Synthesis report

Assessment of surface water and sediment quality in the vicinity of power stations and coal ash repositories in Lake Macquarie, NSW

Department of Climate Change,
Energy, the Environment and Water

Acknowledgement of Country

Department of Climate Change, Energy, the Environment and Water acknowledges the Traditional Custodians of the lands where we work and live.

We pay our respects to Elders past, present and emerging.

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Report prepared by DCCEEW for the New South Wales Environmental Protection Authority (NSW EPA)

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Executive summary

This report provides a synthesis of recent investigations into surface water quality and sediment quality in the vicinity of power stations and coal ash repositories in Lake Macquarie, NSW, Australia. Lake Macquarie holds significant natural capital due to its ecological diversity, recreational opportunities, and aesthetic value for communities. The natural resources of the region have also contributed to the rich industrial history and urban development surrounding the lake.

Previous studies have shown significant concentrations of trace metals and metalloids (hereafter referred to as “metals” for simplicity) above background levels within the sediments of Lake Macquarie. These studies identified that the metals of potential ecological concern in the northern section of the lake are primarily cadmium, lead, zinc, and to a lesser extent selenium, and copper, and in the southern section of the lake they are primarily selenium and to a lesser extent lead, cadmium, copper, and zinc (Maher, 2021).

This study specifically focused on the southern section of Lake Macquarie in the vicinity of the coal-fired power stations and coal ash repositories and examined the concentrations of metals and nutrients in surface waters as well as current metal concentrations in the lake sediments and their trends over the last decade. Furthermore, a multiple-lines-of-evidence approach within a weight-of-evidence framework was employed, thereby increasing confidence in the outcomes of the assessment and the conclusions.

The main findings of the assessment were as follows:

Water quality

- Elevated temperatures (of as much as 5 to 10°C) were observed within the Eraring Power Station’s and Vales Point Power Station’s cooling water outlet canals, as well as their nearby receiving waters.
- The total nitrogen and total phosphorus concentrations in the lake were below guideline values for NSW estuaries, but some inorganic, potentially more bio-available forms of nitrogen and phosphorus were elevated in certain areas (e.g., Wyee Bay, Bonnells Bay, and Myuna Bay). The guidelines are based on measurements from relatively undeveloped lake basins and suggest that development in the Lake Macquarie catchment has affected nutrient loads entering the lake. However, the lake basin seems to be relatively resilient to nutrient enrichment.
- The concentrations of eight metals (cadmium, chromium, lead, mercury, nickel, selenium, silver, and vanadium) were below the screening criteria for all surface water samples collected. Seven metals (aluminium, arsenic, cobalt, copper, manganese, molybdenum, and zinc) had at least one exceedance during the monitoring program. Arsenic, cobalt, and molybdenum concentrations were below the screening criteria on ≥99% of all occasions and were not considered contaminants of concern in surface waters. Aluminium, copper, manganese, and zinc exceeded the screening criteria at some sites, indicating potential concerns. However, concentrations were below the criteria on 96%, 78%, 99%, and 96% of all sampling occasions, respectively. Localised exceedances of aluminium, zinc, and manganese appear to stem from freshwater inflows carrying these contaminants from the surrounding catchment (via Dora Creek and Wyee Creek in the southern section of the lake) into the southern part of the lake. However, within the lake basin the concentrations of these metals are largely reduced to levels below the screening criteria. Copper concentrations were low and relatively consistent across the lake, typical of diffuse sources.
- The Power Station’s coal ash repositories/return waters are a reservoir for some metals and nutrients, however, discharges to Lake Macquarie are rare as water is recirculated and

reused under normal operating conditions. There was no evidence of adverse impacts on water in Lake Macquarie as a result of the presence of metals and nutrients within the coal ash repositories/return waters.

Sediment quality

- The weight-of-evidence assessment of sediment quality demonstrated that all of the samples collected from the southern section of Lake Macquarie, were below the screening criteria (ANZG, 2018; Buchman, 2008), based on bioavailable contaminant assessment, and no significant effects due to metals were observed on the ecosystem.
- Two sites in the northern section of the lake exceeded the sediment quality guideline value (SQGV) for lead (ANZG, 2018) based on the dilute acid-extractable metal concentrations. This suggests that lead remains at a level of concern to ecosystem health within the northern section of Lake Macquarie. Further investigation of metals of concern within the northern section of the lake was outside the scope of this investigation.
- Comparisons of the surface sediment quality data (top 5 cm, collected in 2022) with historical sediment quality data (top 5 cm, collected in 2011) and newly depositing sediment quality data (collected in sediment deposition traps) suggest that sediment metal concentrations within the southern section of Lake Macquarie have shown a marked reduction overtime (especially arsenic, cadmium and selenium) or have remained the same.
- Comparisons of the surface sediment quality data (top 5 cm, collected in 2022) with historical sediment quality data (top 5 cm, collected in 2011) showed a marked reduction in selenium concentrations; arsenic and cadmium concentrations were mostly lower or remained similar; while copper, lead, and zinc were lower or remained similar in all areas except for the northeast corner of the southern lake and surrounding Pulbah Island where higher concentrations were observed in 2022 compared to those measured in 2011.
- Comparisons of the surface sediment data (top 5 cm, collected in 2022) and newly depositing sediment data (collected in sediment deposition traps) found that concentrations of copper, lead and zinc were lower in the newly deposited sediment than in the surface sediments, whereas the concentrations of arsenic and mercury were similar in magnitude to the surface sediments for hotspot regions. The newly deposited sediments showed a marginal increase in selenium compared to the surface sediments. Selenium is potentially being adsorbed from the water column onto suspended particles and transported around the lake. While this might suggest an increase in surface sediment concentrations across the lake with time, previous research indicates that selenium concentrations within the sediment have reduced partly due to selenium volatilisation and bioturbation.

Table of contents

List of tables

List of figures

List of appendix figures

1. Introduction

1.1 Project overview

The Science and Insights Division (S&I) of the New South Wales (NSW) Department of Climate Change, Energy, the Environment and Water (DCCEEW) was engaged by the NSW Environment Protection Authority (EPA) to undertake an independent assessment of surface water and sediment quality within the southern section of Lake Macquarie, NSW, Australia. The main purpose of this investigation was to obtain information to facilitate the EPA's contribution to the NSW Government's response to the recommendations in the NSW Parliamentary Inquiry's report into the costs of remediation of coal ash repositories (Parliament of NSW, 2021). The information gathered herein provides a present-day assessment of the contamination status of Lake Macquarie against which future changes, impacts, and/or mitigation and remediation activities can be assessed.

The scope of works outlined in the Sampling, Analysis, and Quality Plan (SAQP) (DPE, 2023) was developed to: (i) determine present-day concentrations of metals and metalloids (hereafter referred to as "metals" for simplicity) and nutrients to assess surface water quality; (ii) delineate the extent of metal contamination in sediments; and (iii) assess the potential risks to ecological receptors in the vicinity of the power stations, coal ash repositories, and more broadly within the southern section of Lake Macquarie. The project was broken up into a series of stages (or lines of evidence), with the results documented in five separate reports:

- Surface water quality – chemical assessment (hereafter referred to as the S*urface water quality report*; DCCEEW, 2024a)
- Surface sediment quality – chemical assessment (hereafter referred to as the S*urface sediment quality report*; DCCEEW, 2024b)
- Surface sediment quality – toxicity assessment (hereafter referred to as the T*oxicity assessment report*; DCCEEW, 2024c)
- Surface sediment quality – newly deposited sediment assessment (hereafter referred to as the N*ewly deposited sediment assessment report*; DCCEEW, 2024d)
- Benthic community composition – Lake Macquarie (hereafter referred to as the B*enthic community composition report*; Dafforn et al., 2024)

This report synthesises these individual lines of evidence into a weight-of-evidence framework. This allows for a more comprehensive and integrated analysis, leading to more reliable conclusions and recommendations based on the overall findings.

