of trees at all sites, suggests that all sites potentially had suboptimal habitat to support stygofauna. Accordingly, organisational indicators were down weighted in the GHI calculations for all sites (Appendix 2). At these sites, results relied more heavily on microbial and water quality data to assess groundwater health.

Drivers for the poor groundwater health rankings included high nutrient and carbon concentrations, as well as the absence of stygofauna at several sites. Indeed, the high DOC concentrations may reflect the effects of clouding that occurred prior to the June sampling, and the high concentrations recorded in November suggest that the influx of carbon to the system from those floods had remained in the system. Further studies in this area should be undertaken to establish the sources and fate of elevated nutrients, particularly if those nutrient rich groundwaters are discharging to the river as indicated by modelling (DCCEEW 2025). Further sampling in dry periods will provide an important reference point to these samples that were collected during a relatively wet climatic period.

Samples were collected for analysis of Environmental DNA, and the results are still being analysed for inclusion into the GHI assessment. The assessment will be updated with the eDNA results at a later date. The inclusion of eDNA in the GHI would only change the assessment outcomes based on stygofauna and microbial richness and abundances found in those samples.

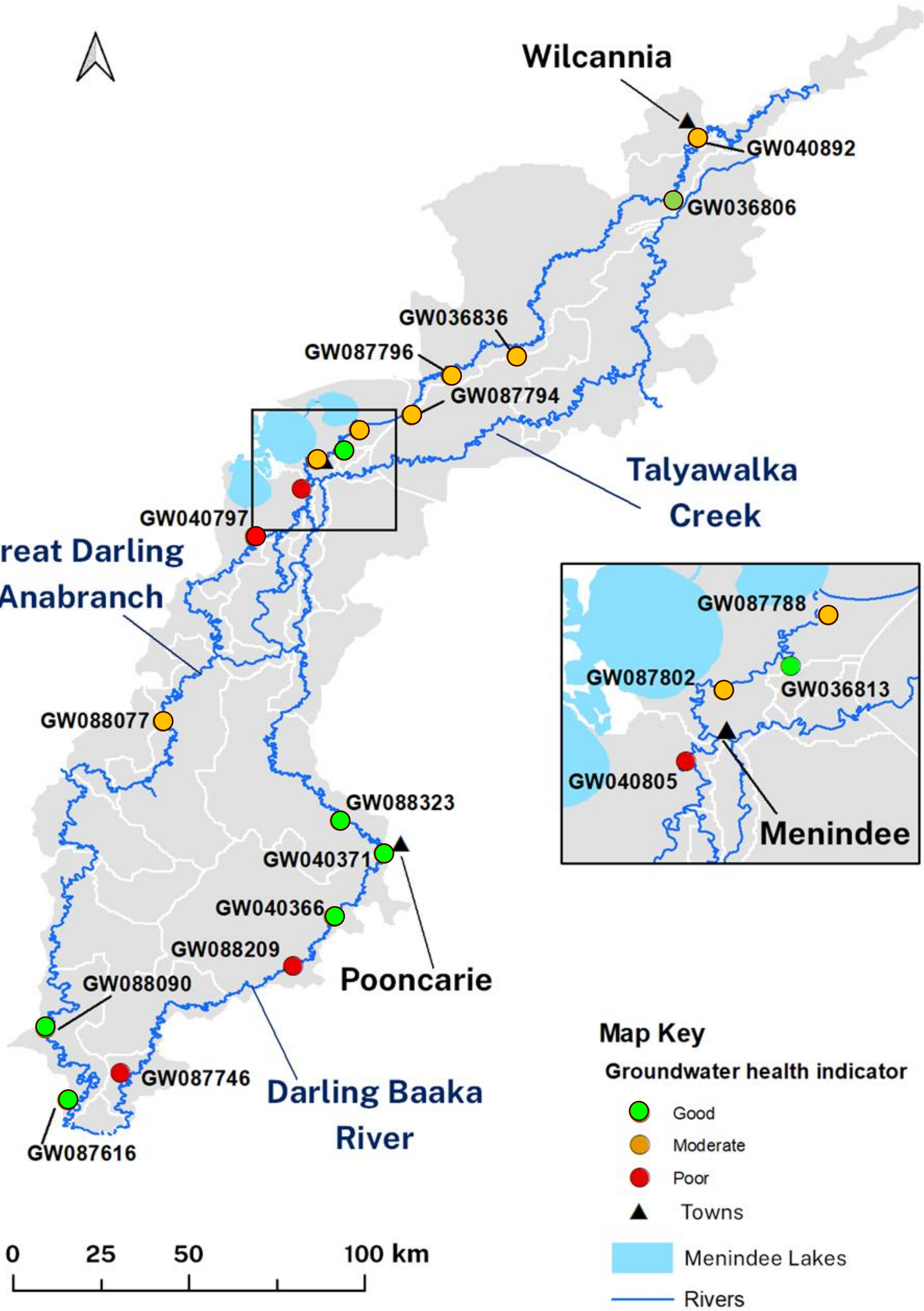

Figure 9. Tier 2 groundwater health assessments across the Darling Baaka catchment. Values reflect the combined assessment over June and November 2024, in which the worst-case assessment of the two assessments is presented as a conservative summary.

Future outlook

The GHI framework provides a flexible tool for assessing the health and condition of shallow aquifers. It can be modified to accommodate specific management foci and budgets and is sensitive to threatening processes common in agricultural settings. Furthermore, the GHI is easy to apply, can be used in a modified form to suit citizen science programs (Korbel and Hose 2024), and importantly, outputs are readily understandable by resource managers and the community. The framework provides environmental managers a much needed, cost-effective tool with which to monitor groundwater health over time and space with proven scientific rigour.

