Gladstone Healthy Harbour Partnership

Water and Sediment Quality Indicators for the Gladstone Harbour Report Card 2017

Disclaimer

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Gladstone Healthy Harbour Partnership partners

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Executive Summary

Water and sediment quality are important and interconnected aspects of the harbour ecosystem. A healthy water and sediment system sustain the health of a large number of aquatic species, including fish, turtles, dugongs, seagrass, mangroves and benthic invertebrates. Catchment-related, anthropogenic and climatic factors play a major role in determining the water and sediment quality recorded in the harbour.

The water and sediment quality of Gladstone Harbour is reported annually in the Gladstone Harbour Report Card. The report card describes the environmental health of 13 reporting zones in and around Gladstone Harbour and the overall social, cultural and economic health of the harbour. The 2017 report card covers monitoring undertaken in the period 1 July 2016 to 30 June 2017.

The water and sediment quality indicators contribute to the overall environmental score and are based on data collected by the Port Curtis Integrated Monitoring Program (PCIMP) and used in the report card under a data sharing agreement with the Gladstone Healthy Harbour Partnership (GHHP).

Throughout the report card indicator scores range between 0.00 and 1.00 and are converted into grades ranging from A to E (Figure 1).

A **Very good** (0.85 – 1.00)

B **Good** (0.65 – 0.84)

C **Satisfactory** (0.50 – 0.64)

D **Poor** (0.25 – 0.49)

E **Very poor** (0.00 – 0.24)

Figure 1: Grading scheme used to convert scores to grades in the 2017 Gladstone Harbour Report Card for each component of harbour health.

In 2017 the water and sediment quality indicator group received a score of 0.87 (A). The water quality indicator received a score of 0.78 (B) and sediment quality a score of 0.95 (A). These grades were consistent with the grades received in 2015 and 2016 when water and sediment quality also received grades of B and A respectively.

Water quality was relatively uniform across the harbour and all zones received good or very good scores except for Boat Creek which received a satisfactory score (Table 1). Similar to 2016, water quality received a B, although the overall score (0.78) improved from 2016. The scores for nutrients improved in 10 of the 13 harbour zones. The scores for dissolved metals remained very good in all zones.

Table 1: Overall water quality indicator scores for Gladstone Harbour zones (2015–2017).

Water quality	Physico-chemical score	Nutrients score	Dissolved metals score	Zone score 2017	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.76	0.44	0.93	0.71	*0.68*	*0.82*
2. Graham Creek	0.99	0.69	0.94	0.88	*0.75*	*0.86*
3. Western Basin	0.74	0.64	0.93	0.77	*0.70*	*0.82*
4. Boat Creek	0.58	0.32	0.89	0.59	*0.58*	*0.70*
5. Inner Harbour	0.76	0.69	0.95	0.79	*0.78*	*0.88*
6. Calliope Estuary	0.68	0.70	0.94	0.77	*0.71*	*0.86*
7. Auckland Inlet	0.83	0.60	0.94	0.79	*0.71*	*0.77*
8. Mid Harbour	0.85	0.59	0.95	0.79	*0.77*	*0.80*
9. South Trees Inlet	0.91	0.68	0.95	0.84	*0.79*	*0.85*
10. Boyne Estuary	1.00	0.53	0.95	0.83	*0.71*	*0.70*
11. Outer Harbour	1.00	0.74	0.95	0.90	*0.72*	*0.84*
12. Colosseum Inlet	1.00	0.55	0.95	0.83	*0.73*	*0.78*
13. Rodds Bay	0.80	0.50	0.95	0.75	*0.73*	*0.80*

Similar to 2016 and 2015, sediment quality scores were uniformly very good (A) across all Gladstone Harbour reporting zones. This is a result of low concentrations of all measures (arsenic, cadmium, copper, lead, nickel, mercury and zinc) (Table 2). Sediment mercury levels were assessed for the first time in 2017.

Table 2: Sediment quality indicator scores for Gladstone Harbour zones (2015–2017).

Sediment quality	Zone score 2017	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.92	*0.92*	*0.94*
2. Graham Creek	0.92	*0.96*	*0.98*
3. Western Basin	0.97	*0.98*	*0.99*
4. Boat Creek	0.98	*0.90*	*0.96*
5. Inner Harbour	0.93	*0.94*	*0.98*
6. Calliope Estuary	0.94	*0.99*	*0.98*
7. Auckland Inlet	0.87	*0.94*	*0.94*
8. Mid Harbour	0.95	*0.97*	*0.99*
9. South Trees Inlet	0.98	*0.95*	*0.96*
10. Boyne Estuary	0.97	*0.98*	*1.00*
11. Outer Harbour	0.97	*0.96*	*0.96*
12. Colosseum Inlet	0.99	*1.00*	*1.00*
13. Rodds Bay	0.95	*0.99*	*0.98*

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1. Introduction

Water and sediment quality are important and interconnected aspects of the harbour ecosystem. A healthy water and sediment system sustain the health of a large number of aquatic species, including fish, turtles, dugongs, seagrass, mangroves and benthic invertebrates. Catchment-related, anthropogenic and climatic factors play a major role in determining the water and sediment quality recorded in the harbour.

1.1. Gladstone Harbour

Gladstone Harbour is located in central Queensland just below the Tropic of Capricorn and approximately 500 km north of Brisbane. The regions climate is sub-tropical with an average maximum temperature of 27°C and an average minimum of 18°C. Consistent with a sub-tropical climate, the summer months are generally wetter than the winter months, although rainfall patterns can be highly variable.

Gladstone Harbour is the largest port in Queensland and the fifth largest multi-commodity port in Australia. In the 2016–17 financial year it was visited by 1,908 ships for a total throughput of 121.2 million tonnes. Major cargos handled by the harbour include coal, liquefied natural gas (LNG), bauxite, alumina and aluminium (GPC, 2018). Located on the southern side of the harbour, the city of Gladstone is an industrial hub of international significance owing to its large-scale production and export facilities. In 2016 the Gladstone region had a population of 67,426 (Gladstone Regional Council, 2017).

The Port Curtis estuary is a composite system that includes the estuaries of the Calliope and Boyne rivers; Graham, Boat and Auckland creeks; and several other smaller creeks and inlets. At the northern end of the system The Narrows provides a linkage between the Fitzroy River Delta and Gladstone Harbour. The harbour itself is naturally deep, with water depths of up to 18.3 m occurring at the southern entrance and depths in the Mid Harbour and the northern sector of 5 to 9 m. The depth of the jetty at Auckland Inlet was recorded at 34 ft (10.4 m) at high water when construction was completed in 1885 (Duke et al., 2003).

1.2. Factors affecting water quality

Flushing rate

The flushing rate is an important physical characteristic of an estuary determining the dispersion of contaminants (Apte et al., 2005). Higher flushing rates result in shorter flushing times, the time required to replace the fresh water contained in the estuary with freshwater inflow. In 2015, a hydrodynamic model of Gladstone Harbour was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to describe water movements within the harbour and exchanges with surrounding waters. Using this three-dimensional hydrodynamic model, CSIRO determined flushing rates and flushing times of 11 monitoring zones (Condie et al., 2015). Flushing rate was calculated by plotting the number of particles initially within a zone that were retained within that zone over time. An exponential decay curve was then fitted and the e-folding time (flushing time) estimated from the curve. E-folding time is the time for the number of particles to decrease to 1/e or 36.8% of their initial value.

The flushing rates were generally high in the estuaries (e.g. Calliope and Boyne estuaries) and low in the harbour zones (e.g. Western Basin, Inner Harbour, Mid Harbour and Outer Harbour) (Figure 1.1). Values ranged from 0.24 per day in Western Basin to 0.91 in Calliope Estuary, which correspond to flushing times of 4.2 and 1.1 days respectively. However, flushing times were highly variable and within any single 20-day period ranged between 0.53 and 7.1 days. In general, estuarine zones were more variable than harbour zones (Condie et al., 2015).

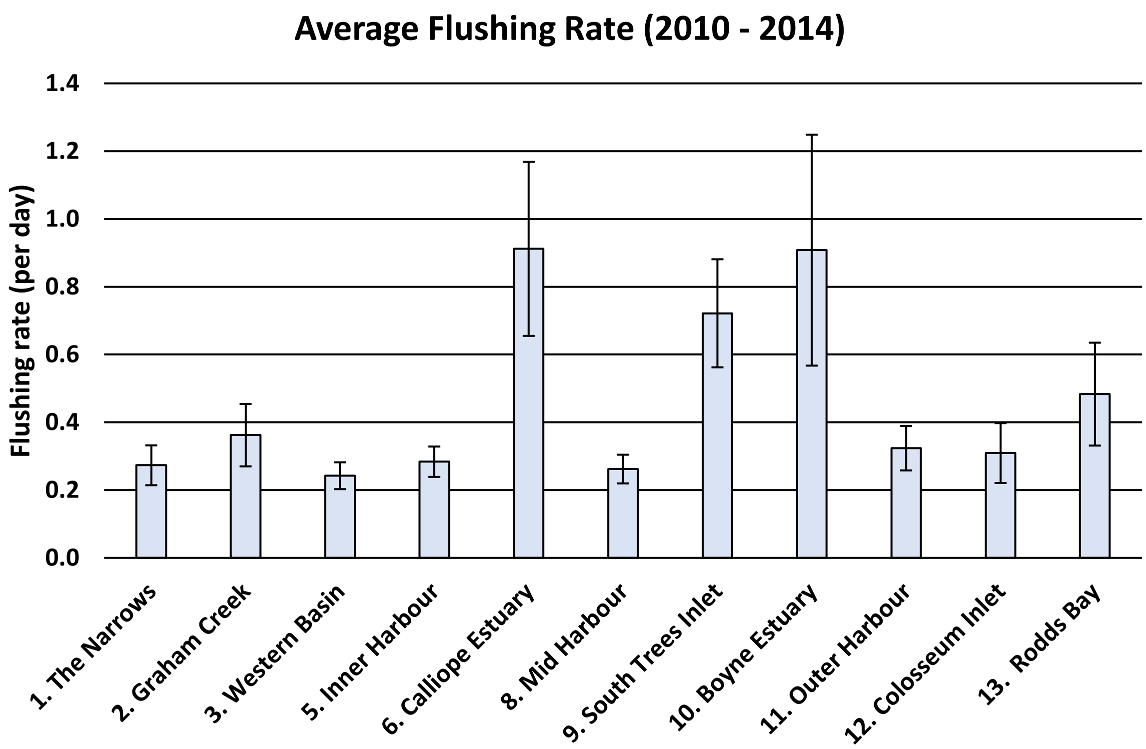

Figure 1.1: Four-year average flushing rates for 11 Gladstone Harbour monitoring zones. The flushing rate was calculated as the average of 20-day time slices over the four-year period. The error bars indicate ± one standard deviation (Source Condie et al., 2015).

Freshwater inflows

Average annual rainfall for Gladstone is 894 mm (BOM data). Gladstone Harbour is bordered by five drainage basins, the Fitzroy (142,545 km^2), the Calliope (2,241 km^2), the Boyne (2,496 km^2), Curtis Island (577 km^2) and Baffle Creek (4,085 km^2) (Queensland Government, 2016) (Figure 1.2). The predominant land use within these catchments is grazing with smaller areas of natural vegetation, dryland cropping and irrigated cropping.

The two major sources of freshwater flow into Gladstone Harbour are the Boyne River that discharges into the Mid Harbour and the Calliope River that discharges into the Western Basin. Streamflow in the

Boyne River is highly modified owing to the presence of Awoonga Dam, whereas flow in the Calliope River is relatively unmodified. Since European settlement, significant changes in land use in both catchments have resulted in increased sediment and nutrient loads into the Port of Gladstone (DSEWPaC, 2013). Freshwater flows may also enter the harbour via The Narrows when the Fitzroy River floods.

While Port Curtis generally has salinities ranging from 30 to 35 ppt, fresh water inflows such as wet season storms can reduce salinities (Apte et al., 2005) within the harbour and increase the flushing rates in estuarine zones (Gorton et al., 2017). Reduced salinity levels from freshwater run-off in flood plumes is a recognised cause of coral mortality. Major flooding of the Boyne and Calliope rivers, a result of heavy rainfalls associated with Tropical Cyclone Oswald in January 2013, temporarily lowered salinity levels within Gladstone Harbour. The sustained low levels are likely to have caused high coral mortality within the harbour (Thompson et al., 2016). Berkelmans et al. (2012) demonstrated a salinity threshold for *Acropora* (e.g. staghorn and elkhorn corals) of 22 psu for three days; beyond this threshold mortality can be expected.

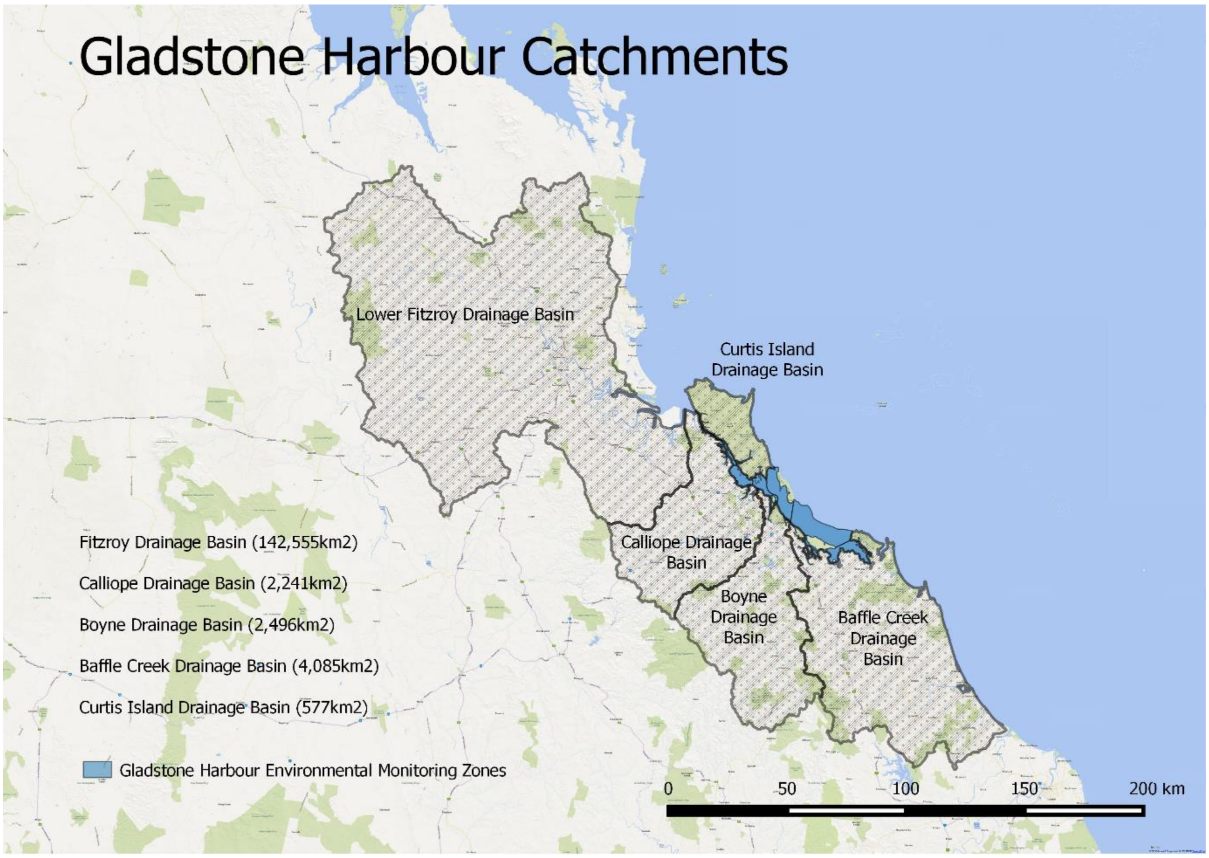

Figure 1.2: Drainage basins surrounding Gladstone Harbour.

Catchment run-off

Catchment run-off can strongly influence water quality within estuarine systems. It is a major source of sediments, nutrients and pesticides delivered to marine waters (Bartley et al., 2017). Land use within a catchment will influence the type and volume of material exported from that catchment. Suspended sediments are dominated by grazing inputs, while pesticides are sourced from dryland and irrigated cropping and grazing lands (Dougall et al., 2014). Catchment pollutant load exports are modelled for the 35 major basins that discharge into the Great Barrier Reef Lagoon including the

Boyne, Calliope and Fitzroy rivers (McCloskey et al., 2017). Modelling is used to isolate changes to water quality resulting from changes in land management practices. The pre-development model is representative of a pre-agricultural development scenario while the baseline model is reflective of the baseline management practice for 2012/13. Average annual loads reported for both pre-development and baseline scenarios were estimated over the model run period of July 1986 – June 2014. The modelled data show increases in a range of parameters from the pre-development load compared to the baseline load (McCloskey et al., 2017; Table 1.1). For example, the modelled average annual loads of fine sediments from the Calliope River increased to 57,000 tonnes per year in the baseline scenario from a pre-development load of 7,000 tonnes per year (approximately an 8-fold increase).

Table 1.1: Modelled pre-development and baseline catchment load exports from the Boyne and Calliope catchments (McCloskey et al., 2017).

Catchment	Pre-development load	Baseline load (2012/13)	Increase factor from pre-development load to baseline load
Total fine sediments (kilo-tonnes per year)			
Boyne River	8	24	3.0
Calliope River	7	57	8.1
Total phosphorous (tonnes per year)			
Boyne River	76	105	1.4
Calliope River	74	281	3.8
Particulate phosphorus (tonnes per year)			
Boyne River	48	60	1.3
Calliope River	41	221	5.4
Total nitrogen (tonnes per year)			
Boyne River	195	266	1.4
Calliope River	208	639	3.1
Particulate nitrogen (tonnes per year)			
Boyne River	90	113	1.3
Calliope River	81	439	5.4
PSII herbicides toxic equivalent load (kilograms per year)			
Boyne River	0	1	NA
Calliope River	0	2	NA

Sediments

Port Curtis is a macro-tidal estuary with large barotropic tides. Tides undergo a neap-spring cycle with a period of approximately 14 days, with a spring tide range of ~4 m and a neap tide range of ~1 m. The large tides ensure that the water column is well mixed and are responsible for significant resuspension of fine sediments (Figure 1.3). In conjunction with a high degree of sediment movement into the harbour during floods, the estuarine areas generally remained turbid (Condie et al., 2015). Fine sediments (silt and clays) can also become a sink for metals and nutrients within waterways as they have a net negative charge, while metals and nutrients are positively charged. When resuspended these fine sediments can become a source of metals and nutrients.

Within Gladstone Harbour the highest proportions of fine sediments (<63µm) are recorded in estuarine zones such as Auckland Inlet and Graham Creek while more oceanic zones such as the Outer Harbour and Mid Harbour have sediments with very low proportions of fine sediments (Figure 1.4).

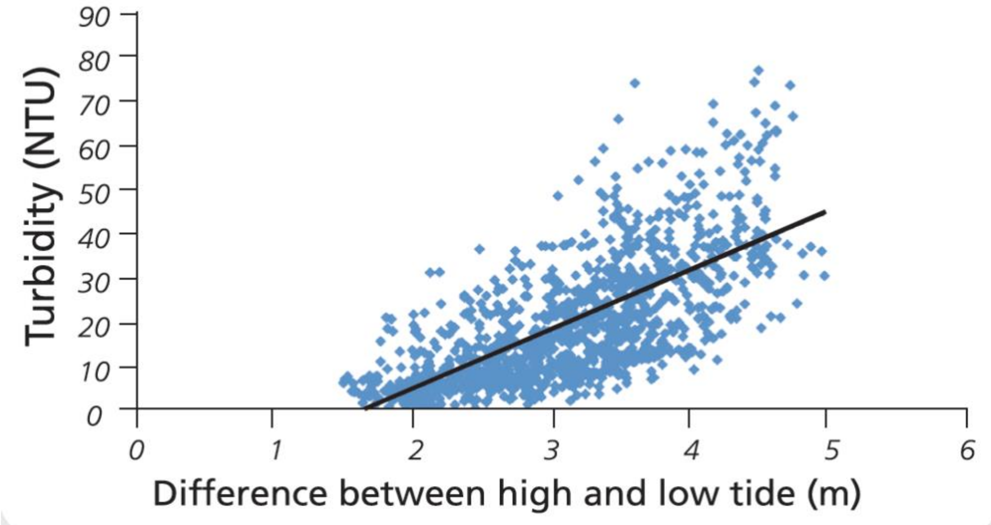

Figure 1.3: The relationship between tidal movement and turbidity in Gladstone Harbour (DEHP 2014 personal communication). NTU: Nephelometric Turbidity Unit.

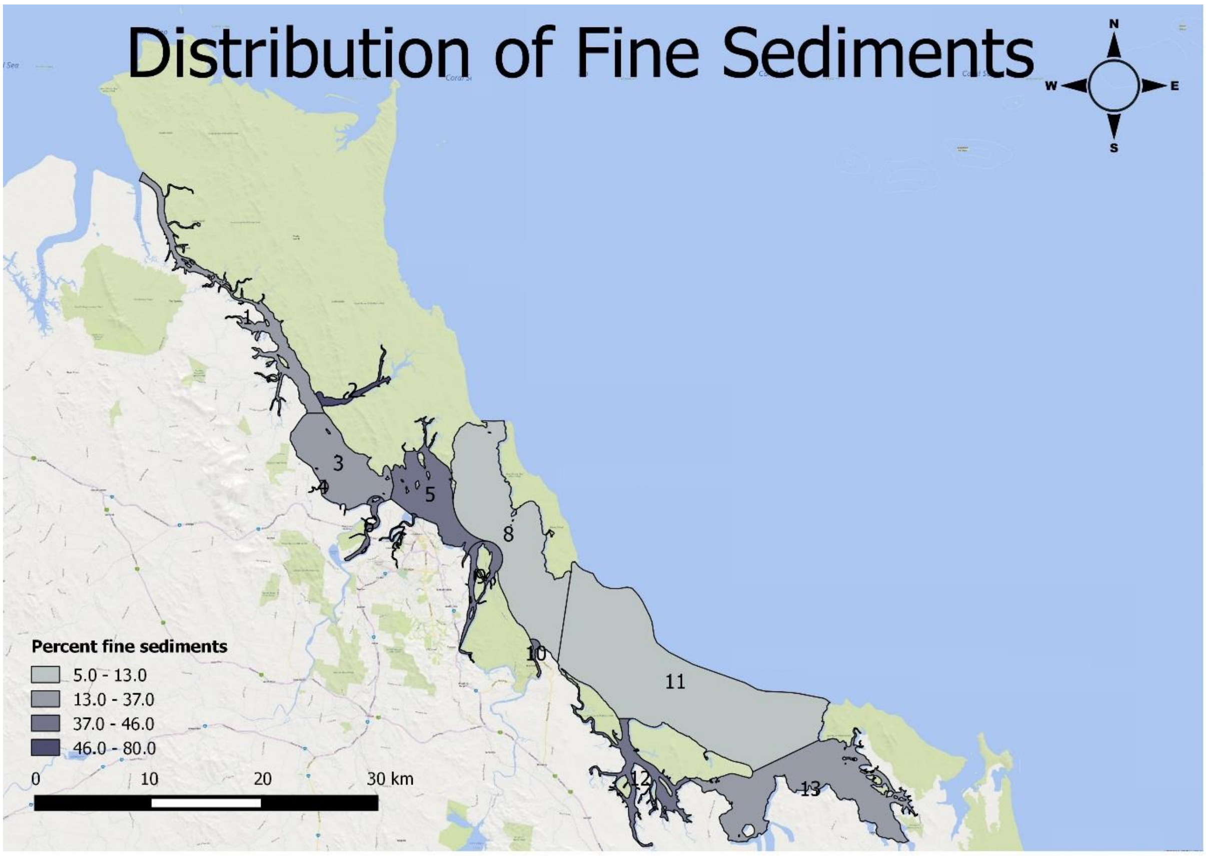

Figure 1.4: Average percentage of fine sediments (<63 µm) within sediment samples from the 13 Gladstone Harbour environmental monitoring zones on 17 June 2017. Fine sediment classifications were generated in QGIS™ using the Jenks natural breaks optimization function. This method reduces the variance within classes and maximizes the variance between classes. Percent fine sediment classes: 5.0 - 13.0 (zones 8, 11); 13.0 - 37.0 (zones 1, 3, 4, 13); 37.0 – 46.0 (zones 5, 6, 9, 10, 12); 46.0 - 80.0 (zones 2, 7).

Discharge from portside industries

Gladstone is a major industrial centre that accommodates a number of portside industries including an aluminium refinery and smelter, chemical plants, three LNG Plants, a cement production works and Queensland's largest coal-fired power station. The National Pollutant Inventory (www.npi.gov.au) provides annual loads of toxic substances discharged into the air and waterways reported by individual facilities. In the 2016–17 reporting year there were 28 reporting facilities, 20 which listed air emissions and 8 which listed air and water emissions. Discharges into waterways included 25 reportable chemical compounds (Table 1.2). Fluoride compounds represented the greatest volume of discharge (~160,000 kg) followed by the nutrients, total nitrogen (~130,000 kg), total phosphorus (~14,000 kg) and ammonia (~4,000 kg).