1.2 Project location

1.2.1 Physical characteristics

Lake Macquarie (Awaba) is the largest coastal saltwater lake in the Southern Hemisphere. It is located in the Lower Hunter Region of NSW, Australia, approximately 90 km north of Sydney. The lake is described as a temperate, wave-dominated barrier estuary with a small tidal range (maximum tidal range of around 30 cm) and a permanent entrance connecting it to the Pacific Ocean at Swansea Channel. Shallow waters exist between Swansea and Wangi Wangi Point and allow for the lake to be operationally defined into northern and southern sections about this latitudinal axis (Figure 1).

The lake's catchment area is about 604 km2 (Roper et al., 2011) and receives an average total surface flow from the catchment of about 85 GL/year (DPIE, 2020). The largest sub-catchments discharging into the lake are Dora Creek and Wyee Creek in the southern section and Cockle Creek and Stony Creek in the northern section. The estuary hydrodynamic processes are primarily wind-driven circulation, catchment flows from rainfall and, in the southern section of the lake, the intake and discharge of cooling waters from the Eraring and Vales Point Power Stations.

1.2.2 Land-use

The Lake Macquarie region is home to more than 213,000 people residing in almost 89,000 dwellings (Australian Bureau of Statistics, 2021). Most of the land surrounding the lake is urbanised, with small pockets of bushland mainly located in the south. The urban development has resulted in changes to the lake's shoreline (e.g., by removing vegetation and constructing seawalls, boat ramps, jetties, stormwater outlets, and industrial infrastructure), leading to subsequent alterations of hydrological and ecological processes (DPIE, 2020).

The lake has a long history of industrial activity dating back to at least the 1890s (Batley, 1987). Former and current heavy industries have largely been situated on the northern, western, and southern shores of the lake (Figure 1). In the northern section of the lake, significant industries have included a lead and zinc smelter, a fertiliser plant, a steel foundry, collieries, and wastewater treatment works (Batley, 1987). In the southern section of the lake, significant industries have included coal-fired power stations, coal washeries, and wastewater treatment works (Batley, 1987). The Vales Point Power Station (established in 1963, currently operated by Delta Electricity), the Eraring Power Station (established in 1981, currently operated by Origin Energy), and the decommissioned Wangi Power Station (operated between 1956 and 1986) are the three coal-fired power stations that have been situated on the southern shores of Lake Macquarie.

A significant source of contaminants to Lake Macquarie has been legacy inputs from past industrial activity (such as metal smelting, steelworks, power stations, and wastewater treatment effluents) before more stringent environmental protection measures were put in place. Other sources of contaminants in the lake include urban stormwater and run-off, agricultural run-off, and boating activities. Previous studies investigating metal concentrations in Lake Macquarie were recently reviewed by Maher (2021). This review identified that the metals of potential ecological concern in the northern section of the lake were primarily cadmium, lead, zinc, and to a lesser extent selenium and copper, and in the southern section of the lake, primarily selenium and to a lesser extent lead, cadmium, copper, and zinc. Some of the earlier studies identified the power stations as a significant source of the metal contaminants in the southern lake, such as from untreated discharges from the ash repositories. These findings led to the implementation of improved coal ash handling procedures at the Vales Point Power Station ash dam in 1995 and changes to ash dam management at Eraring Power Station in the late 1990s.

1.2.3 Ecological characteristics and community values

The lake is environmentally significant, supporting a diverse range of habitats, including seagrass meadows (covering about 13 km^2), wetlands (20 km^2), mangroves (1.6 km^2), salt marshes (0.78 km^2), as well as sand flats, mud flats, and deep, open water (DPIE, 2020). Seagrass meadows fringe most of the lake, with *Zostera capricorni* being the most common species present (Figure 1). The threatened species *Posidonia australis* can also be found, along with others like *Halophila ovalis* and *Ruppia megacarpa*. Estuarine wetlands, mangroves, and saltmarshes are present near the lake entrance and fringe some of the bays (Figure 1). These habitats support a diverse range of fauna, including migratory seabirds, and are important nursery areas for fish and other aquatic species.

Lake Macquarie is the traditional land of the Awabakal people, who have utilised the aquatic resources around the lake for more than 8,000 years (LMCC, 2023). The Awabakal people have a deep connection to the lake and its surroundings. The diverse vegetation, fauna, foreshores, and catchment are highly valued by the Awabakal people, who are custodians of these resources (LMCC, 2023).

The rich industrial history and natural capital have made the Lake Macquarie region a popular place to live and work. The lake offers significant recreational value for both residents and visitors, making it a popular destination for activities such as swimming, recreational boating and fishing (DPIE, 2020).

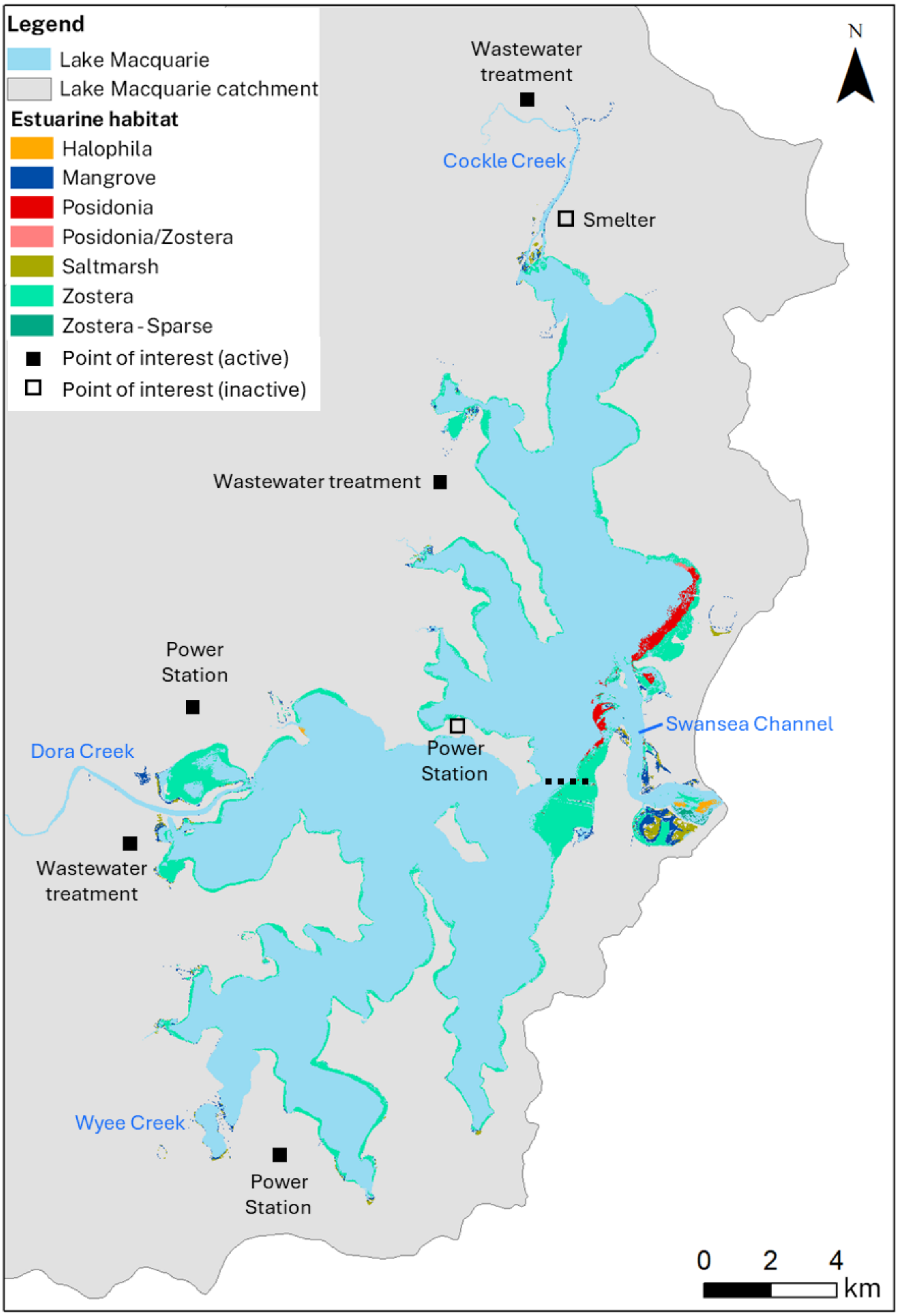

Figure 1. Habitats and points of interest mapped in Lake Macquarie. The black dotted line designates the regions described as the northern section of the lake (above the line) and the southern section of the lake (below the line). The map was produced in ArcGIS using data from DPI (2023).