This study has highlighted the benefits of using a framework that can evolve and adapt to new scientific methods and knowledge. The GHI was expanded to include stygofauna habitat suitability as an indicator. The inclusion of the DNA-based characterisation of the groundwater biota into the assessment will also provide additional data and information. In particular, eDNA data will allow quantification and comparison of important microbial functions in relation to water quality and the detection of non-groundwater taxa (stygoxenes) that may reflect changing groundwater conditions. eDNA will also complement the traditional stygofauna collection approach, particularly detecting small and cryptic taxa that can be missed by traditional methods (Korbel et al. 2022). Incorporating eDNA will require adjustments to the GHI framework, as benchmarks for stygofauna diversity and abundance were set using traditional methods. There are currently insufficient data available from reference sites on which to set reliable benchmarks for the eDNA based metrics. As such, the richness and abundances data in the present report are based solely on traditional count methods.

Further analysis of the reference conditions across the Darling Baaka River catchment should be investigated, with a view to establishing catchment-specific benchmarks and progressing from using those set based on other catchments within the MDB. The GHI utilises Tier 2 benchmarks for stygofauna that were established in the northern MDB, where abundance and richness of taxa appear to be generally higher than in the lower MDB catchments (Hose and Korbel unpub. data). To account for these differences, there was a habitat suitability weighting applied to those sites that have clay-dominated sediments, high EC and low tree coverage.

Additionally, the groundwater was sampled after a major wet weather event, where several bores were covered in water. Although this is a natural event, the recent floodings have resulted in the disrupting 'usual' groundwater conditions with influxes of carbon, nitrogen and oxygen likely to have occurred. Such events typically result in a boom of microbial activity, increase in stygoxenes and higher than typical nutrients (as evidenced in this study). Groundwater ecosystems can take a long time to recover from such events. The GHI assessment needs to be treated with caution when applied in such circumstances, as this sampling period would not be considered indicative of 'typical' conditions.

Further studies in the southwestern NSW MDB should be conducted to further our understanding of groundwater biodiversity and GDEs within this region, with evidence in the northern and mid NSW regions indicating a minimum of 4 sample events is required to adequately characterise the population and diversity of stygofauna within a site (Hancock and Boulton 2009). Further sampling would also allow the setting of new DNA-based benchmarks and further testing of existing metrics.