Table 1.2: Annual loads (2016–17) from eight industrial facilities as reported to the National Pollutant Inventory (www.npi.gov.au). Total annual loads rounded to two significant figures.

	Substance (including compounds)	Annual Load (kg)								Total Annual Load (kg)
		RGT	BS	WIC	RTY	QAL	OY	GPS	GT	
Metals and Metalloids	Antimony			0.03						0.03
	Arsenic			0.06	273	465	7.96	4.61		750
	Beryllium			0.009						0.009
	Boron			0.06						0.06
	Cadmium	0.08	0.26	0.002	18.8	1.58	0.04			21
	Chromium	0.18	1.96	0.04	68.5		3.81			3.8
	Cobalt			0.05		2.86				2.9
	Copper	0.53	9.13	0.1		1.79	9.29			11
	Lead	0.28	1.63	0.03	59.0		0.65			0.65
	Manganese		34.1	0.4	72.2	538		163		160
	Mercury	0.018			0.38		0.04			0.04
	Nickel	0.18	17.2	0.1		6.43	2.27			8.7
	Zinc	3.56	239	0.03	279	30.4	304			860
Other Substances	Ammonia						4036			4000
	Benzene								0.001	0.001
	Chlorine						58.73			59
	Cyanide						11.4			11
	Ethylbenzene								0.0007	0.0007
	Fluoride		16500		61690	94300				160000
	PAH (B[a]Peq)		1.14							1.1
	Selenium			0.02						0.02
	Tolulene								0.003	0.003
	Total Nitrogen				75778	47600	3693			130000
	Total Phosphorus				8583	4270	770			14000
	Xylenes								0.002	0.002

RGT (Gladstone Ports Corporation), BS (Boyne Smelters), WIC (Wiggins Island Coal Export Terminal), RTY (Rio Tinto Yarwun), QAL (Queensland Alumina LTD), OY (Orica Yarwun), GPS (Gladstone Power Station), GT (Gladstone Terminal)

Other factors

Other factors that can influence water and sediment quality in Gladstone Harbour reported by Flint et al. (2015) include:

- Urban sources such as urban development and stormwater runoff which can be a source of phosphorus, other nutrients and litter.
- Shipping activities, ship movements can result in resuspension of sediments from propeller wash, while other impacts can include dumping of rubbish, discharge of ballast water and anti-fouling chemicals.
- Port activities including maintenance and capital dredging and wharf/loading facilities.
- Marine industries and recreation including commercial fishing, recreational fishing and boating, and shore-based recreation.
- Climate change, where potential impacts include ocean acidification, sea temperature rise and increased frequency and intensity of tropical storms, storm surges and overland floods.

2. Water and sediment quality measures

A total of 18 water and sediment quality measures were assessed and reported on for the 2017 Gladstone Harbour Report Card. These measures were selected by the Gladstone Healthy Harbour Partnership (GHHP) Independent Science Panel (ISP) to be indicative of the factors relevant to the harbour and its condition. The importance of each measure to overall harbour health are described in the sections below.

2.1. Physicochemical indicators

pH

The pH of water is a measure of its alkalinity or acidity. By assessing the concentration of free hydrogen and hydroxyl ions in water, pH indicates whether the water is acidic (pH 0–6), neutral (7) or alkaline (pH 8–14). The pH is an important property of marine and estuarine water as it determines the solubility and biological availability of many nutrients and metals. As a rule of thumb, the solubility of most metals tends to increase at low pH. Plant and animal species usually tolerate a narrow pH range outside of which their ecology and behaviour are adversely impacted.

Turbidity

Turbidity is a measure of water clarity and is affected by the levels of suspended sediment (sand, silt and clay), organic matter and plankton in the water. Coloured substances such as pigments and tannins from decaying plant matter may also contribute to turbidity. High turbidity decreases the light levels reaching the seabed which reduces photosynthesis and the production of dissolved oxygen. This can lead to mortality of algae, seagrasses and corals. The suspended material in the water may also clog fish gills and smother benthic invertebrates.

2.2. Nutrients

Nitrogen (N) and phosphorus (P) are essential nutrients for all organisms and occur in a number of forms in the natural environment. However, excess concentrations of these nutrients in the marine environment may lead to increased biomass of phytoplankton and other aquatic plants, which as they decay, may deplete the oxygen available for aquatic animals.

Total nitrogen

Total nitrogen (TN) is the sum of the four major chemical forms of nitrogen in the marine environment: nitrate, nitrite, organic nitrogen and ammonia nitrogen. Nitrogen is an essential nutrient for all organisms, but at high levels it can lead to algal blooms, deplete oxygen in the water (eutrophication) and impact the growth of corals.

Total phosphorus

In aquatic systems, phosphorus exists in different forms such as dissolved orthophosphate, organically bound phosphate and particulate phosphate. The total phosphorus (TP) measure gives an indication of all forms of phosphorus in the water body. Key sources of phosphorus in water include cleaning products, urban run-off, fertiliser run-off, rock weathering, partially-treated sewage effluent and animal faeces. Phosphorus is an essential nutrient for all organisms, but at high levels it can lead to algal blooms, deplete oxygen in the water (eutrophication) and impact coral growth.

Chlorophyll-a

Chlorophyll-*a* is a plant pigment used in photosynthesis. In marine systems it is found in algae such as seaweeds and phytoplankton. High levels of chlorophyll-*a* may indicate blooms of algae which can occur when nutrients levels are elevated. This can lead to depleted levels of oxygen in the water and to fish kills.

2.3. Dissolved metals and metalloids

A suite of dissolved metals and one metalloid (arsenic) have been selected as indicators of harbour health.

Aluminium

The element aluminium (Al) is a silvery white metal and the most abundant metal in the Earth's crust (Zumdahl and DeCost, 2010); therefore, it is common to find traces of this element in soil, sediment and water. Aluminium in seawater can be derived from sources that are natural (e.g. weathering of mineral rocks, urban run-off) or anthropogenic (e.g. mining waste, industrial discharges). High levels of dissolved aluminium in aquatic systems are toxic to algae and marine animals.

Arsenic

Arsenic (As) is a naturally occurring element in the environment. It can be introduced into aquatic environments through natural contamination (e.g. by geothermal activity) or anthropogenically, principally through mining-related activities that may disturb arsenic deposits (Garelick et al., 2008). Arsenic may also be mobilised from bauxite residues remaining after aluminium extraction and is typically stored in red mud dams (Lockwood et al., 2014). In sediment, arsenic is available as As (III), As (V) and in methylated forms. It is a highly soluble and mobile element that may be toxic to aquatic species.

Cadmium

Cadmium (Cd) is a non-essential element in plants and animals. The sources of cadmium in oceanic waters may be natural (e.g. volcanic activities, rock weathering) or anthropogenic (e.g. releases from open burning or incineration of municipal waste, mining activities, releases from landfills). In water, cadmium is mostly adsorbed onto sediment and suspended particles. Increased concentrations of cadmium in aquatic systems can lead to a range of toxic effects in fish, invertebrates, amphibians and aquatic plants (UNEP, 2010).

Copper

Copper (Cu) is an essential micro-nutrient for plants and animals. Similar to other metals, the sources of copper in oceanic waters may be natural (e.g. release from sediments) or anthropogenic (e.g. as a biocide in antifouling marine paint). Increased concentrations of copper in aquatic systems can lead to a range of toxic effects on algae, invertebrates, fish and other animals.

Lead

Lead (Pb) is a toxic heavy metal that may have anthropogenic (e.g. industrial discharge, mining discharge) or natural origins. In water, lead is mostly adsorbed onto sediment and suspended particles. Its tendency to bioaccumulate up the food chain poses a potential hazard to higher level consumers, including humans. This metal has no known benefits to aquatic plants or animals.

Manganese

Manganese (Mn) is the 11th most abundant element in the Earth's crust and an essential nutrient for the wellbeing of plants and animals. Its origin can be either anthropogenic or natural. The overall toxicity of manganese to marine biota (except corals) is low. Two manganese deposits near Gladstone Harbour have previously been mined and produced over 1,000 tonnes of manganese ore. Those deposits were at Auckland Inlet (mined 1882–1900) and Boat Creek (mined 1901–1902) (Wilson & Anastasi, 2010).

Mercury

Mercury (Hg) is a toxic heavy metal that can have natural (e.g. weathering of rocks over time) or anthropogenic origins (e.g. coal burning power stations). In sediments it can be converted to methylmercury by microorganisms. This highly toxic chemical can build up in shellfish, fish and animals that eat fish. Potential effects of mercury exposure include a reduction in growth rate and development, abnormal behaviour and death.

Nickel

Nickel (Ni) is the 24th most abundant metal in the Earth's crust and is essential for all organisms (Cempel & Nikel, 2006). Nickel in waterways can come from sources that are industrial (e.g. industrial discharges, coal handling) or natural (e.g. through rock weathering). In water, nickel is mostly adsorbed onto sediment and suspended particles. At high concentrations, nickel becomes toxic to organisms, but it does not tend to bioaccumulate through the food web.

Zinc

Zinc (Zn) is an essential trace element for animals and plants. Anthropogenic sources include zinc from sacrificial anodes in ships, industrial discharges (e.g. mines, galvanic industries and battery production), sewage effluent, surface run-off and some fungicides and insecticides. At high concentrations zinc becomes toxic to organisms.

3. Report card grades and scores

3.1. Aggregation of water and sediment quality indicators

The GHHP ISP recommended the measures for water and sediment quality that are used in the 2017 Gladstone Harbour Report Card. The measures were selected to be indicative of the factors relevant to the harbour and its condition. Eleven water quality and seven sediment quality measures were reported in the 2017 report card (Figure 3.1) although three other measures – ammonia, NOx and orthophosphate – were assessed but not included in 2017 owing to data quality issues (see section 5.2). Aggregation from these measures to an overall indicator group score uses a hierarchical approach—so that scores for a range of reporting levels (indicator group, indicators, sub-indicators) could be generated from the individual measures. The lowest level of reporting (e.g. measures such as aluminium, copper, lead, manganese, nickel and zinc for a site) are aggregated to the next level (e.g. dissolved metals) using bootstrapped distributions rather than direct means of each measure. The bootstrapping method resamples the original data many times to yield multiple means which are used to develop a series of distributions for measures, sub-indicators, indicators and indicator groups. By aggregating distributions (rather than individual means), the rich distributional properties could be preserved, sample bias could be avoided, and means (the report card score) and variances could be calculated for reporting.

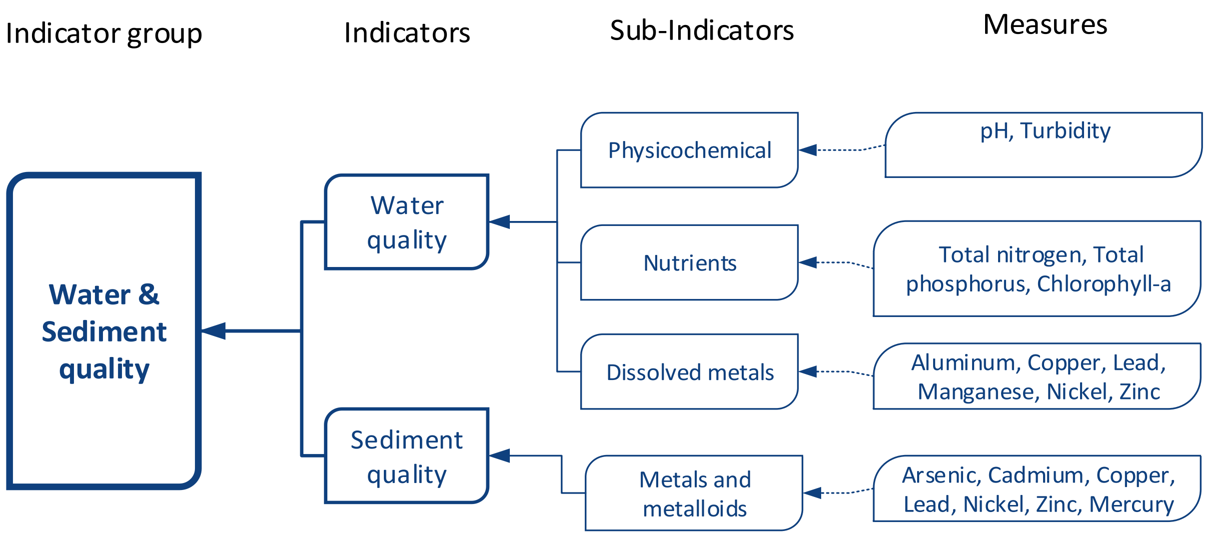

Figure 3.1: The aggregation hierarchy showing the indicators, sub-indicators and measures used to calculate the overall water and sediment quality grade for the Gladstone Harbour Report Card.

3.2. Water and sediment guidelines

All water and sediment measure scores are calculated relative to a guideline value. For the report card these guideline values were provided by:

- DEHP Water Quality Objectives for the Capricorn Curtis Coast (DEHP, 2014) for pH, turbidity and nutrients.
- ANZECC/ARMCANZ (2000) for most metals in water and sediments.
- Golding et al. (2014) for dissolved aluminium in water.
- COAG Standing Council on Environment and Water (2013) for manganese in water.

The water quality guideline values used to calculate report card scores differ among geographic zones within Gladstone Harbour for all physicochemical and nutrient measures but are consistent for all metals (Table 3.1). The aluminium guidelines developed by Golding et al. (2014) ranged from 2.1 µg/L in high ecological value (HEV) zones in Gladstone Harbour (The Narrows, Colosseum Inlet, Rodds Bay) to 24 µg/L in moderately disturbed (MD) zones (all other zones). This led to similar actual concentrations of aluminium being graded as very poor in HEV zones and very good in MD zones. This created the misleading impression that the aluminium concentrations were far worse in HEV zones than in MD zones. For this reason, the ISP applied the MD guideline of 24 µg/L across all zones for aluminium. For the same reason, the ISP also selected a consistent guideline of 140 µg/L for manganese which was the appropriate guideline for MD systems with coral (COAG Standing Council on Environment and Water, 2013). Manganese guidelines varied between 20 µg/L and 390 µg/L depending on whether the zone was classified as HEV or MD and whether corals were present or absent.

The sediment metal guidelines are consistent across all harbour zones (Table 3.2).

Table 3.1: Water quality guidelines used to calculate water quality scores.

Zone	Physicochemical													
	Turbidity		pH range		Nutrients			Metals						
	Dry (NTU)	Wet (NTU)	<40 ms/cm	>40 ms/cm	TN (µg/L)	TP (µg/L)	Chl-*a* (µg/L)	Al (µg/L)	Cu (µg/L)	Pb (µg/L)	Mn (µg/L)	Ni (µg/L)	Zn (µg/L)
1. The Narrows	7	15	7.2–8.2	7.4–8.3	170	20	1	24	1.3	4.4	140	7	15
2. Graham Creek	8	13	7.2–8.2	7.4–8.3	170	20	1	24	1.3	4.4	140	7	15
3. Western Basin	8	13	7.2–8.2	7.4–8.3	170	18	1	24	1.3	4.4	140	7	15
4. Boat Creek	14	25	7.2–8.2	7.4–8.3	190	22	2	24	1.3	4.4	140	7	15
5. Inner Harbour	8	13	7.2–8.2	7.4–8.3	160	21	1	24	1.3	4.4	140	7	15
6.Calliope Estuary	11	11	7.2–8.2	7.4–8.3	175	22	1.7	24	1.3	4.4	140	7	15
7.Auckland Inlet	6	8	7.2–8.2	7.4–8.3	160	16	1.9	24	1.3	4.4	140	7	15
8.Mid Harbour	4	9	7.2–8.2	7.4–8.3	135	14	1	24	1.3	4.4	140	7	15
9. South Trees Inlet	11	13	7.2–8.2	7.4–8.3	170	20	1.1	24	1.3	4.4	140	7	15
10. Boyne Estuary	3	5	7.2–8.2	7.4–8.3	120	11	0.8	24	1.3	4.4	140	7	15
11. Outer Harbour	3	7	8.0–8.2		130	13	1	24	1.3	4.4	140	7	15
12. Colosseum Inlet	3	7	7.2–8.2	7.4–8.3	130	10	0.8	24	1.3	4.4	140	7	15
13. Rodds Bay	4	5	7.2–8.2	7.4–8.3	160	13	1	24	1.3	4.4	140	7	15

Turbidity: The 50th percentile from the guideline values is applied to all harbour zones. Dry season guidelines apply from May to October. Wet season guidelines apply from November to April.

pH range: The pH range falls between the 20th and 80th percentile of the guideline values. Different guideline values are applied for conductivity measurements of <40 ms/cm and >40 ms/cm.

Nutrients: For all nutrients, total nitrogen (TN), total phosphorus (TP) and chlorophyll-*a* (Chl-*a*) the 50th percentile from the guideline values is applied.

Aluminium: The aluminium (Al) guideline for moderately disturbed (MD) systems (24 µg/L, 95% species protection) is applied to all harbour zones.

Manganese: A single manganese (Mn) guideline for MD systems (140 µg/L, 95% species protection with corals present) is applied to all harbour zones.

Other Metals: The 95% species protection value from the ANZECC/ARMCANZ (2000) water quality guidelines is applied to copper (Cu), lead (Pb), and zinc (Zn) while the 99% species protection value is applied to nickel (Ni). Trigger values were selected for moderately disturbed systems.

Table 3.2: Sediment quality guidelines used to calculate sediment quality scores. Derived from ANZECC/ARMCANZ (2000).

Sediment quality measure	Concentration (mg/kg)
Arsenic (As)	20
Cadmium (Cd)	1.5
Copper (Cu)	65
Lead (Pb)	50
Mercury (Hg)	0.15
Nickel (Ni)	21
Zinc (Zn)	200

3.3. Calculation of grades and scores

The starting point for water quality score calculation was the annual mean for a measure at each site. This was calculated by averaging measure values on four occasions as a result of quarterly data collection. Water and sediment quality scores for individual measures were calculated relative to the zone-specific guideline value (GV) using the scaled modified amplitude method (Logan, 2016). Steps involved include:

1) Calculation of the amplitude as mean/GV[1]
2) Conversion of this amplitude to Log2 scale
3) Cap the amplitude to be bound within -1 and +1 corresponding to minimum and maximums of twice and half the GV to ensure values that are twice and half the GV will yield amplitudes of the same magnitude
4) Scale the indices to the range 0 – 1 (Score = 0.5 * (index + 1))

This method generates indices (report card scores) as an expression of the degree of deviation from the zone-specific guideline value for a measure. Where the average concentration of a measure exceeds the guideline value it receives a low score and conversely where a measure is below a guideline value it receives a high score (Figure 3.2). A satisfactory score (C) is given when the average concentration of a measure meets the guideline value (0.50) or exceeds that value (0.50 – 0.64). All scores range between 0.00 and 1.00 and are converted into grades on an A to E scale (Figure 3.3).

Site-level measure scores are aggregated to zone-level scores using bootstrapped distributions rather than direct means of each measure. The bootstrapping method resamples the original data to yield a bootstrap distribution of 10,000 samples. By aggregating distributions (rather than individual means), the rich distributional properties could be preserved, sample bias could be avoided, and means (the report card score) and variances could be calculated for reporting. Bootstrapping is used to create distributions when aggregating measure scores to higher hierarchical levels (e.g. sub-indicators, indicators, indicator groups) for the same reasons.

Refer to Table 3.3 and Figure 3.4 for a worked example of the calculation of grades and scores.

[1] For sediment quality, a single measure is used owing to the annual sampling regime.

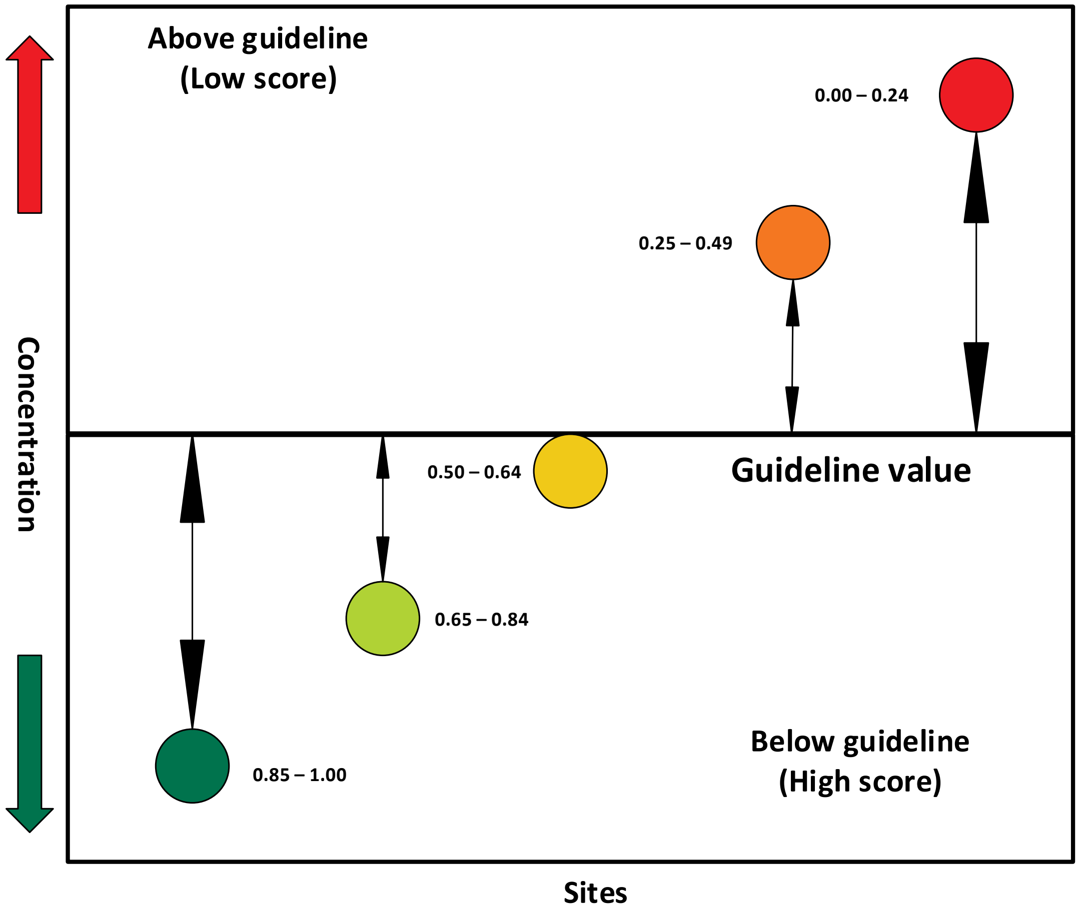

Figure 3.2: Water and sediment quality measures are scored relative to zone and measure specific guideline values. Where the concentration of a measure is low it receives a high score and conversely where the concentration of a measure is high it receives a low score.

- **A** **Very good** (0.85 – 1.00)
- **B** **Good** (0.65 – 0.84)
- **C** **Satisfactory** (0.50 – 0.64)
- **D** **Poor** (0.25 – 0.49)
- **E** **Very poor** (0.00 – 0.24)

Figure 3.3: Grading scheme used to convert scores to grades in the 2017 Gladstone Harbour Report Card for each component of harbour health.

Table 3.3: Quarterly measure and annual mean values for dissolved copper at Calliope Estuary from 2016 Gladstone Harbour Report Card.

