Gladstone Healthy Harbour Partnership

Water and Sediment Quality Indicators for the 2018 Gladstone Harbour Report Card

May 2020

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 are 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 2018 report card includes monitoring undertaken in the period 1 July 2017 to 30 June 2018.

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). 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 2018 Gladstone Harbour Report Card for each component of harbour health.

In 2018, the water and sediment quality indicator group received a score of 0.86 (A). At the indicator level, water quality received a score of 0.76 (B) and sediment quality a score of 0.95 (A). Since the first full report card in 2015, water quality has consistently been rated as good and sediment quality has consistently been rated as very good.

For the water quality indicator, all zones received a good or very good score except for Boat Creek which received a satisfactory grade for the third consecutive year (Table 1). Zone physicochemical scores improved in eight zones as a result of higher scores for turbidity. The overall grade for nutrients (0.47, D) was slightly lower than the 2017 grade (0.50, C) due to the combined effects of lower scores for total nitrogen and chlorophyll-*a*. Comparable to previous years, dissolved metal scores were relatively uniform across the harbour and received very good overall scores in each of the 13 reporting zones.

Table 1: Overall water quality indicator scores for Gladstone Harbour zones (2015–2018).

Water quality	Physico-chemical score	Nutrients score	Dissolved metals score	Zone score 2018	*Zone score 2017*	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.77	0.39	0.95	0.71	*0.71*	*0.68*	*0.82*
2. Graham Creek	0.96	0.43	0.94	0.78	*0.88*	*0.75*	*0.86*
3. Western Basin	0.87	0.34	0.94	0.72	*0.77*	*0.70*	*0.82*
4. Boat Creek	0.77	0.17	0.90	0.63	*0.59*	*0.58*	*0.70*
5. Inner Harbour	0.93	0.54	0.94	0.80	*0.79*	*0.78*	*0.88*
6. Calliope Estuary	0.94	0.42	0.91	0.76	*0.77*	*0.71*	*0.86*
7. Auckland Inlet	0.83	0.47	0.92	0.74	*0.79*	*0.71*	*0.77*
8. Mid Harbour	0.92	0.56	0.94	0.81	*0.79*	*0.77*	*0.80*
9. South Trees Inlet	0.93	0.40	0.94	0.76	*0.84*	*0.79*	*0.85*
10. Boyne Estuary	0.93	0.49	0.94	0.79	*0.83*	*0.71*	*0.70*
11. Outer Harbour	1.00	0.82	0.95	0.92	*0.90*	*0.72*	*0.84*
12. Colosseum Inlet	0.99	0.58	0.94	0.83	*0.83*	*0.73*	*0.78*
13. Rodds Bay	0.79	0.47	0.94	0.74	*0.75*	*0.73*	*0.80*
Whole harbour	**0.89**	**0.47**	**0.93**	**0.76**	***0.78***	***0.72***	***0.81***

Sediment quality has been uniformly very good (A) in all harbour zones since the first full report card in 2015 (Table 2). This is a result of low concentrations of all measures (arsenic, cadmium, copper, lead, nickel and zinc). Although included in the 2017 report card, sediment mercury was not included in 2018.

Table 2: Sediment quality indicator scores for Gladstone Harbour zones (2015–2018).

Sediment quality	Zone score 2018	*Zone score 2017*	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.90	*0.92*	*0.92*	*0.94*
2. Graham Creek	0.94	*0.92*	*0.96*	*0.98*
3. Western Basin	0.98	*0.97*	*0.98*	*0.99*
4. Boat Creek	0.91	*0.98*	*0.90*	*0.96*
5. Inner Harbour	0.95	*0.93*	*0.94*	*0.98*
6. Calliope Estuary	0.95	*0.94*	*0.99*	*0.98*
7. Auckland Inlet	0.91	*0.87*	*0.94*	*0.94*
8. Mid Harbour	0.95	*0.95*	*0.97*	*0.99*
9. South Trees Inlet	0.94	*0.98*	*0.95*	*0.96*
10. Boyne Estuary	0.97	*0.97*	*0.98*	*1.00*
11. Outer Harbour	0.96	*0.97*	*0.96*	*0.96*
12. Colosseum Inlet	0.99	*0.99*	*1.00*	*1.00*
13. Rodds Bay	0.97	*0.95*	*0.99*	*0.98*
Whole harbour	**0.95**	*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, climatic and other environmental or physical 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 south of the Tropic of Capricorn and approximately 500 km north of Brisbane. The region's 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.

The Port of Gladstone is Queensland's largest multi-commodity port (GPC, 2017). All shipping to and from the port is through Gladstone Harbour. In the 2017–18 financial year, Gladstone Harbour was visited by 1,799 ships for a total throughput of 119.4 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 2018, the Gladstone region had a population of 62,979 (GRC, 2019).

Gladstone Harbour is located within the Port Curtis estuary—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 link 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 section of 5 to 9 m. The depth of the jetty at Auckland Inlet was recorded as 34 ft (10.4 m) at high water when construction was completed in 1885 (Duke et al., 2003).

1.2. Factors affecting water quality

Several climactic, environmental and anthropogenic external drivers influence water quality in the harbour. These drivers include:

- Rainfall and freshwater inflow/river discharge;
- Inputs such as catchment-derived pollutant loads and discharge from portside industries; and
- The hydrodynamics of the harbour such as tidal cycles and flushing rates.

Rainfall and freshwater inflows

In the 2017–18 reporting year, total rainfall recorded at Gladstone Airport was 754 mm, which is below the annual average of 882 mm (Figure 1.1). Total monthly rainfall for all months except July, October and February were below the monthly average over the past 24 years. The total October 2017 rainfall of 215 mm was nearly four times the October average of 58 mm. No rainfall was recorded in September 2017 and the period between March and June was also dry, with total rainfall below the average in all months (Figure 1.2).

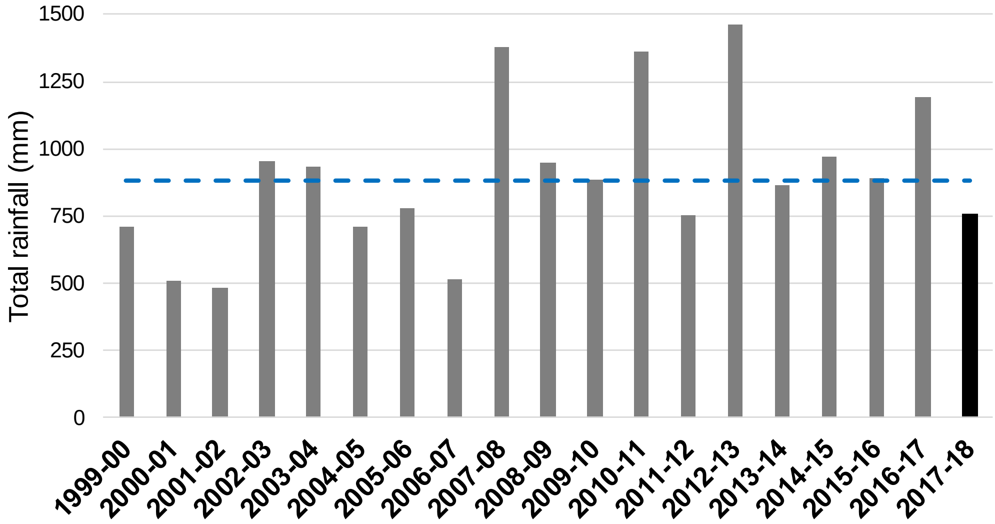

Figure 1.1: Annual rainfall by reporting year at the Gladstone Airport weather station from 1999–2000 to 2017–18 (Australian Bureau of Meteorology data). Blue dashed line represents the annual mean of total rainfall from 1994–2018.

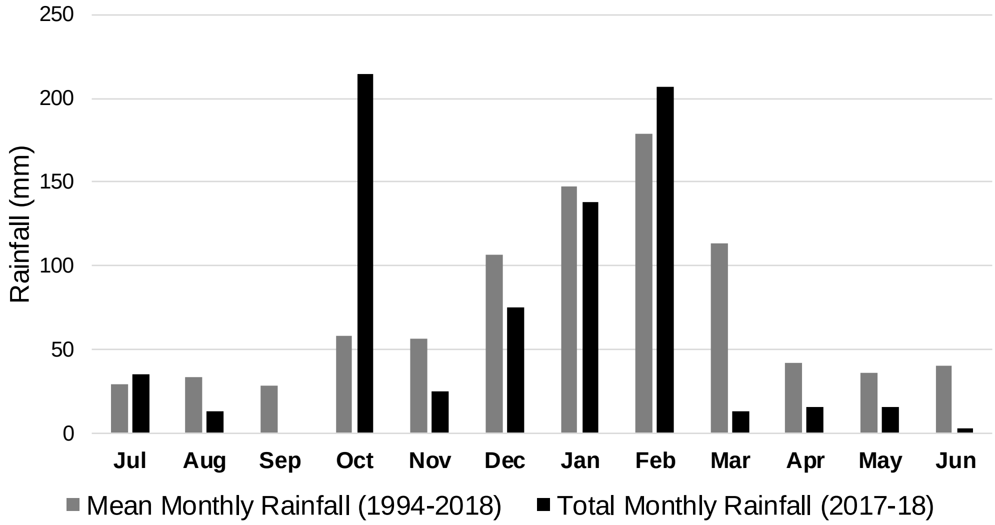

Figure 1.2: Mean monthly rainfall (mm) at the Gladstone Airport weather station (1994–2018) compared to total monthly rainfall for the 2017–18 reporting year (Australian Bureau of Meteorology data).

From 1957–2018, average annual rainfall for Gladstone was 894 mm (Australian Bureau of Meteorology 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 1.3). The predominant land use within these catchments is grazing with smaller areas of natural vegetation, dryland cropping and irrigated cropping.

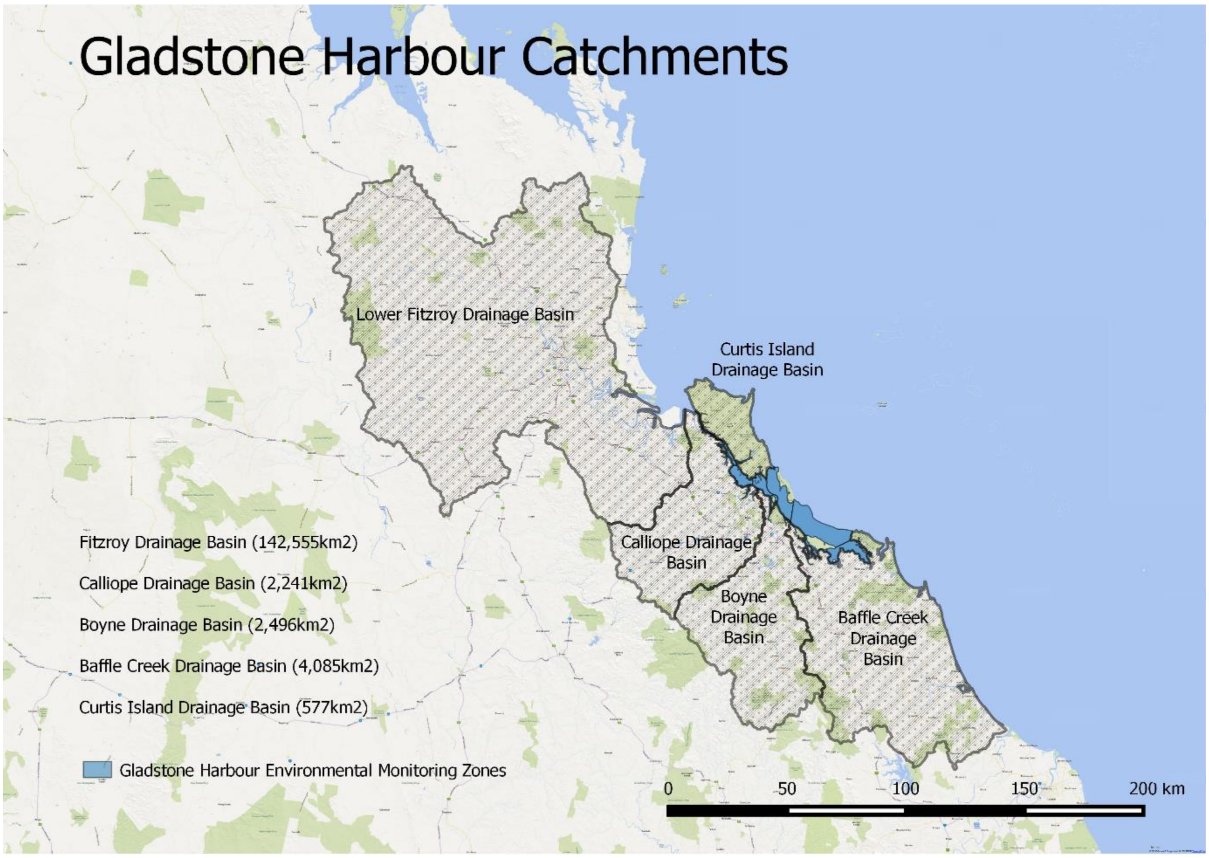

Figure 1.3: Drainage basins surrounding Gladstone Harbour.

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; see section below). Small amounts of freshwater flow may also enter the harbour via The Narrows when the Fitzroy River floods.

Table 1.1 shows the annual water discharge of the Calliope and Boyne rivers and Baffle Creek in the Gladstone Harbour catchment (1 October 2017 to 30 September 2018, inclusive), annual discharge from 2010–11 to 2017–18 and long-term median discharge (1986–87 to 2017–18). This shows that the Calliope and Boyne river discharge was similar to the long-term median discharge in 2017–18, and greater than three times the long-term median discharge in Baffle Creek.

Table 1.1. Annual water discharge of the Calliope and Boyne rivers and Baffle Creek in the Gladstone Harbour catchment (1 October 2017 to 30 September 2018, inclusive), annual discharge from 2010–11 to 2017–18 and long-term (LT) median discharge (1986–87 to 2017–18). Colours indicate levels above the long-term median: yellow for 1.5 to 2 times, orange for 2 to 3 times and red greater than 3 times. Discharge values are in gigalitres. Values were obtained from DNRM (http://watermonitoring.dnrm.qld.gov.au/host.htm) and modified as described in Gruber et al. (2018), Appendix D.

Basin (Gauge)	LT median	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18
Calliope River (Calliope River at Castlehope)	153	1000	346	1558	284	480	149	406	141
Boyne River (*estimated from Calliope River at Castlehope)	39	253	87	394	72	121	38	103	36
Baffle Creek (Baffle Creek at Mimdale)	465	3650	1776	2031	276	710	257	829	1845

While Port Curtis normally has salinities ranging from 30 to 35 ppt, freshwater 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 are 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. Converting temperature and conductivity data to practical salinity units (psu) for the Mid Harbour revealed a period of approximately three days (27–29 January 2013) where salinity levels remained below 20 psu at a depth of 0 m (Vision Environment Qld 2013a; 2013b). The sustained low levels are likely to have caused high coral mortality within the harbour (Jones et al., 2015; 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.