2. Lines of evidence

The lines of evidence gathered for the assessment of the impact of contaminants of concern in the vicinity of coal ash repositories on water and sediment quality in the southern section of Lake Macquarie are detailed below. These lines of evidence included water and sediment chemistry, sediment toxicity, and benthic ecology.

2.1 Water quality

2.1.1 Chemistry line of evidence

The investigation of surface water chemistry is detailed in the *Surface water quality report*. Sampling for water quality was carried out monthly between March 2022 and February 2023 at 19 sites within Lake Macquarie and an additional 10 sites on the Eraring and Vales Point Power Station premises, within the coal ash repository or nearby creeks that receive water flows and/or emergency discharges from the repositories. The contaminants of potential concern within the surface waters of Lake Macquarie were identified based on nutrient concentrations (50th percentile for each individual site) exceeding the NSW Estuary Water Quality Guideline Values (DCCEEW, 2024e) and metal concentrations (95th percentile for each individual site) exceeding the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG, 2018) default guideline values (DGVs), where available. Where DGVs were not available, indicative interim working levels or third-party proposed guideline values were adopted. The rationale for the adopted screening criteria for the current investigation is provided in Section 2.4 of the *Surface water quality report*. Collectively these values are referred to as the screening criteria.

A summary of findings for the Lake Macquarie sample sites as outlined in the S*urface water quality report* are:

- The physicochemical parameters of dissolved oxygen, pH, total suspended solids, and turbidity were within guideline values for NSW estuaries except for a few localised exceedances.
- Temperature differences were observed across the lake, with variations of as much as 5 to 10°C observed within a single sampling event. Elevated temperatures relative to other sites were observed within the receiving waters for the Eraring Power Station cooling water outlet and the Vales Point Power Station cooling water outlet, as well as their nearby receiving waters.
- For nutrients, total nitrogen and total phosphorus concentrations were below NSW guideline values at all sites. There were some exceedances of the NSW guideline values for oxidised nitrogen, ammonia nitrogen, and dissolved phosphorus concentrations around the foreshore areas in the southern and southwestern basin (e.g., Bonnells Bay, Myuna Bay, and Wyee Bay). Free reactive phosphorus concentrations also exceeded NSW guideline values, and this was evident at all sites, including the main body of the lake. Sites where nutrient concentrations exceed the screening criteria are summarised in Figure 2.
- The cooling water outlet canal samples from the Eraring and Vales Point Power Stations had similar levels of total nitrogen and phosphorus but slightly higher levels of oxidised nitrogen, ammonia-N, dissolved phosphorus, and free reactive phosphorus compared to the inlet canal and the lake.
- The concentrations of eight metals (cadmium, chromium, lead, mercury, nickel, selenium, silver, and vanadium) within the lake were generally below the screening criteria for all

surface water samples collected. Seven metals (aluminium, arsenic, cobalt, copper, manganese, molybdenum, and zinc) had at least one exceedance during the monitoring program. Arsenic, cobalt, and molybdenum concentrations were below the screening criteria on ≥99% of all occasions (n=227) and were not considered contaminants of concern in surface waters. Aluminium, copper, manganese, and zinc exceeded the screening criteria at some sites, indicating potential concerns. However, they were below the criteria on 96%, 78%, 99%, and 96% of all sampling occasions (n=227), respectively. A relatively even distribution of low dissolved copper concentrations (<0.001 - 0.004 mg/L) was observed across the lake, while aluminium and zinc concentrations were similar between the northern and southern sections of the lake and appear to be related to freshwater inflows bringing these contaminants from the catchment. The manganese screening criterion was only exceeded at one site near the outflow of Dora Creek into the lake. Sites where the 95th percentile concentrations of metals exceed the screening criteria are summarised in Figure 3.

Notable metals and nutrients found in the Power Stations' water reservoirs as well as the creeks leading into the southern section of Lake Macquarie, as outlined in the *Surface water quality report,* are summarised in Figure 4 and discussed below.

- Surface waters receiving catchment run-off (such as Wyee Creek, Dora Creek and Crooked Creek) contributed significant amounts of both total and dissolved nitrogen and total phosphorus to the lake.
- The coal ash repository/return waters at both Power Stations appear to be significant reservoirs for nutrients.
- Surface waters receiving catchment run-off (such as Wyee Creek, Dora Creek and Crooked Creek) were characterised by elevated concentrations of aluminium, cobalt, iron, lead, manganese, nickel, and zinc. With the exception of aluminium, manganese and zinc, which have already been discussed, none of these metals exceeded screening criteria (where available) and, therefore, were not identified as potential contaminants of concern within the surface waters of the lake. No screening criteria was available for iron in marine waters. Total and dissolved iron were elevated in the creeks, but low concentrations were observed within the lake basin.
- Coal ash repository/return waters at both Power Stations were characterised by elevated concentrations of arsenic, barium, boron, chromium, iron, manganese, molybdenum, selenium, and vanadium. None of these metals exceeded screening criteria (where available) in the lake and, therefore, were not identified as contaminants of concern. Metals without screening criteria included barium, boron and iron. Barium and boron were both within the range of typical concentrations in marine waters. Total and dissolved iron were elevated in the creeks, but low concentrations were observed within the lake basin.