Conclusions

Groundwater is essential for sustaining rural communities and industries across NSW. By establishing a groundwater health monitoring program, this project is informing the sustainable management of groundwaters and their dependent ecosystems in the lower Darling Baaka River system.

The main aims of this project were to benchmark groundwater health and biodiversity within the lower Darling Baaka River system, and to complement the 2025 Darling Baaka RCI. These aims were achieved and, in doing so, provided the first comprehensive database of groundwater biota and condition of groundwater ecosystem health for the area.

Most sites in the study area were assessed as being in good or moderate health in Tier 2 of the assessment. Sites assessed with good health were spread across the study area. Two sites in the lower Darling River and two sites on the Darling Anabranch were assessed as having poor groundwater health, all of these are in the region where DCCEEW modelling indicate groundwaters are discharging into the Darling Baaka River.

The groundwaters in the region had higher nutrient phosphorus and carbon concentrations than expected, which may reflect inputs to the groundwater from flooding prior to the first sampling in June 2024. The impacts of those events were still evident in the groundwater in November 2024. The source and fate of the high nutrient concentration warrants further investigation, particularly in areas where the shallow groundwater is contributing to river flows.

By continuing this monitoring program using the GHI, the NSW Government will be able to:

- evaluate long-term impacts and changes within the lower Darling Baaka River system as an area of NSW Government concern
- evaluate long-term impacts and identify changes in ecosystem health and water quality over time to across the entire MDB to enable Basin Plan Matter 8 reporting, and WSP evaluation reporting
- detect impacts on groundwater in specific locales to provide targeted management actions
- measure improvements in health due to improved environmental performance
- investigate the contributions of groundwater to river health in the region

The project has increased scientific knowledge of groundwater ecosystems and their responses to environmental change. The project has provided the first baseline data on groundwater health throughout the lower Darling Baaka River system to allow for the monitoring of future impacts on this resource. This data should also be used for reporting on groundwater dependent ecosystems as required under NSW policy.

Acknowledgments

This report was prepared by Grant Hose, Jodie Dabovic and Kathryn Korbel. All data were collected by Grant Hose, Kathryn Korbel, Kitty McKnight, Bella Campbell, Ben Humphreys, Eloise Clarke, Sharon Bowen and Jodie Dabovic. The project leaders would like to thank DCCEEW and the EPA for funding this project.

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Appendix 1

Table A1-1 Water Quality at groundwater sites across the lower Darling Baaka River system (2024)