Catchment-derived pollutant loads

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. Across the Great Barrier Reef (GBR) catchments, suspended sediment inputs are dominated by grazing lands, nutrients are largely derived from cropping lands and pesticides are sourced from dryland and irrigated cropping and grazing lands (Dougall et al., 2014). In the Gladstone Harbour catchments, the majority of land is used for grazing followed by conservation/natural environments (Table 1.2). The remaining land use encompasses intensive use (i.e. residential, industry, transport and utilities), forestry, water (i.e. marsh/wetland, river and reservoir/dam) and cropping.

Catchment pollutant load exports are modelled for the 35 major basins that discharge into the GBR including the Boyne, Calliope and Fitzroy rivers (McCloskey et al., 2019). Catchment modelling is used to isolate changes to annual average end of catchment loads resulting from changes in land management practices as distinct from the changes that are associated with climate variability. 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. Annual average loads reported for both pre-development and baseline scenarios are estimated over the period of July 1986 to June 2014. The anthropogenic baseline load was calculated by subtracting the pre-development load from the baseline load. The modelled data for the Calliope and Boyne catchments is shown in Table 1.3 and shows increases in a range of parameters from the pre-development load compared to the anthropogenic baseline load (McCloskey et al., 2019). For example, the modelled average annual loads of fine sediments from the Calliope River increased to 46,000 tonnes per year in the anthropogenic baseline scenario from a pre-development load of 6,000 tonnes per year (approximately a 7-fold increase).

Table 1.2. Proportion (%) of land under various land uses for the Boyne and Calliope catchments.

Land Use	Calliope	Boyne
Grazing	75.5%	71.8%
Conservation / Natural Environments	8.0%	16.2%
Forestry	5.2%	5.2%
Intensive Use	5.5%	2.1%
Water Bodies	4.6%	4.1%
Cropping / Farming	1.3%	0.6%

Source: Derived from Queensland Land Use Mapping Program 2017 dataset. Land use areas calculated in ArcGIS® Pro 2.2.0.

Table 1.3. Modelled pre-development and baseline catchment load exports from the Boyne and Calliope catchments (McCloskey et al., 2019). Increase factor from pre-development load to anthropogenic baseline load.

Basin Name	Pre-Development	Baseline 2012/13	Anthropogenic Baseline	Increase factor
Total suspended solids load (kilotonnes per year)				
Calliope	6	52	46	7.3
Boyne	2	17	15	7.8
Total phosphorous load (tonnes per year)				
Calliope	87	336	250	2.9
Boyne	40	113	74	1.9
Particulate phosphorous load (tonnes per year)				
Calliope	53	277	224	4.2
Boyne	12	69	56	4.6
Total nitrogen load (tonnes per year)				
Calliope	230	740	509	2.2
Boyne	127	278	151	1.2
Particulate nitrogen load (tonnes per year)				
Calliope	104	541	437	4.2
Boyne	22	126	104	4.7
PSII herbicides toxic equivalent load (kilograms per year)				
Calliope	0	2	2	NA
Boyne	0	1	1	NA

Discharge from portside industries

Gladstone is a major industrial centre that accommodates a number of portside industries including two alumina refineries, an aluminium smelter, a chemical plant, three LNG export facilities, a cement production works, two coal terminals and Queensland's largest coal-fired power station. The National Pollutant Inventory (NPI; www.npi.gov.au) provides annual loads of toxic substances discharged into the air and waterways reported by individual facilities. In the 2017–18 reporting year there were 30 reporting facilities in Gladstone Harbour, all of which listed air emissions and seven which listed water emissions. Discharges into waterways included 24 reportable chemical compounds (Table 1.4). As in the previous reporting year, fluoride compounds represented the greatest volume of discharge (~200 tonnes) followed by the nutrients—total nitrogen (~130 tonnes), total phosphorus (~14 tonnes) and ammonia (~4 tonnes). This represents an additional total nitrogen and total phosphorous load of 13% and 3% respectively when compared to the modelled total baseline load (Table 1.3) as NPI data is not included in the modelled catchment estimates. Compared to the modelled total anthropogenic baseline load, portside discharge in Gladstone Harbour accounts for an additional total nitrogen and total phosphorous load of 20% and 4% respectively.

Table 1.4. Annual loads (2017–18) from seven 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							Total Annual Load (kg)
		AR	BPSF	BR	CET	EAM	EG	PSC	
Metals and Metalloids	Antimony				0.008				0.008
	Arsenic	250		615	0.02		12	8.07	890
	Boron				0.2		1610		1600
	Cadmium	19		2.62		0.164		0.06	22
	Chromium	66.97			0.1	0.684		3.49	71
	Cobalt			6.55	0.01				6.6
	Copper			2.99	0.04	2.61		9.52	15
	Lead	57.62			0.07	0.205		2.33	60
	Manganese	70.395		500	0.1	26.5	183		780
	Mercury	0.38			0.0006			0.04	0.42
	Nickel			22.2	0.04	8.89	2.95	2.95	37
	Selenium				0.007				0.007
	Zinc	272.47		13	0.08	165		528.32	980
Other Substances	Ammonia							4118	4100
	Benzene		0.0082						0.0082
	Chlorine							36	36
	Cyanide							12	12
	Ethylbenzene		0.0165						0.017
	Fluoride	60148		126000		11200			200000
	PAH (B[a]Peq)					0.664			0.66
	Toluene		0.0165						0.017
	Total Nitrogen	73849		52500				2894.8	130000
	Total Phosphorus	8368.3		4850				785.06	14000
	Xylenes		0.0165						0.017

AR (alumina refining), BPSF (bulk petroleum storage facility), BR (bauxite refining), CET (coal export terminal), EAM (electrolytic aluminium manufacturing), EG (electricity generation), PSC (production and storage of chemicals)

In 2017–18 Gladstone Harbour had a comparable discharge of total nitrogen from portside industries to the Port of Newcastle (NSW) and Port Kembla (NSW) respectively. Ammonium nitrate manufacturing at Kooragang Island, which is located in the Port of Newcastle, resulted in 140 t of total nitrogen emissions in water while steel manufacturing in Port Kembla accounted for 110 t of total nitrogen discharge in 2017–18 (www.npi.gov.au). Both Newcastle and Port Kembla also have considerable nutrient discharges from wastewater treatment facilities, whereas wastewater in the Gladstone area is recycled.

Tidal cycles and flushing rates

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 1.4).

The flushing rate is an important physical characteristic of an estuary determining the dispersion of contaminants (Apte et al., 2005). Higher tidal 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) between 2010 to 2014 (Figure 1.5). 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). These variations affect the water quality of the harbour, with the areas that have lower flushing rates typically being more susceptible to poorer water quality.

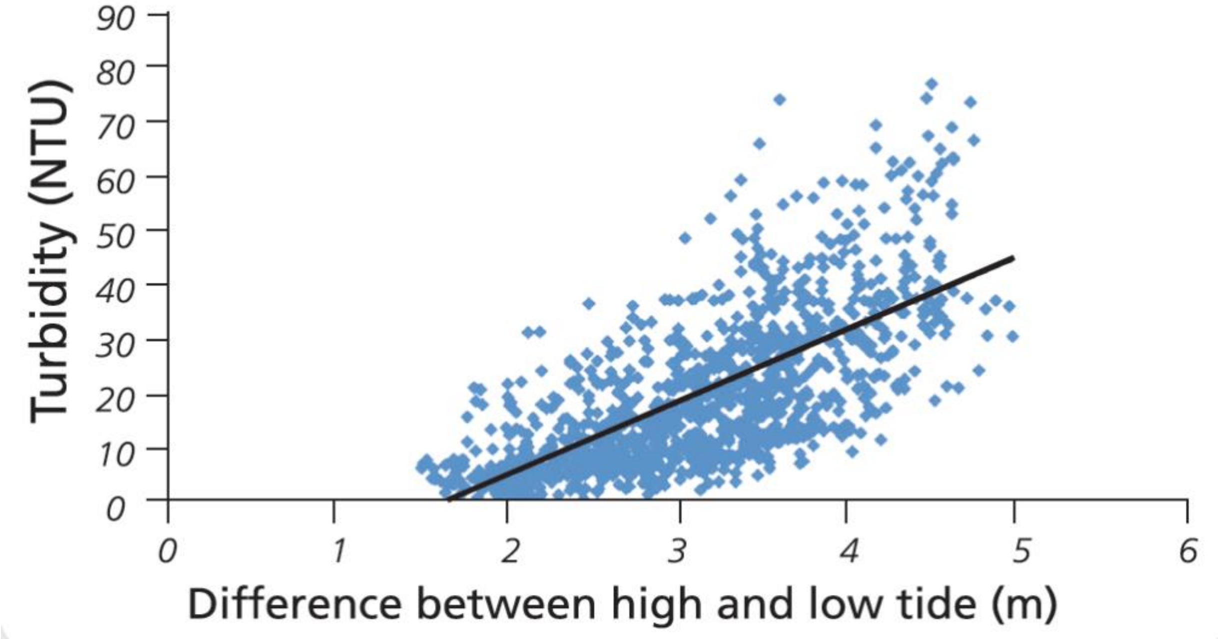

Figure 1.4: The relationship between tidal movement and turbidity in Gladstone Harbour (DEHP 2014 personal communication). NTU: Nephelometric Turbidity Unit.

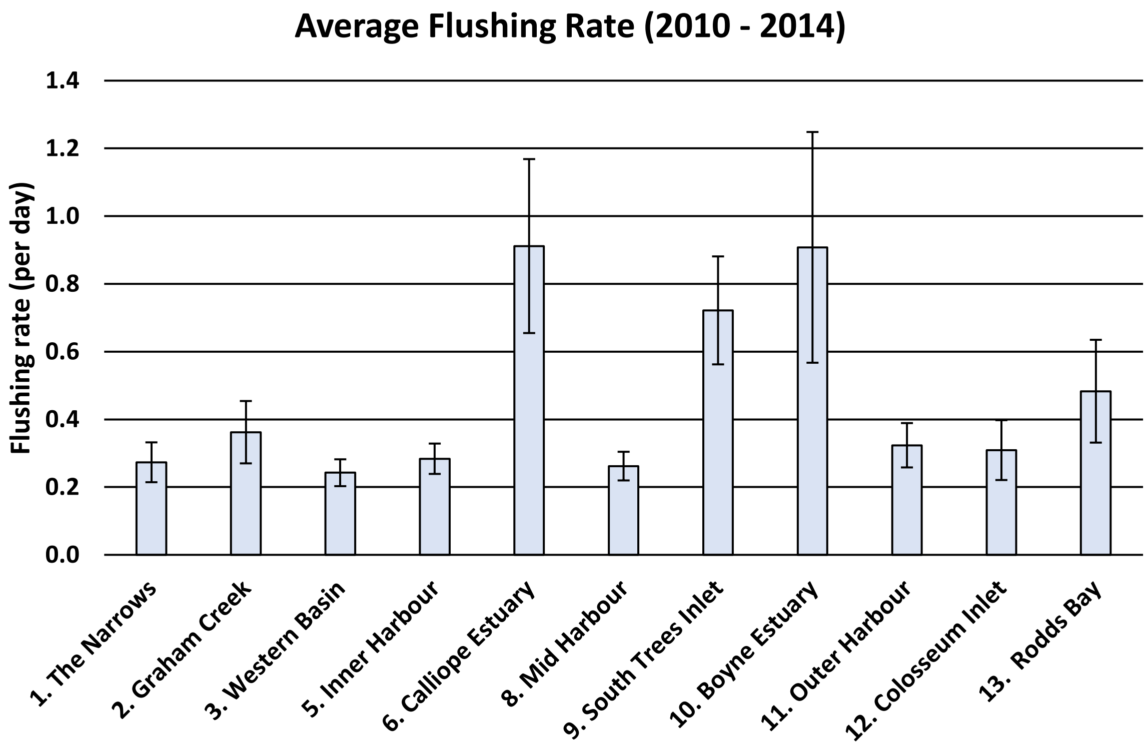

Figure 1.5: Four-year average flushing rates for 11 Gladstone Harbour monitoring zones. The flushing rate was calculated as the average of 20-day time slices over the four-year period. The error bars indicate ± one standard deviation (Source Condie et al., 2015).

Resuspension of fine sediment (silt and clays) by tides, wind and waves is also an important factor influencing turbidity in the harbour (Condie et al., 2015). In addition, when resuspended, fine sediments can become a source of metals and nutrients. This is because fine sediments can become a sink for metals and nutrients within waterways as they have a net negative charge, while metals and nutrients are positively charged.

The distribution of fine sediments in Gladstone Harbour is therefore an important factor influencing turbidity and nutrient results. Based on PCIMP data from the current reporting year, the highest proportions of fine sediments (<63µm) were recorded in estuarine zones such as Auckland Inlet and The Narrows (Figure 1.6). More oceanic zones such as the Outer Harbour and Mid Harbour had sediments with very low proportions of fine sediments.

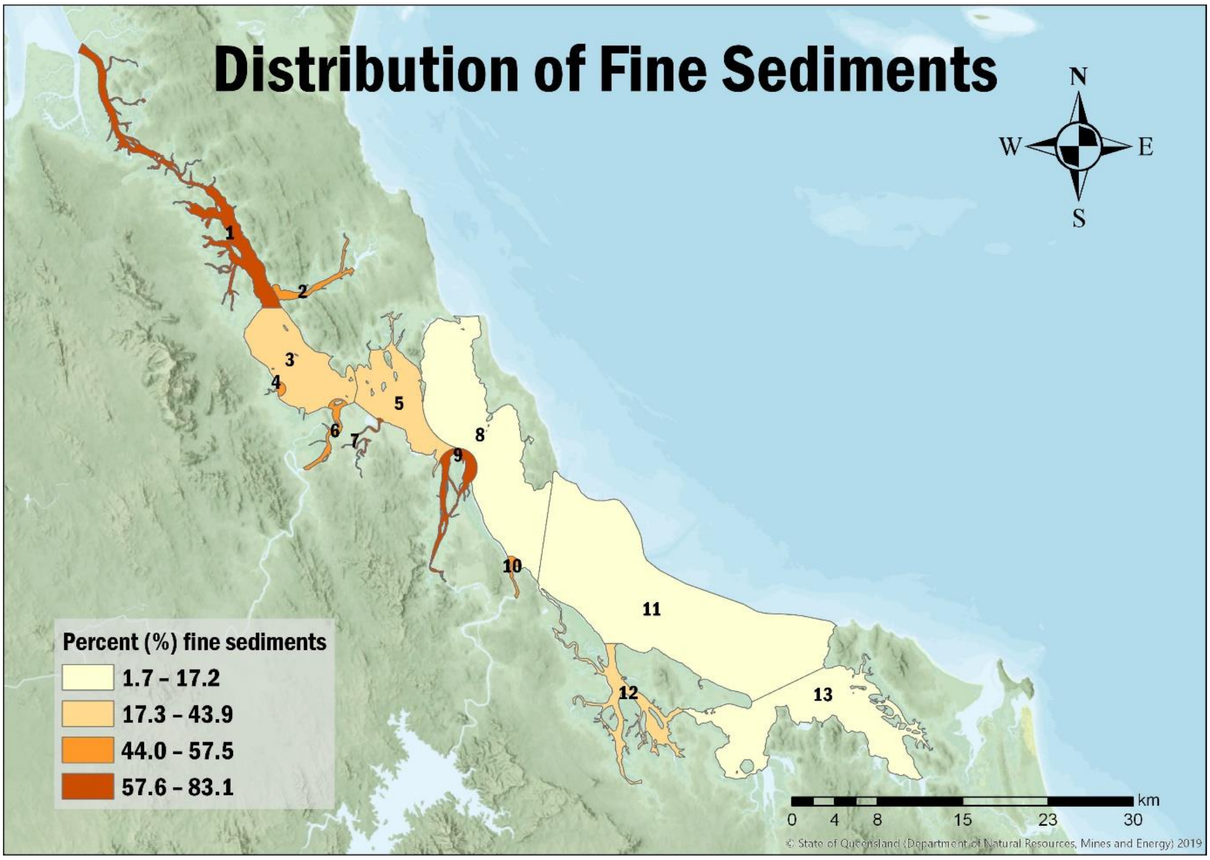

Figure 1.6: Average percentage (%) of fine sediments (<63 µm) within sediment samples from the 13 Gladstone Harbour environmental monitoring zones in May 2018. Fine sediment classifications were generated in ArcGIS® Pro 2.2.0 using the Jenks natural breaks symbology function. This method reduces the variance within classes and maximizes the variance between classes.