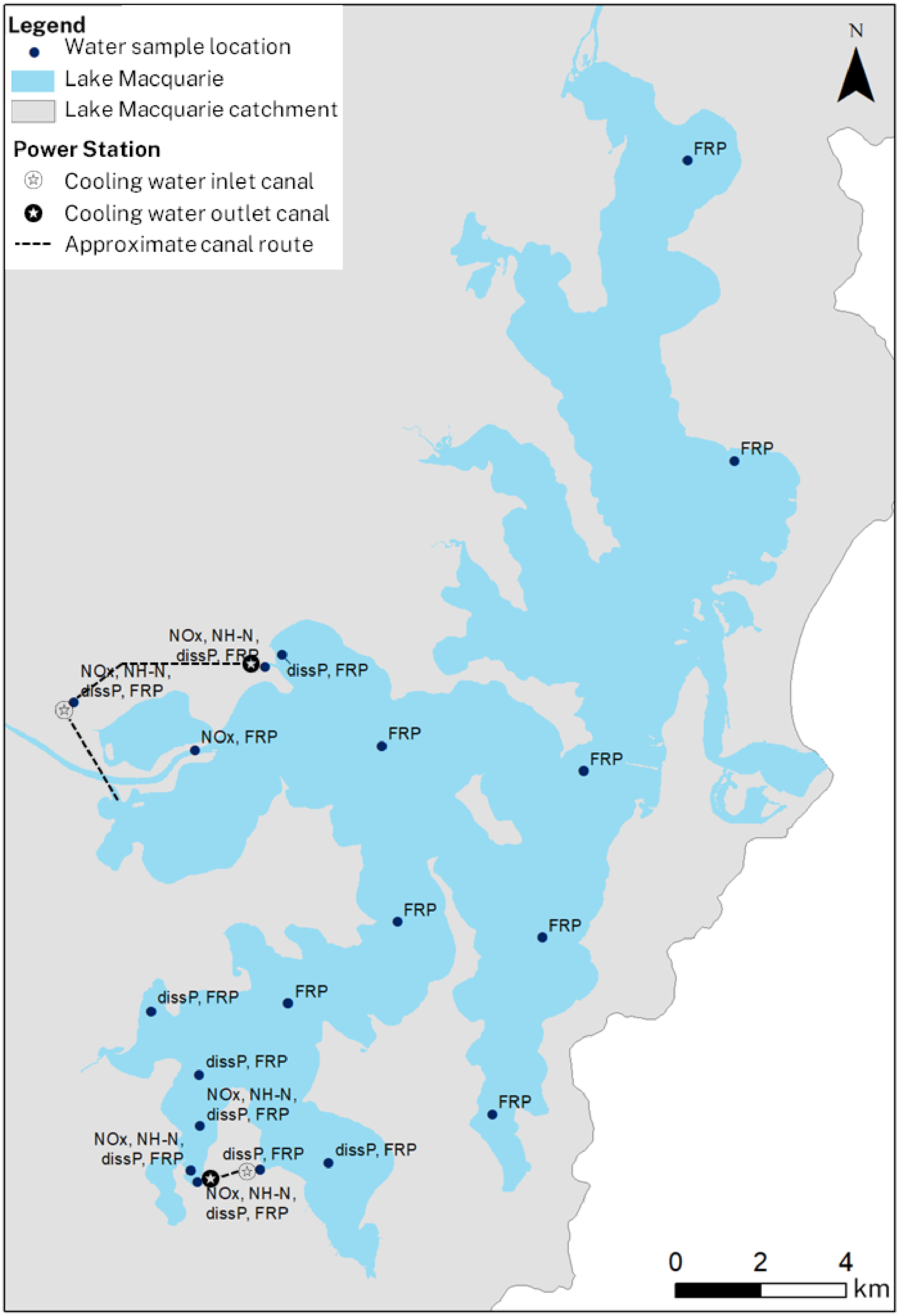

Figure 2. Map of the Lake Macquarie water sampling locations (blue circles). The sites where the 50th percentile concentration of nutrients exceeded the screening criteria are labelled with the analyte that exceeded (NOx = nitrate + nitrite, NH-N = ammonia + ammonium, dissP = dissolved phosphorus; FRP = free reactive phosphorus).

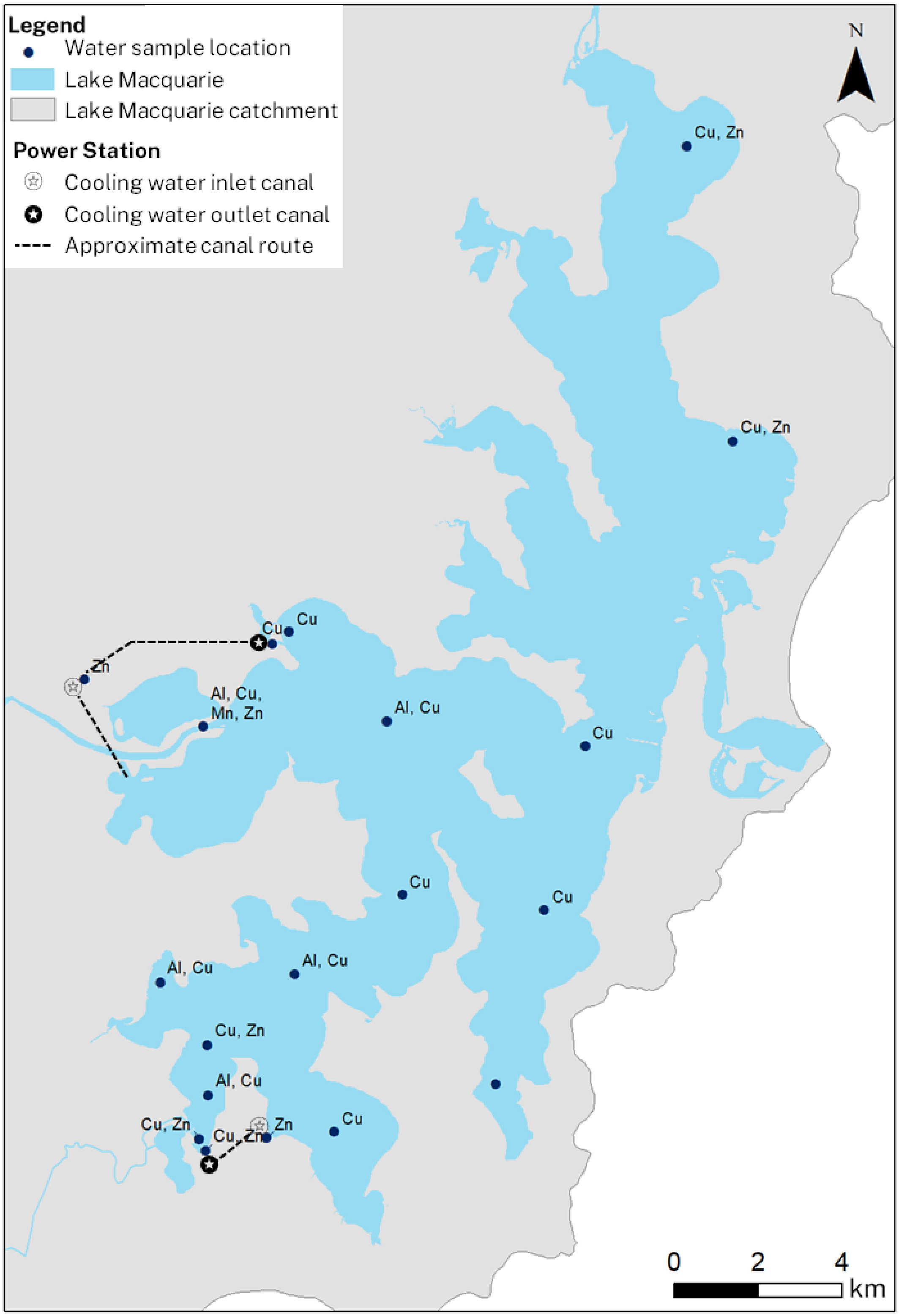

Figure 3. Map of the Lake Macquarie water sampling locations (blue circles). The sites where the 95th percentile dissolved metal concentration exceeded the screening criteria are labelled with the analyte that exceeded (Al = aluminium, Cu = copper, Mn = manganese, and Zn = zinc).