		Sulfate (SO_4) (mg/L)	Chloride (mg/L)	Calcium mg/L)	Magnesium (mg/L)	Sodium mg/L)	Potassium(mg/L)	Aluminium (mg/L)	Arsenic (mg/L)	Barium (mg/L)	Cadmium (mg/L)	Chromium (mg/L)	Cobalt (mg/L)	Copper (mg/L)	Lead (mg/L)
40366	Jun-24	11	58	46	17	71	5	<0.01	0.034	0.190	<0.0001	<0.001	<0.001	<0.001	<0.001
40797	Jun-24	5	38	37	13	53	14	<0.01	0.003	0.090	<0.0001	<0.001	<0.001	<0.001	<0.001
87616	Jun-24	5530	28200	1180	2090	15600	65	<0.10	<0.010	0.022	<0.0010	<0.010	0.016	0.014	<0.010
87746	Jun-24	16	56	55	20	75	4	<0.01	<0.001	0.131	<0.0001	<0.001	<0.001	<0.001	<0.001
88077	Jun-24	74	634	95	50	367	14	<0.01	0.008	0.174	<0.0001	<0.001	0.002	<0.001	<0.001
88090	Jun-24	207	544	73	58	492	13	<0.01	0.008	0.013	<0.0001	<0.001	<0.001	<0.001	<0.001
88209	Jun-24	96	983	48	50	710	18	<0.01	0.011	0.138	<0.0001	<0.001	<0.001	<0.001	<0.001
40892	Jun-24	2	128	61	31	71	8	<0.01	<0.001	0.204	<0.0001	<0.001	<0.001	<0.001	<0.001
36806	Jun-24	118	550	39	27	394	6	<0.01	0.001	0.049	<0.0001	<0.001	<0.001	<0.001	<0.001
36813	Jun-24	78	243	7	6	343	3	<0.01	0.004	0.043	<0.0001	<0.001	<0.001	<0.001	<0.001
36836	Jun-24	32	181	39	20	146	5	<0.01	0.003	0.108	<0.0001	<0.001	<0.001	<0.001	<0.001
40371	Jun-24	22	147	24	14	174	5	<0.01	0.003	0.096	<0.0001	<0.001	<0.001	<0.001	<0.001
40805	Jun-24	3	70	54	21	53	9	<0.01	0.015	0.097	<0.0001	<0.001	<0.001	<0.001	<0.001
87788	Jun-24	1270	1440	47	43	1660	7	<0.01	0.003	0.043	<0.0001	<0.001	0.002	0.002	<0.001
87794	Jun-24	1	59	49	27	89	6	<0.01	0.003	0.416	<0.0001	<0.001	<0.001	<0.001	<0.001
87796	Jun-24	12	236	97	36	104	10	<0.01	0.001	0.937	<0.0001	<0.001	0.014	<0.001	<0.001
87802	Jun-24	316	1300	382	102	512	13	<0.01	0.009	0.235	<0.0001	<0.001	<0.001	<0.001	<0.001
88323	Jun-24	7	154	42	33	121	7	<0.01	<0.001	0.181	<0.0001	<0.001	<0.001	<0.001	<0.001
36806	Nov-24	121	529	37	26	448	6	<0.01	<0.001	0.298	<0.0001	<0.001	<0.001	<0.001	<0.001
36813	Nov-24	75	218	10	7	376	3	<0.01	0.004	0.137	<0.0001	<0.001	<0.001	<0.001	<0.001
36836	Nov-24	31	170	41	20	166	5	<0.01	0.003	0.155	<0.0001	<0.001	<0.001	<0.001	<0.001
40366	Nov-24	9	69	49	16	70	5	<0.01	0.051	0.235	<0.0001	<0.001	<0.001	<0.001	<0.001
40371	Nov-24	19	168	26	14	180	5	<0.01	0.002	0.100	<0.0001	<0.001	<0.001	<0.001	<0.001
40797	Nov-24	31	171	38	15	188	14	<0.01	0.001	0.114	<0.0001	<0.001	<0.001	<0.001	<0.001
40805	Nov-24	18	65	46	16	63	8	<0.01	0.005	0.092	<0.0001	<0.001	<0.001	<0.001	<0.001
40892	Nov-24	9	192	67	37	96	8	<0.01	<0.001	0.346	<0.0001	<0.001	<0.001	<0.001	<0.001
87616	Nov-24	5660	28700	1240	2110	16100	61	<0.10	<0.010	0.084	<0.0010	<0.010	<0.010	<0.010	<0.010
87746	Nov-24	14	161	57	21	136	6	<0.01	<0.001	0.264	<0.0001	<0.001	<0.001	0.004	0.004
87788	Nov-24	1480	1460	59	54	1990	8	<0.01	0.001	0.149	<0.0001	<0.001	<0.001	<0.001	<0.001
87794	Nov-24	67	72	57	31	98	8	<0.01	0.007	0.571	<0.0001	<0.001	0.002	0.008	0.012
87796	Nov-24	9	232	101	38	104	9	<0.01	0.013	0.840	<0.0001	<0.001	0.012	<0.001	<0.001