Other factors

While there is insufficient data to assess these potential drivers, other factors that may 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 and 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 in the 2018 Gladstone Harbour Report Card. These measures were recommended by the Gladstone Healthy Harbour Partnership (GHHP) Independent Science Panel (ISP) as indicative of the factors relevant to the harbour and its condition. The importance of each measure to overall harbour health is 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 reduce water clarity, but to a lesser extent. High turbidity decreases the light levels reaching the seabed which reduces photosynthesis and the production of dissolved oxygen. This can lead to supressed growth and reproduction and if exposed to low light for prolonged periods, eventually mortality of algae, seagrasses and corals. Suspended material in water with very high turbidity levels may also clog fish gills and smother benthic invertebrates.

2.2. Nutrients

Nitrogen and phosphorus 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 in enclosed or poorly flushed waters.

Total nitrogen

Total nitrogen is the sum of the four major chemical forms of nitrogen in the marine environment: nitrate, nitrite, ammonia nitrogen and organic nitrogen. Nitrogen is an essential nutrient for all organisms, but at high levels it can lead to algal blooms, increased growth of macroalgae, 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 phosphorus and particulate phosphorus. The total phosphorus 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 and increased growth of macroalgae, both of which may 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 phytoplankton, seagrasses and seaweeds. High levels of chlorophyll-*a* may indicate blooms of algae which can occur when nutrient concentrations are elevated. In enclosed or poorly flushed waters, this can lead to depleted levels of oxygen in the water and potentially, to fish kills. Algal blooms may also contribute to reduced light reaching the seabed which may influence coral and seagrass ecosystems.

2.3. Metals and metalloids

A suite of metals and one metalloid (arsenic) have been selected as indicators of harbour health. General information on the descriptions of metals, factors affecting toxicity and toxicology were retrieved from ANZG (2018).

Aluminium

The element aluminium 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, inorganic forms of which may be toxic to aquatic species. Most biota convert inorganic arsenic to less toxic organic forms (e.g. arsenosugars, arsenobetaine).

Cadmium

Cadmium 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 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. released 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 is a toxic heavy metal that may have anthropogenic (e.g. industrial discharge, mining discharge) or natural origins. Natural waters generally have very low concentrations of lead. In water, lead is mostly adsorbed onto sediment and suspended particles. This metal has no known benefits to aquatic plants or animals.

Manganese

Manganese 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).

Nickel

Nickel 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 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 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 is 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 were used in the 2018 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 six sediment quality measures were reported (Figure 3.1) although four other measures—ammonia, NOx, orthophosphate and sediment mercury—were assessed but not included 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 are preserved, sample bias is avoided, and means (the report card score) and variances are calculated for reporting.

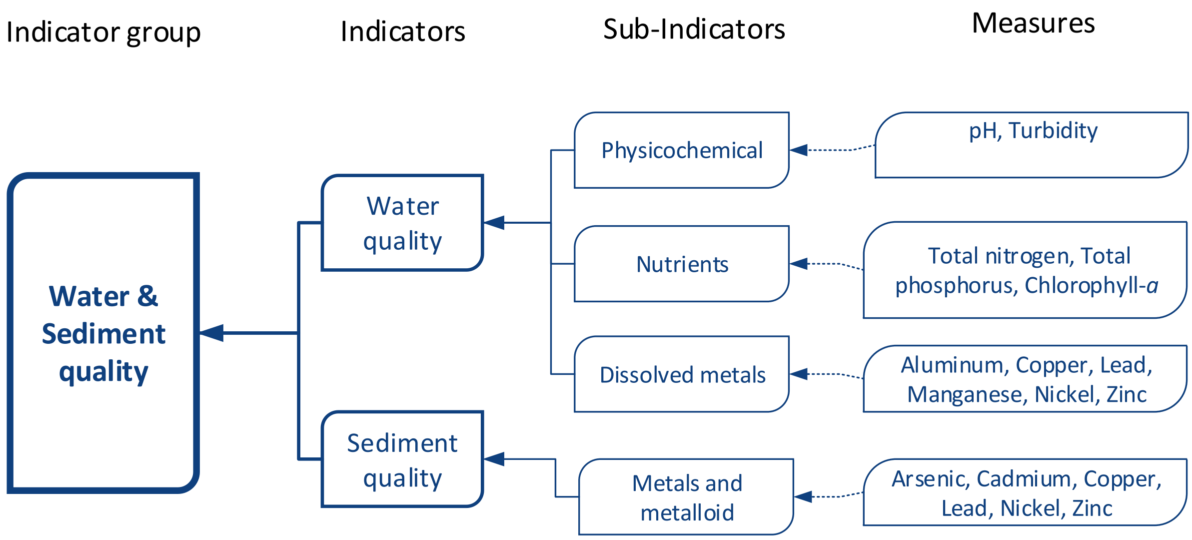

Figure 3.1: The aggregation hierarchy showing the indicators, sub-indicators and measures used to calculate the overall water and sediment quality grade for the Gladstone Harbour Report Card.

3.2. Water and sediment guidelines

All water and sediment measure scores were 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 95% species protection value from the ANZECC/ARMCANZ (2000) water quality guidelines was applied to copper, lead and zinc, while the 99% species protection value is applied to nickel. Water quality guideline values were selected for moderately disturbed systems.

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				Nutrients			Metals					
	Turbidity		pH range										
	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	20
Cadmium	1.5
Copper	65
Lead	50
Nickel	21
Zinc	200

3.3. Calculation of grades and scores

The starting point for water quality score calculations was the annual mean for a measure at each site. This was calculated by averaging measure values on four occasions from 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 Log_2 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.

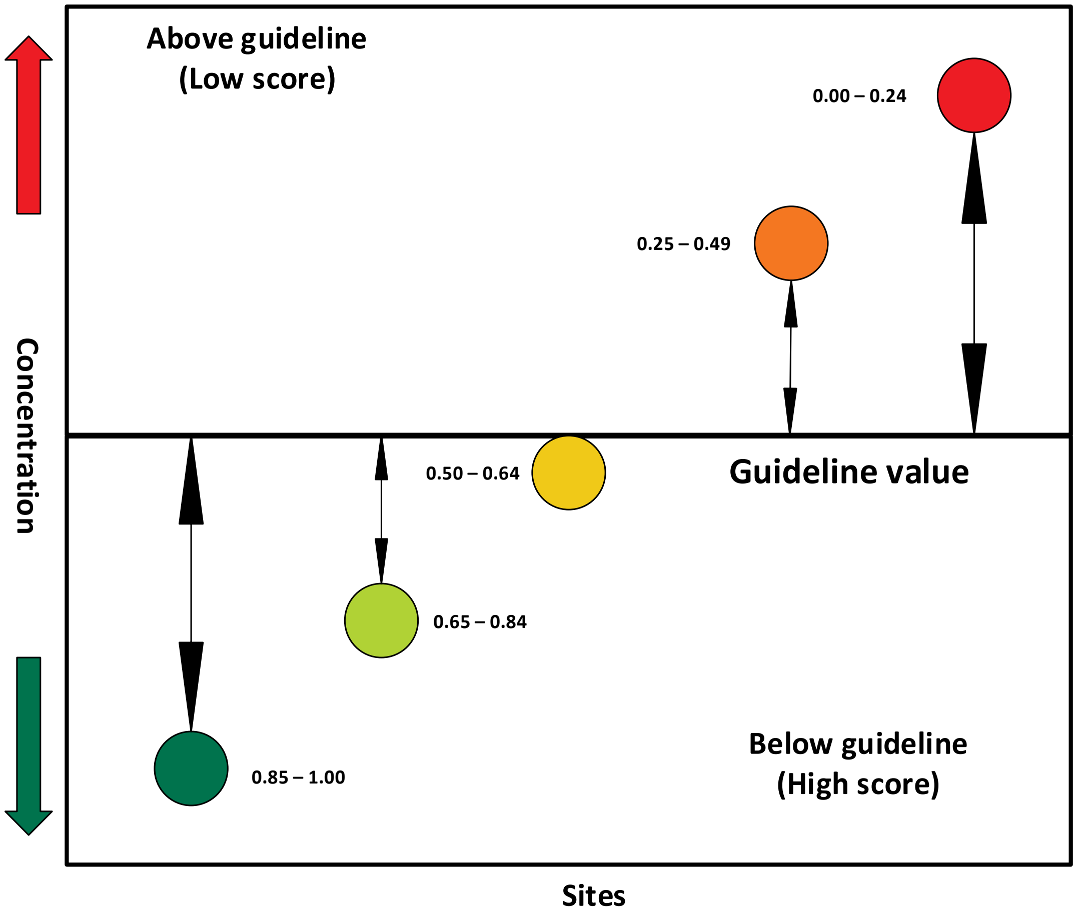

Figure 3.2: Water and sediment quality measures are scored relative to zone and measure specific guideline values. Where the concentration of a measure is low it receives a high score and conversely where the concentration of a measure is high it receives a low score.

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 2018 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

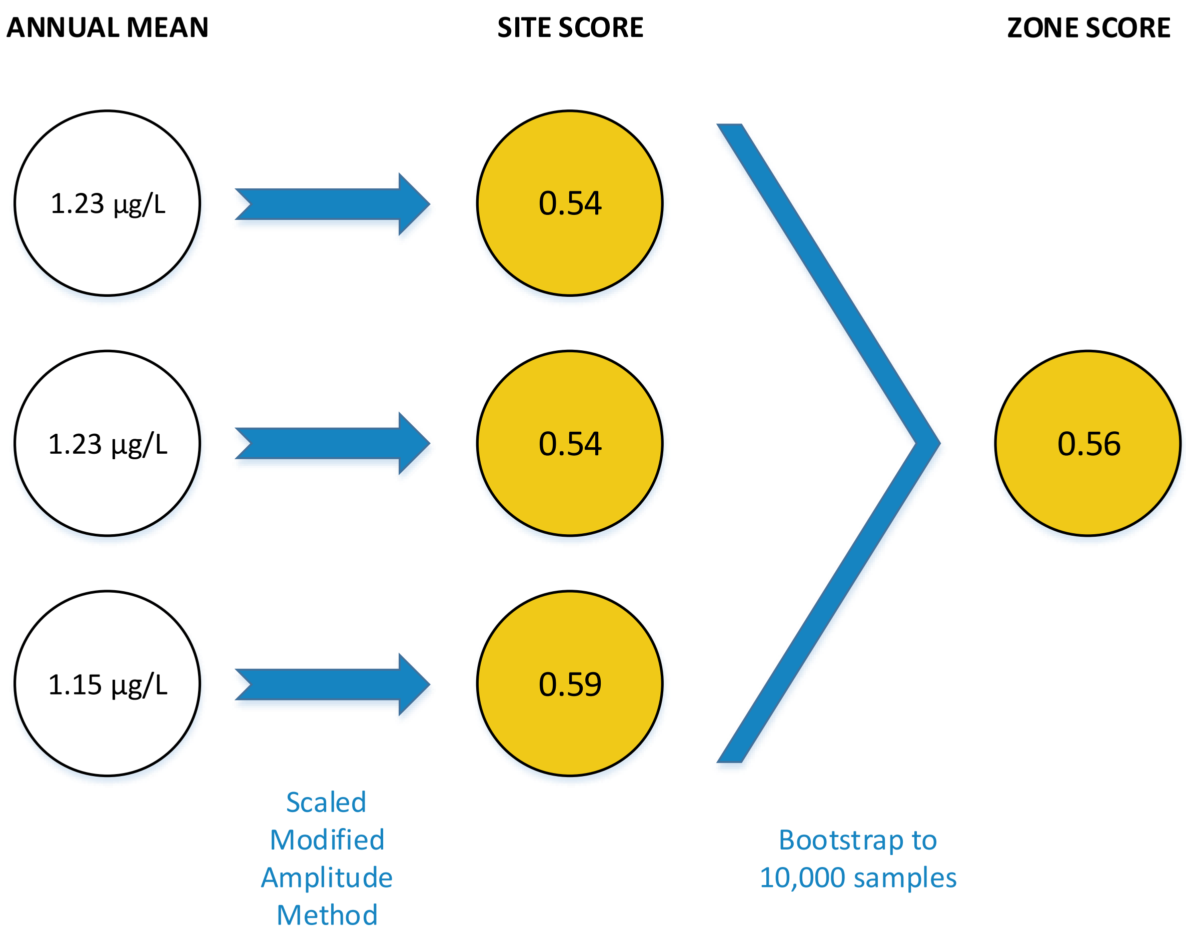

Figure 3.4: Flow diagram of site and zone-level calculation of dissolved copper scores at Calliope Estuary from 2016 Gladstone Harbour Report Card. Guideline value of 1.3 µg/L. Zone score is the mean of the 10,000 resamples from bootstrap distribution.

4. Water and sediment quality data collection

All water and sediment quality data for the 2018 Gladstone Harbour Report Card were provided under a data-sharing agreement between GHHP and the 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).

While PCIMP collects samples from 54 sites, water quality samples were collected from 51 sites across the 13 harbour zones in August and November 2017 and March and June 2018. Sediment samples were collected from the same 51 sites in May 2018 (Figure 4.1). Three of the 54 PCIMP sites (one in the Calliope River, two in the Boyne River) were excluded as GHHP does not assess freshwater health.