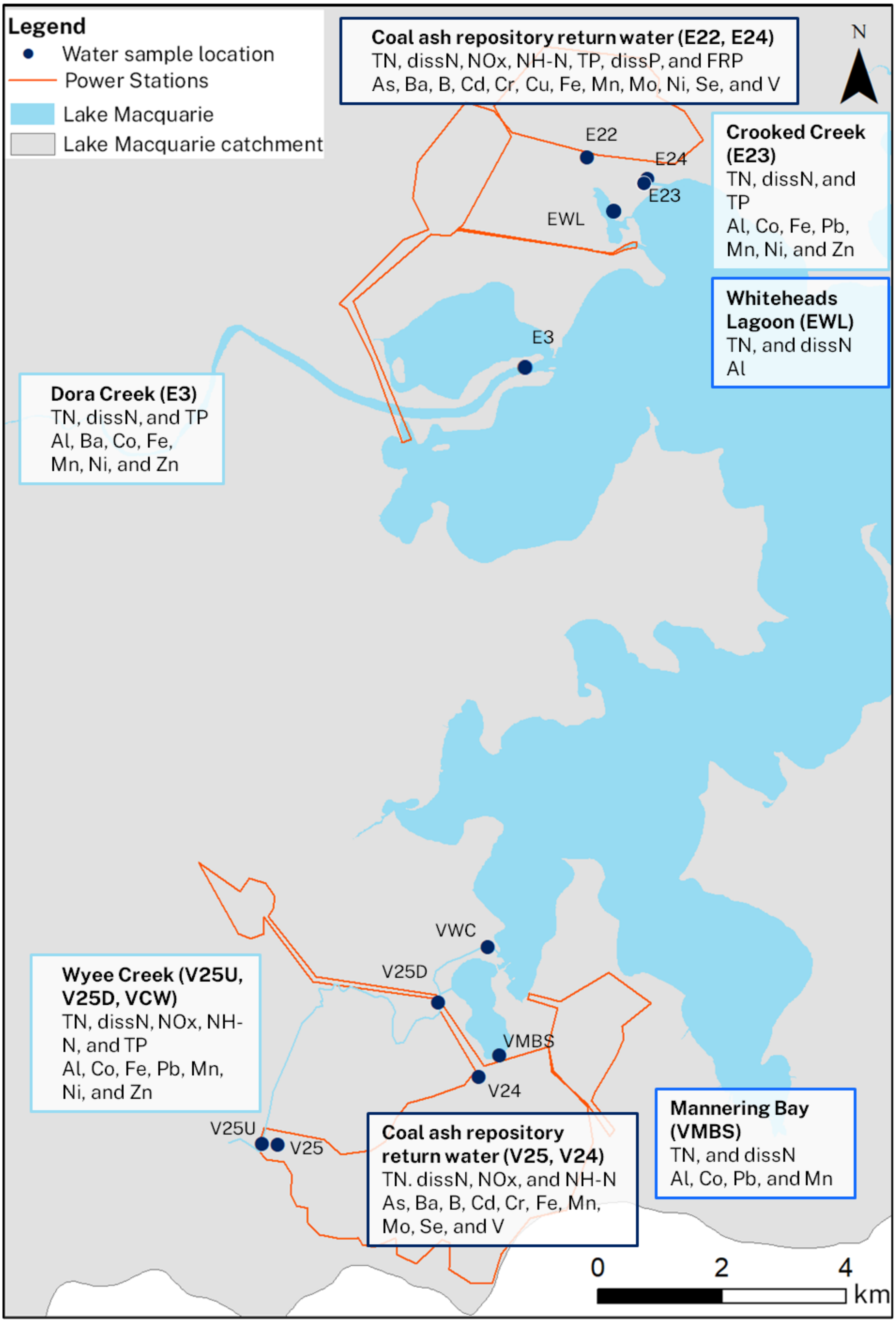

Figure 4. Map of the sampling locations (blue circles) in close proximity to Eraring and Vales Point Power Stations and lists of contaminants of potential concern that were identified within the water reservoirs and creeks. TN = total nitrogen; dissN = dissolved nitrogen, NOx = nitrate + nitrite, NH-N = ammonia + ammonium, TP = total phosphorus, dissP = dissolved phosphorus; FRP = free reactive phosphorus), Al = aluminium, As = arsenic, Ba = barium, B = boron, Cd = cadmium, Co = cobalt, Cu = copper, Fe = iron, Mn = manganese, Mo = molybdenum, Ni = nickel, Pb = lead, Se = selenium, V = vanadium, and Zn = zinc

2.2 Sediment quality

2.2.2 Chemistry line of evidence

The investigation of surface sediment chemistry is detailed in the *Surface sediment quality report*, with further sampling also presented in the *Toxicity assessment report* and the *Newly deposited sediment assessment report*. Contaminants of potential concern were identified as those for which the total recoverable metal concentration and the dilute acid-extractable metal concentration (the estimated bioavailable fraction) exceeded the Australian sediment quality guideline values (SQGVs; ANZG, 2018), where available, in any individual sediment sample. Since there was no SQGV available for selenium, the apparent effect threshold from Buchman (2008) was used for screening purposes. Collectively these values are referred to as the screening criteria.

Stage 1, carried out in 2022, involved high-resolution sediment sampling (top 5 cm) within the southern part of the lake (the *Surface sediment quality report*) and chemical analysis of 24 metals (Ag, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Ti, Tl, V, Zn, and Hg). Summary of findings:

- Of the 73 sampling sites in the southern section of the lake, no sites exceeded the screening criteria for any of the metals investigated based on their dilute acid-extractable metal concentrations.
- Of the seven sampling sites in the northern section of the lake, two sites exceeded the SQGV for lead (ANZG, 2018) based on their dilute acid-extractable metal concentrations (Figure 5).

Stage 2, carried out in 2023 and 2024, involved sediment sampling (top 10 cm) at 10 areas of interest within the southern section of the lake (*Toxicity assessment report* and the B*enthic community composition report*). Summary of findings:

- None of the sites investigated exceeded the screening criteria based on their dilute acid-extractable metal concentrations.
- These sediments were further investigated for toxicity and ecology lines of evidence (see Sections 2.2.3 and 2.2.4).

Stage 3, carried out between November 2023 and May 2024, involved using sediment deposition samplers to collect newly deposited sediment at 10 sites within the southern section of Lake Macquarie (the *Newly deposited sediment assessment report*). The sediments were analysed for total recoverable metals and compared to the results of the surface sediments (top 5 cm) (Stage 1 above; the S*urface sediment quality report*). Summary of findings:

- Broadly, the newly deposited sediments had similar metal concentrations across the sites sampled despite being collected from different regions of the southern section of Lake Macquarie.
- Minor hotspot regions for metal accumulation on the newly deposited sediment were consistent with those identified in the surface sediments, with slightly elevated concentrations of arsenic near Myuna Bay and Bonnells Bay, mercury and zinc concentrations around Pulbah Island, and copper and selenium concentrations near Myuna Bay and Wyee Bay.
- Concentrations of copper, lead and zinc observed in the newly deposited sediments were generally lower than those measured in the surface sediment for those hotspot regions, whereas the concentrations of arsenic and mercury were similar in magnitude to the surface sediments for those hotspot regions.
- Selenium showed marginally greater concentrations in the newly deposited sediments than the surface sediments. Selenium is potentially being adsorbed from the water column onto suspended particles and transported around the lake. While this might suggest an increase

in surface sediment concentrations across the lake with time, previous research indicates that selenium concentrations within the sediment have reduced over time, partly due to selenium volatilisation and bioturbation (Maher et al., 2022).

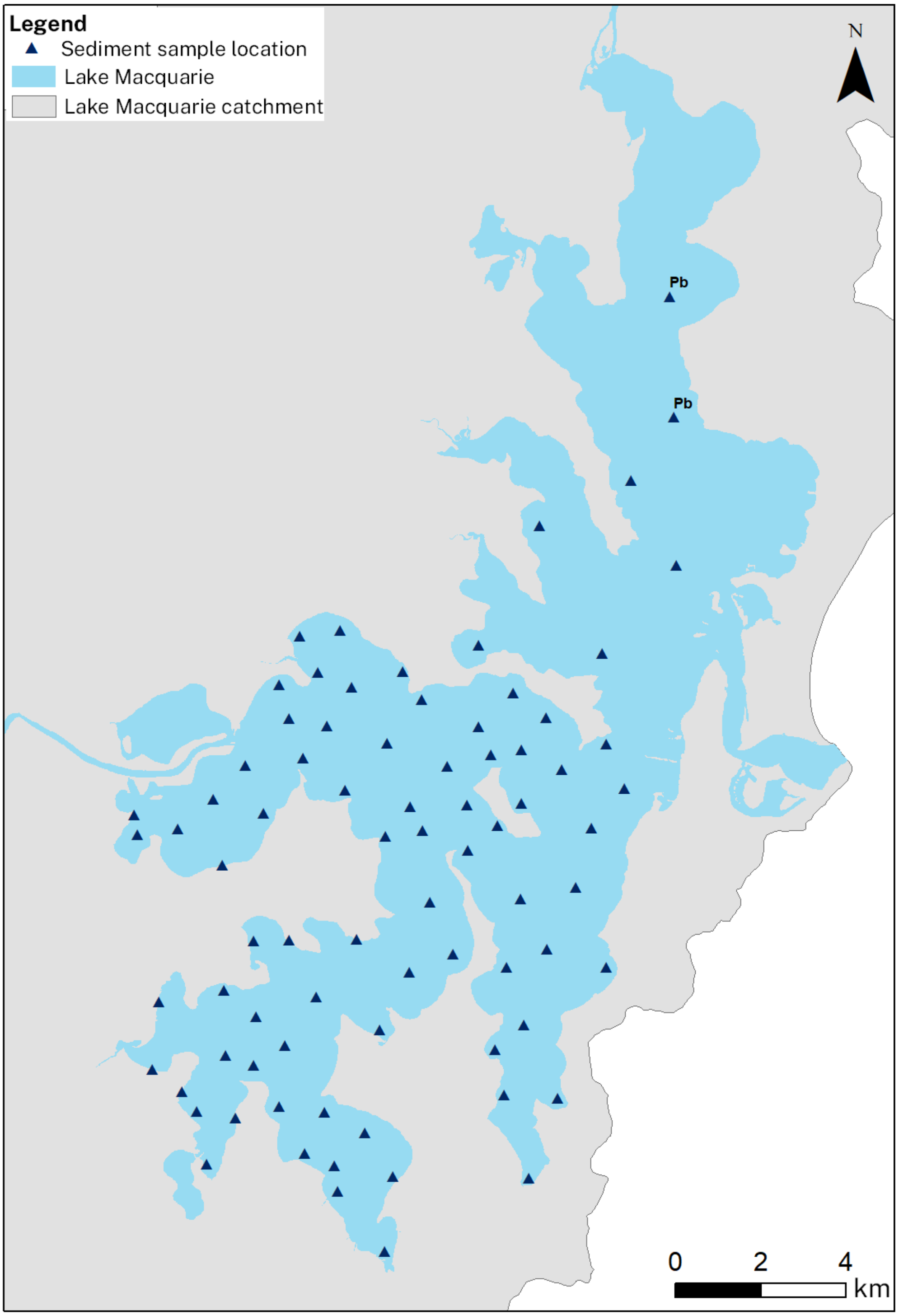

Figure 5. Map of the Lake Macquarie surface sediment sampling locations (blue triangles). The sites where the total recoverable metal concentration and the dilute acid-extractable metal concentration (the estimated bioavailable fraction) exceeded the screening criteria (ANZG, 2018) are labelled with the analyte that exceeded (Pb = lead)