Sample	Site		
	CR10 (μg/L)	**CR20** (μg/L)	**CR30** (μg/L)
Aug-15	1.00	-	1.00
Nov-15	1.60	1.10	1.20
Mar-16	1.30	1.10	1.20
Jun-16	1.00	1.50	1.20
Annual Mean	1.23	1.23	1.15

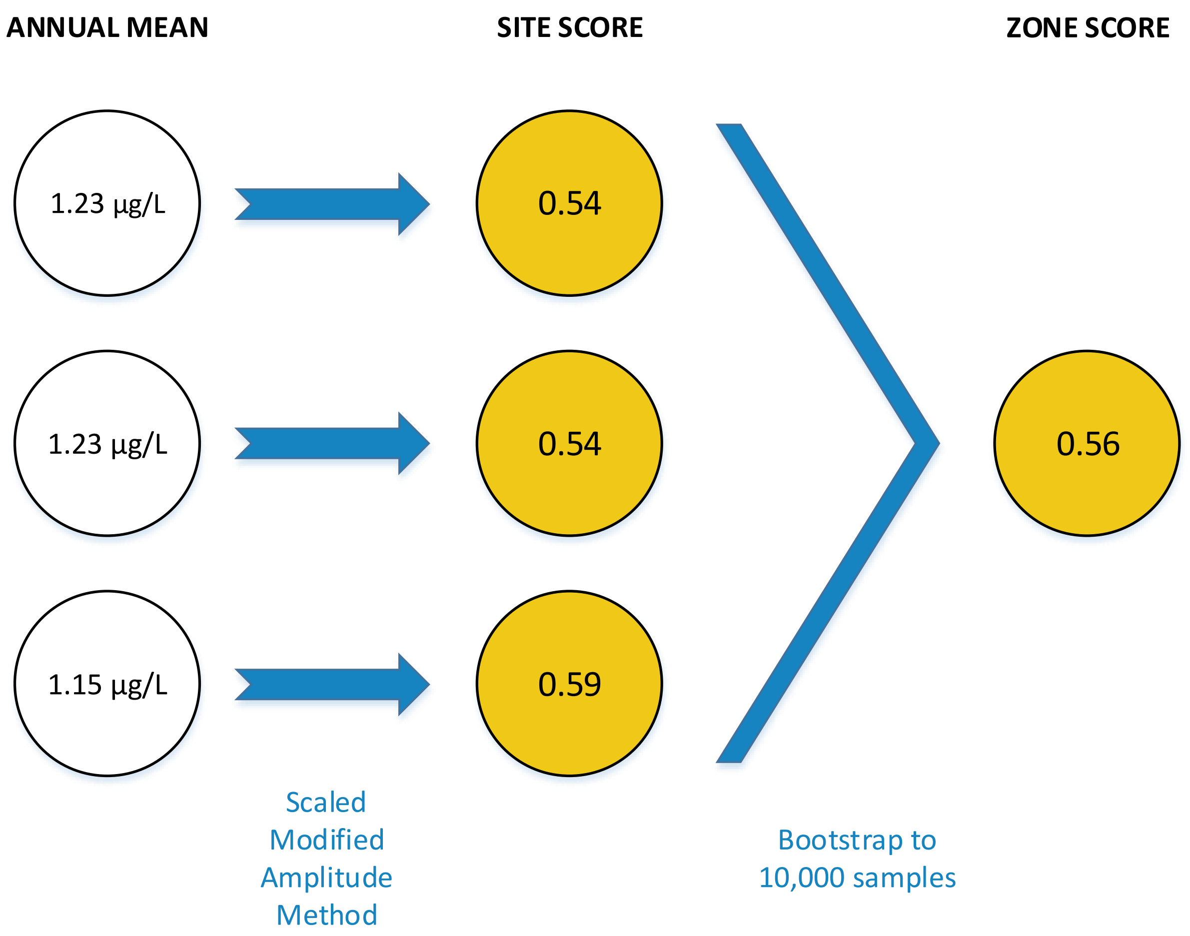

Figure 3.4: Flow diagram of site and zone-level calculation of dissolved copper scores at Calliope Estuary from 2016 Gladstone Harbour Report Card. Guideline value of 1.3 μg/L. Zone score is the mean of the 10,000 resamples from bootstrap distribution.

4. Water and sediment quality data collection

All water and sediment quality data for the 2017 Gladstone Harbour Report Card was provided under a data-sharing agreement between GHHP and Port Curtis Integrated Monitoring Program (PCIMP).

4.1. Water and sediment quality monitoring sites

Water and sediment quality monitoring is conducted within 13 zones in Gladstone Harbour. These zones have developed over time from an initial seven zones proposed by Jones et al. (2005) in a risk assessment for contaminants in Gladstone Harbour. In 2007 PCIMP increased the number of zones to nine by including oceanic and estuarine reference sites (Storey et al., 2007). However, these two reference zones were combined in the Port Curtis Eco Card 2008 – 2010 (PCIMP 2010) resulting in eight zones. The current 13 zones have been developed through an agreement between PCIMP and the Queensland Department of Environment and Science. That agreement was part of a larger project to legislate regionally specific water quality objectives for the Capricorn Coast (DEHP 2014).

Water quality samples were collected from 51 sites across the 13 harbour zones in August and November 2016 and March and June 2017. Sediment samples were collected from the same 51 sites in June 2017 (Figure 4.1).

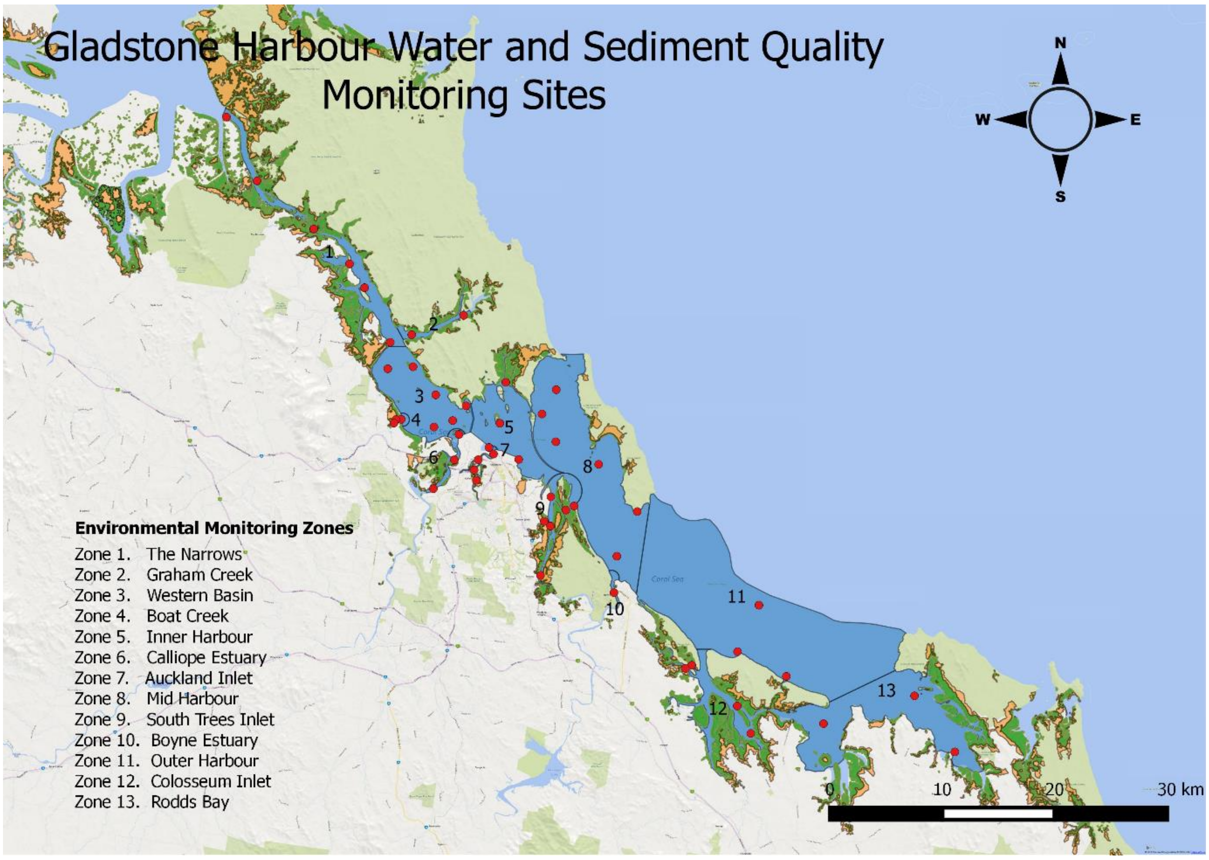

Figure 4.1: Water and sediment quality sites within the 13 Gladstone Harbour environmental monitoring zones.

Gladstone Healthy Harbour Partnership

4.2. Water quality sampling methods

Eleven water quality parameters were assessed for the 2017 Gladstone Harbour Report Card; two physicochemical measures, three nutrient measures and six dissolved metals (Table 4.1). Physicochemical parameters were measured using a multi-parameter water quality sonde (YSI6820). Measurements were taken at 0.5 m depth intervals through the water column until the seabed was reached. At very shallow sites, data were recorded at 0.25 m intervals. Water samples for nutrient and dissolved metal analysis were collected from a depth of about 0.5 m using a Perspex pole sampler and a 1L acid-rinsed Nalgene bottle. Prior to sample collection at each site, the Nalgene bottle was triple rinsed in ambient water. Powder free gloves were worn to avoid contamination. Sample water was added directly to laboratory-provided sample bottles for total nitrogen, total phosphorous and chlorophyll-*a*. A sub-sample of water was added directly to a syringe and filtered (0.45 µm sterile surfactant free cellulose acetate membrane syringe filter, Minisart 16555K) *in-situ* into laboratory-provided sample bottles for dissolved metals and nutrients. Syringes were pre-rinsed in site water, and filters came pre-packaged from the supplier. All samples were placed immediately on ice and dispatched to arrive at the nominated analysing laboratories within their recommended holding times.

All analysing laboratories were National Association of Testing Authorities, Australia (NATA) accredited. Water samples were sent to the National Measurement Institute (NMI) with the exception of chlorophyll-*a* which were sent to Australian Laboratory Services (ALS) and dissolved nutrients which were sent to the Queensland Health Laboratories in 2017.

Methods in this section were provided by Anastasi (2017).

Please refer to section 5 for additional quality assurance and quality control (QA/QC) information.

Table 4.1: Water quality indicators included in the 2017 Gladstone Harbour Report Card.

Indicator	Sub-indicator	Measure	Guideline source
Water quality	Physicochemical	pH	DEHP, 2014
		Turbidity	DEHP, 2014
	Nutrients	Total nitrogen (TN)	DEHP, 2014
		Total phosphorus (TP)	DEHP, 2014
		Chlorophyll-*a* (Chl-*a*)	DEHP, 2014
	Dissolved metals	Aluminium (Al)	Golding et al., 2014
		Copper (Cu)	ANZECC/ARMCANZ, 2000
		Lead (Pb)	ANZECC/ARMCANZ, 2000
		Manganese (Mn)	COAG Standing Council on Environment and Water (2013)
		Nickel (Ni)	ANZECC/ARMCANZ, 2000
		Zinc (Zn)	ANZECC/ARMCANZ, 2000

See Table 3.1 for a full list of water quality guideline values.

4.3. Sediment quality sampling methods

The 2017 Gladstone Harbour Report Card assessed six sediment metals and one metalloid (arsenic) (Table 4.2). Sediment nutrients were not included as there are no relevant national or international guidelines. They may be included in future report cards should relevant guidelines become available.

Sediment samples were collected from the 51 harbour monitoring sites in June 2017 from the same sites used for water quality sampling. Grab samples were collected for the sediment quality measurements using a stainless steel Ponar grab sampler (0.008 m^3 volume). These samples were deposited into a collection tub that had been triple rinsed with seawater and then photographed. All sediment quality measurements used the top 100 mm of the sample, which were deposited into laboratory-provided sample containers using pre acid-washed polypropylene trowels.

All sample containers were bagged and stored at 4°C and transported to the analysing laboratory, NMI, within their recommended holding times. Sediment particle size distribution was subcontracted to HRL Technology for analysis and was reported as fine (<63 µm), medium (63 µm to 2 mm) and coarse (>2 mm). See Figure 1.4 for information on the distribution of fine sediments.

Methods in this section were provided by Anastasi (2017).

Please refer to section 5 for additional QA/QC information.

Table 4.2: Sediment quality indicators included in the 2017 Gladstone Harbour Report Card.

Indicator	Sub-indicator	Measure	Guideline Source
Sediment quality	Metals and metalloid	Arsenic (As)	ANZECC/ARMCANZ, 2000
		Cadmium (Cd)	ANZECC/ARMCANZ, 2000
		Copper (Cu)	ANZECC/ARMCANZ, 2000
		Lead (Pb)	ANZECC/ARMCANZ, 2000
		Mercury (Hg)	ANZECC/ARMCANZ, 2000
		Nickel (Ni)	ANZECC/ARMCANZ, 2000
		Zinc (Zn)	ANZECC/ARMCANZ, 2000

See Table 3.2 for sediment quality guideline values.

5. Water and sediment quality QA/QC

The water and sediment quality data were subjected to a range of quality assurance and quality control (QA/QC) procedures from field data collection stage to the final score calculation stage for the report card (Figure 5.1). These steps were taken to yield a high-quality dataset prior to the calculation of the report card scores.

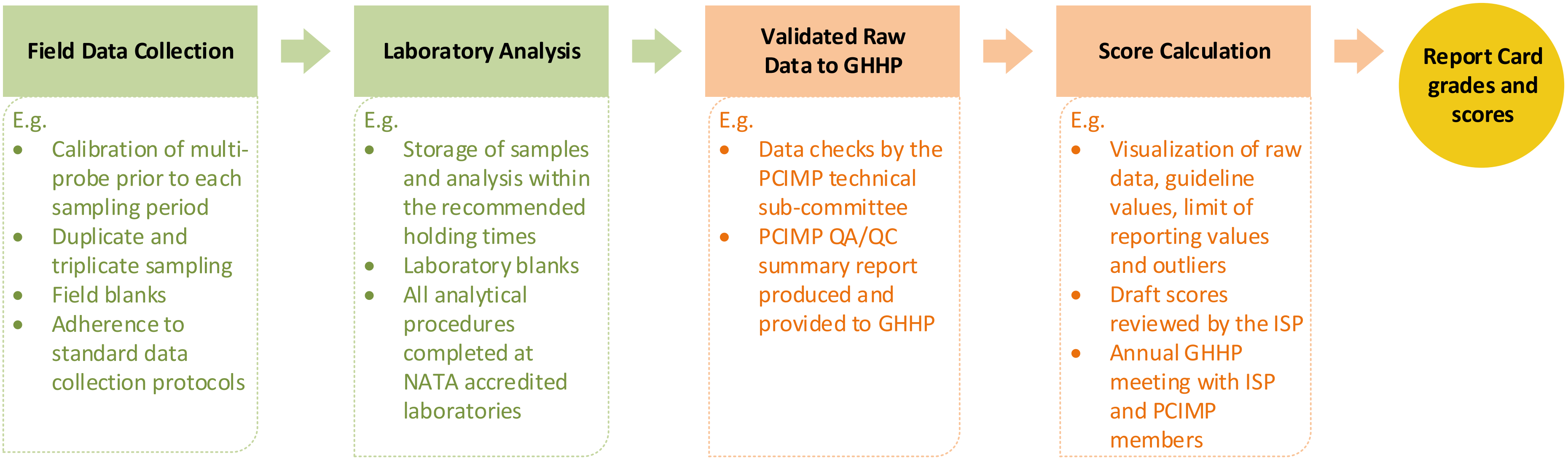

Figure 5.1: A flow diagram showing examples of QA/QC procedures applied to the raw and processed water and sediment quality data. Detailed QA/QC procedures for field data collection, laboratory analysis and validated raw data to GHHP are covered in section 5.1. Score calculation analysis was completed independently by GHHP and the ISP. Please refer to section 5.2 for more details on QA/QC of score calculation.

5.1. Field data collection and laboratory analysis

Vision Environment Queensland (VEQ) collected the water and sediment field samples and prepared them for laboratory analysis. Water and sediment quality data were collected in accordance with the following standards and procedures:

- Australian and New Zealand Standards for water quality and sediment sampling (AS/NZS 5667.1:1998, 5667.4:1998, 5667.6:1998, 5667.9:1998 and 5667.10:1998)
- American Public Health Association standard methods for the examination of water and wastewater (APHA, 2005)
- Australian and New Zealand water quality guidelines (ANZECC, 1992, 1998; ANZECC/ARMCANZ, 2000)
- Handbook for sediment quality assessment (Simpson et al., 2013)
- Department of Environmental Resource Management monitoring and sampling manual (DERM, 2010).

Please refer to sections 4.2 and 4.3 for detailed VEQ field methods for water and sediment quality.

Upon collection, all water samples were placed immediately on ice and dispatched to arrive at the nominated analysing laboratories within their recommended holding times. In order to address potential holding time breaches (48 hr) for chlorophyll *a*, all chlorophyll *a* samples were pre-processed at VEQ by lab-filtering (0.45 µm) samples within 24 hours of collection and freezing filter paper until dispatch, resulting in an extending holding time of 28 days, in accordance with APHA method 12000H.

Water quality laboratory and field QA/QC were monitored using field blanks (FB), field spikes (FS), duplicate and triplicate samples in 2016. From 2017, laboratory and field QA/QC was monitored using FB, laboratory blanks and duplicate samples. Laboratory blanks (LB) were added to the program to assist in the identification of potential contamination sources. Each quarterly sampling event included the following QA/QC procedures:

- 3 to 4 FB samples
- 3 to 4 LB samples (in 2017 quarters only)
- 6 FS samples (in 2016 quarters only)
- 10 duplicate samples
- 5 triplicate samples (in 2016 quarters only)

For sediment quality QA/QC, separate grabs were made for duplicate (n = 10) and triplicate (n = 5) samples.

All laboratories that analyse PCIMP data were NATA accredited. This is to ensure compliance with the relevant international and Australian standards and competency in providing consistently reliable testing, calibration, and measurement and inspection data. National Measurement Institute (NMI) is the Australian Government's peak measurement body for biological, chemical, legal, physical and trade measurement. Primary, duplicate, FB, FS and LB of water samples were sent to the NMI except for chlorophyll-*a* which were sent to ALS and dissolved nutrients which were sent to the Queensland Health Laboratories in 2017. All sediment samples were analysed by NMI. Triplicate water samples were sent to Envirolab, Sydney in 2016 and discontinued in 2017. All laboratory limit of reporting (LOR) values used are included in Table 5.1.

The report card datasets were further checked for QA/QC purposes by the PCIMP technical sub-committee before being submitted to the GHHP for report card score generation. Information on VEQ QA/QC field and laboratory methods, QA/QC results and monitoring methods were outlined in the PCIMP QA/QC summary report (Anastasi, 2017). This document provided the source material used in this section.

Table 5.1: Limit of reporting values during laboratory analysis of water and sediment samples for 2016–17 reporting year.

Indicator	Sub-Indicator	Measure	LOR value (µg/L) 2016	2017
Water quality	Dissolved metals	Aluminium	5	5
		Copper	1	1
		Lead	1	1
		Manganese	1	1
		Nickel	1	1
		Zinc	1	1
	Nutrients	Total Phosphorous	5	5
		Total Nitrogen	50	50
		Chlorophyll-*a*	0.02	0.02
	Dissolved nutrients	NOx	NR	2
		Orthophosphate	5	2
		Ammonia	2	2
		Nitrate-N	5	NR
		Nitrite-N	5	NR
Indicator	**Sub-Indicator**	**Measure**	**LOR value (mg/kg) 2016-2017**	
Sediment quality	Metals and metalloid	Arsenic	0.5	
		Cadmium	0.5	
		Copper	0.5	
		Lead	0.5	
		Mercury	0.2	
		Nickel	0.5	
		Zinc	0.5	

LOR – limit of reporting; NR – not reported

5.2. Data validation and score generation

A range of additional data checks were carried out by the GHHP upon receiving the raw data set from PCIMP with the help of the state-of-the-art Data and Information Management System (DIMS). Data checks noted extremely high or low values, higher dissolved metal concentrations than the total metal concentrations, missing values, LOR values and guideline values (GV) (see Appendix 1 and Appendix 2). Prior to the final analysis the ISP held a meeting with PCIMP to discuss any known data quality issues associated with the water and sediment quality data collected for the 2017 report card.

Following the meeting, the ISP recommended to omit the following measures prior to the score calculation:

- **Remove NOx from the report card**
  Reasons:
  - NOx data was not available consistently over the four quarters. March and June 2017 results were available as NOx but data for the other two quarters were only available as Nitrate-N and Nitrite-N
  - For a majority of the harbour zones, the GV (3 µg/L) is close to the LOR (2 µg/L) for NOx. For two zones, the GV (1 µg/L) is below the LOR (2 µg/L) for NOx, resulting in failing scores for all NOx readings at these zones. Please refer to the end of this section for more detail.

- **Remove orthophosphate from the report card**
  Reasons:
  - The LOR (5 µg/L) for orthophosphate was higher than the orthophosphate GV (1-4 µg/L depending on the zone) in August and November 2016, resulting in failing scores for all orthophosphate readings in these quarters.
  - The LOR was improved in March and June 2017 (2 µg/L), however, like NOx, the orthophosphate GV (1-4 µg/L depending on the zone) is close to or below the orthophosphate LOR (2 µg/L). Please refer to the end of this section for more detail.

- **Remove ammonia from the report card**
  Reasons:
  - The FB and LB collected in March and June 2017 gave non-zero readings for ammonia (i.e. exhibit some level of contamination). Although PCIMP indicated that the QA/QC procedures were adequate, all FBs and LBs resulted in non-zero readings, leading to concerns that there may be some level of contamination in all readings. No laboratory blanks were provided in the 2016 quarters, making it difficult to identify if contamination occurred.
  - For a majority of the harbour zones, the GV (3 µg/L) is close to the LOR (2 µg/L) for ammonia. Please refer to the end of this section for more detail.
  - The guideline values legislated for ammonia in Gladstone Harbour may be too low. Further information may be required from DES on how this GV was determined.
  - Ammonia is not included in other marine report cards.
  - Total nitrogen is already measured so including ammonia would lead to some double continuity.

- **Remove 10 dissolved metal data cases from analysis (approximately 4% of overall water and sediment data)**
  Reason: For these samples, the dissolved metal concentrations were higher than the total metal concentrations, most likely due to contamination either during collection, filtration or analysis.

One key reason contributing to the removal of NOx, orthophosphate and ammonia from the report was the proximity of the LOR values to their respective guideline values. When the reported values are near analytical detection limits (or LOR), even small analytical errors can move the value closer to an exceedance of the guideline. For a majority of the harbour zones, the guideline value (3 µg/L) is close to the LOR (2 µg/L) for measures of all three dissolved nutrients. The indexing method used (scaled modified amplitude method[2]) gives a fail score to any measure that is more than two times the guideline value. This makes the measure extremely sensitive when the guideline value is very low (often close to the LOR values). This also means that elevated concentrations due to any analytical error could generate poor grades. Instances where the guideline value is below the LOR (e.g. some zones for NOx and orthophosphate) result in guaranteed failing scores.

These issues were reviewed by the ISP and discussed with the PCIMP technical sub-committee. Subsequently the GHHP management committee approved the removal NOx, orthophosphate, ammonia and the above-mentioned dissolved metal cases from the 2017 Gladstone Harbour Report Card, Technical Report and Water and Sediment Quality Report. These measures and similar dissolved metal cases were also removed from preceding GHHP publications in 2016.

[2] The steps in score calculation include: **1)** Calculation of the annual mean per site, **2**) Calculation of the amplitude as mean/GV, **3**) Conversion of this amplitude to Log2 scale, **4**) Cap the amplitude to be bound within -1 and +1 corresponding to minimum and maximums of twice and half the GV to ensure values that are twice and half the GV will yield amplitudes of the same magnitude, **5**) Scale the indices to the range 0 – 1 (Score = 0.5 * (index + 1))

6. Water and sediment quality results

6.1. Water quality

The overall water quality score was derived from three sub-indicator groups, physicochemical, nutrients and dissolved metals. The physicochemical group comprised pH and turbidity; the nutrients group comprised chlorophyll-*a*, total nitrogen and total phosphorus; and the dissolved metals group comprised aluminium, copper, lead, manganese, nickel and zinc.

The overall grade for water quality in the 2017 report card was a B (0.78). Two harbour zones, Graham Creek and Outer Harbour, received very good scores for overall water quality (0.88 and 0.90 respectively). Boat Creek received a satisfactory score. The remaining zones received good scores (Table 6.1).

Table 6.1: Overall water quality, physicochemical, nutrient and dissolved metal scores for the 13 zones in the 2017 Gladstone Harbour Report Card. Overall zone scores for the 2016 and 2015 are shown for comparison.

Water quality	Physico-chemical score	Nutrients score	Dissolved metals score	Zone score 2017	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.76	0.44	0.93	0.71	*0.68*	*0.82*
2. Graham Creek	0.99	0.69	0.94	0.88	*0.75*	*0.86*
3. Western Basin	0.74	0.64	0.93	0.77	*0.70*	*0.82*
4. Boat Creek	0.58	0.32	0.89	0.59	*0.58*	*0.70*
5. Inner Harbour	0.76	0.69	0.95	0.79	*0.78*	*0.88*
6. Calliope Estuary	0.68	0.70	0.94	0.77	*0.71*	*0.86*
7. Auckland Inlet	0.83	0.60	0.94	0.79	*0.71*	*0.77*
8. Mid Harbour	0.85	0.59	0.95	0.79	*0.77*	*0.80*
9. South Trees Inlet	0.91	0.68	0.95	0.84	*0.79*	*0.85*
10. Boyne Estuary	1.00	0.53	0.95	0.83	*0.71*	*0.70*
11. Outer Harbour	1.00	0.74	0.95	0.90	*0.72*	*0.84*
12. Colosseum Inlet	1.00	0.55	0.95	0.83	*0.73*	*0.78*
13. Rodds Bay	0.80	0.50	0.95	0.75	*0.73*	*0.80*

Of the two physicochemical measures, pH received very good scores in all zones. Turbidity received very good scores in four zones (Graham Creek, Boyne Estuary, Outer Harbour and Colosseum Inlet), three zones received good scores (Auckland Inlet, Mid Harbour and South Trees Inlet) three zones received satisfactory scores (The Narrows, Western Basin and Rodds Bay), Calliope Estuary received a poor score and Boat Creek a very poor score (Table 6.2).