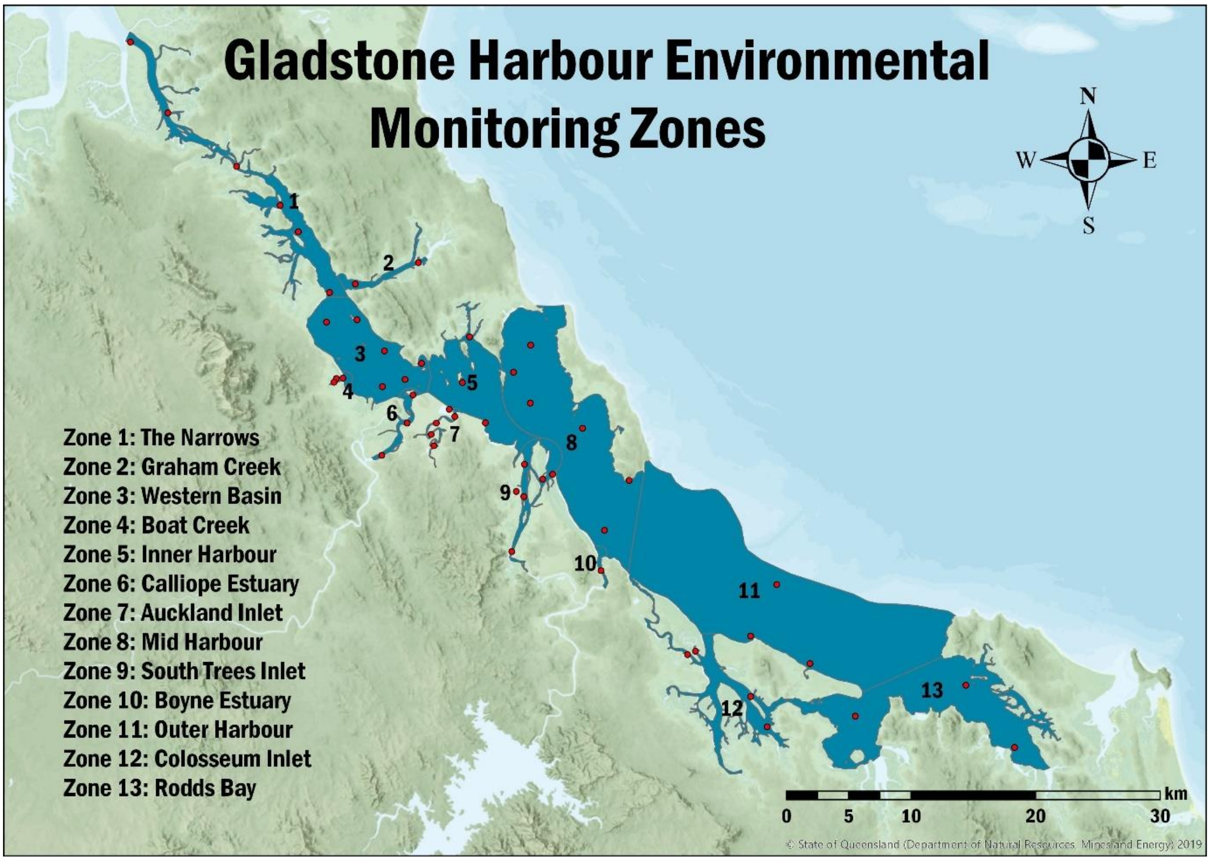

Figure 4.1: Water and sediment quality sites within the 13 Gladstone Harbour environmental monitoring zones.

4.2. Water quality sampling methods

Eleven water quality parameters were assessed for the 2018 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 analyses 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 cellulose acetate/surfactant-free membrane syringe filter, Minisart 16555K) *in-situ* into laboratory-provided sample bottles for dissolved metals and dissolved nutrients. Syringes were pre-rinsed in site water, and filters came pre-packaged from the supplier. Individually packaged cellulose acetate membrane pre-filters with a pore size of 1.2 µm (Minisart 17593K) were used at more turbid sites if required, to assist in filtration, before filtration with Minisart 16555K filters. 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* samples which were sent to Australian Laboratory Services (ALS) and dissolved nutrients samples which were sent to the Queensland Health Laboratories (QHL).

Methods in this section were provided by PCIMP (Anastasi, 2018).

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

Table 4.1: Water quality indicators included in the 2018 Gladstone Harbour Report Card.

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

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

4.3. Sediment quality sampling methods

The 2018 Gladstone Harbour Report Card assessed five 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 May 2018 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 (0.005 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 PCIMP (Anastasi, 2018).

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

Table 4.2: Sediment quality indicators included in the 2018 Gladstone Harbour Report Card.

Indicator	Sub-indicator	Measure	Guideline Source
Sediment quality	Metals and metalloid	Arsenic	ANZECC/ARMCANZ, 2000
		Cadmium	ANZECC/ARMCANZ, 2000
		Copper	ANZECC/ARMCANZ, 2000
		Lead	ANZECC/ARMCANZ, 2000
		Nickel	ANZECC/ARMCANZ, 2000
		Zinc	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 the 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.

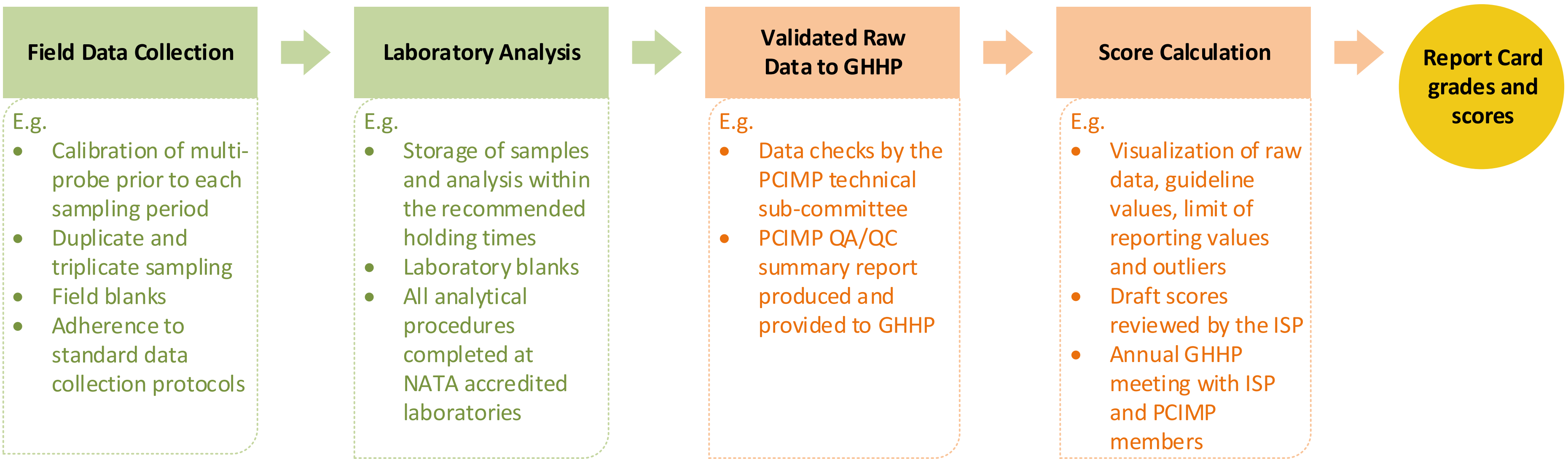

Figure 5.1: A flow diagram showing examples of QA/QC procedures applied to the raw and processed water and sediment quality data. Detailed QA/QC procedures for field data collection, laboratory analysis and validated raw data to GHHP are reported in Section 5.1. Score calculation analysis was completed 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 on behalf of PCIMP 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)
- Revision of the ANZECC/ARMCANZ Sediment Quality Guidelines (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. To address potential holding time breaches (48 h) 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 papers until dispatch, resulting in an extended holding time of 28 days, in accordance with APHA method 12000H.

Water quality laboratory and field QA/QC were monitored using field blanks, laboratory blanks and duplicate samples in 2017–18. Each quarterly sampling event included the following QA/QC procedures:

- 3 or 4 field blanks
- 3 or 4 laboratory blanks
- 10 duplicate samples

Laboratory blanks were prepared at the VEQ laboratory using Milli-Q water and filtered where appropriate. Field blanks were prepared in the field using a supply of Milli-Q water stored in acid-washed Nalgene bottles. The Milli-Q water used in the field was treated in the same fashion as main/duplicate samples—thus undergoing identical processes—and filtered where appropriate. Laboratory and field blanks were used in combination to identify potential sources of contamination: field or laboratory processes, Milli-Q water or laboratory-provided sample bottles.

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

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. NMI is the Australian Government's peak measurement body for biological, chemical, legal, physical and trade measurement. Primary samples, duplicates, field blanks and laboratory blanks were sent to the NMI except for chlorophyll-*a* which were sent to ALS and dissolved nutrients which were sent to the QHL. Sediment metal samples were analysed by NMI and sediment particle size distribution was subcontracted to HRL Technology. 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, 2018). 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 2017–18 reporting year.

Indicator	Indicator Group	Measure	LOR value (µg/L)
Water quality	Dissolved metals	Aluminium	5
		Copper	1
		Lead	1
		Manganese	1
		Nickel	1
		Zinc	1
	Nutrients	Total Phosphorous	5[a] 2[b] 3[cd]
		Total Nitrogen	50[ab] 20[cd]
		Chlorophyll-*a*	0.02
	Dissolved nutrients	NOx	2
		Orthophosphate	2
		Ammonia	2
Indicator	**Indicator Group**	**Measure**	**LOR value (mg/kg)**
Sediment quality	Metals and metalloid	Arsenic	0.5
		Cadmium	0.5
		Copper	0.5
		Lead	0.5
		Nickel	0.5
		Zinc	0.5

Note: Limit of reporting (LOR) values differ between sampling quarters for total phosphorous and total nitrogen. Sampling quarters are denoted as (a) Aug-17 (b) Nov-17 (c) Mar-18 and (d) Jun-18.

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 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 (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 2018 report card. Following the meeting, the ISP recommended omitting the following measures prior to the score calculation:

- **Do not include ammonia in the report card and in all future report cards**
  Reasons:
  - Ammonia is not very stable in water bodies, and particularly in the marine environment, so it is difficult to interpret this measure with a high level of confidence.
  - The scoring is unduly sensitive because the guideline values (3–6 µg/L depending on the zone) are very close to the limit of detection value (2 µg/L).
  - Although PCIMP indicated that the QA/QC procedures were adequate, the majority of field and laboratory blanks resulted in non-zero readings for ammonia, leading to concerns that there may also be some level of contamination in primary and duplicate water samples.
  - Total nitrogen is already included as a measure of water quality, so reporting ammonia (which is a component of total nitrogen) as an additional measure is duplication.
  - Ammonia is not included in other marine report cards.

- **Remove NOx from the report card**
  Reasons:
  - The guideline value for NOx varies from 1–6 µg/L depending on the zone. For a majority of zones, the guideline value (3 µg/L) is close to the analytical detection limit (2 µg/L) for NOx. For two zones, the guideline value (1 µg/L) is below the LOR value.
  - The majority of field and laboratory blanks collected gave non-zero readings for NOx (i.e. exhibit some level of contamination).

- **Remove orthophosphate from the report card**
  Reason: Like NOx, orthophosphate guideline values (1–4 µg/L depending on the zone) are close to or below the LOR value (2 µg/L) in each of the 13 monitoring zones.

- **Remove sediment mercury from the report card**
  Reason: The sediment mercury LOR value (0.2 mg/kg) was above the guideline value (0.15 mg/kg) resulting in guaranteed failing scores. When different laboratory procedures were used in the previous report card, sediment mercury levels across the harbour were found to be very good condition—well below the guideline value. These methods were discontinued with consideration of the extremely low sediment mercury concentrations and the additional analysis cost.

- **Remove 14 dissolved metal data cases from analysis (approximately 4% of overall dissolved metals in water data)**
  Reason: For these samples the dissolved metal concentrations were 50% 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 ammonia, NOx, orthophosphate and sediment mercury from the report was the proximity of the LOR values to their respective guideline values. When the reported values are near analytical detection limits, even small analytical errors can move the value closer to an exceedance of the guideline. LOR values for these measures were insufficient to enable a reliable comparison to guideline values. 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 value (e.g. some zones for NOx and orthophosphate and all zones for sediment mercury) 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 of NOx, orthophosphate, ammonia, sediment mercury and the above-mentioned dissolved metal cases from the 2018 Gladstone Harbour Report Card, Technical Report and Water and Sediment Quality Report. These measures (excluding sediment mercury in 2017) and similar dissolved metal cases were also removed from preceding GHHP publications (2015–2017). Additionally, the GHHP Management Committee approved the permanent removal of ammonia from future Gladstone Harbour report cards.

[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. Please refer to Appendix 3 for graphical water quality score summaries for each of the 13 monitoring zones.

The overall grade for water quality in the 2018 Gladstone Harbour report card was a B (0.76). Outer Harbour received a very good score, while Boat Creek received a satisfactory score (0.92 and 0.63 respectively). The remaining zones received good scores (Table 6.1). A good overall water quality score was also evident in previous reporting years (2015–2017).

Table 6.1: Overall water quality, physicochemical, nutrient and dissolved metal scores for the 13 zones in the 2018 Gladstone Harbour Report Card. Overall zone scores for 2015–2017 are shown for comparison.

Water quality	Physico-chemical score	Nutrients score	Dissolved metals score	Zone score 2018	*Zone score 2017*	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.77	0.39	0.95	0.71	*0.71*	*0.68*	*0.82*
2. Graham Creek	0.96	0.43	0.94	0.78	*0.88*	*0.75*	*0.86*
3. Western Basin	0.87	0.34	0.94	0.72	*0.77*	*0.70*	*0.82*
4. Boat Creek	0.77	0.17	0.90	0.63	*0.59*	*0.58*	*0.70*
5. Inner Harbour	0.93	0.54	0.94	0.80	*0.79*	*0.78*	*0.88*
6. Calliope Estuary	0.94	0.42	0.91	0.76	*0.77*	*0.71*	*0.86*
7. Auckland Inlet	0.83	0.47	0.92	0.74	*0.79*	*0.71*	*0.77*
8. Mid Harbour	0.92	0.56	0.94	0.81	*0.79*	*0.77*	*0.80*
9. South Trees Inlet	0.93	0.40	0.94	0.76	*0.84*	*0.79*	*0.85*
10. Boyne Estuary	0.93	0.49	0.94	0.79	*0.83*	*0.71*	*0.70*
11. Outer Harbour	1.00	0.82	0.95	0.92	*0.90*	*0.72*	*0.84*
12. Colosseum Inlet	0.99	0.58	0.94	0.83	*0.83*	*0.73*	*0.78*
13. Rodds Bay	0.79	0.47	0.94	0.74	*0.75*	*0.73*	*0.80*
Whole harbour	**0.89**	**0.47**	**0.93**	**0.76**	***0.78***	***0.72***	***0.81***

Of the two physicochemical measures, pH received very good scores in all zones. Turbidity received good or very good scores in the majority of zones (Table 6.2). Only three zones (The Narrows, Boat Creek, Rodds Bay) had satisfactory scores.

Similar to previous report cards, nutrients (nitrogen, phosphorous, chlorophyll-*a*) received the lowest scores amongst the water quality sub-indicators (Table 6.1). While Outer Harbour had a good overall score and Inner Harbour, Mid Harbour and Colosseum Inlet had satisfactory overall scores, all other zones had poor or very poor scores. This was a result of poor scores for total nitrogen, except Boat Creek which had a very poor score, and poor to very poor scores for chlorophyll-*a*, except Outer

Harbour which had a very good (0.99) score. With the one exception of Boat Creek (0.27), scores for total phosphorus were satisfactory to very good (Table 6.2).