2.2.3 Toxicity line of evidence

The investigation of surface sediment toxicity is detailed in the *Toxicity assessment report*. The toxicity assessment method chosen was the 10-day whole sediment acute (mortality) and chronic sub-lethal (reproduction) toxicity test using the epibenthic amphipod *Josephosella plumulosa*, previously known as *Melita plumulosa* (Zeidler, 1989).

Summary of findings:

- No acute toxicity to *J. plumulosa* was observed in any of the ten test sediments (i.e., there was >80% survival of adult organisms across all test sediments).
- Low-level chronic toxicity to *J. plumulosa* (20-50% effect relative to the control) was observed in two of the 10 test sediments (Sites 6 and 9) when reproductive output was compared to the control sediments (Figure 6). The differences observed at these two sites were, however, not significantly different from the other test sediments collected within Lake Macquarie.
- No toxic effects were observed on the test organisms located closest to the Eraring Power Station and the Vales Point Power Station discharge outflows.
- No relationships between reproductive output and metal concentrations of the sediment or porewater were found.
- The lower reproductive output of the test organisms exposed to sediments from Sites 6 and 9 may be due to differences in abiotic factors (such as the sediment's physical properties, an unmeasured chemical, or the availability of food and nutrients for the test organism) between the Lake Macquarie test sediments and the control sediments.

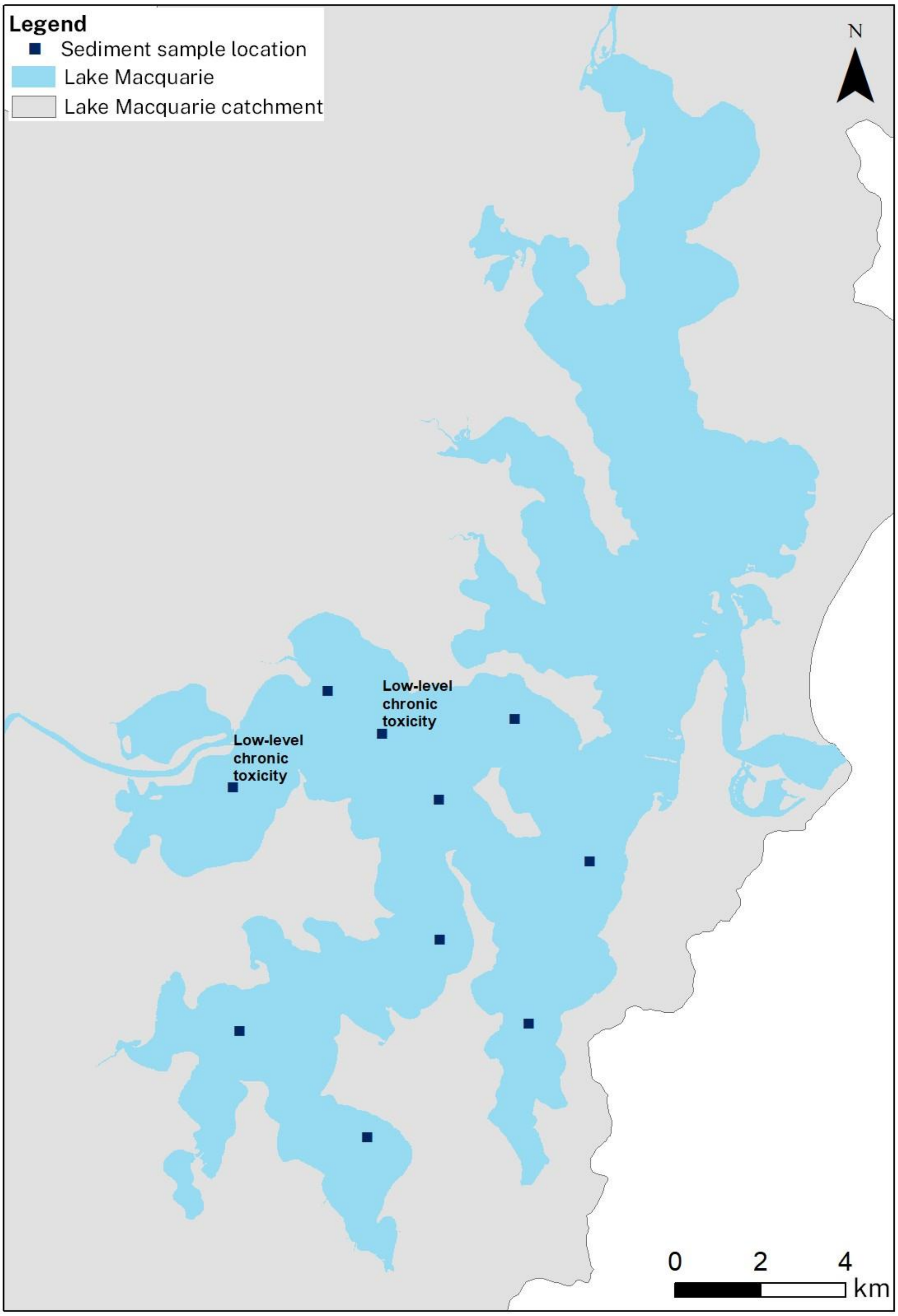

Figure 6. Map of the Lake Macquarie surface sediment sampling locations (blue squares) for toxicity testing using the 10-day amphipod bioassay. The sites where a toxic response (relative to the control) was measured are labelled.

2.2.4 Ecology line of evidence

The ecological assessment is detailed in the *Benthic community composition report*. It involved the parallel use of traditional and DNA-based identification methods of the benthic community from 10 sediments collected within the southern section of Lake Macquarie. The study targeted five locations (Sites 1 to 5) with the highest total recoverable metal concentrations as identified in the *Surface sediment quality report* and paired them with five site-specific reference sites (Sites 6 to 10) located nearby with similar sediment physicochemical properties but lower total recoverable metal concentrations.

The traditional method identified and quantified macrofauna (>500 µm) present, while the DNA-based method used primers to target the sediment's eukaryotic (18S rRNA gene), bacterial (16S rRNA gene), and archaeal (A 16S gene) community profiles. The findings for the macrofauna and eukaryotic communities have been integrated into the weight-of-evidence assessment due to their widely recognised status as indicators of sediment quality and ecosystem health. Well-established biological metrics exist for identifying contaminant-impacted environments based on the sensitivity or tolerance of certain groups of macrofauna/eukaryotes to contaminants. The use of eDNA for bacterial and archaeal communities is still an emerging area of research, with ongoing efforts to refine its application within established environmental monitoring frameworks. The study has provided important insights into the microbial communities present in Lake Macquarie and a dataset that can be used to further refine interpretive frameworks for making ecologically meaningful conclusions.