Scores for nutrients were typically satisfactory or above, however two harbour zones (The Narrows and Boat Creek) received poor scores (0.44 and 0.32 respectively). Total phosphorus received the lowest scores for nutrients with Boat Creek receiving a very poor score (0.15), six zones received poor scores (0.36–0.47), and the remaining six zones were satisfactory and good (0.56–0.76), indicating that the total phosphorus concentrations in these six zones were below guideline values (Table 4.1). Total nitrogen had only one poor score, 0.27 in Boat Creek. All other zones had satisfactory to good scores (0.50–0.67). Chlorophyll-a received poor scores in two zones, The Narrows (0.48) and Rodds Bay (0.47), satisfactory scores in three zones (0.54–0.64) and good to very good scores (0.65–1.00) in the remaining eight zones (Table 6.2).

Low concentrations of dissolved metals were recorded across all 13 harbour zones. Very good scores (0.85–1.00) were recorded for aluminium, lead, manganese, nickel and zinc across all zones. Copper scores were either satisfactory or good in 12 zones, with scores ranging from 0.59 to 0.69. One zone Boat Creek (0.49) had a poor score (Table 6.2).

Please refer to Appendix 3 for additional textual and graphical score summaries for each of the 13 monitoring zones.

Table 6.2: Scores for water quality measures for each of the 13 zones in the 2017 Gladstone Harbour Report Card.

Zone	Physicochemical		Nutrients			Metals						
	pH	Turbidity	TN*	TP**	Chl-*a****	Aluminium	Copper	Lead	Manganese	Nickel	Zinc
1. The Narrows	1.00	0.53	0.50	0.36	0.48	1.00	0.59	1.00	1.00	1.00	1.00
2. Graham Creek	1.00	0.98	0.67	0.76	0.64	1.00	0.64	1.00	1.00	1.00	1.00
3. Western Basin	1.00	0.50	0.61	0.56	0.75	1.00	0.61	1.00	1.00	1.00	1.00
4. Boat Creek	1.00	0.17	0.27	0.15	0.54	1.00	0.49	1.00	0.86	1.00	1.00
5. Inner Harbour	1.00	0.52	0.64	0.60	0.83	1.00	0.69	1.00	1.00	1.00	1.00
6. Calliope Estuary	1.00	0.37	0.57	0.60	0.94	1.00	0.66	1.00	1.00	1.00	1.00
7. Auckland Inlet	1.00	0.65	0.52	0.37	0.92	1.00	0.67	1.00	1.00	1.00	1.00
8. Mid Harbour	1.00	0.71	0.57	0.38	0.85	1.00	0.69	1.00	1.00	1.00	1.00
9. South Trees Inlet	1.00	0.81	0.67	0.57	0.81	1.00	0.69	1.00	1.00	1.00	1.00
10. Boyne Estuary	1.00	1.00	0.55	0.41	0.62	1.00	0.69	1.00	1.00	1.00	1.00
11. Outer Harbour	1.00	1.00	0.59	0.63	1.00	1.00	0.69	1.00	1.00	1.00	1.00
12. Colosseum Inlet	1.00	1.00	0.52	0.47	0.65	1.00	0.69	1.00	1.00	1.00	1.00
13. Rodds Bay	1.00	0.60	0.58	0.45	0.47	1.00	0.69	1.00	1.00	1.00	1.00

*Total nitrogen
**Total phosphorus
***Chlorophyll-*a*

Comparisons of the 13 monitoring zones based on water quality measures

In order to compare the 13 environmental reporting zones based on the 11 water quality measures, a hierarchical cluster analysis was used. Cluster analysis is a non-parametric, exploratory data analysis tool that identifies homogenous groups based on their natural characteristics. In this instance the zones are separated into groups based on 11 water quality measures so that each zone is more similar to other zones in its group than to zones outside the group. The cluster analysis was conducted using the mean values of each of the water quality parameters for the 2016–17 water quality data. Owing to differing units (pH, NTU and µg/L) and different scales all data was standardised to have a range of 0 – 1 before conducting the analysis using the hclust function in R version 3.5.0 (https://www.r-project.org/). The agglomeration method used is ward/simple average/centroid with six cluster solution.

The cluster with the largest geographic area (Cluster 3) consisted of the Inner Harbour, Mid Harbour, the Outer Harbour and Boyne Estuary (Figure 6.1; Figure 6.2). With the exception of Boyne Estuary this cluster contained the largest and least confined (greater oceanic influence) of the reporting zones. The water quality parameters were characterised by higher pH, lower turbidity, and lower concentrations of nutrients and manganese (Table 6.3). Cluster 4 (Figure 6.1) contained the largest number of zones (n = 5) and consisted of the three largest estuaries Rodds Bay, Colosseum Inlet, South Trees Inlet, and Western Basin and Auckland Inlet. This cluster was most closely associated with Cluster 3 and compared to this cluster was characterised by lower values for pH, higher values for turbidity and higher concentrations of nutrients and manganese (Table 6.3). The remaining four clusters consisted of one zone each owing to the unique water quality characteristics of the zones. Cluster 1 (Boat Creek) had the highest average concentrations of nutrients manganese and copper and the highest value for turbidity. The remaining three clusters (2, 5 and 6) had lower pH values and higher concentrations of nutrients in comparison to Cluster 3 (Table 6.3).

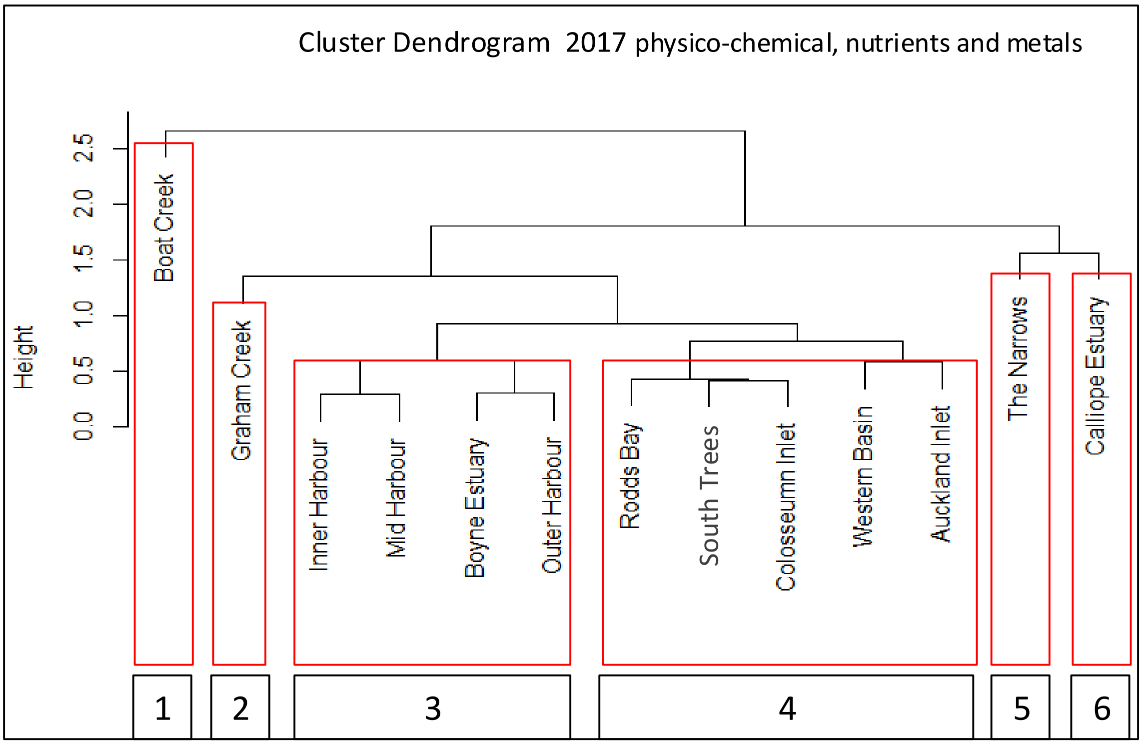

Figure 6.1: Hierarchical cluster analysis of the physicochemical, nutrient and metal measures (mean values for 2016–17) for 13 harbour zones. As indicated by the boxes the 13 zones were split into six distinct groups based on similar water quality properties. The cluster height is the value of the distance metric between clusters.

Table 6.3: Mean water quality values for the six clusters identified in Figure 6.1.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
pH	7.8	7.7	8.1	7.9	7.8	7.9
Turbidity (NTU)	43	4	4	5	24	10
TP (µg/L)	41	14	15	16	30	20
TN (µg/L)	256	135	121	142	172	159
Chl-*a* (µg/L)	2.5	0.9	0.6	1.0	1.2	1.0
Al (µg/L)	6.5	5.0	7.1	7.5	6.5	7.2
Cu (µg/L)	1.3	1.1	1.0	1.0	1.2	1.1
Pb (µg/L)	1.0	1.0	1.0	1.0	1.0	1.0
Mn (µg/L)	45	13	2	7	4	9
Ni (µg/L)	1.0	1.0	1.0	1.0	1.0	1.2
Zn (µg/L)	1.0	1.0	1.2	1.1	1.5	2.1

TP – total phosphorous; TN – total nitrogen; Chl-*a* – chlorophyll-*a*; Al – aluminium; Cu – copper; Pb – lead; Mn – manganese; Ni – nickel; Zn - zinc

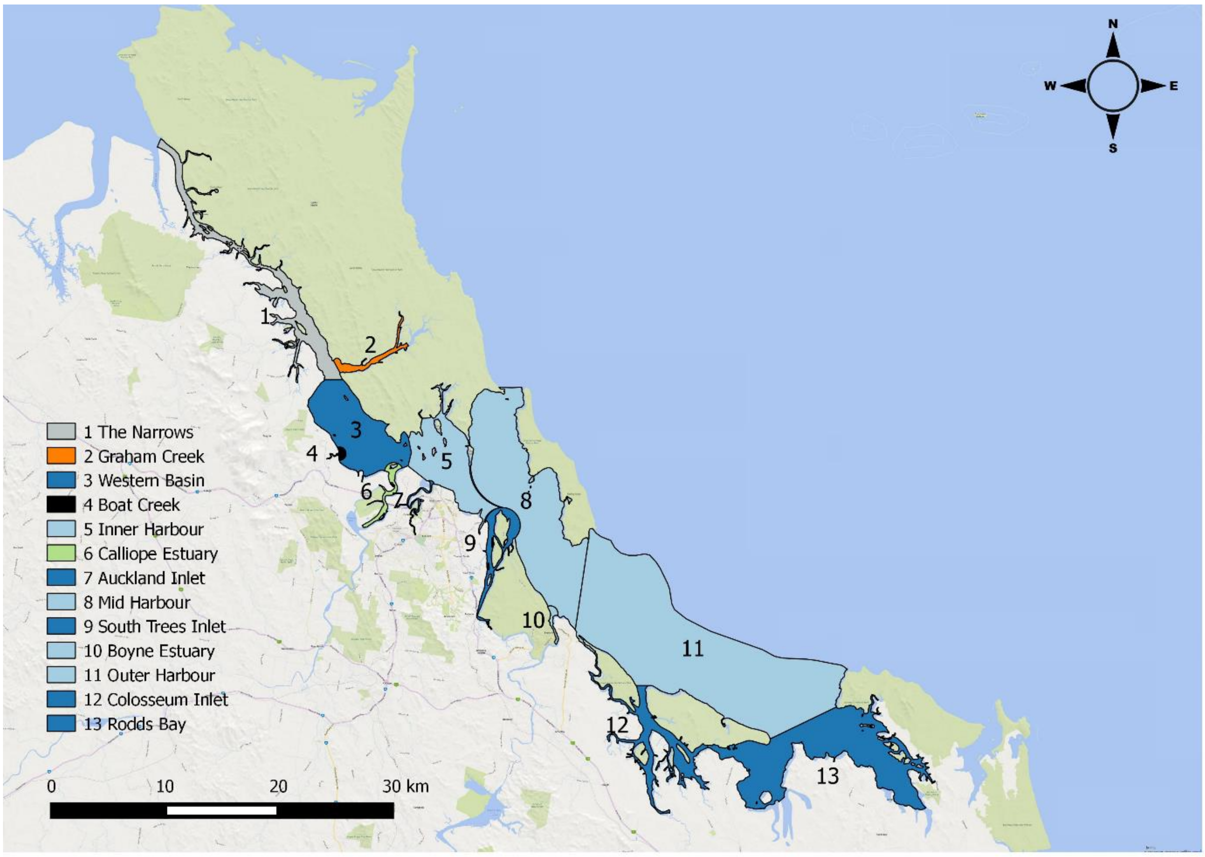

Figure 6.2: Hierarchical cluster analysis of mean water quality measures for the 2016–17 reporting year. Of the six clusters the cluster with the largest geographical area consisted of the Inner, Mid and Outer Harbor and Boyne Estuary, the group that contained the largest number of zones (n = 5) included the larger estuaries, Rodds Bay, Colosseum Inlet, South Trees Inlet and Western Basin and Auckland Inlet. The Narrows, Graham Creek, Boat Creek and Calliope Estuary were all grouped on their own (see Figure 6.1).

6.2. Sediment quality

The overall sediment quality score was derived from one sub-indicator: metals and metalloids. Six metals (cadmium, copper, lead, mercury, nickel and zinc) and the metalloid arsenic were assessed. Mercury was included as a measure for the first time in this report card.

The overall grade for sediment quality was an A (0.95) indicating concentrations that were well below the guideline values.

Zone scores for sediment quality ranged from 0.87 in Auckland Inlet to 0.99 in Colosseum Inlet (Table 6.4) indicating low concentrations of sediment metals across the harbour. Cadmium, lead, mercury and zinc received very good scores (0.85–1.00) in all zones (Table 6.5). Arsenic received very good scores in 6 of the 13 zones, good scores in six zones and a satisfactory score in the Inner Harbour (0.62). Nickel received very good scores in nine harbour zones, good scores in Graham Creek (0.77) and Calliope Estuary (0.73) and a satisfactory score in Auckland Inlet (0. 62) and The Narrows (0.60).

Table 6.4: Overall sediment quality scores for the 13 zones in the 2017 Gladstone Harbour Report Card. Overall zone scores for the 2016 and 2015 are shown for comparison.

Sediment quality	Zone score 2017	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.92	*0.92*	*0.94*
2. Graham Creek	0.92	*0.96*	*0.98*
3. Western Basin	0.97	*0.98*	*0.99*
4. Boat Creek	0.98	*0.90*	*0.96*
5. Inner Harbour	0.93	*0.94*	*0.98*
6. Calliope Estuary	0.94	*0.99*	*0.98*
7. Auckland Inlet	0.87	*0.94*	*0.94*
8. Mid Harbour	0.95	*0.97*	*0.99*
9. South Trees Inlet	0.98	*0.95*	*0.96*
10. Boyne Estuary	0.97	*0.98*	*1.00*
11. Outer Harbour	0.97	*0.96*	*0.96*
12. Colosseum Inlet	0.99	*1.00*	*1.00*
13. Rodds Bay	0.95	*0.99*	*0.98*

Table 6.5: Scores for sediment quality measures for each of the 13 zones in the 2017 Gladstone Harbour Report Card.

Zone	Metals and Metalloids						
	Arsenic	Cadmium	Copper	Lead	Mercury	Nickel	Zinc
1. The Narrows	0.86	1.00	1.00	1.00	1.00	0.60	1.00
2. Graham Creek	0.65	1.00	1.00	1.00	1.00	0.77	1.00
3. Western Basin	0.91	1.00	1.00	1.00	1.00	0.89	1.00
4. Boat Creek	0.98	1.00	1.00	1.00	1.00	0.87	1.00
5. Inner Harbour	0.62	1.00	1.00	1.00	1.00	0.91	1.00
6. Calliope Estuary	0.92	1.00	0.95	1.00	1.00	0.73	1.00
7. Auckland Inlet	0.82	1.00	0.79	1.00	1.00	0.62	0.89
8. Mid Harbour	0.69	1.00	1.00	1.00	1.00	1.00	1.00
9. South Trees Inlet	0.90	1.00	1.00	1.00	1.00	0.94	1.00
10. Boyne Estuary	0.76	1.00	1.00	1.00	1.00	1.00	1.00
11. Outer Harbour	0.82	1.00	1.00	1.00	1.00	1.00	1.00
12. Colosseum Inlet	0.95	1.00	1.00	1.00	1.00	1.00	1.00
13. Rodds Bay	0.68	1.00	1.00	1.00	1.00	1.00	1.00

7. Water and sediment quality conclusions

7.1. Water quality

Scores for the water quality indicator have remained high since the first full Gladstone Harbour Report Card in 2015 receiving a good grade (B) in all years. The overall score improved from 0.72 in 2016 to 0.78 in 2017. Water quality was relatively uniform across the harbour and all zones received good or very good scores (0.71–0.90) except Boat Creek (0.59) which received a satisfactory score. The two zones with the highest scores were Graham Creek (0.88) and Outer Harbour (0.90).

Physicochemistry

Physicochemical scores (pH and turbidity) were good to very good (0.68 – 1.00) in all zones except Boat Creek (0.58). While scores for pH were uniformly very good (1.00) across the harbour, turbidity was highly variable in the past three report cards.

Boat Creek received the lowest score for turbidity (0.17) as these shallow areas can be prone to high turbidity levels caused by the resuspension of sediments owing to wind and tidal movement. This zone has received consistently low scores for turbidity since the first full report card in 2015 and the 2017 score was lower than the 2016 score of 0.24. Turbidity scores improved in all other zones.

The turbidity scores provide an annual measure of how each zone performed in relation to its zone-specific turbidity guideline (Table 3.1). However, there are differences in guideline values between zones so the scores may not allow a direct comparison of actual turbidity values (NTU) within the harbour. These differences can be seen in Figure 7.1 which maps average turbidity (NTU) for the four sampling periods conducted in the 2016–17 reporting year. In general, the map shows that the more oceanic sites such as the Outer and Mid Harbour and the associated large estuaries were the least turbid areas of the harbour while the more confined zones and smaller estuaries and inlets in the northern section of the harbour were in general more turbid.

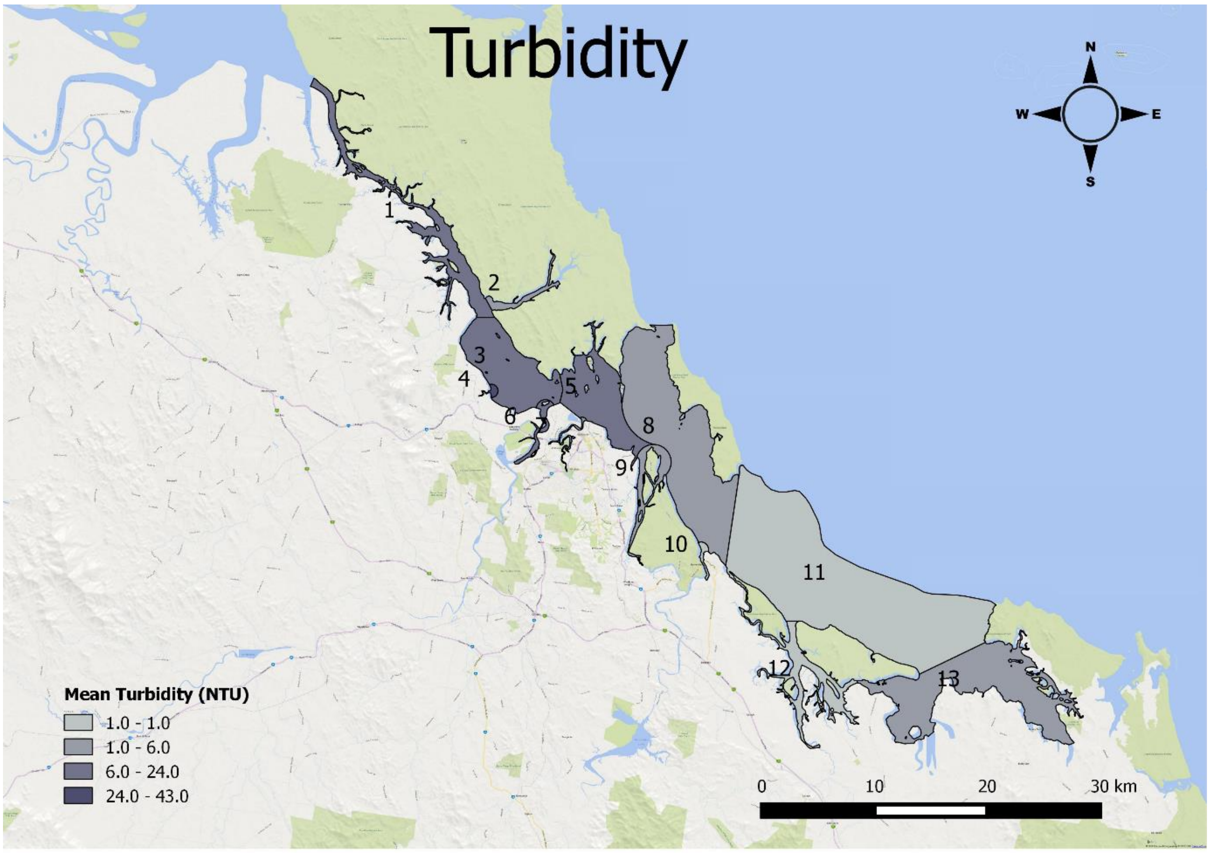

Figure 7.1: Mean turbidity for 13 Harbour zones for the 2016–17 reporting year. Mean turbidity classes were generated in QGIS™ using the Jenks natural breaks optimization function. This method reduces the variance within classes and maximize the variance between classes.

Nutrients

Scores for the nutrient sub-indicator (total nitrogen, total phosphorus, and chlorophyll-*a*) were satisfactory to good in all zones except The Narrows (0.44) and Boat Creek (0.32) which received poor scores. These two zones – The Narrows and Boat Creek – also had the lowest nutrient scores in the 2016 Report Card, 0.38 and 0.22 respectively. Comparisons with the 2015 report card were not made as chlorophyll-*a* was not included in that year.

While scores for total nitrogen and chlorophyll-*a* were generally satisfactory and above across all zones, the scores for total phosphorus were lower with seven zones recording poor or very poor scores. Since 2015 Boat Creek has consistently received the lowest scores for this measure (0.05 in 2015, 0.16 in 2016, 0.15 in 2017). Graham Creek (0.76) and the Outer Harbour (0.63) received the highest scores for total phosphorus in 2017.

As with the scores for other measures with specific zone guidelines, total phosphorus provides an annual measure of how each zone performed in relation to its guideline (Table 3.1). However, owing to the differences in guideline values between zones, the scores may not allow a direct comparison of actual total phosphorus values (µg/L) within the harbour. Figure 7.2 maps the zone average for total phosphorus for the four sampling periods conducted in the 2016–17 reporting year. Boat Creek had the highest mean total phosphorus concentrations and the Outer Harbour and Colosseum Inlet had the lowest. The zones located near the city of Gladstone, Inner Harbour, Calliope Estuary, Auckland Inlet, South Trees Inlet and Mid Harbour, and The Narrows located in the north of the harbour had higher total phosphorus concentrations than the remaining zones with the exception of Boat Creek.