All zones had very good scores (0.90–0.95) for dissolved metals (Table 6.1). Scores for individual metal measures were predominantly very good, although manganese received a good score in Boat Creek (0.83). Scores for copper were lower than for the other metals, with six zones rated as good and six zones receiving a satisfactory score. The only zone to receive a poor score for this measure was Calliope Estuary (0.48) (Table 6.2).

Table 6.2: Scores for water quality measures for each of the 13 zones in the 2018 Gladstone Harbour Report Card.

Zone	Physico-chemical		Nutrients			Metals					
	pH	Turbidity	TN	TP	Chl-*a*	Al	Cu	Pb	Mn	Ni	Zn
1. The Narrows	1.00	0.54	0.38	0.63	0.16	1.00	0.67	1.00	1.00	1.00	1.00
2. Graham Creek	1.00	0.92	0.40	0.82	0.06	1.00	0.65	1.00	1.00	1.00	1.00
3. Western Basin	1.00	0.74	0.32	0.56	0.14	1.00	0.62	1.00	1.00	1.00	1.00
4. Boat Creek	1.00	0.56	0.22	0.27	0.03	1.00	0.60	1.00	0.83	1.00	1.00
5. Inner Harbour	1.00	0.87	0.41	0.88	0.32	1.00	0.61	1.00	1.00	1.00	1.00
6. Calliope Estuary	1.00	0.88	0.34	0.73	0.21	1.00	0.48	1.00	1.00	1.00	1.00
7. Auckland Inlet	1.00	0.65	0.35	0.65	0.42	0.96	0.53	1.00	1.00	1.00	1.00
8. Mid Harbour	1.00	0.85	0.41	0.80	0.48	1.00	0.65	1.00	1.00	1.00	1.00
9. South Trees Inlet	1.00	0.86	0.36	0.69	0.15	1.00	0.64	1.00	1.00	1.00	1.00
10. Boyne Estuary	1.00	0.86	0.31	0.75	0.41	1.00	0.64	1.00	1.00	1.00	1.00
11. Outer Harbour	1.00	1.00	0.48	0.99	0.99	1.00	0.67	1.00	1.00	1.00	1.00
12. Colosseum Inlet	1.00	0.97	0.39	0.89	0.44	0.95	0.67	1.00	1.00	1.00	1.00
13. Rodds Bay	1.00	0.56	0.41	0.67	0.34	1.00	0.67	1.00	1.00	1.00	1.00

TN (total nitrogen), TP (total phosphorous), Chl-*a* (chlorophyll-*a*), Al (aluminium), Cu (copper), Pd (lead), Mn (manganese), Ni (nickel), Zn (zinc)

Comparisons of the 13 monitoring zones based on water quality measures

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. The aim of this tool is to segregate groups with similar traits—in this case water quality measures—and assign them into clusters. Clusters are used for analytical purposes only to show the degree of similarity among the 13 environmental monitoring zones.

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 2017–18 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 3.6.1 (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 4) consisted of Mid Harbour and Outer Harbour (Figure 6.1; Figure 6.2). 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 2 (Colosseum Inlet) and Cluster 3 (Boyne Estuary) were also characterized by lower turbidity and lower concentrations of nutrients, however, had slightly elevated manganese concentrations compared to Cluster 4.

Cluster 6 (Figure 6.1) contained the largest number of zones (n = 7) and consisted of The Narrows, Graham Creek, Inner Harbour, Rodds Bay, Calliope Estuary, Western Basin and South Trees Inlet. This cluster was most closely associated with Cluster 5 (Auckland Inlet), both of which were characterised by lower pH, higher turbidity and higher concentrations of nutrients (Table 6.3). The key difference separating Auckland Inlet from Cluster 6 was an elevated manganese concentration.

The final single-zone cluster, Cluster 1 (Boat Creek), had the highest average concentrations of total nitrogen, total phosphorous and chlorophyll-*a* and the highest value of turbidity and dissolved manganese. Boat Creek showed a comparable dissimilarity to other zones in the previous report, *Water and Sediment Quality Indicators for the Gladstone Harbour Report Card 2017* (Schultz et al. 2019). Cluster 4 and Cluster 6 showed similar characteristics to the largest geographic area cluster and largest number of zones cluster, respectively, to the previous reporting year.

Potential reasons for cluster differences are noted in respective sub-indicator conclusion sections.

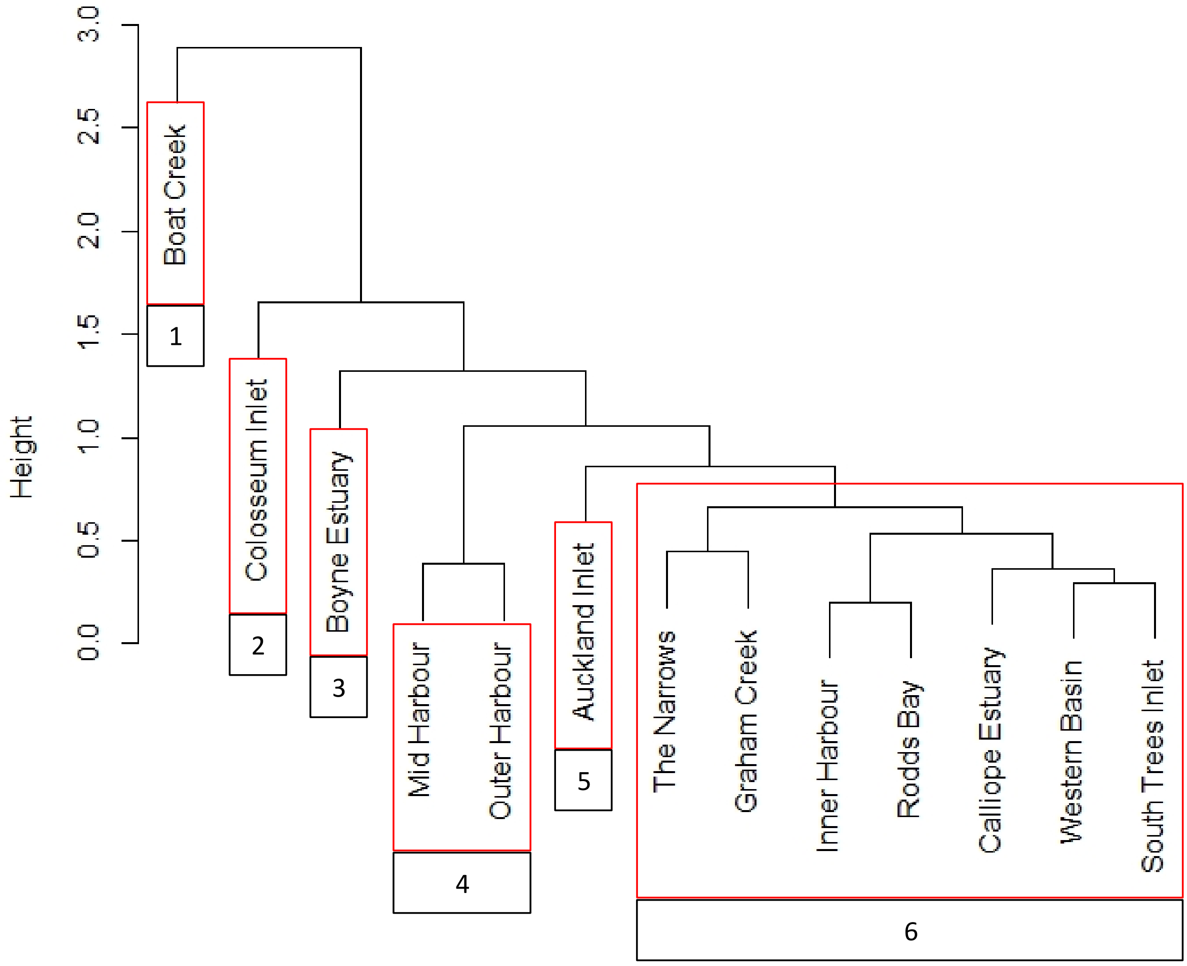

Figure 6.1: Hierarchical cluster analysis of the physicochemical, nutrient and metal measures (mean values for 2017–18) for the 13 environmental monitoring zones. As indicated by the boxes, the 13 zones were split into six distinct groups based on similar water quality properties. The cluster height 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.

Parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
pH	7.6	7.9	8.1	8.1	7.9	7.9
Turbidity (NTU)	30.6	1.9	1.5	2.1	6.3	7.2
TN (µg/L)	305	154	160	143	200	201
TP (µg/L)	37.4	6.1	7.8	7.7	13.3	14.6
Chl-*a* (µg/L)	4.0	0.9	0.9	0.8	2.2	1.7
Al (µg/L)	5.1	8.4	5.8	6.1	7.3	5.5
Cu (µg/L)	1.1	4.3	1.1	1.1	1.2	1.1
Pb (µg/L)	1.0	1.0	1.0	1.0	1.0	1.0
Mn (µg/L)	58.3	4.5	2.8	1.6	16.4	5.2
Ni (µg/L)	1.1	1.0	1.0	1.0	1.0	1.0
Zn (µg/L)	1.1	1.0	1.3	1.0	1.0	1.0

TN (total nitrogen), TP (total phosphorous), Chl-*a* (chlorophyll-*a*), Al (aluminium), Cu (copper), Pd (lead), Mn (manganese), Ni (nickel), Zn (zinc)

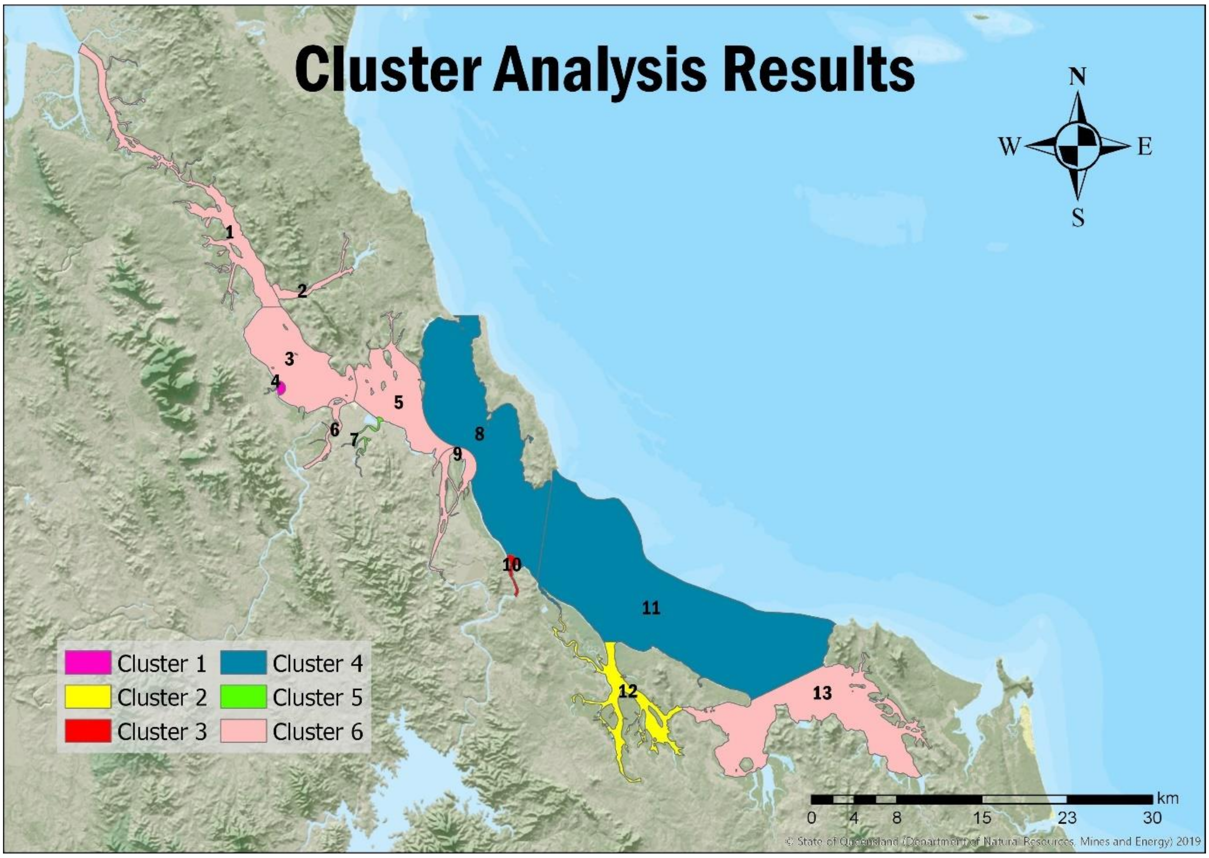

Figure 6.2: Hierarchical cluster analysis of mean water quality measures for the 2017–18 reporting year. Of the six clusters the cluster with the largest geographical area consisted of the Mid and Outer Harbor, the group that contained the largest number of zones (n = 7) The Narrows, Graham Creek, Inner Harbour, Rodds Bay, Calliope Estuary, Western Basin and South Trees Inlet. Boat Creek, Colosseum Inlet, Boyne Estuary and Auckland Inlet were all grouped separately (see Figure 6.1).

6.2. Sediment quality

The overall sediment quality score was derived from one sub-indicator: metals and metalloids. Five metals (cadmium, copper, lead, nickel and zinc) and the metalloid arsenic were assessed. 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 were all very good and ranged from 0.90 in The Narrows to 0.99 in Colosseum Inlet (Table 6.4) indicating very low concentrations of sediment metals across the harbour. This was a result of low concentrations of all measures—arsenic, cadmium, copper, lead, nickel and zinc (Table 6.5). The one metalloid and one metal—arsenic and nickel respectively—showed slightly lower scores than the other tested metals, however, all scores were good or above.

Table 6.4: Overall sediment quality scores for the 13 zones in the 2018 Gladstone Harbour Report Card. Overall zone scores for 2015–2017 are shown for comparison.

Sediment quality	Zone score 2018	*Zone score 2017*	*Zone score 2016*	*Zone score 2015*
1. The Narrows	0.90	*0.92*	*0.92*	*0.94*
2. Graham Creek	0.94	*0.92*	*0.96*	*0.98*
3. Western Basin	0.98	*0.97*	*0.98*	*0.99*
4. Boat Creek	0.91	*0.98*	*0.90*	*0.96*
5. Inner Harbour	0.95	*0.93*	*0.94*	*0.98*
6. Calliope Estuary	0.95	*0.94*	*0.99*	*0.98*
7. Auckland Inlet	0.91	*0.87*	*0.94*	*0.94*
8. Mid Harbour	0.95	*0.95*	*0.97*	*0.99*
9. South Trees Inlet	0.94	*0.98*	*0.95*	*0.96*
10. Boyne Estuary	0.97	*0.97*	*0.98*	*1.00*
11. Outer Harbour	0.96	*0.97*	*0.96*	*0.96*
12. Colosseum Inlet	0.99	*0.99*	*1.00*	*1.00*
13. Rodds Bay	0.97	*0.95*	*0.99*	*0.98*
Whole harbour	**0.95**	***0.95***	***0.99***	***0.98***

Table 6.5: Scores for sediment quality measures for each of the 13 zones in the 2018 Gladstone Harbour Report Card.