87802	Nov-24	345	1510	405	112	583	12	<0.01	0.008	0.285	<0.0001	<0.001	<0.001	<0.001	<0.001
88090	Nov-24	204	643	101	81	452	14	<0.01	0.008	0.233	<0.0001	<0.001	<0.001	0.001	<0.001
88209	Nov-24	285	966	47	51	804	17	<0.01	0.010	0.333	<0.0001	<0.001	<0.001	<0.001	<0.001
88323	Nov-24	7	177	39	33	146	6	<0.01	<0.001	0.467	<0.0001	<0.001	<0.001	<0.001	<0.001

Table A1-2 Water Quality at groundwater sites across the lower Darling Baaka River system (2024)

		Manganese (mg/L)	Zinc (mg/L)	Iron (mg/L)	Ferros Iron (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)	Reactive Phosphorus (PO_4) (mg/L)	Dissolved Organic Carbon (DOC) (mg/L)	Temperature (°C)	pH	Electrical Conductivity (EC) (µS/cm)	Dissolved Oxygen (DO) (mg/L)
40366	Jun-24	0.097	<0.005	<0.05	<0.05	0.04	0.02	1.2	1.93	0.14	7	19.6	7.18	480.5	0.86
40797	Jun-24	0.129	<0.005	<0.05	0.05	<0.01	0.19	1.2	0.38	0.27	11	21	7.28	356	1.7
87616	Jun-24	1.06	<0.050	<0.10	<0.05	0.09	0.08	3.1	2.81	0.04	2	19.2	6.51	47632	1.04
87746	Jun-24	2.45	<0.005	<0.05	0.10	0.47	0.02	0.8	0.88	0.84	5	19.7	6.79	509	0.44
88077	Jun-24	0.532	<0.005	0.82	0.97	0.37	0.04	0.5	0.74	0.48	3	20.1	6.69	643	3.5
88090	Jun-24	0.318	0.007	<0.05	<0.05	0.24	0.02	3.6	3.26	0.06	8	19	7.17	2310	1.65
88209	Jun-24	0.062	<0.005	<0.05	<0.05	0.05	<0.01	3.8	5.89	0.61	3	20	7.52	2966	1.18
40892	Jun-24	0.646	<0.005	0.94	1.03	0.11	0.03	0.9	0.60	<0.01	5	21.4	6.73	596	1.08
36806	Jun-24	0.243	<0.005	<0.05	<0.05	1.62	<0.01	3.2	2.20	0.04	4	22.3	7.45	607	0.12
36813	Jun-24	0.007	<0.005	<0.05	<0.05	<0.01	0.07	0.5	0.34	0.13	3	22	7.48	1233	1.46
36836	Jun-24	0.021	<0.005	<0.05	0.09	0.09	<0.01	0.4	0.37	0.31	<1	22.4	7.15	800	1.5
40371	Jun-24	0.967	0.008	2.15	2.37	0.25	<0.01	0.5	1.29	0.40	40	20.6	6.74	749	20.2
40805	Jun-24	1.84	<0.005	0.12	0.17	0.98	<0.01	2.6	1.26	0.02	20	19.4	6.91	492	0.5
87788	Jun-24	0.115	<0.005	<0.05	0.07	0.03	0.40	0.8	0.14	0.04	2	21.6	8.2	4990	8.21
87794	Jun-24	0.542	0.007	<0.05	<0.05	0.33	<0.01	1.0	0.62	0.02	3	20	7.2	624	3.21
87796	Jun-24	2.20	0.011	7.52	9.07	0.08	<0.01	1.1	1.45	<0.01	5	21.7	6.69	976	0.33
87802	Jun-24	7.51	<0.005	27.0	32.2	0.18	<0.01	0.6	0.24	<0.01	6	21.7	6.53	4045	1.66
88323	Jun-24	0.413	<0.005	<0.05	<0.05	0.36	<0.01	3.1	1.48	0.03	6	20.5	6.88	741	1.13
36806	Nov-24	0.242	0.012	0.23	0.27	0.81	<0.01	<1.0	0.97	0.06	13	23.4	7.39	2182	0.03
36813	Nov-24	0.010	0.032	<0.05	<0.05	0.02	0.03	<1.0	5.44	0.13	2	25.6	7.45	1656	0.95
36836	Nov-24	0.004	0.033	<0.05	<0.05	0.06	<0.01	0.1	0.34	0.29	1	23	7.1	1008	0.65
40366	Nov-24	0.109	0.016	1.12	1.47	0.05	<0.01	0.3	0.47	0.16	7	24.4	7.16	580	2.57
40371	Nov-24	1.08	0.010	3.52	3.85	0.3	<0.01	0.9	1.19	0.11	6	22	6.75	795	1.9