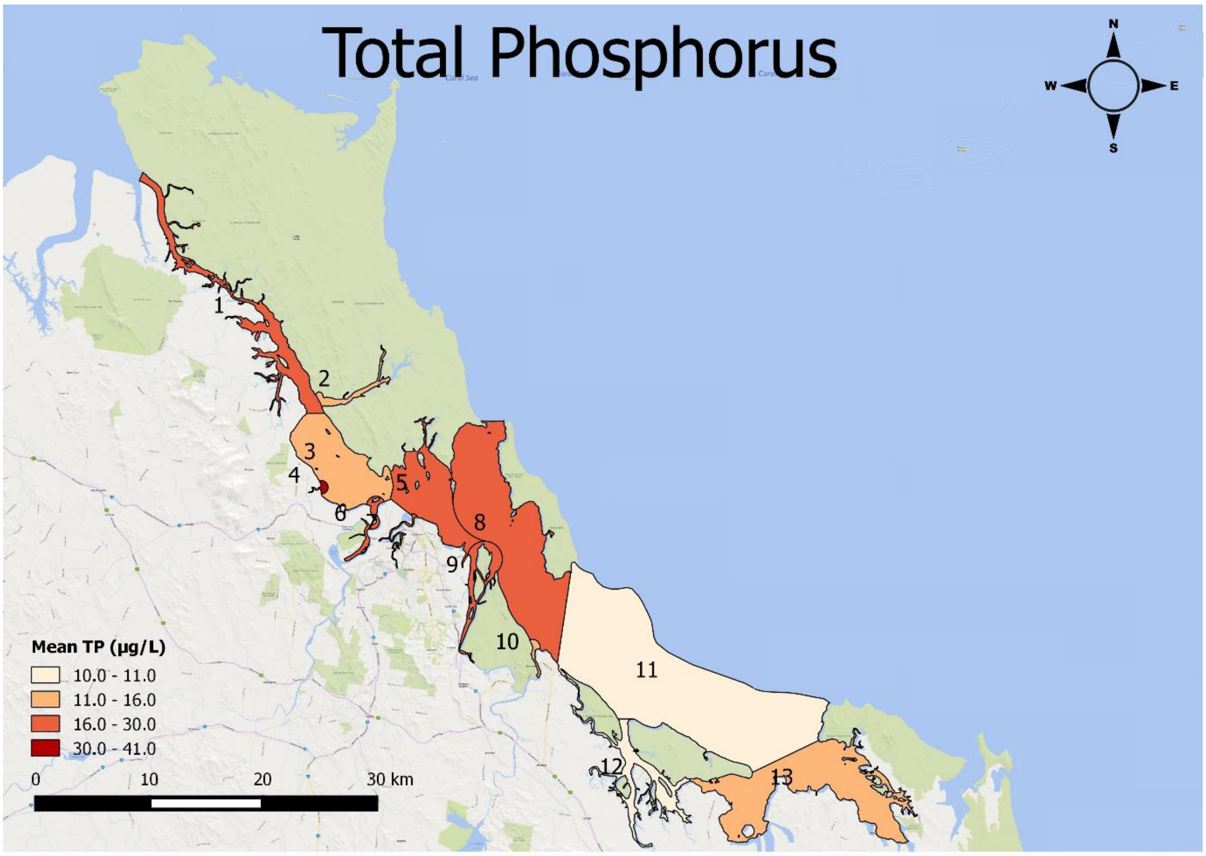

Figure 7.2: Mean total phosphorus for 13 Harbour zones for the 2016–17 reporting year. Mean total phosphorus classes were generated in QGIS™ using the Jenks natural breaks optimization function. This method reduces the variance within classes and maximize the variance between classes.

Metals

As the guideline values for the individual metal measures are uniform across all harbour zones (Table 3.1) direct comparisons of these scores between the zones are possible. In 2017 report card scores for aluminium (1.00), lead (1.00), manganese (1.00), nickel (1.00) and zinc (1.00) were all very good indicating very low concentrations of these metals across the harbour zones. This pattern was also evident in the 2015 and 2016 report cards, although a good score was received for aluminium and manganese at one zone each in both reporting years. Across the period 2015 to 2017 scores for copper have been lower than for other metals, but in only two instances – Calliope Estuary (0.23) in 2015 and Boat Creek (0.49) in 2017 – did the average concentrations exceed the guideline values.

In a comparison of dissolved metal concentrations with other harbours Angel et al. (2012) concluded that Gladstone Harbour compares favourably with other industrialised harbours and has relatively low metal concentrations (Table 7.1). They did note, however, that copper was closer to its ANZECC/ARMCANZ (2000) guideline value than other metals.

Table 7.1: Comparison of dissolved metal concentrations from Gladstone Harbor and other locations (Source Angel et al., 2012).

Location	Dissolved Metal Concentration, ng/L				Reference
	Cadmium	Copper	Nickel	Zinc	
Port Curtis, Dec 2011	4	717	538	306	Angel et al., 2012
Port Curtis Harbour	7.0	510	340	170	Angel et al., 2010
The Narrows	8.0	530	650	110	Angel et al., 2010
Port Jackson, Australia	6 – 104	932–2550	175–1610	3270–9660	Hatje et al., 2003
Torres Straight and Gulf of Papua	<1–29	36–986	940–4600	–	Apte and Day, 1998
Port Phillip Bay. Australia	<5–70	400–630	540–1100	250–1050	Fabris and Monahan, 1995
Nine estuaries, Australia	1.4–7.2	150–5500	120–4250	<10–11300	Munksguard and Parry, 2001
Humber Estuary, UK	80–450	180–10100	2500–12000	3000–11300	Comber et al., 1995
Scheldt Estuary, Netherlands	15–100	750–1800	1000–6800	1000–10000	Baeyens et al., 2005
San Francisco Bay Estuary, USA	22–123	315–2230	140–2410	160–1960	Sanudo-Wilhelmy et al., 1996
NSW coast	2.5	3.0	180	<22	Apte et al., 1998
North Pacific Ocean	0.3–112	–	–	15–520	Bruland et al., 1994
Australian guideline values (95% species protection)	5500	1300	70000	15000	ANZECC/ARMCANZ, 2000

7.2. Sediment quality

Measures of sediment quality are restricted to six metals (cadmium, copper, lead, nickel, mercury, zinc) and one metalloid (arsenic). Sediment mercury levels were assessed for the first time in 2017. PAHs were not monitored in 2017 owing to the very low concentrations recorded in the 2015 sediment monitoring.

Since the first full report card in 2015 overall sediment quality scores have been uniformly very good (A) across all Gladstone Harbour reporting zones. This is a result of very low concentrations of all metals assessed. Between 2015 and 2017 the lowest score for an individual measure was for arsenic. All these scores were generally very good and never fell below a satisfactory level. Angel et al. (2012) also reported low levels of sediment metals and metalloids within Gladstone Harbour below the guideline values, however, particulate arsenic concentrations exceeded the ANZECC/ARMNCANZ ISQG[3]-low trigger value in two samples from The Narrows and one sample near Quoin Island. They noted that the source of this arsenic is natural (geological formation on the area) and is not associated with anthropogenic inputs.

[3] ISQG refers to the Interim Sediment Quality Guideline. For sediment arsenic and cadmium this guideline is used in the report card.

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9. Glossary

Terms and acronyms	Definition
ALS	Australian Laboratories Services
Barotropic	A fluid type whose density is a function of pressure only
BOM	Bureau of Meteorology
Chl-*a*	Chlorophyll-*a*
component	The highest level of aggregation employed to determine the grades and scores in the Gladstone Harbour Report Card. The Gladstone Harbour Report Card reports on the condition of four components of harbour health: environmental, cultural, social and economic.
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEHP	Department of Environment and Heritage Protection
DIMS	Data and Information Management System
environmental indicators	Metrics derived from observation used to identify indirect drivers of environmental problems (e.g. population growth), direct pressures on the environment (e.g. overfishing), environmental condition (e.g. contaminant concentrations), broader impacts of environmental condition (e.g. health outcomes) or effectiveness of policy responses (de Sherbinin et al., 2013)
FB	Field Blank – A water sample free of the analytes of interest used for water quality QC. A field blank is prepared in the laboratory and exposed to the sampling environment while the sampling is performed. This type of QC identifies environmental contamination from the field.
FS	Field Spike – A seawater water sample spiked with a high concentration of the analyte of interest after field collection, used for water quality laboratory QC.
GHHP	Gladstone Healthy Harbour Partnership
GPC	Gladstone Ports Corporation
GV	Guideline Value
guidelines and criteria	Science-based numerical concentration limits or descriptive statements recommended to support a designated water use. Guidelines are not legally enforceable.
HEV	high ecological value
indicator	Numerical values that provide insight into the state of the environment, human health, etc. As the environment is highly complex, indicators provide a simple, practical way to track changes in the state of the environment over time.

ISP	Independent Science Panel
ISQG	Interim Sediment Quality Guideline
LB	Laboratory Blank - A water sample free of the analytes of interest used for water quality QC. A laboratory blank is prepared in the laboratory and not exposed to the sampling environment while the sampling is performed. This type of QC identifies contamination sources such as reverse osmosis, sample bottles or the analytical laboratory.
LNG	Liquefied Natural Gas
LOR	Limit of Reporting
MD	Moderately Disturbed
Macro-tidal	coastal areas where the tidal range is in excess of 4 m
Model/modelling	The creation of conceptual, graphical or mathematical models to describe, visualise or test abstract concepts and processes. Models help explain complex real-world interactions and add to our ability to understand how human actions impact on ecosystems. Models can be used to analyse scenarios to support decision making.
NATA	National Association of Testing Authorities, Australia
NMI	National Measurement Institute
NTU	Nephelometric Turbidity Units
outlier	an observation that lies an abnormal distance – which is defined by the analyst or analysis protocol – from other values in a random sample from a population
PCIMP	Port Curtis Integrated Monitoring Program
Physicochemical (or physico-chemical)	physical and chemical forces that influence the environment, its biodiversity and the people within (e.g. temperature, salinity, pH)
TN	Total Nitrogen
TP	Total Phosphorus
QA/QC	Quality assurance/quality control – the processes used to ensure the quality of a product (QA), and then to assess whether the product or services meet quality standards then correct where necessary to meet those standards (QC). Raw data may contain errors or be in formats unsuitable for further analysis, so appropriate QC needs to be applied to assess and correct data.
VEQ	Vision Environment Queensland

Appendix 1: Water quality QA/QC plot nutrients

A DIMS generated dot plot describing the guideline value (red vertical line), limit of reporting value (blue vertical line), observed measures (•), and outliers (green numbers: below guideline, red numbers: above guideline) for Ammonia, Chlorophyll-a, NOx, Total Nitrogen (TN), Orthophosphate and Total Phosphorus (TP). Values more than twice or less than half the guideline value were classed as outliers. The guideline values used for these measures are 3-6 µg/L-Ammonia, 0.8-2.0 µg/L-Chlorophyll-*a*, 1-6 µg/L-NOx, 120-190 µg/L-TN, 1-4 µg/L-Orthophosphate, and 10-22 µg/L-TP depending on the zone. The limit of reporting values used for these measures are 2 µg/L-Ammonia, 0.02 µg/L-Chlorophyll-*a*, 2 µg/L-NOx, 50 µg/L-TN, 2 µg/L-Orthophosphate, and 5 µg/L-TP. The light red band represents the range of values in which non-outlying values would occur.

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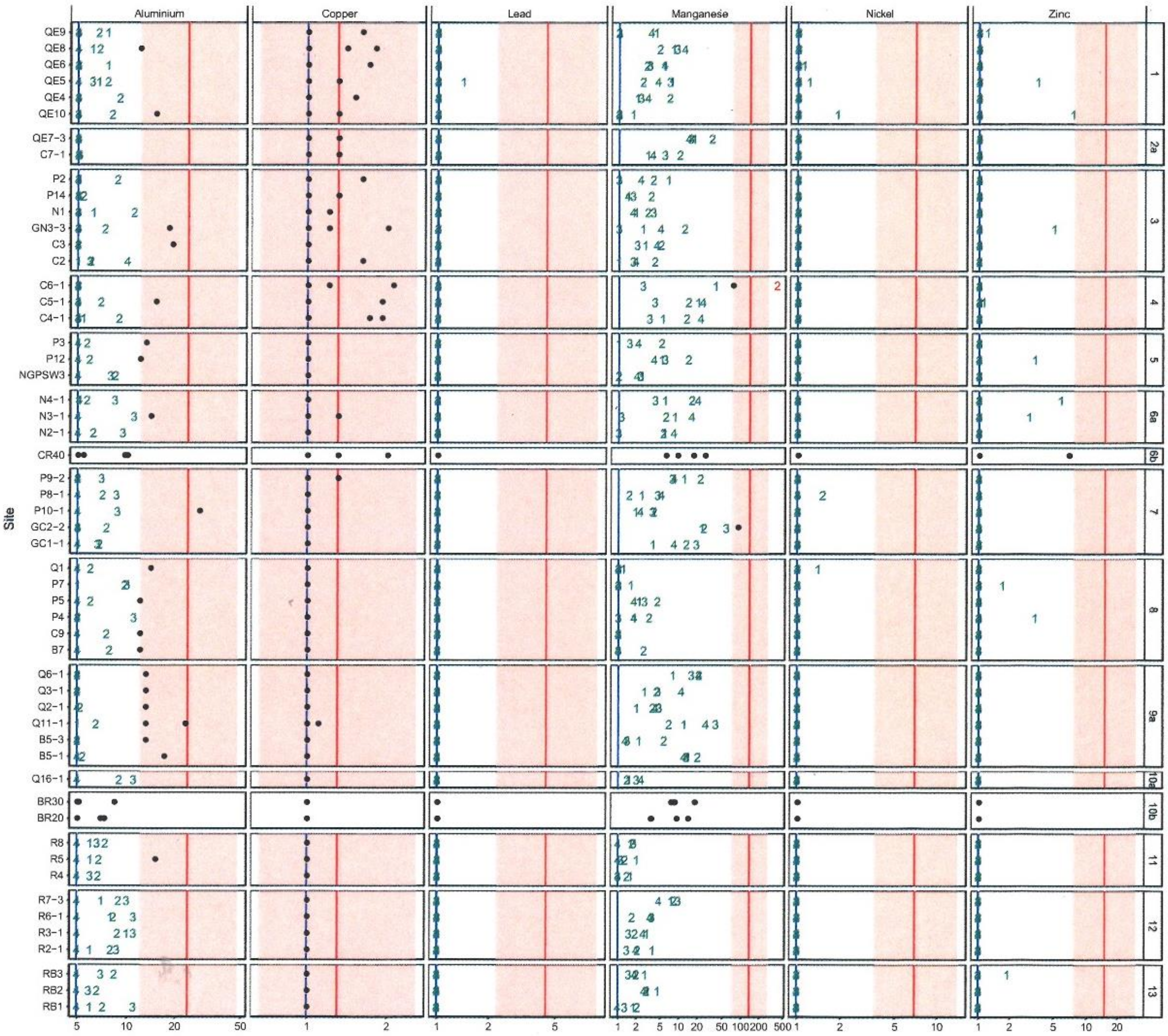
Appendix 2: Water quality QA/QC plot metals

A DIMS generated dot plot describing the guideline value (red vertical line), limit of reporting value (blue vertical line), observed measures (•), and outliers (green numbers: below guideline, red numbers: above guideline) for Aluminium, Copper, Lead, Manganese, Nickel and Zinc. Values more than twice or less than half the guideline value were classed as outliers. The limit of reporting values used for these measures are 5 µg/L-Aluminium, 1 µg/L-Copper, 1 µg/L-Lead, 1 µg/L-Manganese, 1 µg/L-Nickel, and 5 µg/L-Zinc. The guideline values used for these measures are 24 µg/L-Aluminium, 1.3 µg/L-Copper, 4.4 µg/L-Lead, 140 µg/L-Manganese, 7 µg/L-Nickel, and 15 µg/L-Zinc. The light red band represents the range of values in which non-outlying values would occur.



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Appendix 3: Water quality score summaries for the 13 environmental monitoring zones

Zone 1: The Narrows (Figure A.1)

The Narrows received an overall water quality score of 0.71 (B), which was comprised of a score of 0.76 (B) for physicochemical condition, 0.44 (D) for nutrients and 0.93 (A) for dissolved metals (Figure A.2).

The Narrows received a very good score of 1.00 for pH indicating levels well within the guideline values for this zone. This zone received a satisfactory score for turbidity (0.53) indicating turbidity values were within the guideline values (Figure A.3).

Five of the six dissolved metals received very good scores of 1.00, indicating concentrations that were well below the water quality guideline values. Copper (0.59) received a good score, indicating that average copper concentrations met the water quality guideline (Figure A.3).

In common with other zones, The Narrows received its lowest sub-indicator score for nutrients. Total phosphorus (0.36) and chlorophyll-*a* (0.48) had poor scores indicating that levels for these measures were above the guideline values. Total nitrogen (0.50) had a satisfactory score and met the guideline value (Figure A.3).

While the overall zone grade has remained a B, over the three years of the report card the score has declined from 0.82 in 2015 to 0.71 in 2017 (Figure A.4).

Zone 2: Graham Creek (Figure A.5)

Graham Creek received a very good overall water quality score of 0.88 (A) which was comprised of a score of 0.99 (A) for physicochemical condition, 0.69 (C) for nutrients and 0.94 (A) for dissolved metals (Figure A.6).

Graham Creek received very good scores for pH (1.00) and turbidity (0.98) indicating levels well within the guideline values for this zone (Figure A.7).

Five of the six dissolved metals received very good scores of 1.00, indicating concentrations that were well below the water quality guideline values. Copper received a satisfactory score of 0.64, indicating that average copper concentrations in Graham Creek met the guideline value (Figure A.7).

Graham Creek received a good overall score for nutrients. Total nitrogen (0.67) and total phosphorus (0.76) received good scores and chlorophyll-*a* (0.64) received a satisfactory score (Figure A.7).

Water quality in this zone has been very good (A) or good (B) since 2015 (Figure A.8).

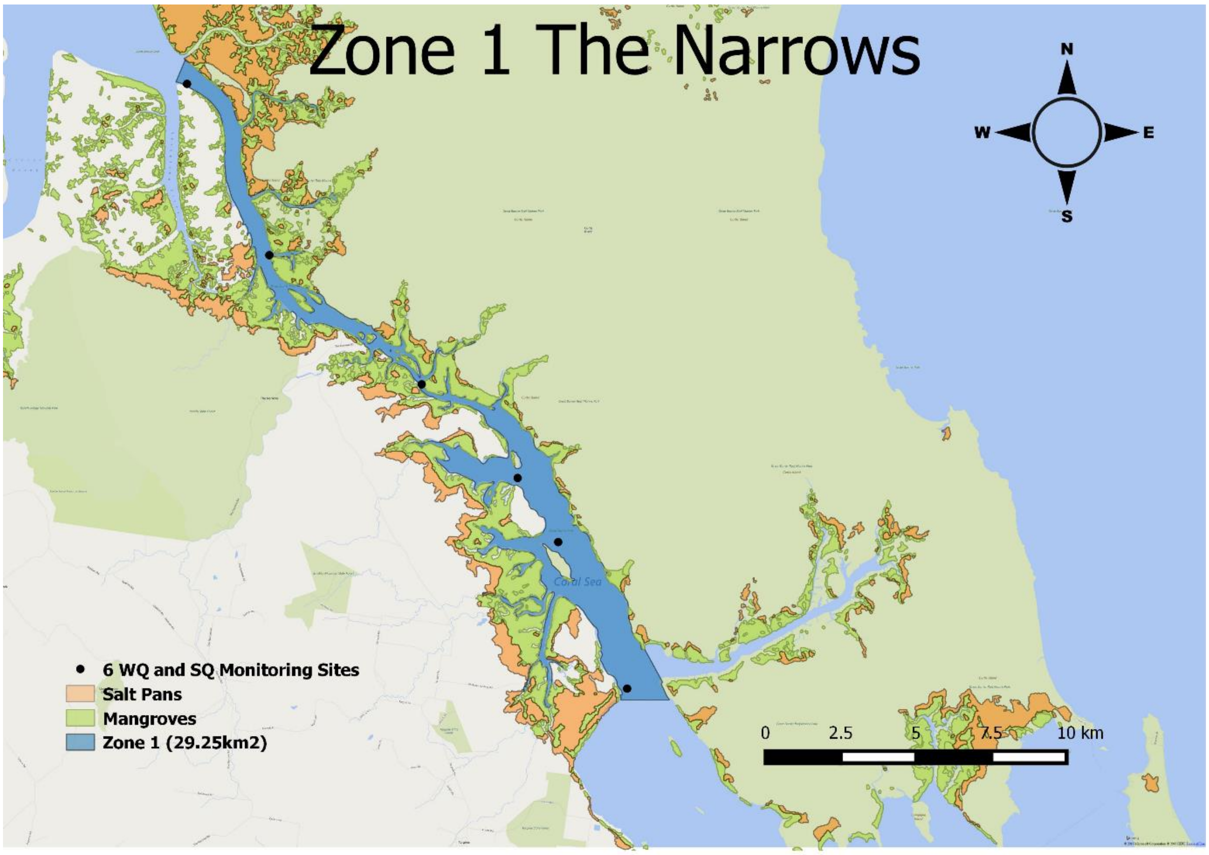

Figure A.1: Water and sediment quality sampling sites in The Narrows.

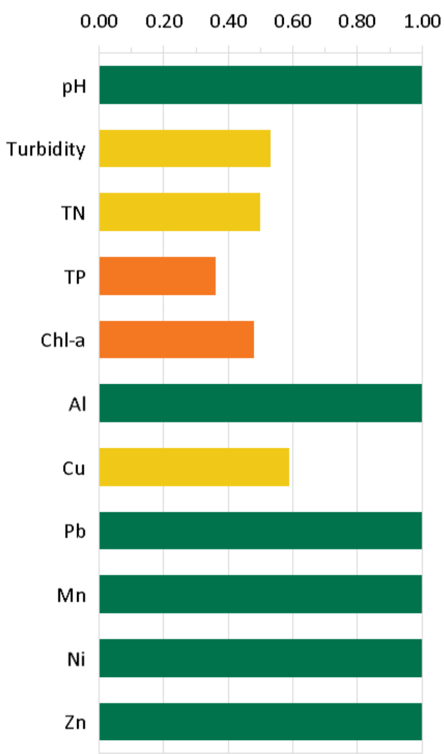

Figure A.3: Zone 1 measure scores.

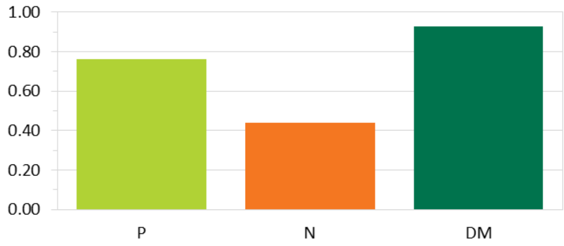

Figure A.2: Zone 1 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

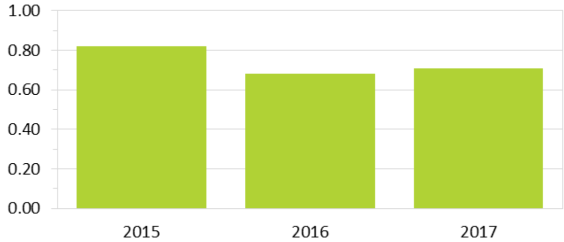

Figure A.4: Zone 1 overall water quality scores.

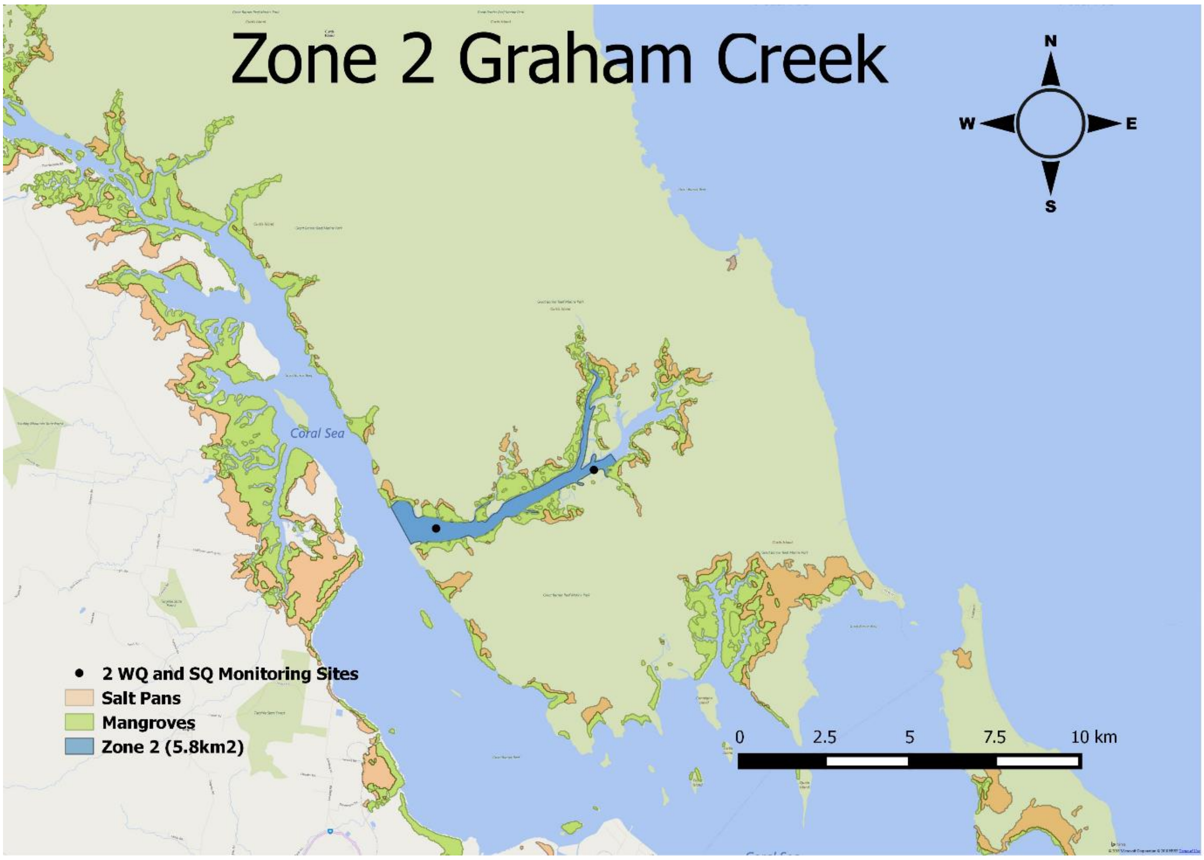

Figure A.5: Water and sediment quality sampling sites in Graham Creek.