Zone	Metals and metalloid					
	Arsenic	Cadmium	Copper	Lead	Nickel	Zinc
1. The Narrows	0.74	1.00	1.00	1.00	0.66	1.00
2. Graham Creek	0.83	1.00	1.00	1.00	0.83	1.00
3. Western Basin	0.91	1.00	1.00	1.00	0.95	1.00
4. Boat Creek	0.76	1.00	1.00	1.00	0.76	1.00
5. Inner Harbour	0.72	1.00	1.00	1.00	1.00	1.00
6. Calliope Estuary	0.88	1.00	1.00	1.00	0.87	1.00
7. Auckland Inlet	0.84	1.00	1.00	1.00	0.75	1.00
8. Mid Harbour	0.71	1.00	1.00	1.00	1.00	1.00
9. South Trees Inlet	0.78	1.00	1.00	1.00	1.00	1.00
10. Boyne Estuary	0.81	1.00	1.00	1.00	1.00	1.00
11. Outer Harbour	0.79	1.00	1.00	1.00	1.00	1.00
12. Colosseum Inlet	0.93	1.00	1.00	1.00	1.00	1.00
13. Rodds Bay	0.84	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 (Figure 7.1). The overall score in 2018 (0.76) was similar to the 2017 score (0.78). Water quality was relatively uniform across the harbour and all zones received good or very good scores (0.71–0.92) except Boat Creek (0.63) which received a satisfactory score. The two zones with the highest scores were Colosseum Inlet (0.83) and Outer Harbour (0.92).

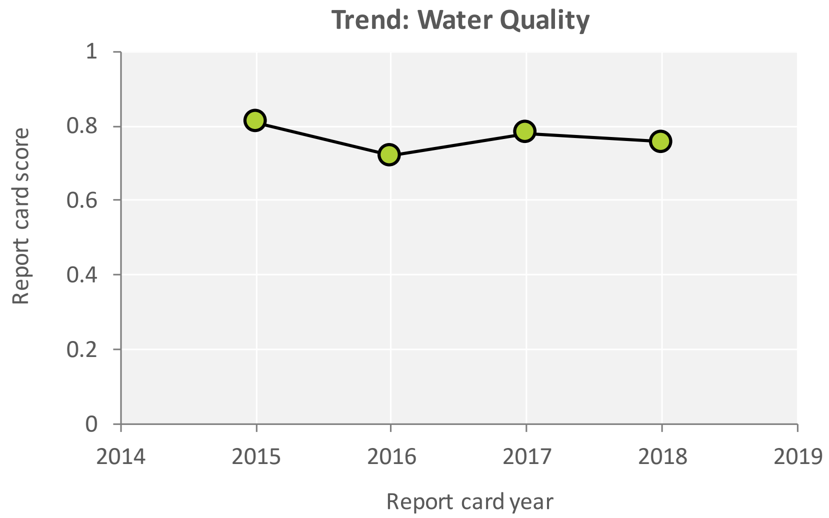

Figure 7.1: Changes in the overall water quality grade from 2015–2018.

Physicochemistry

Physicochemical scores (pH and turbidity) were good to very good (0.77–1.00) in all zones. While scores for pH were uniformly very good (1.00) across the harbour, turbidity was somewhat variable in 2018 and more so in previous report cards.

Boat Creek received the lowest score for turbidity (0.56) 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 consistently received low scores for turbidity since the first full report card in 2015, though 2018 marks the first year in which Boat Creek received a satisfactory turbidity score. Turbidity scores improved or showed a similar score at all other zones compared to the previous year.

Turbidity scores were higher in 2017–18 compared to the scores received in the previous three reporting years. This may have been influenced by the lower-than-average rainfall and median-level river discharge in the Gladstone area in 2017–18 (Figure 1.1; Figure 1.2; Table 1.1). Excluding October, monthly rainfall in the 2017–18 reporting year was similar to or lower than the monthly average over the past 24 years. Moreover, annual water discharge from the Boyne and Calliope catchments was similar to the long-term median discharge (Table 1.1). Higher turbidity levels in the Gladstone Harbour occur when the rivers discharge higher sediment loads, which typically occurs during the wet season (Angel et al., 2012). The more benign weather conditions may have positively influenced the turbidity scores received in 2017–18.

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 scores may not allow a direct comparison of actual turbidity values (NTU) within the harbour. These differences can be seen in Figure 7.2 which maps average turbidity (NTU) for the four sampling periods conducted in the 2017–18 reporting year. The map shows that the more oceanic sites such as the Outer and Mid Harbour were the least turbid areas of the harbour while Boat Creek and The Narrows were more turbid than the other zones.

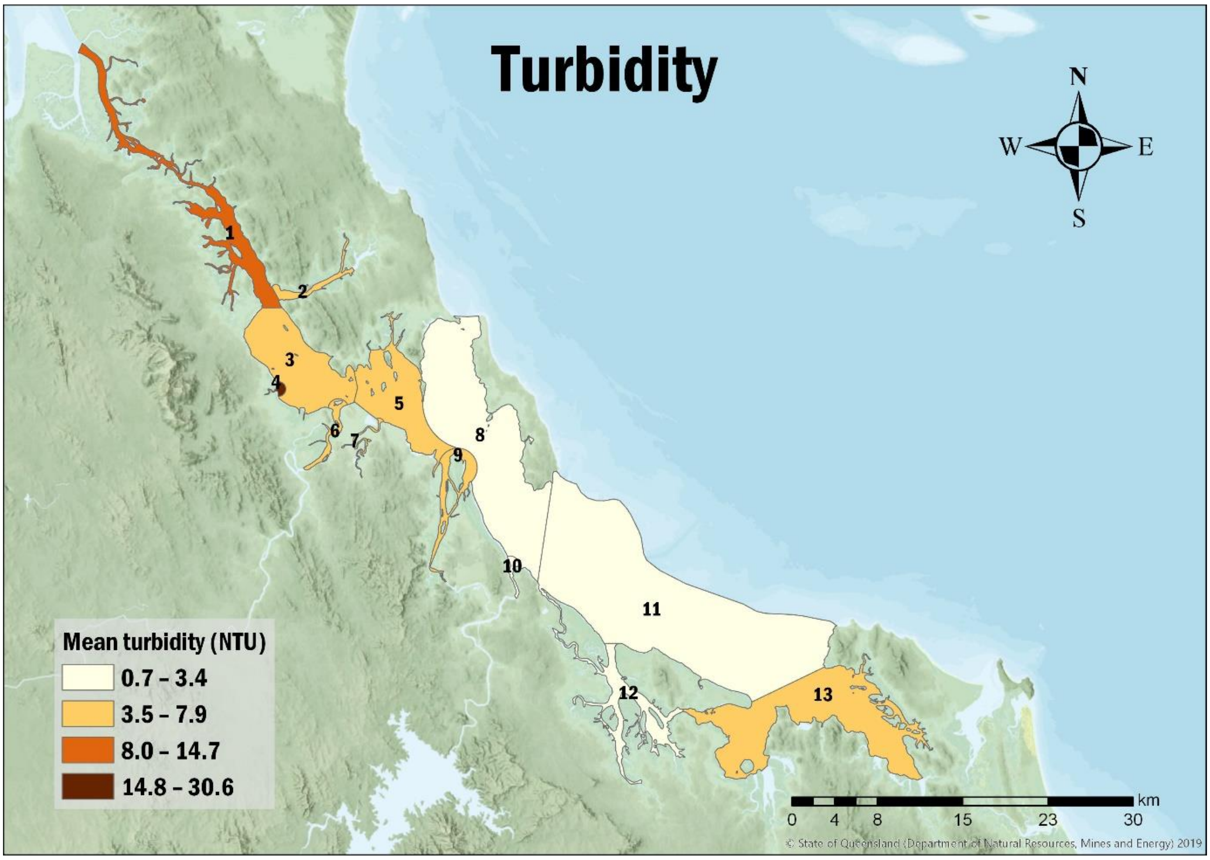

Figure 7.2: Mean turbidity (NTU) for 13 environmental monitoring zones for the 2017–18 reporting year. Mean turbidity classes were generated in ArcGIS® Pro 2.2.0 using the Jenks natural breaks symbology function. This method reduces the variance within classes and maximizes the variance between classes.

Nutrients

Scores for the nutrient sub-indicator (total nitrogen, total phosphorus, and chlorophyll-*a*) were mostly poor. Notable exceptions were Inner Harbour, Mid Harbour and Colosseum Inlet—which received satisfactory scores—and Outer Harbour which received a good score. Boat Creek received a very poor score. Although the nutrient sub-indicator scores were lower than the previous year, nutrients have consistently scored the lowest of the three sub-indicators since the first full report card in 2015.

Lower nutrient sub-indicator scores were the result of consistently poor scores for total nitrogen, poor to very poor grades for chlorophyll-*a* and satisfactory to very good scores for total phosphorous. Exceptions included Boat Creek which received a very poor total nitrogen score, Outer Harbour which received a very good chlorophyll-*a* score and Boat Creek which received a poor total phosphorous score.

Although nutrient sources are difficult to define, catchment run-off is a major source of nutrients in estuarine waters such as Gladstone Harbour (Hale & Box, 2014). The level of nutrients entering the harbour can also be influenced by land use (urban, industrial, agricultural, etc.) and climatic condition with the nutrient load expected to increase with wet season run-off. As nutrients can bind to fine sediments, the resuspension of sediments associated with tidal movements or wave action can also lead to increased nutrient levels within Gladstone Harbour.

As with the scores for other measures with specific zone guidelines, the three measured nutrients provide annual measures 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 nutrient values (µg/L) within the harbour. Figure 7.3 and Figure 7.4 maps the zone average for total nitrogen, total phosphorous and chlorophyll-*a* for the four sampling periods conducted in the 2017–18 reporting year. Comparison of the three nutrient maps shows a general pattern: Boat Creek had the highest concentration of nutrients while Mid Harbour, Outer Harbour, Boyne Estuary and Colosseum Inlet had the lowest (Figure 7.3; Figure 7.4). The generated class groupings were identical between total nitrogen and total phosphorous. Both nutrient maps indicate that The Narrows, Western Basin, Calliope Estuary, Auckland Inlet and South Trees Inlet showed a higher concentration than Graham Creek, Inner Harbour, and Rodds Bay. The chlorophyll-*a* map demonstrated a similar pattern.

The larger estuarine systems showed a higher concentration of nutrients compared to more ocean-influenced zones. Exceptions to this general pattern were Boyne Estuary and Boat Creek. Streamflow in the Boyne River is highly modified owing to the presence of Awoonga Dam, whereas flow in the Calliope River is relatively unmodified. The modified nature of the Boyne River may have influenced the nutrient-load recorded in Boyne Estuary, which overall was more similar to ocean-influenced zones (Figure 6.1; Figure 7.3; Figure 7.4). Boat Creek was overall the most dissimilar of the 13 environmental monitoring zones (Figure 6.1; Figure 7.3; Figure 7.4). This pattern is consistent in previous reporting years, where Boat Creek showed higher—often the highest—concentrations of nutrients. The small and shallow nature of this zone, which is prone to the resuspension of sediments owing to wind and tidal movement, likely influences the higher nutrient concentrations exhibited in Boat Creek.

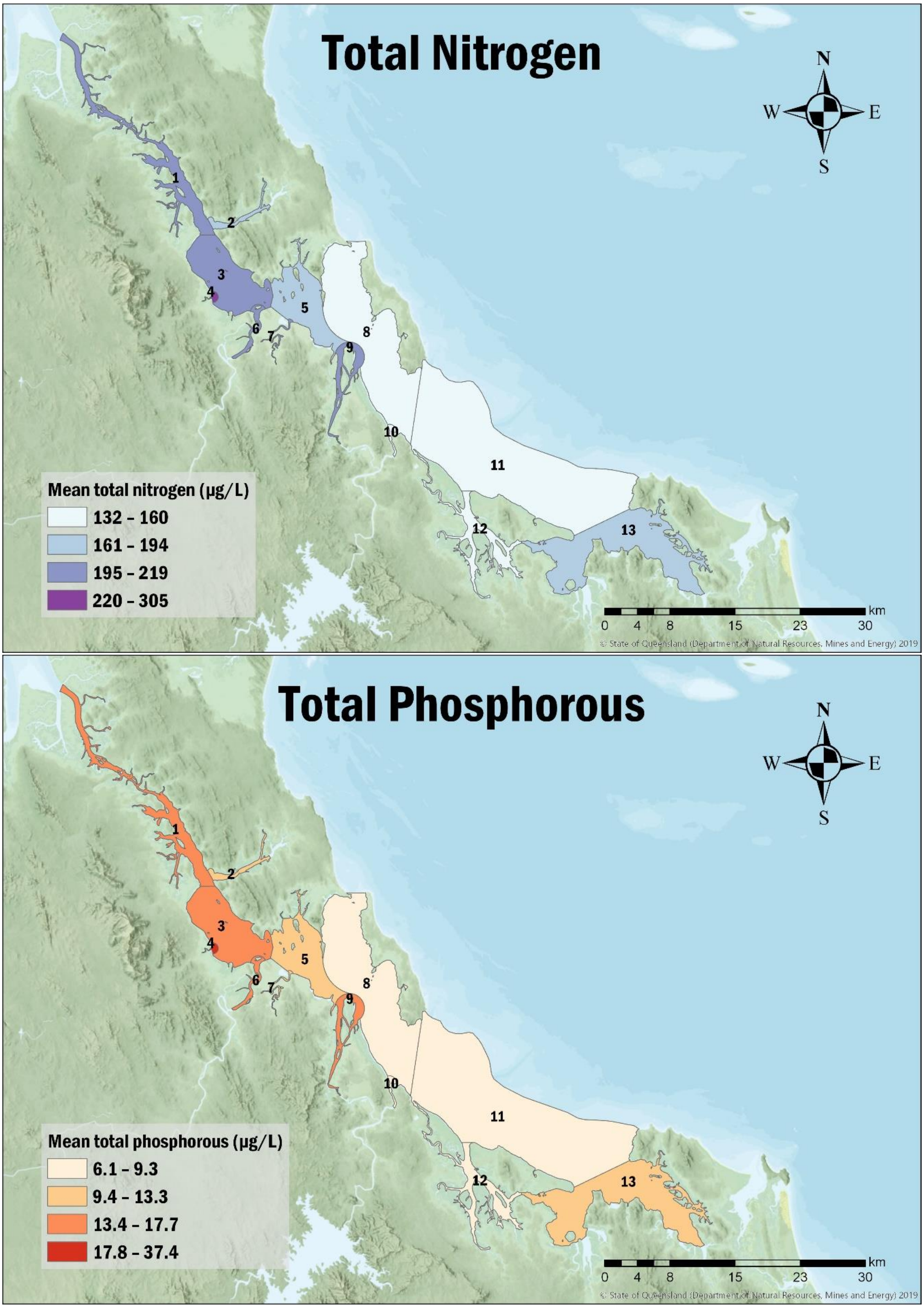

Figure 7.3: Mean total nitrogen (µg/L) and total phosphorous (µg/L) for 13 environmental monitoring zones for the 2017–18 reporting year. Mean total nitrogen and total phosphorous classes were generated in ArcGIS® Pro 2.2.0 using the Jenks natural breaks symbology function. This method reduces the variance within classes and maximize the variance between classes.