40797	Nov-24	0.295	0.014	0.06	0.60	1.63	<0.01	3.40	1.45	1.13	8	22.343	7.81	2060	2.34
40805	Nov-24	1.29	<0.005	<0.05	4.80	0.9	<0.01	1.8	0.82	0.02	13	20.705	7.11	625	2.18
40892	Nov-24	0.652	0.064	3.14	3.59	0.63	<0.01	1.0	0.56	0.02	12	22.2	6.51	944	0.65
87616	Nov-24	0.518	0.160	<0.10	<0.05	0.45	<0.01	1.0	0.32	<0.01	53	22.1	7.08	55484	2.14
87746	Nov-24	2.38	0.076	<0.05	<0.05	3.09	<0.10	3.4	1.22	0.82	16	24.3	7.53	966	5.11
87788	Nov-24	0.218	0.056	<0.05	<0.05	0.16	0.11	<1.0	1.16	<0.01	24	25.9	7.77	8980	4.16
87794	Nov-24	1.05	0.074	0.38	0.48	0.3	0.60	2.0	0.25	<0.01	37	23.753	7.56	927	7.04
87796	Nov-24	2.26	0.097	20.1	23.8	0.25	<0.01	<1.0	0.75	<0.01	10	23.7	6.7	1302	0.48
87802	Nov-24	7.56	0.042	26.6	30.7	0.39	<0.01	0.6	0.23	<0.01	5	21.843	6.82	4887	3.77
88090	Nov-24	0.175	0.068	<0.05	<0.05	0.14	0.28	0.9	0.40	0.08	22	31.4	8.11	2587	3.96
88209	Nov-24	0.071	0.080	<0.05	0.09	0.09	<0.01	0.5	0.91	0.72	8	23.293	7.46	3700	2.35
88323	Nov-24	0.220	0.136	1.04	1.33	0.38	<0.01	<1.0	1.40	0.18	11	23.5	6.83	903	0.97

Appendix 2

Table A2-1. Summary of groundwater health index Tier 1 results.

Site		Trip	Functional	Organisational			Stressor				
		Trip #	DOC	Crustacean	Oligochaetes	Stygoxenes	Nitrate	Reactive phosphorus	Pesticides	TIER 1 Individual Assessment	TIER 1 overall assessment
			>4 mg/L fail	0% is fail	>15% fail	**Present**	>2 mg/L fail	>0.5 mg/L fail	Detection at 2 μg/L	# variables exceeded	Overall assessment
GW036806		Jun-24	4	0.75	0		<0.01	0.04	a	0	Fail
		Nov-24	13	0	0		<0.01	0.06	a	2	
GW036813		Jun-24	3	0	0		0.07	0.13	a	1	Pass
		Nov-24	2	0	0		0.03	0.13	a	1	
GW036836		Jun-24	<1	0.06	0.92		<0.01	0.31	a	2	Fail
		Nov-24	1	0	0.96	y	<0.01	0.29	a	3	
GW040366		Jun-24	7	0	0		0.02	0.14	a	2	Fail
		Nov-24	7	0	0		<0.01	0.16	a	2	
GW040371		Jun-24	40	0	0		<0.01	0.4	a	2	Fail
		Nov-24	6	0	0		<0.01	0.11	a	2	
GW040797		Jun-24	11	0.2	0	y	0.19	0.27	Present (0.42 μg/L)	4	Fail
		Nov-24	8	0	0		<0.01	1.13	a	3	
GW040805		Jun-24	20	0.33	0	y	<0.01	0.02	a	3	Fail
		Nov-24	13	0	0		<0.01	0.02	a	2	
GW040892		Jun-24	5	0.11	0	y	0.03	<0.01	a	3	Fail
		Nov-24	12	0	0		<0.01	0.02	a	2	