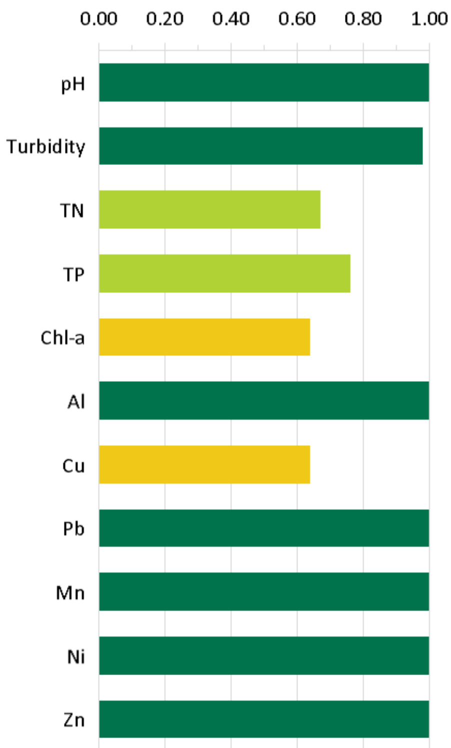

Figure A.7: Zone 2 measure scores.

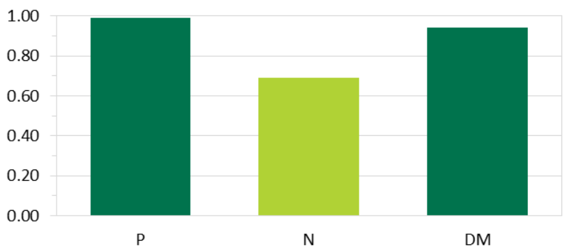

Figure A.6: Zone 2 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

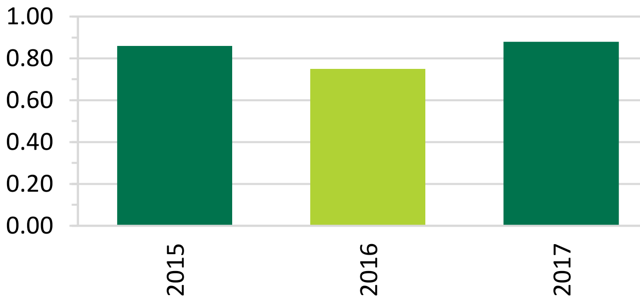

Figure A.8: Overall water quality scores for Zone 2.

Zone 3: Western Basin (Figure A.9)

Western Basin received an overall water quality score of 0.77 (B), which was comprised of a score of 0.74 (B) for physicochemical condition, 0.64 (C) for nutrients and 0.93 (A) for dissolved metals (Figure A.10).

The Western Basin received a very good score for pH (1.00) indicating levels well within the guideline values for this zone. The zone received a satisfactory score for turbidity (0.50) indicating turbidity values were within the guideline value for this zone (Figure A.11).

Five of the six dissolved metals received very good scores of 1.00, indicating concentrations that were well below the water quality guideline values. Copper received a satisfactory score of 0.61, indicating that average copper concentrations in Graham Creek met the guideline value (Figure A.11).

Of the nutrients, chlorophyll-*a* (0.75) received a good score and total nitrogen (0.61) and total phosphorus (0.56) had satisfactory scores (Figure A.11).

Overall water quality scores have been good (B) in this zone since the first report card in 2015 (Figure A.12).

Zone 4: Boat Creek (Figure A.13)

Boat Creek received an overall water quality score of 0.59 (C), which was comprised of a score of 0.58 (C) for physicochemical condition, 0.32 (D) for nutrients and 0.89 (A) for dissolved metals (Figure A.14).

Boat Creek received a very good score for pH (1.00) indicating levels well within the guideline values for this zone. The score for turbidity (0.17) indicated very poor turbidity above the guideline value for this zone (Figure A.15).

Five of the six dissolved metals received very good scores (0.85 – 1.00), indicating concentrations that were well below the water quality guideline values. Copper (0.49) received a poor score indicating that on average copper concentrations were above the water quality guideline (Figure A.15).

Nutrients received the lowest scores of the sub-indicators. Chlorophyll-*a* (0.54) received a satisfactory score and total nitrogen (0.27) received a poor score. Total phosphorus (0.15) received a very poor score indicating average concentrations above the guideline value (Figure A.15).

The overall water quality score in this zone was good (B) in 2015 and satisfactory (C) in 2016 and 2017 (Figure A.16).

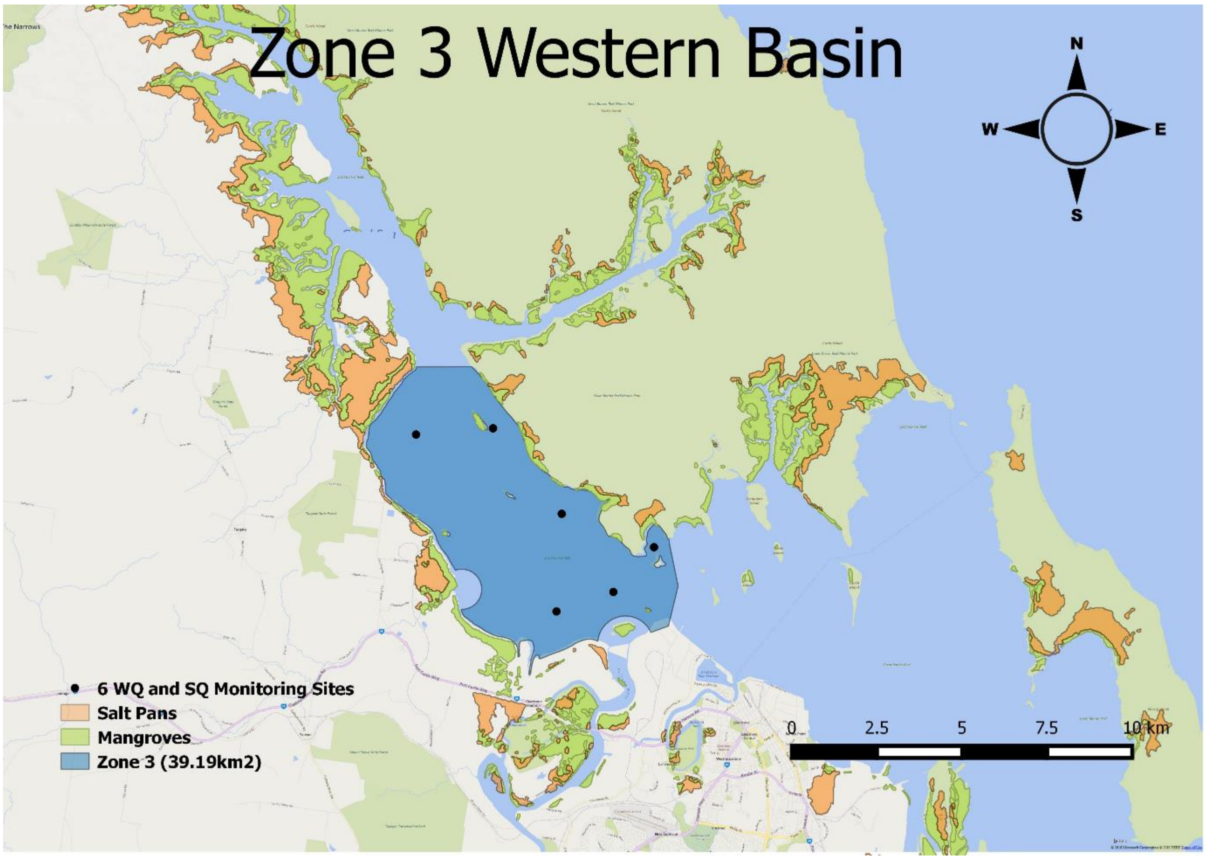

Figure A.9: Water and sediment quality sampling sites in the Western Basin.

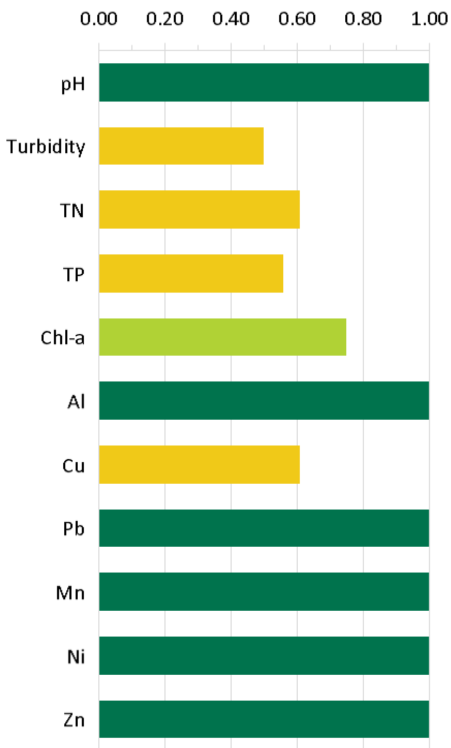

Figure A.11: Zone 3 measure scores.

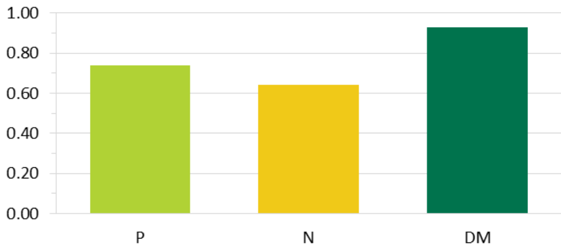

Figure A.10: 2017 Zone 3 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

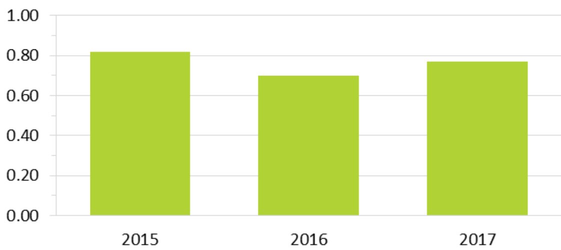

Figure A.12: Overall water quality scores for Zone 3.

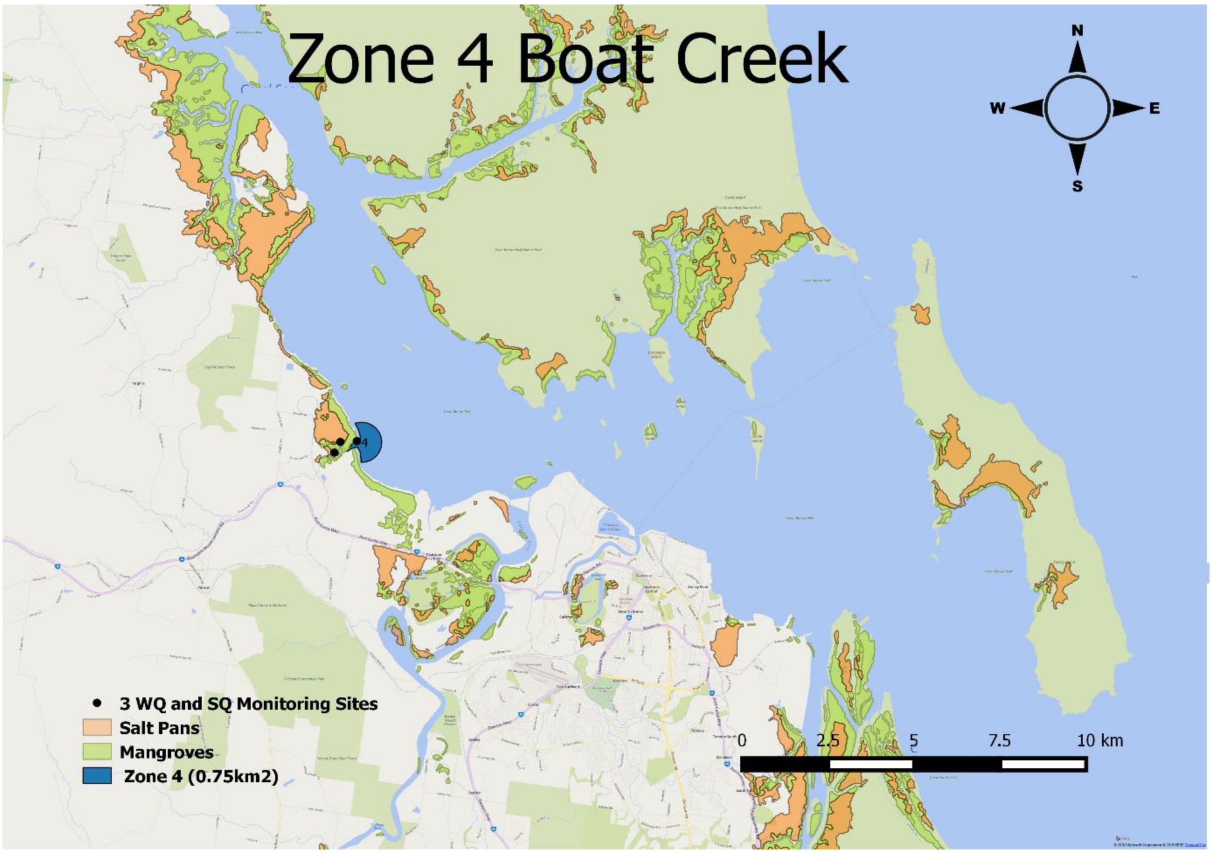

Figure A.13: Water and sediment quality sampling sites in Boat Creek.

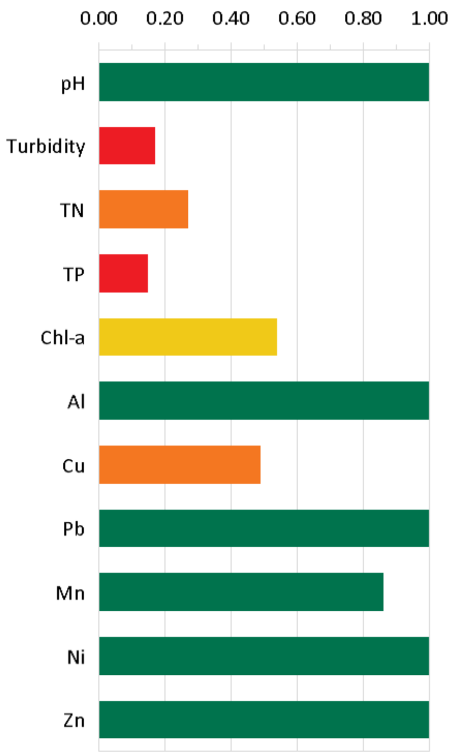

Figure A.15: Zone 4 measure scores.

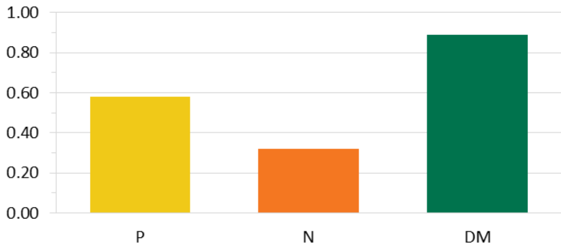

Figure A.14: 2017 Zone 4 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

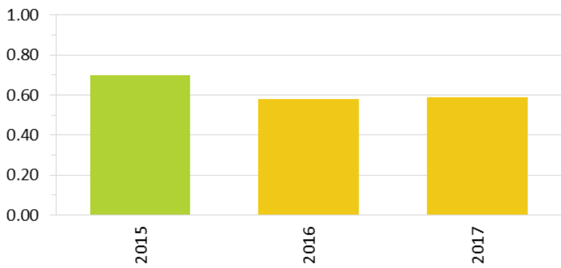

Figure A.16: Overall water quality scores for Zone 4.

Zone 5: Inner Harbour (Figure A.17)

The Inner Harbour received an overall water quality score of 0.79 (B), which was comprised of a score of 0.76 (B) for physicochemical parameters, 0.69 (B) for nutrients and 0.95 (A) for dissolved metals (Figure A.18).

The Inner Harbour received a very good score for pH (1.00) indicating levels well within the guideline values for this zone. Turbidity (0.52) received a satisfactory score indicating that average turbidity values met the guideline value (Figure A.19).

Five of the six dissolved metals received very good scores of 1.00, indicating concentrations that were well below the water quality guideline values. Copper (0.69) received a good score indicating that the average copper concentration was below the guideline value (Figure A.19).

All nutrients received satisfactory or good scores indicating concentrations below the guideline values. Total nitrogen (0.64) and total phosphorus (0.60) received satisfactory scores. Chlorophyll-*a* (0.83) received a good score indicating average concentrations below the guideline value (Figure A.19).

Overall water quality scores were very good (A) in 2015 and good (B) in 2016 and 2017 (Figure A.20).

Zone 6: Calliope Estuary (Figure A.21)

Calliope Estuary received an overall water quality score of 0.77 (B), which was comprised of a score of 0.68 (B) for physicochemical parameters, 0.70 (B) for nutrients and 0.94 (A) for dissolved metals (Figure A.22).

Calliope Estuary received a very good score for pH (1.00) indicating levels well within the guideline values for this zone. Turbidity (0.37) received a poor score indicating average turbidity values were above the guideline value for this zone (Figure A.23).

Five of the six dissolved metals received very good scores of 1.00 indicating concentrations that were well below the water quality guideline values. Copper (0.66) received a good score indicating average copper concentrations in the Calliope Estuary were below the water quality guideline (Figure A.23).

Calliope Estuary received satisfactory scores for total nitrogen (0.57) and total phosphorus (0.52) and chlorophyll-*a* (0.94) received a very good score (Figure A.23).

Overall water quality scores were very good (A) in 2015 and good (B) in 2016 and 2017 (Figure A.24).

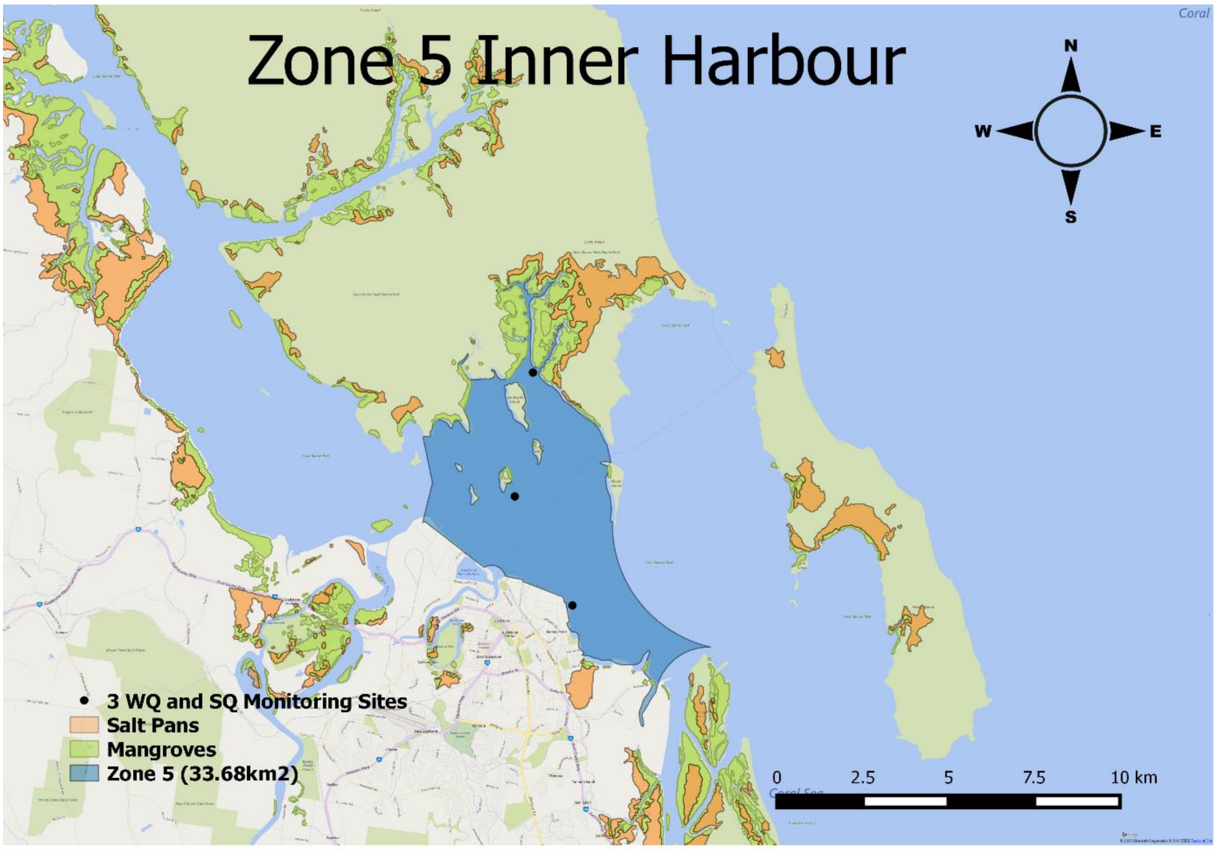

Figure A.17: Water and sediment quality sampling sites in the Inner Harbour.

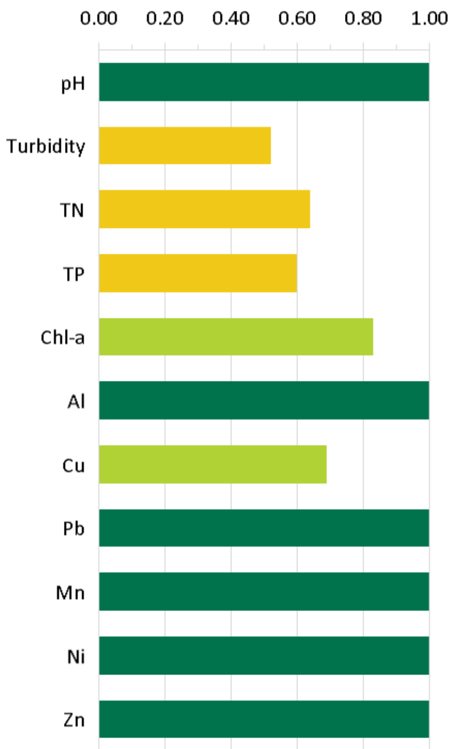

Figure A.19: Zone 5 measure scores.

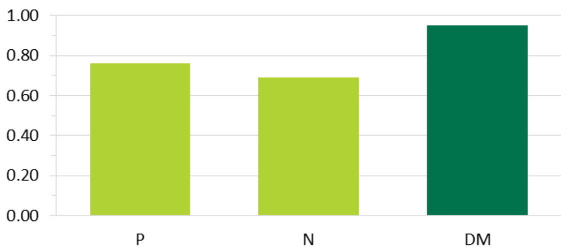

Figure A.18: 2017 Zone 5 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

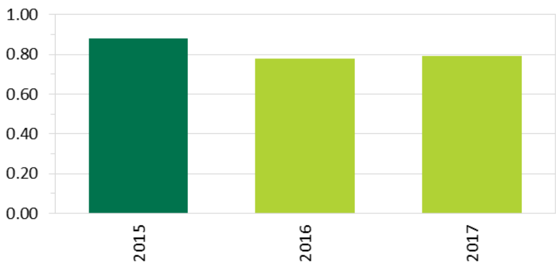

Figure A.20: Overall water quality scores for Zone 5.

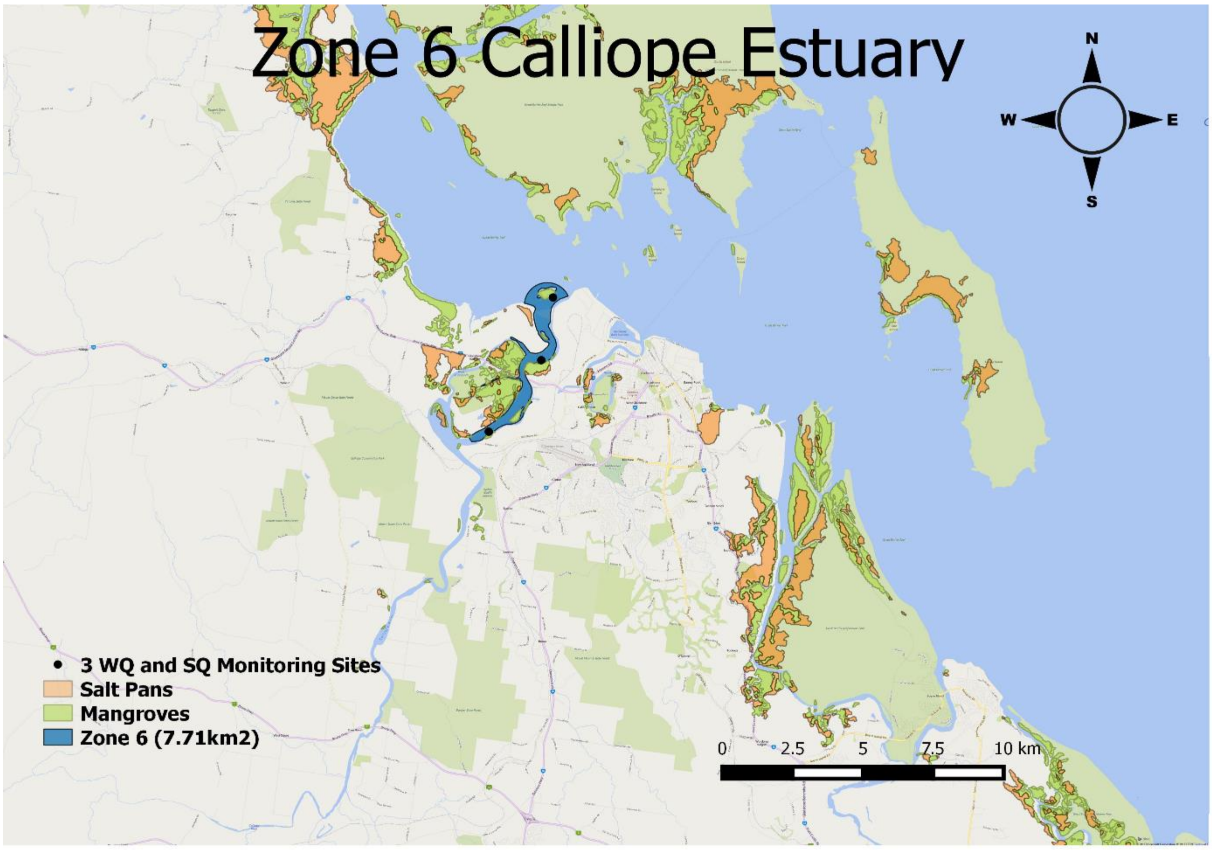

Figure A.21: Water and sediment quality sampling sites in Calliope Estuary.