The biological metrics used in the current study included:

- Taxon richness – the number of taxa present. High diversity typically indicates a healthy environment.
- Abundance – the population size of each species within the community. Differences in the number of individuals present between sites can signal environmental changes.
- Functional group analysis – the presence/absence of different groups of organisms can be an indicator of environmental change or disturbance. For example, it is generally understood that certain groups of macrofauna, such as Molluscs, Amphipods, Diatoms, and Dinoflagellates, which are sensitive to contaminants, would decrease in number if contaminants are having an impact on communities (Dafforn et al., 2013, Suzzi et al., 2023). Conversely, groups of macrofauna tolerant to contaminants, such as Annelids, Polychaetes, and Nematodes, would increase.
- Community structure – quantifies the compositional differences between communities based on the presence and abundance of species. This metric is sensitive to changes in both the presence/absence and abundance of species that can signal environmental changes.

The macroinvertebrate community

- A total of 34 taxa from nine different phyla were identified across the 10 sites. The most abundant phyla were Molluscs, Annelids, Arthropods, and Nematodes.
- No clear trends in taxon richness were observed. Significant effects on total abundance were observed for two pairings which had greater total abundance at sites of interest compared to the reference sites (Site 1>6 and 5>10).
- Analysis of the most abundant phyla, Molluscs and Annelids, found no consistent pattern between sites and years.
- No consistent differences in community structure were found between 2023 and 2024.

Eukaryotic community

- A total of 8,959 eukaryotic ASVs (137 eukaryotic phyla) were found across the 10 sites. Considering only the phyla identified using the traditional technique, Annelids and Arthropods were the dominant invertebrate taxa in the eukaryotic community.
- No clear trends in taxon richness, total abundance, Annelid abundance, Mollusc abundance, Dinoflagellata abundance, or Nematode abundance were identified.
- Trends in Bacillariophyceae (diatom) abundance (Site 5>10) and Dinophyceae (dinoflagellate protists) abundance (Site 3<8 and 4>9) were identified for both 2023 and 2024.
- Differences in community structure were found for both 2023 and 2024 for three of the pairings (Site Pairings 1 and 6, 2 and 7, and 3 and 8). Patterns of difference varied depending on the pairing, with no consistent trends between sites of interest and reference sites, suggesting differences were driven by natural spatial variation.

Overall, there was significant temporal and spatial variability in the indicators assessed, with patterns in tolerant and sensitive species not indicative of a significant impact from metal contamination.

2.2.5 Sediment quality weight-of-evidence assessment

In this sediment quality weight-of-evidence assessment, a semi-quantitative approach using the scoring system of three levels of effect (none, moderate, or high) was adopted as recommended for Australia and New Zealand (Simpson et al., 2013; Simpson and Batley, 2016) (Table A1). The scores for each line of evidence are tabulated in a decision matrix with typical examples of its application shown in Table A2. This approach was selected to provide transparency in how the multiple lines of evidence were integrated.

The southern section of the lake has been designated into numbered regions (based on the sampling locations) for the purpose of the assessment (Figure 7). By breaking up the southern section into regions, the assessment can provide a more nuanced understanding of the variations in sediment chemistry, as well as the potential ecological impacts within different areas of the lake.

A summary of the results from the various lines of evidence are presented in Section 2.2. The tabulated scores and weight-of-evidence decision matrix are presented in Table 1.

The main finding of the weight-of-evidence assessment of sediment quality within the southern section of Lake Macquarie was that the screening criteria (ANZG, 2018; Buchman, 2008) were not exceeded based on bioavailable contaminant assessment and no significant effects due to metals were observed on the ecosystem.

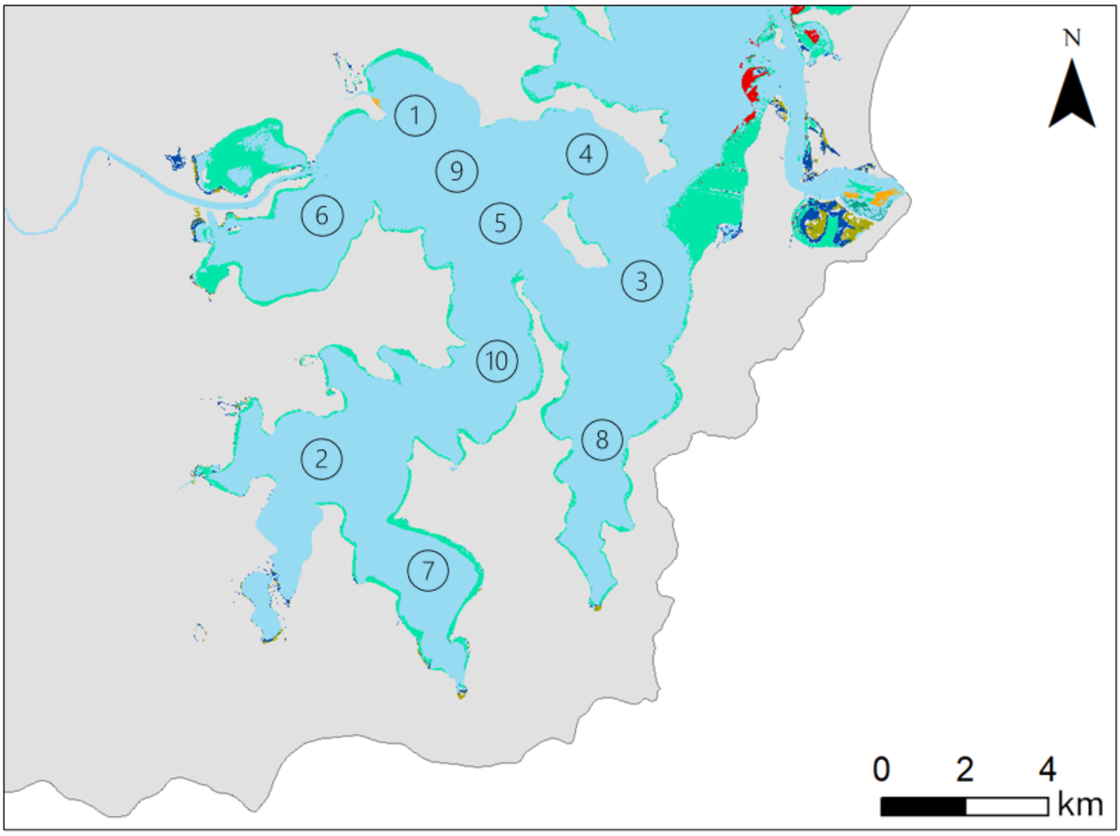

Figure 7. Map of the southern section of Lake Macquarie with key regions indicated: 1. Myuna Bay; 2. Wyee Point – Bluff Point; 3. East Pulbah Island; 4. North Pulbah Island; 5. West Pulbah Island; 6. Bonnells Bay; 7. Chain Valley Bay; 8. Gwandalan – Nords Wharf; 9. Fig Tree Point – Goonda Point; and 10. Fishery Point – Point Wolstoncroft.

Table 1. Weight of evidence assessment of ecological risk for the southern section of Lake Macquarie

Line of evidence		Line of evidence score by region of the lake*										Comment
		①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	
Sediment chemistry	Stage 1 sampling Stage 2 sampling Stage 3 sampling	1	1	1	1	1	1	1	1	1	1	All samples collected within the southern section of Lake Macquarie had estimated bioavailable concentration below the screening criteria†. Concentrations of metals measured in the newly deposited sediments were generally lower than or similar in magnitude to those measured in the surface sediment of the same region.
Toxicity	Amphipod bioassay	1	1	1	1	1	2	1	1	2	1	Low-level chronic toxicity was seen at two sites (Sites 6 and 9). This adverse effect was relative to the control but not significantly different from any of the sites investigated within southern Lake Macquarie. No relationship between metal concentration and toxicity was found, which suggests an abiotic factor (such as the sediment's physical properties, an unmeasured chemical, or the availability of food and nutrients) could be contributing to the ecological effects observed.
Ecology	Macroinvertebrates Eukaryotic community	1	1	1	1	1	1	1	1	1	1	Significant temporal and spatial variability in the indicators assessed was observed, with no clear patterns in tolerant or sensitive species observed for the regions of the lake investigated. Changes observed were likely not indicative of a significant impact from metal contamination.
	Weight of evidence score	1	1	1	1	1	1§	1	1	1§	1	1 = No sites exceeded guideline values and no effects on the ecosystem were observed 1§ = Toxic effects due to unmeasured contaminant(s) or an unidentified stressor

* Region of the lake: 1. Myuna Bay, 2. Wyee Point – Bluff Point, 3. East Pulbah Island, 4. North Pulbah Island, 5. West Pulbah Island, 6. Bonnells Bay, 7. Chain Valley Bay, 8. Gwandalan – Nords Wharf, 9. Fig Tree Point – Goonda Point, and 10. Fishery Point – Point Wolstoncroft.