GW087616		Jun-24	2	0	0		0.08	0.04	a	1	Fail
		Nov-24	53	0	0		<0.01	<0.01	a	2	
GW087746		Jun-24	5	0	0		0.02	0.84	a	3	Fail
		Nov-24	16	0	0		<0.10	0.82	a	3	
GW087788		Jun-24	2	0	0		0.40	0.04	a	1	Fail
		Nov-24	24	0	0		0.11	<0.01	a	2	
GW087794		Jun-24	3	0	0		<0.01	0.02	a	1	Fail
		Nov-24	37	0	0		0.60	<0.01	a	2	
GW087796		Jun-24	5	0	0.13		<0.01	<0.01	a	3	Fail
		Nov-24	10	0	0.17	y	<0.01	<0.01	a	4	
GW087802		Jun-24	6	0.03	0		<0.01	<0.01	a	2	Fail
		Nov-24	5	0	0		<0.01	<0.01	a	2	
GW088077		Jun-24	3	0	0	y	0.04	0.48	a	2	Fail
		Nov-24		0	0				N/A	1	
GW088090		Jun-24	8	0	0		0.02	0.06	a	2	Fail
		Nov-24	22	0	0		0.28	0.08	a	2	
GW088209		Jun-24	3	0	0		<0.01	0.61	a	2	Fail
		Nov-24	8	0	0.40		<0.01	0.72	a	4	
GW088323		Jun-24	6	0	0		<0.01	0.03	a	2	Fail
		Nov-24	11	0	0		<0.01	0.18	a	2	

Table A2-2. Summary of groundwater health index Tier 2 results. Green = similar to reference health, Orange = mild deviation from reference health, Red= major deviation from reference health. Tier 2 assessment scores are derived as per Korbel and Hose (2017), with 0-2 indicating 'reference like' condition, 2-4 indicating mildly impacted sites, and scores of >4 indicating poor groundwater health.

Site	trip	Cotton strip assay (<30%loss)	Dissolved organic carbon (>4 mg/L)	Stygofauna richness (>1)	Stygox (<10%)	Crustacean abundance (>50%)	Oligochaete abundance (<10%)	Nitrate (<2 mg/L)	Reactive phosphorus (<0.5mg/L)	Landuse	Water level decline between sampling events (<0.5 m)	Total indicator fails	Site weighting	Weighted GHI score	GHI overall site assessment#
36806	Jun-24	1	4	2	0	0.75	0	<0.01	0.04	Non-irrigated	na	2	0.5	0.50	1.50
36806	Nov-24	-	13	0	0	0	0	<0.01	0.06	Non-irrigated	0.09	3	0.5	1.50	
36813	Jun-24	1	3	1	0	0	0	0.07	0.13	Non-irrigated	na	2	0.5	1.00	1.00
36813	Nov-24	0.87	2	1	0	0	0	0.03	0.13	Non-irrigated	0.09	2	0.5	1.00	
36836	Jun-24	1	<1	4	0	0.06	0.922	<0.01	0.31	Non-irrigated	na	3	0.75	2.25	2.25
36836	Nov-24	-	1	4	0.018	0	0.965	<0.01	0.29	Non-irrigated	0.12	2	0.75	1.50	
40366	Jun-24	-	7	1	0	0	0	0.02	0.14	Non-irrigated	na	2	0.75	1.50	1.50
40366	Nov-24	-	7	1	0	0	0	<0.01	0.16	Non-irrigated	0.16	2	0.75	1.50	
40371	Jun-24	0.89	40	2	0	0	0	<0.01	0.4	Non-irrigated	na	3	0.5	1.50	1.50
40371	Nov-24	0.18	6	0	0	0	0	<0.01	0.11	Non-irrigated	0.15	3	0.5	1.50	
40797	Jun-24	1	11	6	0.4	0.2	0	0.19	0.27	Non-irrigated	na	5	0.75	3.50	5.50
40797	Nov-24	-	8	0	0	0	0	<0.01	1.13	Non-irrigated	3.51	5	0.75	5.50	
40805	Jun-24	0.96	20	2	0.667	0.333	0	<0.01	0.02	Non-irrigated	na	5	0.5	4.00	4.00
40805	Nov-24	1	13	0	0	0	0	<0.01	0.02	Non-irrigated	0.69	5	0.5	4.00	
40892	Jun-24	0.86	5	6	0.556	0.111	0	0.03	<0.01	Non-irrigated	na	4	0.5	2.00	2.00
40892	Nov-24	0.53	12	0	0	0	0	<0.01	0.02	Non-irrigated	0.38	4	0.5	2.00	
87616	Jun-24	-0.20	2	1	0	0	0	0.08	0.04	Non-irrigated	na	1	0.5	0.50	1.50
87616	Nov-24	-0.21	53	0	0	0	0	<0.01	<0.01	Non-irrigated	0.06	2	0.5	1.50	
87746	Jun-24	1	5	0	0	0	0	0.02	0.84	Non-irrigated	na	4	0.75	5.00	5.50
87746	Nov-24	1	16	0	0	0	0	<0.10	0.82	Non-irrigated	0.21	4	0.875	5.50	