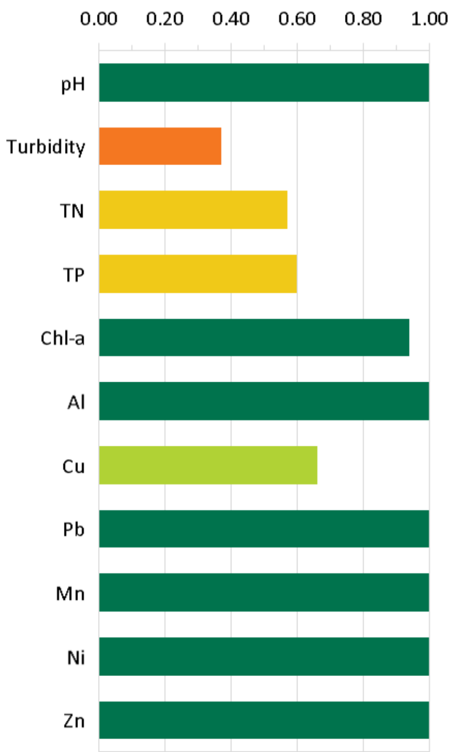

Figure A.23: Zone 6 measure scores.

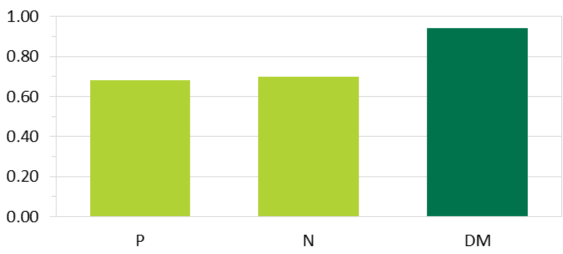

Figure A.22: 2017 Zone 6 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

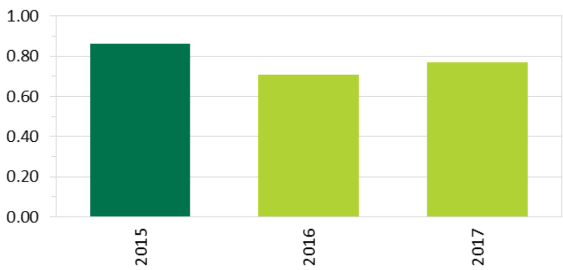

Figure A.24: Overall water quality scores for Zone 6.

Zone 7: Auckland Inlet (Figure A.25)

Auckland Inlet received an overall water quality score of 0.79 (B), which was comprised of a score of 0.83 (B) for physicochemical condition, 0.60 (C) for nutrients and 0.94 (A) for dissolved metals (Figure A.26).

Auckland Inlet received a very good score for pH (1.00) indicating levels well within the guideline values for this zone. Turbidity (0.65) received a good score indicating turbidity values were below the guideline value (Figure A.27).

Five of the six dissolved metals received very good scores of 1.00 indicating concentrations that were well below the water quality guideline values. Copper received a good score of 0.67, indicating that the average copper concentration was below the water quality guideline (Figure A.27).

Auckland Inlet received a very good score for chlorophyll-*a* (0.92), while total nitrogen (0.52) had a satisfactory score. Total phosphorus (0.37) had a poor score (Figure A.27).

Overall water quality scores have been good (B) in this zone since the first report card in 2015 (Figure A.28).

Zone 8: Mid Harbour Figure A.29)

The Mid Harbour received an overall water quality score of 0.79 (B), which was comprised of a score of 0.85 (A) for physicochemical parameters, 0.59 (C) for nutrients and 0.95 (A) for dissolved metals (Figure A.30).

The Mid Harbour received a very good score for pH (1.00) and turbidity (0.71) received a good score indicating both measures were within the guideline values (Figure A.31).

Five of the six dissolved metals received very good scores of 1.00 indicating concentrations that were well below the water quality guideline values. Copper received a good score of 0.69, indicating that the average copper concentration was below the water quality guideline (Figure A.31).

Mid Harbour received a very good score for chlorophyll-*a* (0.85), a satisfactory score for total nitrogen (0.57) and a poor score for total phosphorus (0.38) (Figure A.31).

Overall water quality scores have been good (B) in this zone since the first report card in 2015 (Figure A.32).

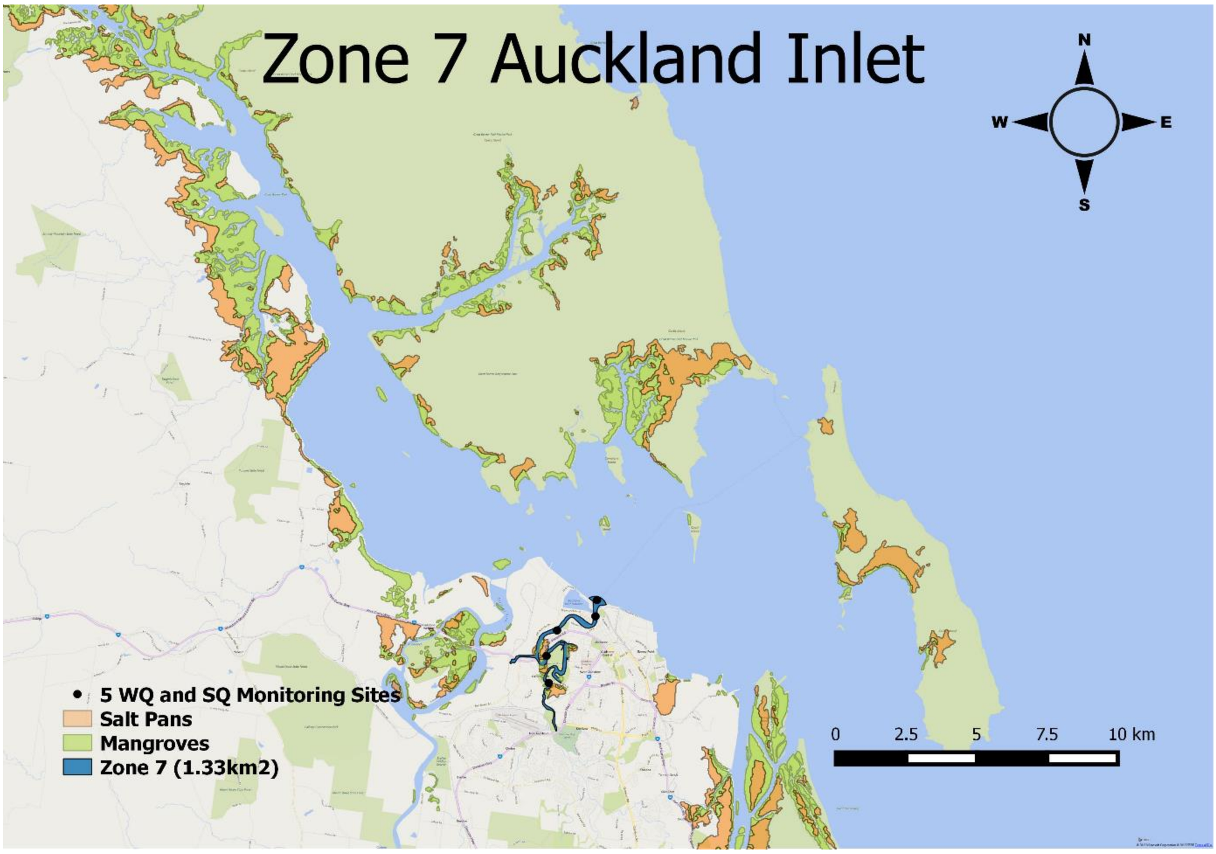

Figure A.25: Water and sediment quality sampling sites in Auckland Inlet.

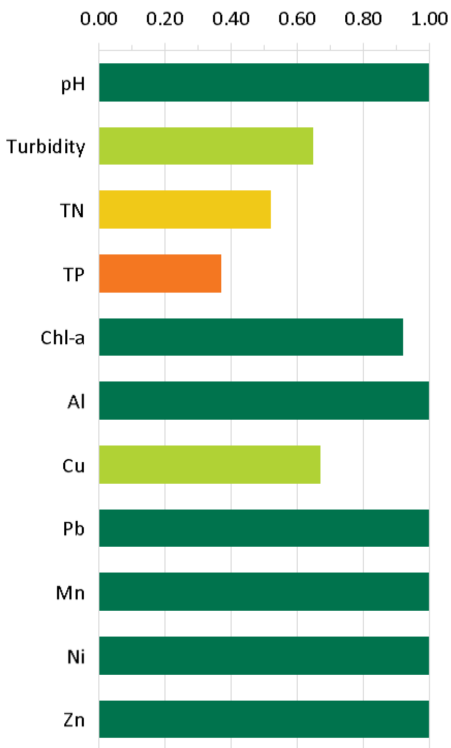

Figure A.27: Zone 7 measure scores.

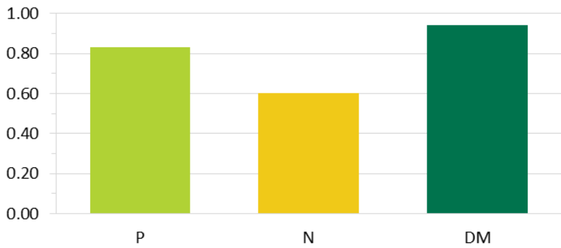

Figure A.26: 2017 Zone 7 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

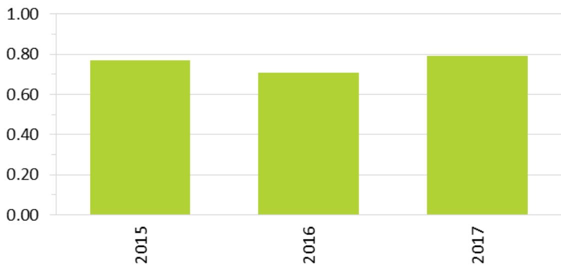

Figure A.28: Overall water quality scores for Zone 7.

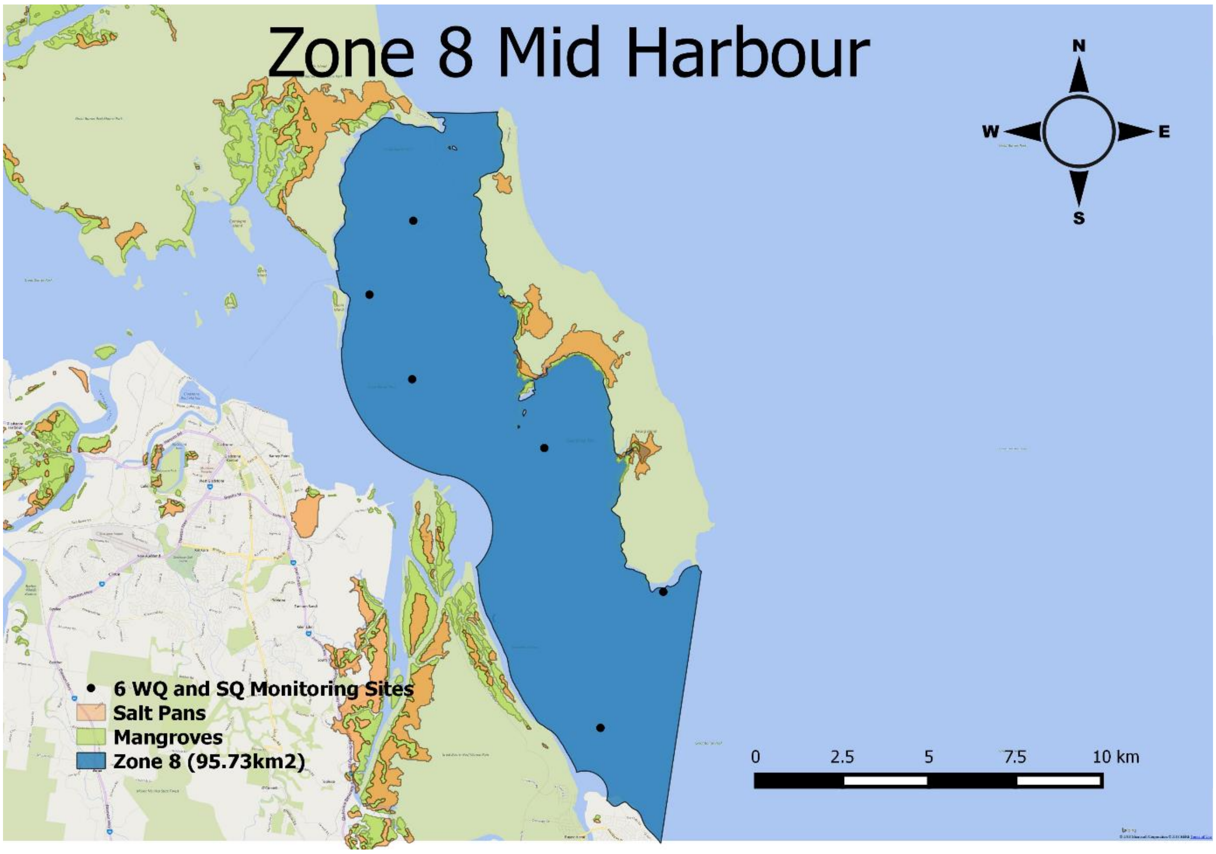

Figure A.29: Water and sediment quality sampling sites in Mid Harbour.

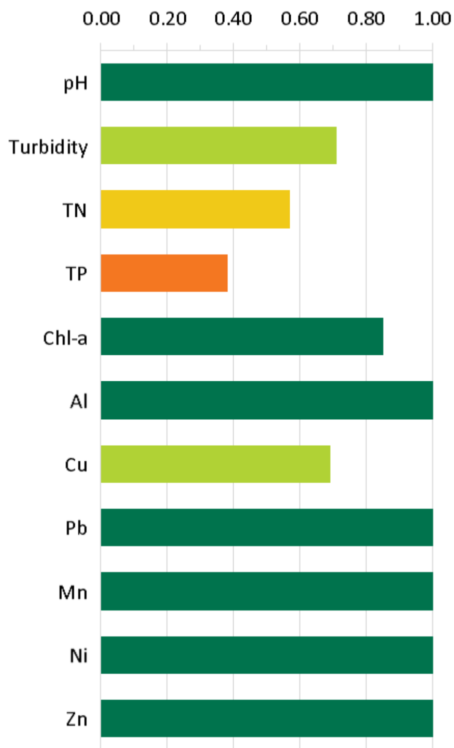

Figure A.31: Zone 8 measure scores.

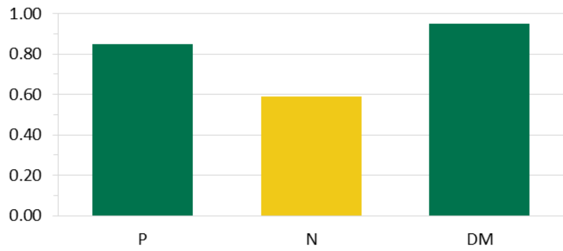

Figure A.30: 2017 Zone 8 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

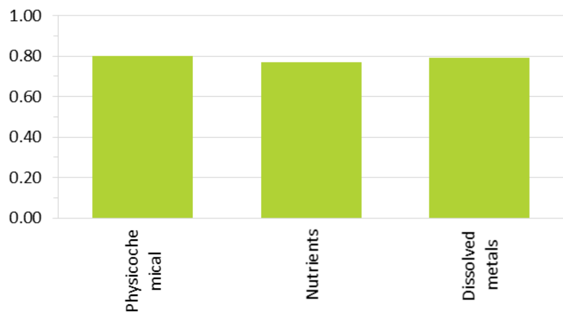

Figure A.32: Overall water quality scores for Zone 8.

Zone 9: South Trees Inlet (Figure A.33)

South Trees Inlet received an overall water quality score of 0.84 (B), which was comprised of a score of 0.91 (A) for physicochemical parameters, 0.68 (B) for nutrients and 0.95 (A) for dissolved metals (Figure A.34).

The South Trees Inlet received a very good score for pH (1.00) and good score for turbidity (0.81) indicating both measures were within the guideline values (Figure A.35).

Five of the six dissolved metals received very good scores (0.85 – 1.00) indicating concentrations that were well below the water quality guideline values. Copper received a good score of 0.69, indicating that average copper concentration in South Trees Inlet were also below the water quality guideline (Figure A.35).

South Trees Inlet received good scores for total nitrogen (0.67) and chlorophyll-*a* (0.81). Total phosphorus (0.57) received a satisfactory score (Figure A.35).

Overall water quality scores were very good (A) in 2015 and good (B) in 2016 and 2017 (Figure A.36).

Zone 10: Boyne Estuary (Figure A.37)

Boyne Estuary received an overall water quality score of 0.83 (B), which was comprised of a score of 1.00 (A) for physicochemical parameters, 0.53 (C) for nutrients and 0.95 (A) for dissolved metals (Fig 5.38).

Boyne Estuary received a very good score of 1.00 for both pH and turbidity indicating levels well within the guideline values for this zone (Figure A.39).

Five of the six dissolved metals received very good scores of 1.00 indicating concentrations were well below the water quality guideline values. Copper received a good score of 0.69, indicating that copper concentrations in the Boyne Estuary were also below the water quality guideline (Figure A.39).

Boyne Estuary received satisfactory scores for chlorophyll-*a* (0.62) and total nitrogen (0.55) indicating that average concentrations for these nutrients met the guideline values. Total phosphorus (0.41) received a poor score indicating average concentrations were above the guideline value (Figure A.39).

Overall water quality scores have been good (B) in this zone since the first report card in 2015 (Figure A.40).

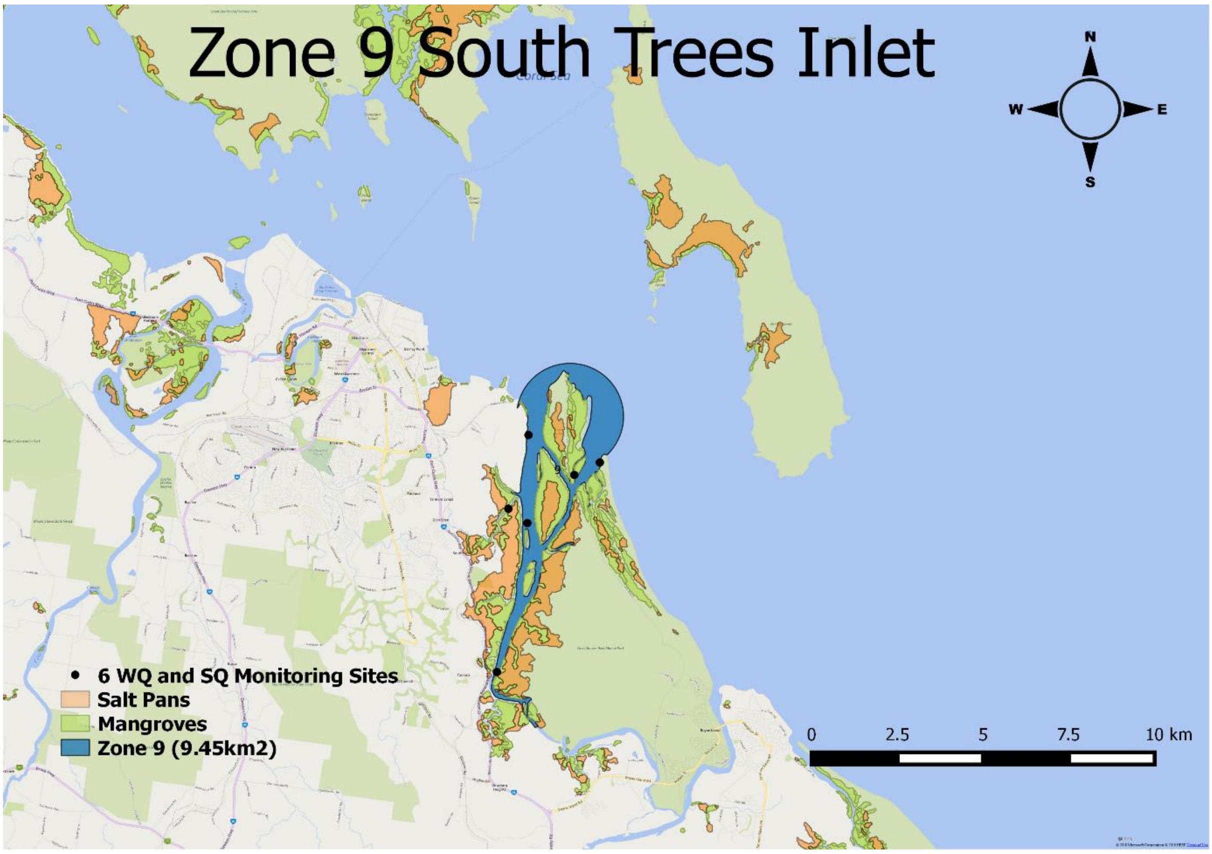

Figure A.33: Water and sediment quality sampling sites in South Trees Inlet.

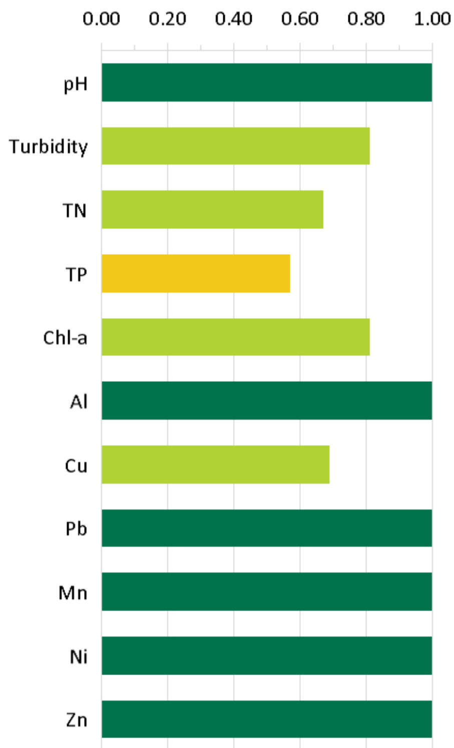

Figure A.35: Zone 9 measure scores.

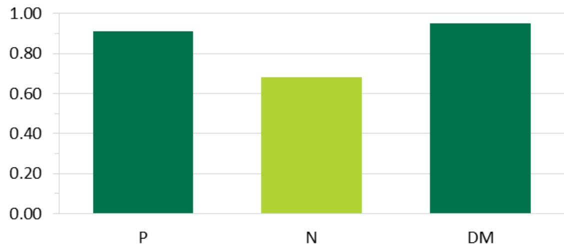

Figure A.34: 2017 Zone 9 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

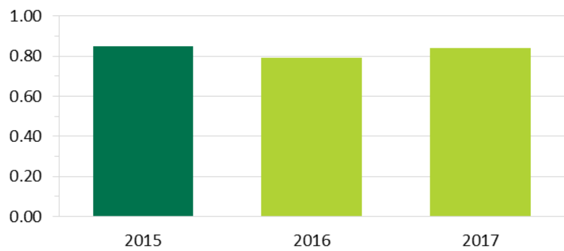

Figure A.36: Overall water quality scores for Zone 9.