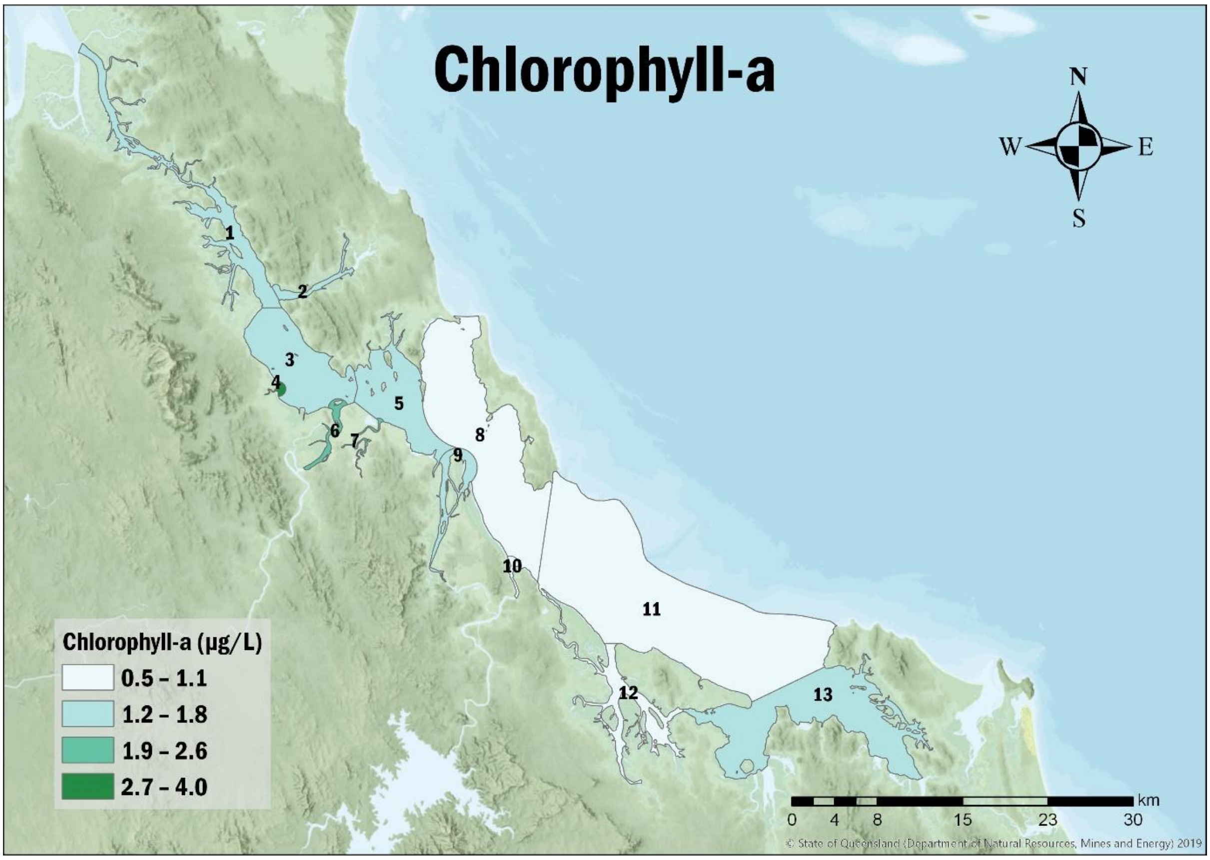

Figure 7.4: Mean chlorophyll-*a* for 13 environmental monitoring zones for the 2017–18 reporting year. Mean chlorophyll-*a* classes were generated in ArcGIS® Pro 2.2.0 using the Jenks natural breaks symbology function. This method reduces the variance within classes and maximize the variance between 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 2018 report card scores for aluminium (0.95–1.00), lead (1.00), manganese (0.83–1.00), nickel (1.00) and zinc (1.00) were all very good—except at Boat Creek for manganese which received a good score—indicating very low concentrations of these metals across the harbour zones. This pattern, including the good score for manganese at Boat Creek, was also evident in the 2015, 2016 and 2017 report cards. For the fourth consecutive year copper scores were lower compared to scores for the other five tested metals. However there were only three instances—Calliope Estuary in 2015 (0.23) and 2018 (0.48) and Boat Creek in 2017 (0.49)—where the average concentration of copper exceeded the guideline value.

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 (ng/L) from Gladstone Harbor and other locations (Source Angel et al., 2012; Apte et al., 2019).

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 Strait and Gulf of Papua	<1 - 29	36 - 986	940 - 4600	-	Apte and Day, 1998
Torres Strait – south and east (mean)	1.8	130	132	41	Apte et al., 2019
Southern Great Barrier Reef QLD	<1.5	40	150	40	Angel et al., 2010
Port Phillip Bay, Australia	<5 - 70	400 - 630	540 - 1100	250 - 1050	Fabris and Monahan, 1995
Nine estuaries, northern Australia	1.4 - 7.2	150 - 5500	120 - 4250	<10 - 11300	Munksgaard 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., 1998
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 five metals (cadmium, copper, lead, nickel, zinc) and one metalloid (arsenic). For the fourth consecutive year, sediment quality scores were uniformly very good (A) across all Gladstone Harbour reporting zones (Table 6.4; Figure 7.5). This is a result of very low concentrations of all metals assessed. Sediment arsenic had slightly elevated concentrations compared to other metals; however, all 13 environmental monitoring zones received a good or very good score.

Between 2015 and 2018 the lowest score for an individual measure was for arsenic. Nevertheless, sediment arsenic 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/ARMCANZ ISQG[3]-low trigger value in two samples from The Narrows and one sample near Quoin Island. They

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

noted that the source of this arsenic is natural (geological formation on the area) and is not associated with anthropogenic inputs.

Sediment mercury was omitted in 2018 as the limit of reporting for this metal was above the guideline value, hence a score could not be determined. When different laboratory procedures were used in 2017, sediment mercury concentrations were found to be well below the guideline values across the harbour. PAHs were not monitored in 2018 due to the very low concentrations recorded in the 2015 sediment monitoring.

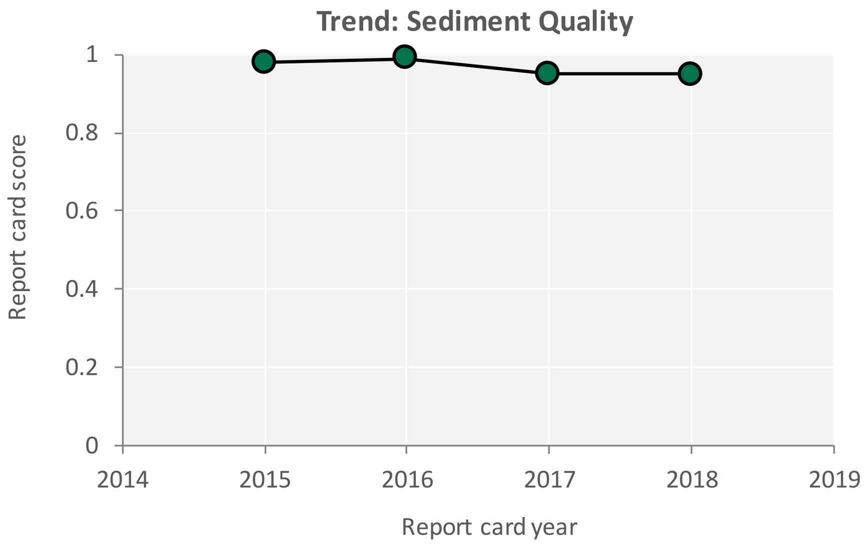

Figure 7.5: Changes in the overall sediment quality grade from 2015–2018.

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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)
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.
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
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

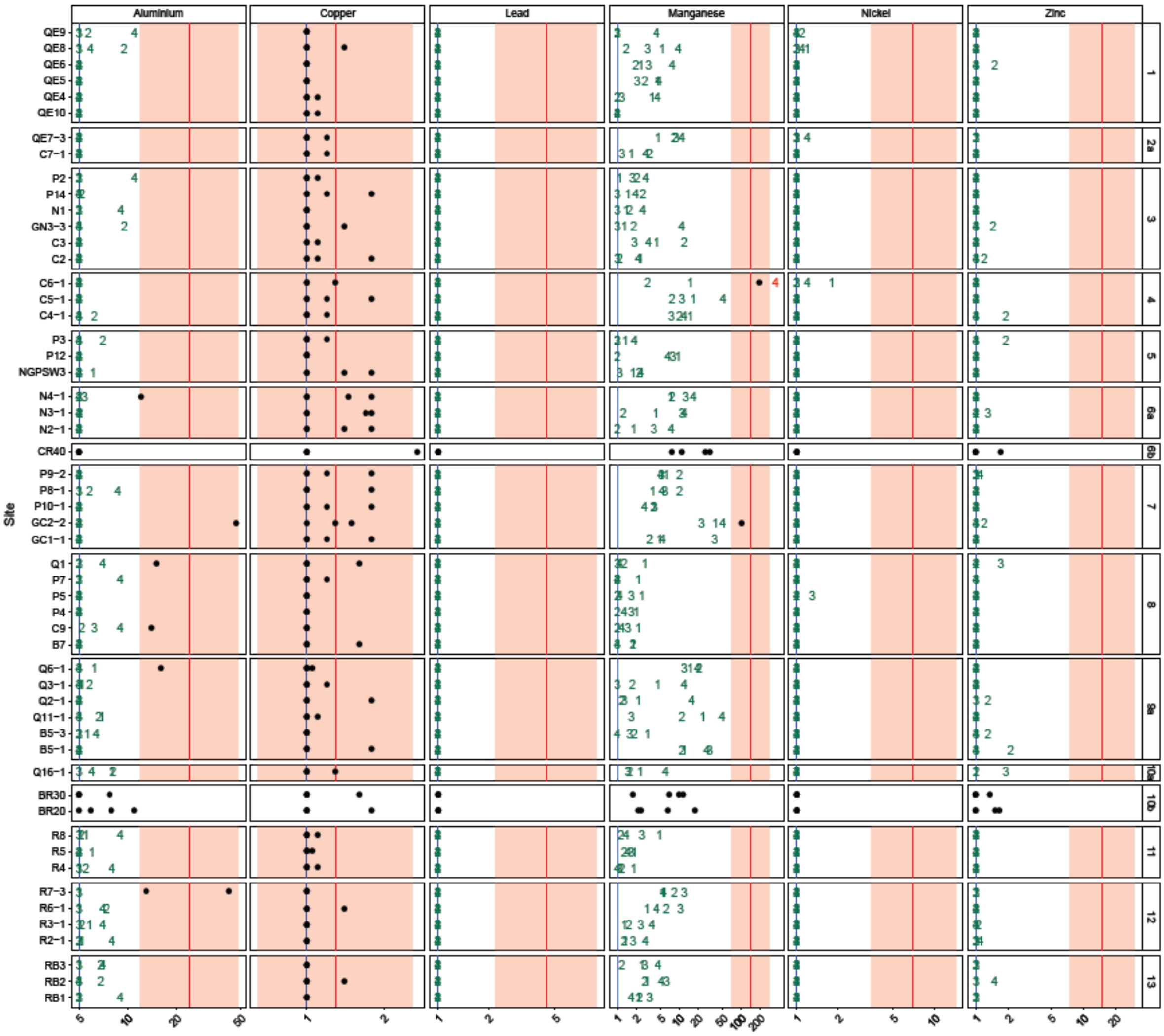
	the sampling environment while the sampling is performed. This type of QC identifies contamination sources such as reverse osmosis, sample bottles or the analytical laboratory.
LNG	Liquefied Natural Gas
LOR	Limit of Reporting
MD	Moderately Disturbed
Macro-tidal	coastal areas where the tidal range is 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 from other values in a random sample from a population. Abnormal distance is defined by the analyst or analysis protocol.
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.
QHL	Queensland Health Laboratories
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 limit of reporting values used for these measures are 2 µg/L-Ammonia, 0.02 µg/L-Chlorophyll-*a*, 2 µg/L-NOx, 20 or 50 µg/L-TN, 2 µg/L-Orthophosphate, and 2, 3 or 5 µg/L-TP. 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 light red band represents the range of values in which non-outlying values would occur.

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 1 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.



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

This section provides the following for each of the 13 monitoring zones:

- A detailed map showing the location of water and sediment quality monitoring sites
- Measure scores for each of the 11 water quality parameters in 2018
- Sub-indicator scores (physicochemical, nutrients, dissolved metals) in 2018
- Harbour-wide water quality scores from 2015–2018

Please note the following abbreviations used for the 2018 zone measure scores:

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

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

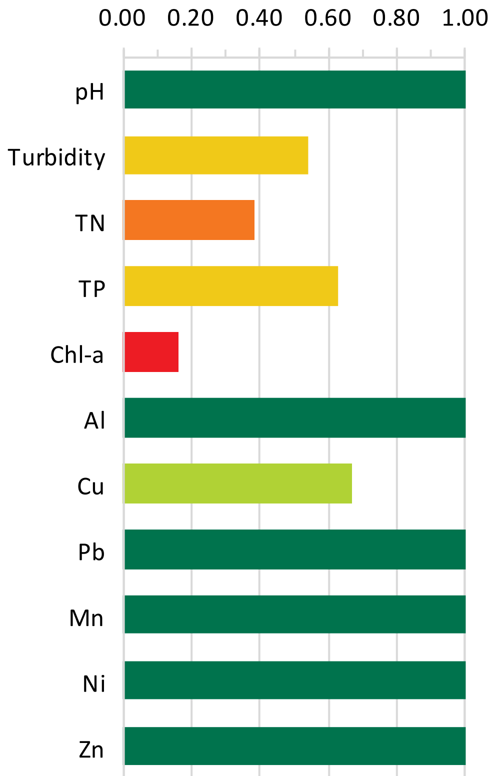


Figure A.3: 2018 Zone 1 measure scores.

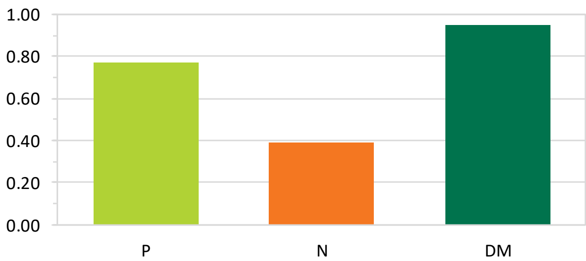


Figure A.2: 2018 Zone 1 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

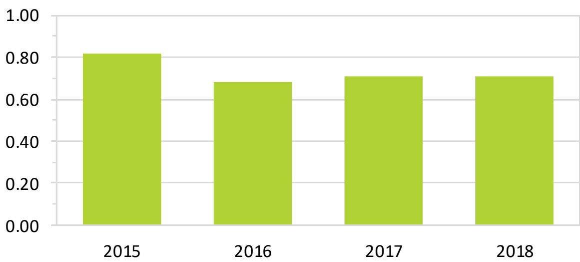


Figure A.4: Zone 1 overall water quality scores.