87788	Jun-24	0.77	2	1	0	0	0	0.40	0.04	Non-irrigated	na	2	0.5	1.00	2.00
87788	Nov-24	0.43	24	0	0	0	0	0.11	<0.01	Non-irrigated	0.26	3	0.5	2.00	
87794	Jun-24	0.28	3	2	0	0	0	<0.01	0.02	Non-irrigated	na	1	0.75	0.75	2.25
87794	Nov-24	-	37	0	0	0	0	0.60	<0.01	Non-irrigated	0.05	3	0.75	2.25	
87796	Jun-24	0.756793261	5	3	0	0	0.133	<0.01	<0.01	Non-irrigated	na	4	0.75	3.00	3.00
87796	Nov-24	na	10	3	0.333	0	0.167	<0.01	<0.01	Non-irrigated	0.09	4	0.75	3.00	
87802	Jun-24	0.930587008	6	4	0	0.025	0	<0.01	<0.01	Non-irrigated	na	3	0.75	2.25	2.25
87802	Nov-24	-0.015536841	5	2	0	0	0	<0.01	<0.01	Non-irrigated	0.14	2	0.875	1.75	
88077	Jun-24	0.401814688	3	11	0.564	0.1	0.004	0.04	0.48	Non-irrigated	na	2	0.875	2.63	2.63
88077	Nov-24	0.447414547		0	0	0	0			Non-irrigated	0.17	3	0.75	2.25	
88090	Jun-24	0.442282608	8	3	0	0	0	0.02	0.06	Non-irrigated	na	2	0.5	1.50	1.50
88090	Nov-24	0.750381605	22	1	0	0	0	0.28	0.08	Non-irrigated	0.21	3	0.5	1.50	
88209	Jun-24	0.855480978	3	3	0	0	0.4	<0.01	0.61	Non-irrigated	na	4	0.5	3.50	4.00
88209	Nov-24	0.880639579	8	0	0	0	0	<0.01	0.72	Non-irrigated	0.11	5	0.5	4.00	
88323	Jun-24	1	6	1	0	0	0	<0.01	0.03	Non-irrigated	na	3	0.5	1.50	1.50
88323	Nov-24	na	11	0	0	0	0	<0.01	0.18	Non-irrigated	0.16	3	0.5	1.50	

Na = data not available. #overall assessment based on worst case assessment for each site over the two sampling occasions.

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