† ANZG (2018) for antimony, arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc; Buchman (2008) for Se.

3. Conclusions

The current study of surface water and sediment quality in the vicinity of power stations and coal ash repositories in Lake Macquarie began with an assessment of the chemistry line of evidence. Additional lines of evidence to further investigate sediment quality were included, including ecotoxicology and benthic ecology, which were considered along with the sediment chemistry in a weight-of-evidence framework.

In summary, the main findings of the assessment were as follows:

Water quality

- Elevated temperatures (of as much as 5 to 10°C) were observed within the Eraring Power Station's and Vales Point Power Station's cooling water outlet canals, as well as their nearby receiving waters.
- The total nitrogen and total phosphorus concentrations in the lake were below guideline values for NSW estuaries, but some inorganic, potentially more bio-available forms of nitrogen and phosphorus were elevated in certain areas (e.g., Wyee Bay, Bonnells Bay, and Myuna Bay). The guidelines are based on measurements from relatively undeveloped lake basins and suggest that development in the Lake Macquarie catchment has affected nutrient loads entering the lake. However, the lake basin seems to be relatively resilient to nutrient enrichment.
- The concentrations of eight metals (cadmium, chromium, lead, mercury, nickel, selenium, silver, and vanadium) were below the screening criteria for all surface water samples collected. Seven metals (aluminium, arsenic, cobalt, copper, manganese, molybdenum, and zinc) had at least one exceedance during the monitoring program. Arsenic, cobalt, and molybdenum concentrations were below the screening criteria on ≥99% of all occasions and were not considered contaminants of concern in surface waters. Aluminium, copper, manganese, and zinc exceeded the screening criteria at some sites, indicating potential concerns. However, they were below the criteria on 96%, 78%, 99%, and 96% of all sampling occasions, respectively. Localised exceedances of aluminium, zinc, and manganese appear to stem from freshwater inflows carrying these contaminants from the surrounding catchment (via Dora Creek and Wyee Creek in the southern section of the lake) into the southern part of the lake. However, within the lake basin, the concentrations of these metals are largely reduced to levels below the screening criteria. Copper concentrations were low and relatively consistent across the lake typical of diffuse sources.
- The Power Station's coal ash repositories/return waters are a reservoir for some metals and nutrients, however, discharges to Lake Macquarie are rare as water is recirculated and reused under normal operating conditions. There was no evidence of adverse impacts on water in Lake Macquarie as a result of the presence of metals and nutrients within the coal ash repositories/return waters.

Sediment quality

- The weight-of-evidence assessment of sediment quality demonstrated that all of the samples collected from the southern section of Lake Macquarie, were below the screening criteria (ANZG, 2018; Buchman, 2008), based on bioavailable contaminant assessment, and no significant effects due to metals were observed on the ecosystem.
- Two sites in the northern section of the lake exceeded the SQGV for lead (ANZG, 2018) based on the dilute acid-extractable metal concentrations. This suggests that lead remains at a level of concern to ecosystem health within the northern section of Lake Macquarie.

Further investigation of metals of concern within the northern section of the lake was outside the scope of this investigation.

- Comparisons of the surface sediment quality data (top 5 cm, collected in 2022) with historical sediment quality data (top 5 cm, collected in 2011) and newly depositing sediment quality data (collected in sediment deposition traps) suggest that sediment metal concentrations within the southern section of Lake Macquarie have shown a marked reduction overtime (especially arsenic, cadmium and selenium) or have remained the same.
- Comparisons of the surface sediment quality data (top 5 cm, collected in 2022) with historical sediment quality data (top 5 cm, collected in 2011) showed a marked reduction in selenium concentrations; arsenic and cadmium concentrations were mostly lower or remained similar; while copper, lead, and zinc were lower or remained similar in all areas except for the northeast corner of the southern lake and surrounding Pulbah Island where higher concentrations were observed in 2022 compared to those measured in 2011.
- Comparisons of the surface sediment data (top 5 cm, collected in 2022) and newly depositing sediment data (collected in sediment deposition traps) found that concentrations of copper, lead and zinc were lower in the newly deposited sediment than in the surface sediments, whereas the concentrations of arsenic and mercury were similar in magnitude to the surface sediments for hotspot regions. The newly deposited sediments showed a marginal increase in selenium compared to the surface sediments. Selenium is potentially being adsorbed from the water column onto suspended particles and transported around the lake. While this might suggest an increase in surface sediment concentrations across the lake with time, previous research indicates that selenium concentrations within the sediment have reduced partly due to selenium volatilisation and bioturbation.

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5. Appendix – Weight-of-evidence ranking

Table A1. Weight-of-evidence scoring system adopted for Australia and New Zealand sediment quality assessments (adapted from Simpson et al., 2013; Simpson and Batley, 2016)

Line of evidence	Ranking of effects		
	3 (high)	2 (moderate)	1 (none)
Water chemistry	Concentration >WQG HC10	WQG HC5 < Concentration <WQG HC10	Concentration <WQG HC5
Sediment Chemistry			
Sediment	Concentration >SQGV-high	Concentration >SQGV <SQGV-high	Concentration <SQGV
Porewater	Concentration >WQG HC10	WQG HC5 < Concentration <WQG HC10	Concentration <WQG HC5
Toxicity	≥50% effect v. control	20-50% effect v. control	<20% effect v. control
Bioaccumulation	Significantly different (P< 0.05) and >3 x control	Significantly different (P< 0.05) and ≤3 x control	Not significantly different from control
Ecology	Significant and high effects on abundance and/or diversity	Significant but moderate effects on abundance and/or diversity	No significant effects on abundance and/or diversity
Biomarkers	Significantly different from the control	Moderate but significant difference from control	Not significantly different from control
Other lines of evidence	An appropriate ranking of effects		
Weight-of-evidence	Significant adverse effects	Possible adverse effects	No adverse effects

SQGV = lower sediment quality guideline value; SQGV-high = upper sediment quality guideline value; HC10 = concentration that is hazardous to 10% of species; HC5 = concentration that is hazardous to 5% of species; WQG = water quality guideline

Table A2. Examples of semi-quantitative ranked weight-of-evidence decisions

Case	Line of evidence				Weight-of-evidence score	Overall assessment
	Chemistry (metals, organics)	Toxicity	Bioaccumulation	Ecology		
1	3	3	2 or 3	3	**3**	Significant adverse effects from sediment contamination
2	3	3	2 or 3	2	**3**	Significant adverse effects from sediment contamination
3	2 or 3	3	2	2	**3**	Significant adverse effects from sediment contamination
4	2 or 3	2	1 or 2	2	**2**	Possible adverse effects from sediment contamination
5	2	2 or 3	1 or 2	2	**2**	Possible adverse effects from sediment contamination
6	2	2	1 or 2	2 or 3	**2**	Possible adverse effects from sediment contamination
7	2 or 3	2 or 3	2 or 3	1	**2**	Toxic chemical is stressing the system but resistance may have developed at community level
8	1	2 or 3	1	2 or 3	**2**	Possibility of unmeasured toxic chemicals causing effects on communities
9	1	2 or 3	1	1	**2**	Unmeasured physical or chemical causes of toxicity
10	2 or 3	1	1	2 or 3	**2**	Chemicals are not bioavailable or community change may not be due to chemicals
11	1	1	1	2 or 3	**1**	Changes probably not due to measured contaminants
12	1 or 2	1	1 or 2	1	**1**	No adverse effects
13	1	1	1	1	**1**	No adverse effects
14	2 or 3	1	1	1	**1**	Contaminants unavailable

6. Acknowledgements

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