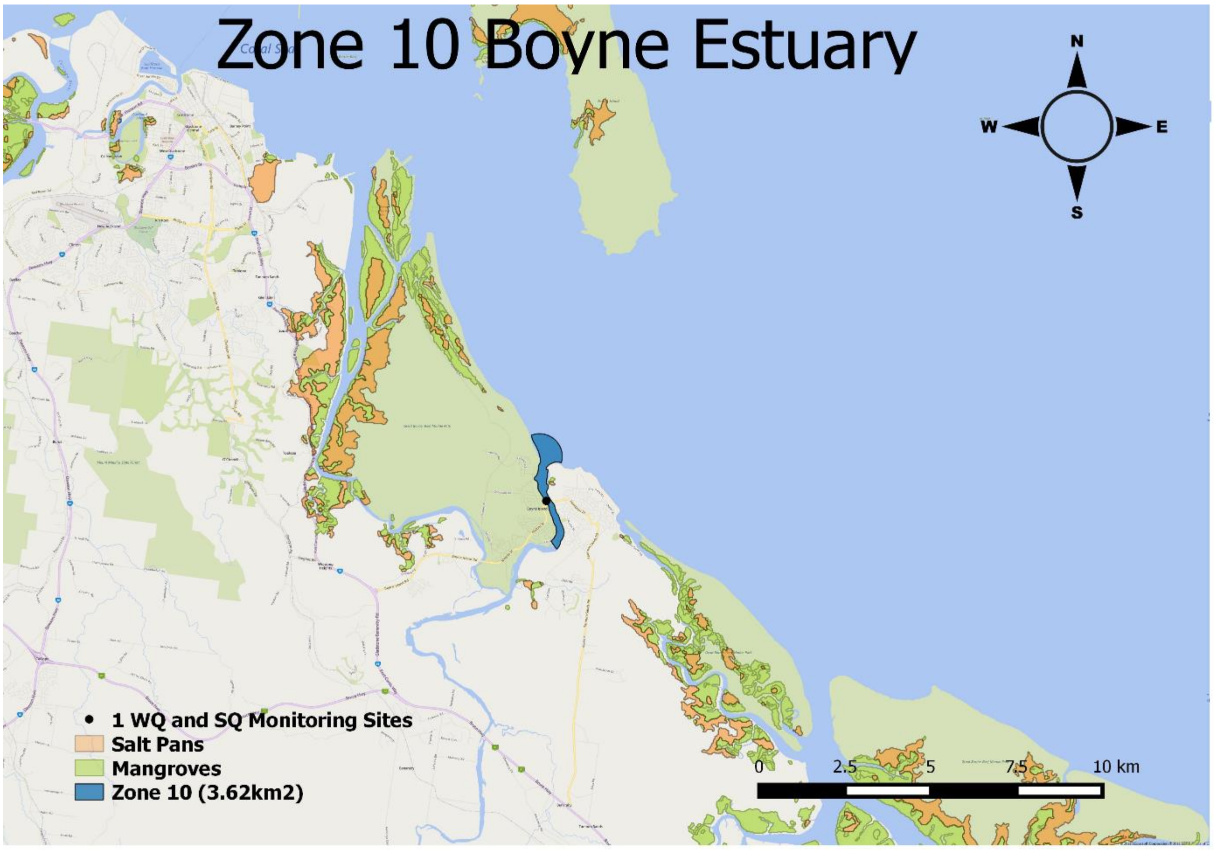

Figure A.37: Water and sediment quality sampling sites in Boyne Estuary.

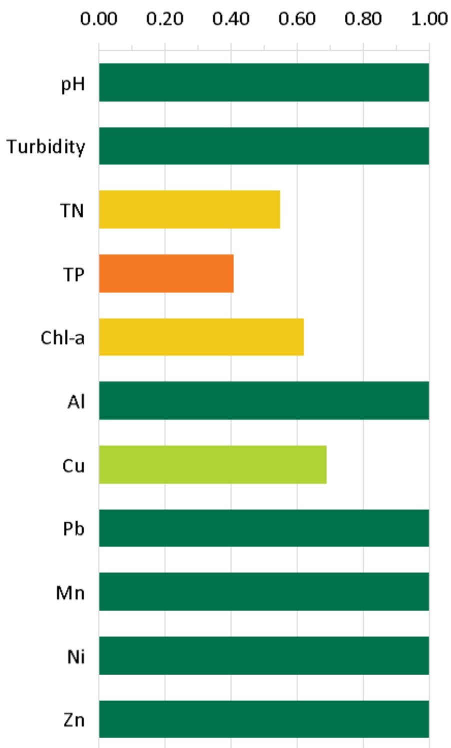

Figure A.39: Zone 10 measure scores.

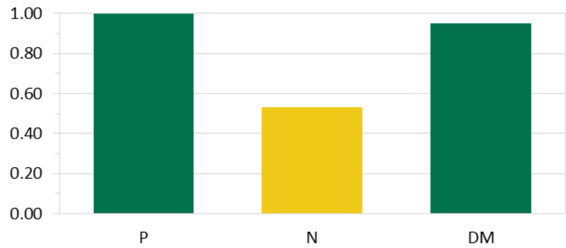

Figure A.38: 2017 Zone 10 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

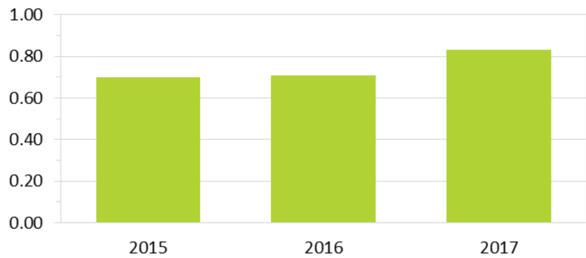

Figure A.40: Overall water quality scores for Zone 10.

Zone 11: Outer Harbour (Figure A.41)

The Outer Harbour received an overall water quality score of 0.90 (A), which was comprised of a score of 1.00 (A) for physicochemical parameters, 0.74 (B) for nutrients and 0.95 (A) for dissolved metals (Figure A.42).

Outer Harbour received a very good score of 1.00 for both pH and turbidity indicating levels well within the guideline values for this zone (Figure A.43).

Five of the six dissolved metals received scores of 1.00 indicating concentrations were well below water quality guidelines. Copper received a good score of 0.69, indicating that average copper concentrations in the Outer Harbour also met the water quality guideline (Figure A.43).

Average concentrations for all nutrients in the Outer Harbour were below the guideline values. Chlorophyll-a (1.00) received a very good score and total nitrogen (0.59) and total phosphorus (0.63) received satisfactory scores (Figure A.43).

The overall water quality score for this zone was good (B) in 2015 and 2016 and very good (A) in 2017 (Figure A.44).

Zone 12: Colosseum Inlet (Figure A.45)

Colosseum Inlet received an overall water quality score of 0.83 (B), which was comprised of a score of 1.00 (A) for physicochemical condition, 0.55 (C) for nutrients and 0.95 (A) for dissolved metals (Figure A.46).

Colosseum Inlet received a very good score of 1.00 for both pH and turbidity indicating levels well within the guideline values for this zone (Figure A.47).

Five of the six dissolved metals received very good scores of 1.00 indicating concentrations were below the water quality guideline values. Copper received a score of 0.69, indicating that average copper concentrations in Colosseum Inlet were also lower than the water quality guideline (Figure A.47).

Total nitrogen (0.52) received a satisfactory score indicating average concentrations met the guideline, while total phosphorous (0.47) received a poor score. Chlorophyll-a (0.65) received a good score (Figure A.47).

Overall water quality scores have been good (B) in this zone since the first report card in 2015 (Figure A.48).

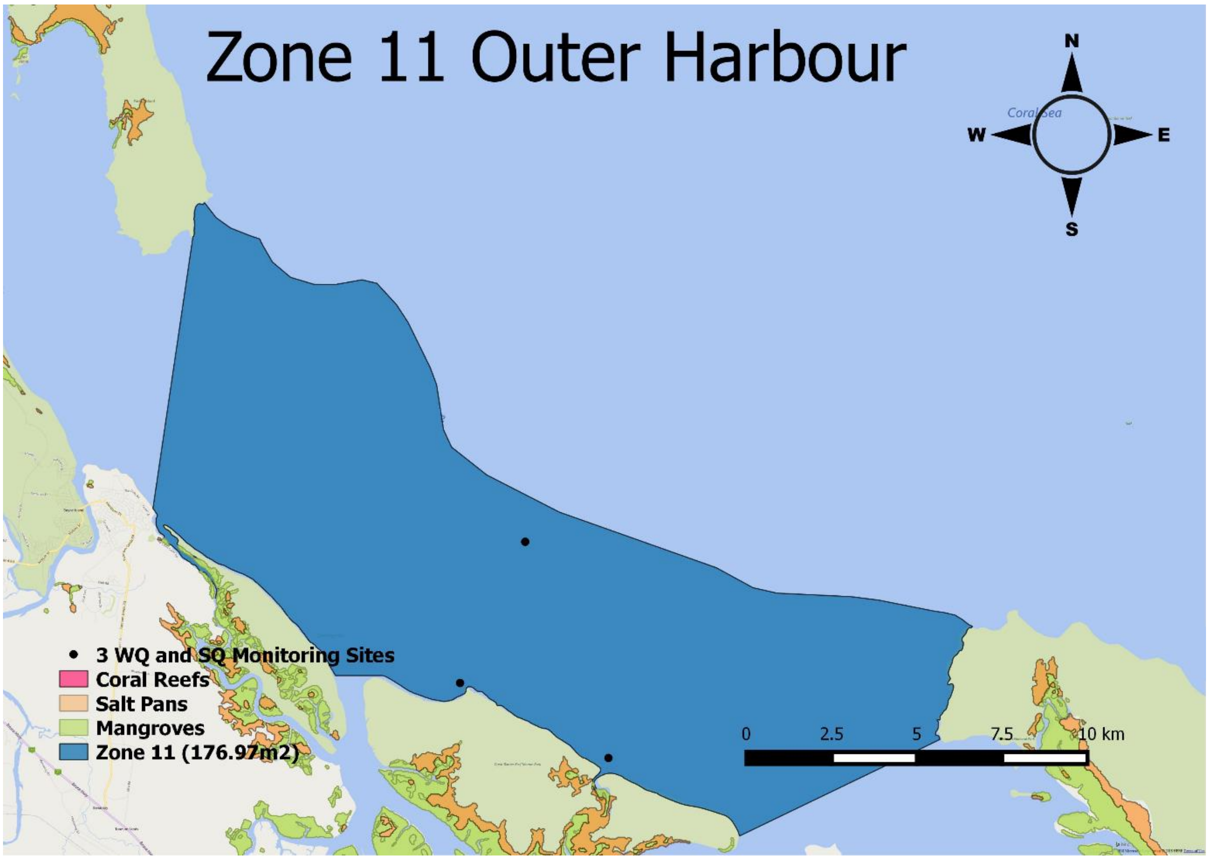

Figure A.41: Water and sediment quality sampling sites in the Outer Harbour.

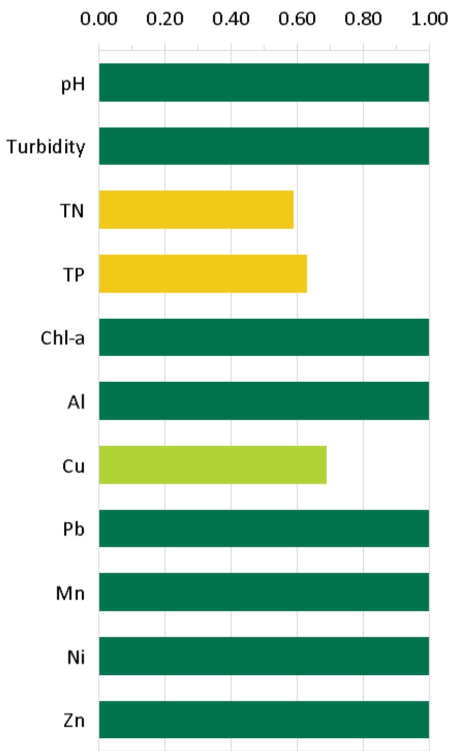

Figure A.43: Zone 11 measure scores.

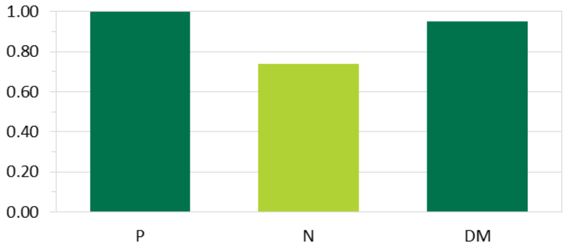

Figure A.42: 2017 Zone 11 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

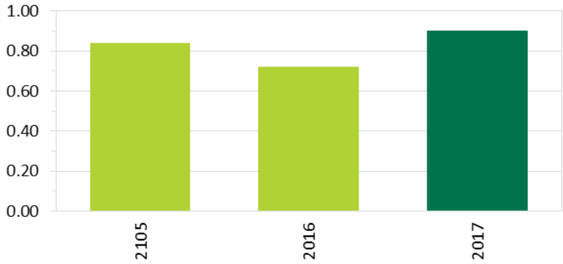

Figure A.44: Overall water quality scores for Zone 11.

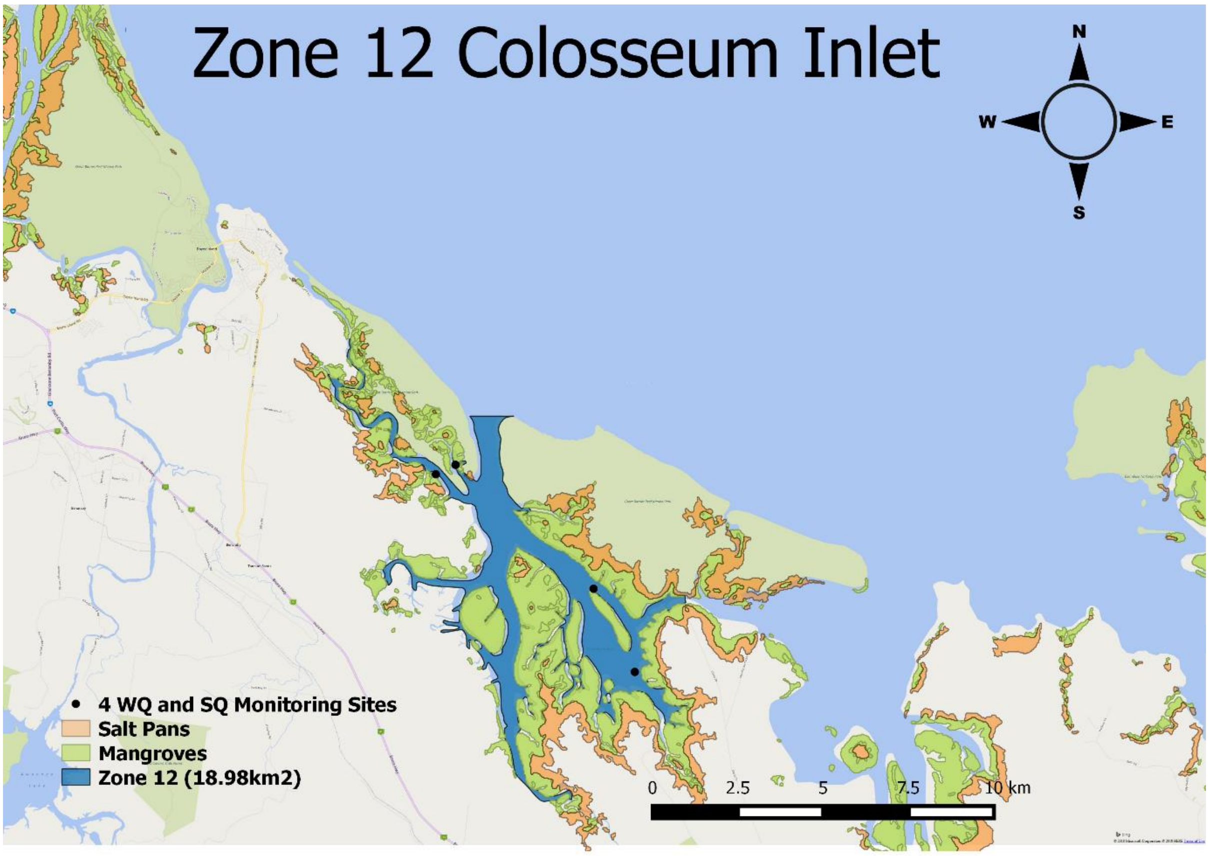

Figure A.45: Water and sediment quality sampling sites in Colosseum Inlet.

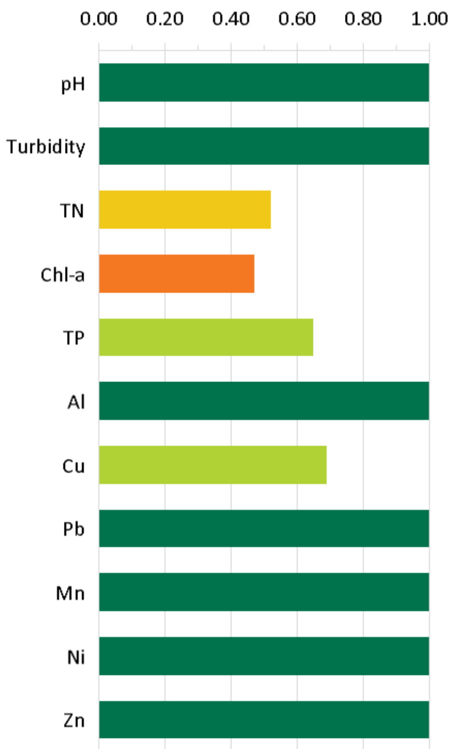

Figure A.45: Zone 12 measure scores.

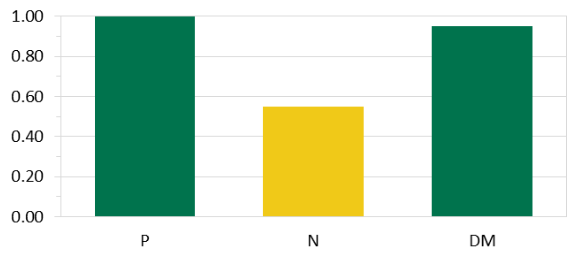

Figure A.46: 2017 Zone 12 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

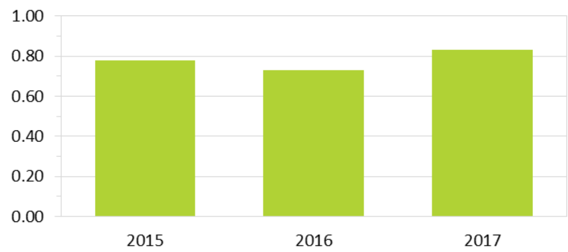

Figure A.48: Overall water quality scores for Zone 12.

Zone 13: Rodds Bay (Figure A.50)

Rodds Bay received an overall water quality score of 0.75 (B), which was comprised of a score of 0.80 (A) for physicochemical parameters, 0.50 (C) for nutrients and 0.95 (A) for dissolved metals (Figure A.51).

Rodds Bay received a very good score of 1.00 for pH indicating levels well within the guideline values for this zone. Turbidity (0.60) received a satisfactory score indicating turbidity met the guideline value for this zone (Figure A.52).

Five of the six dissolved metals received scores of 1.00 indicating concentrations were well below the water quality guideline values. Copper received a score of 0.69, indicating that copper concentrations in Colosseum Inlet met the water quality guideline (Figure A.52).

Total nitrogen (0.58) received a satisfactory score and total phosphorus (0.45) and chlorophyll-*a* (0.47) received poor scores indicating concentrations above the guideline values (Figure A.52).

Overall water quality scores have been good (B) in Rodds Bay since the first report card in 2015 (Figure A.53).

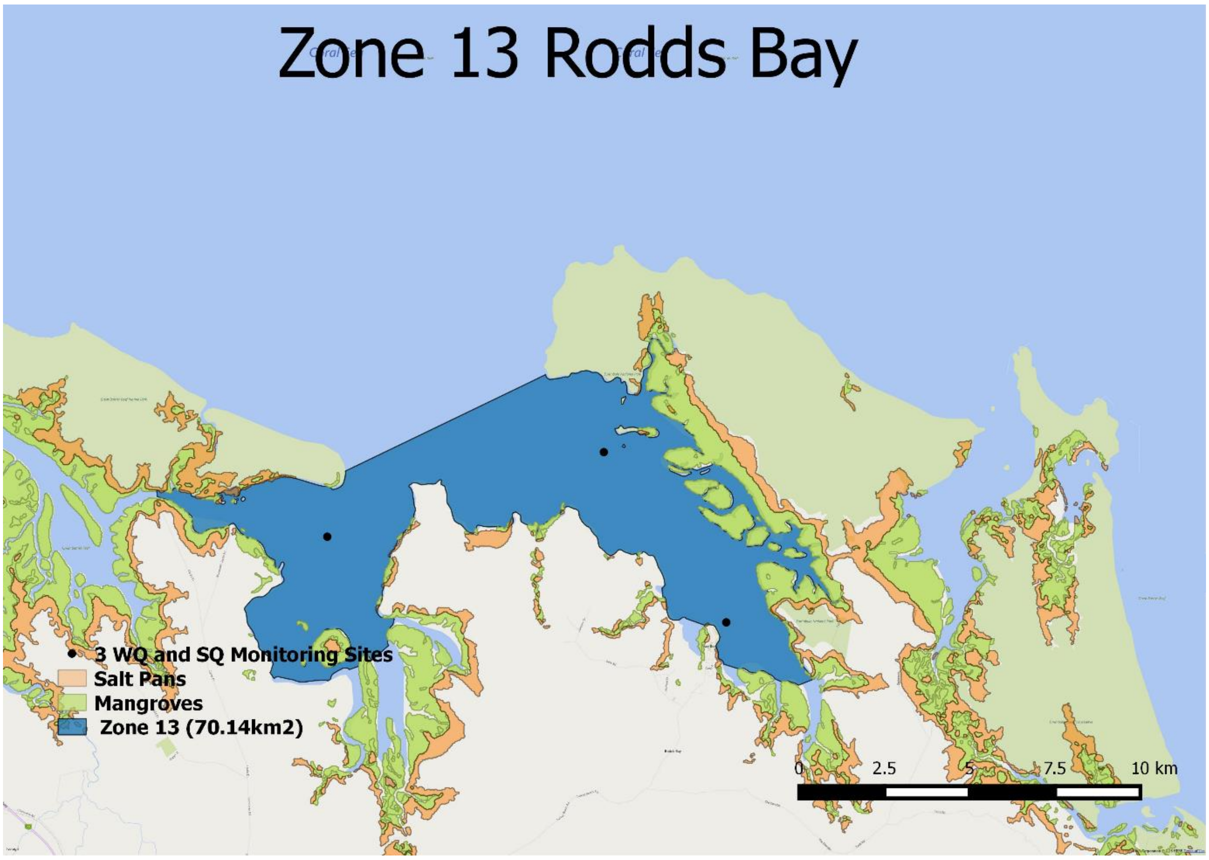

Figure A.49: Water and sediment quality sampling sites in Rodds Bay.

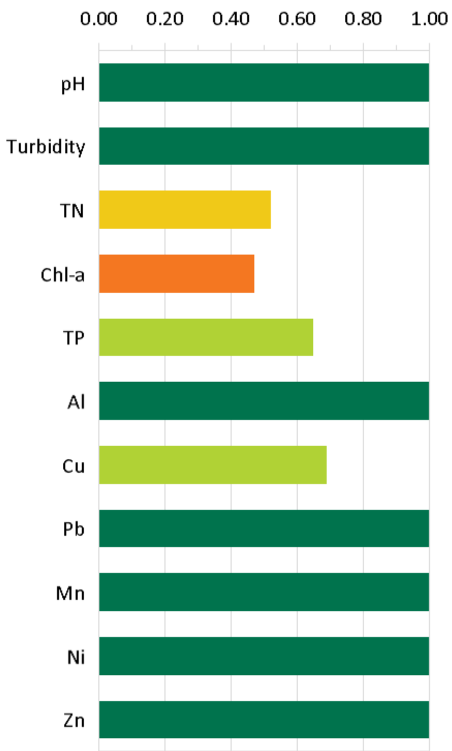

Figure A.51: Zone 12 measure scores.

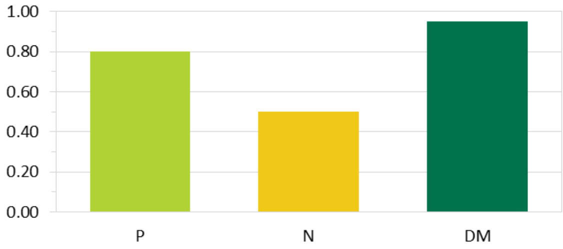

Figure A.50: 2017 Zone 13 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

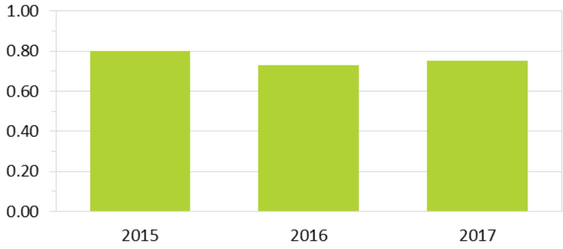

Figure A.52: Overall water quality scores for Zone 13.