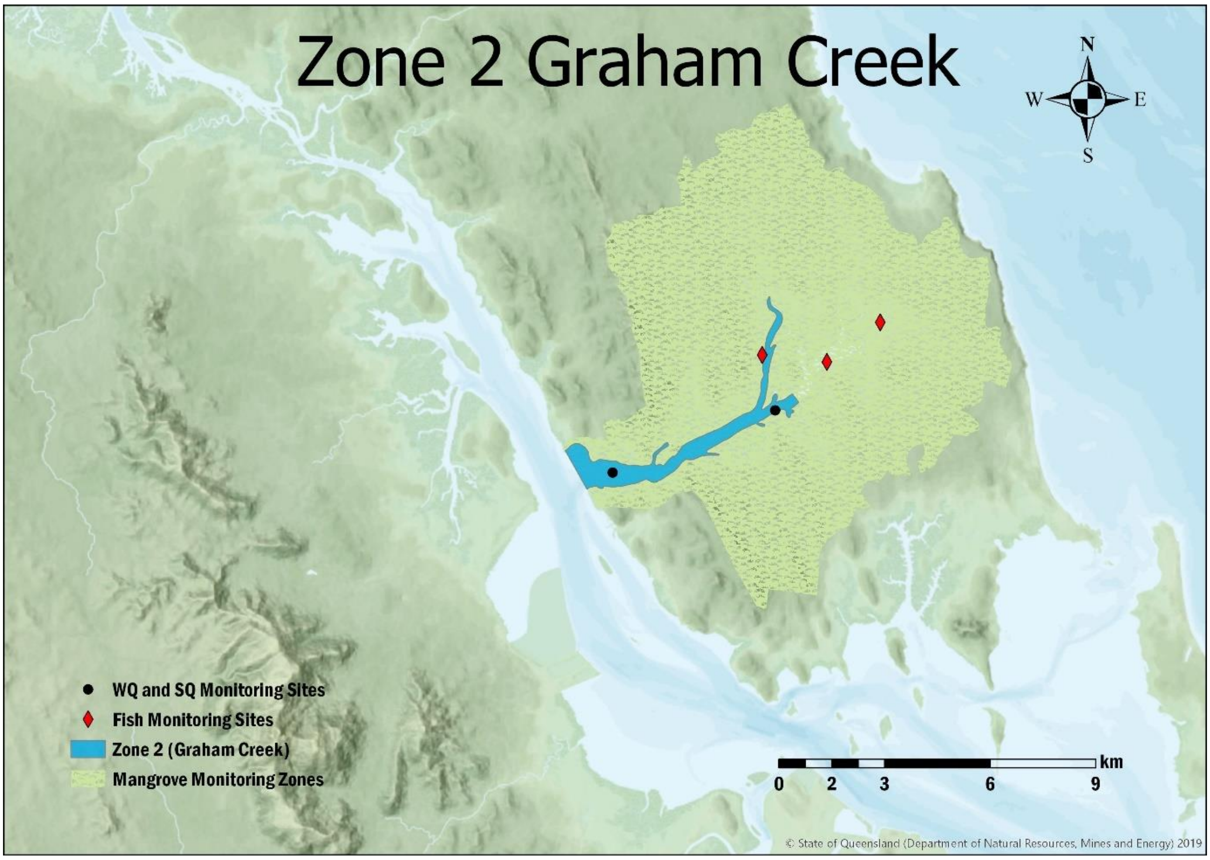


Figure A.5: Water and sediment quality sampling sites in Graham Creek.

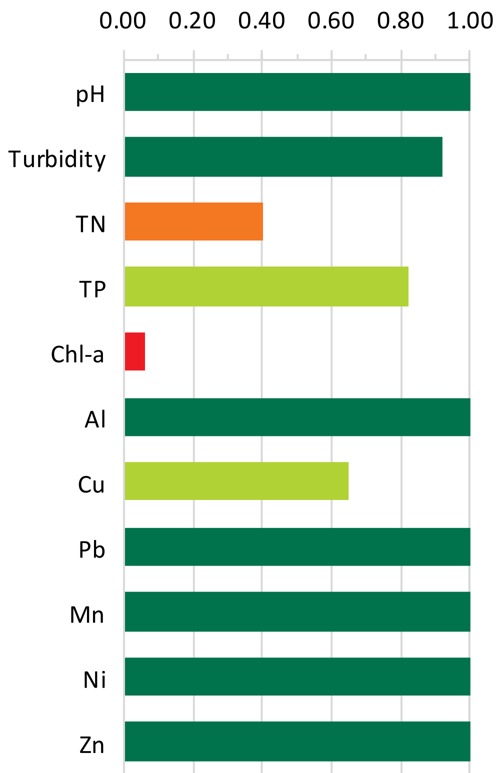


Figure A.7: 2018 Zone 2 measure scores.

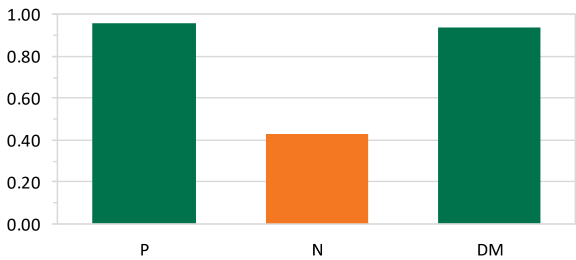


Figure A.6: 2018 Zone 2 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

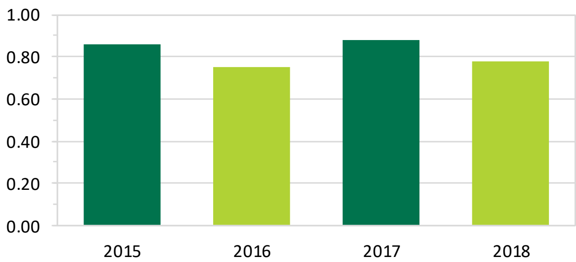


Figure A.8: Zone 2 overall water quality scores.

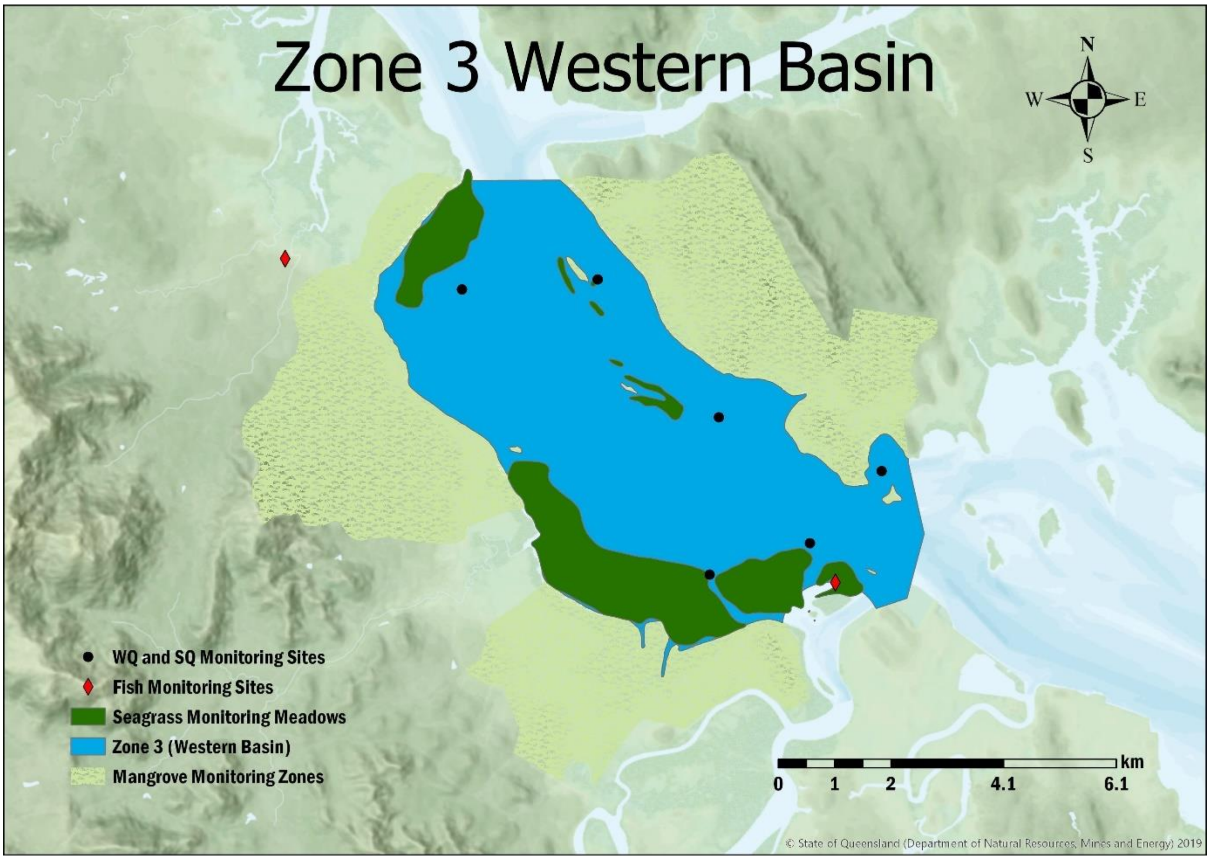


Figure A.9: Water and sediment quality sampling sites in Western Basin.

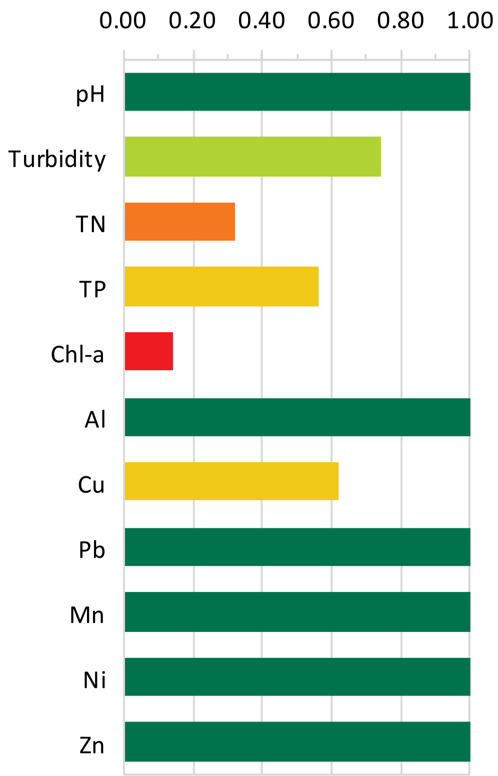


Figure A.11: 2018 Zone 3 measure scores.

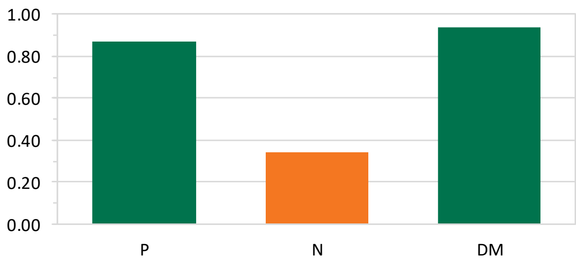


Figure A.10: 2018 Zone 3 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

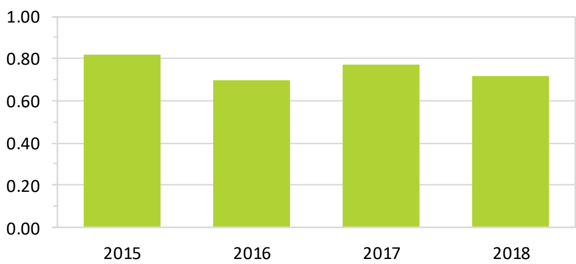


Figure A.12: Zone 3 overall water quality scores.

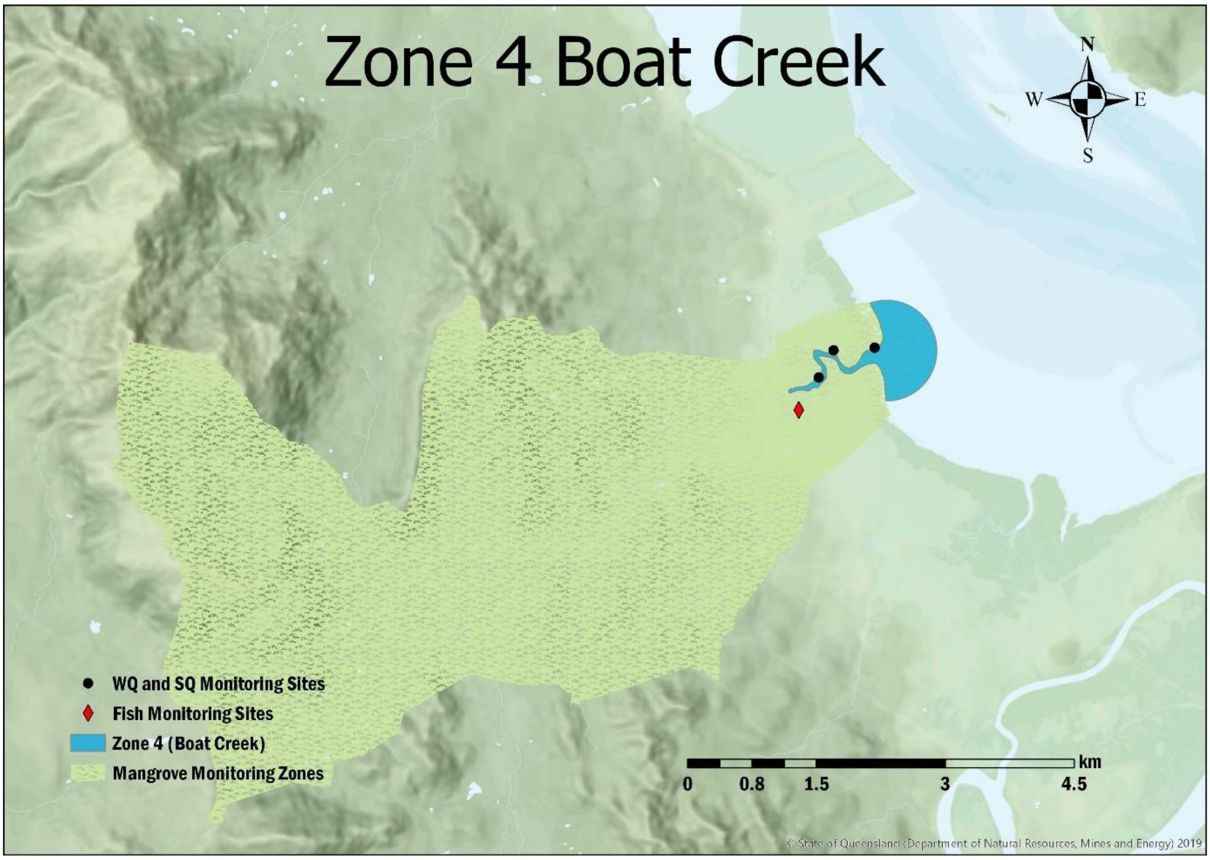


Figure A.13: Water and sediment quality sampling sites in Boat Creek.

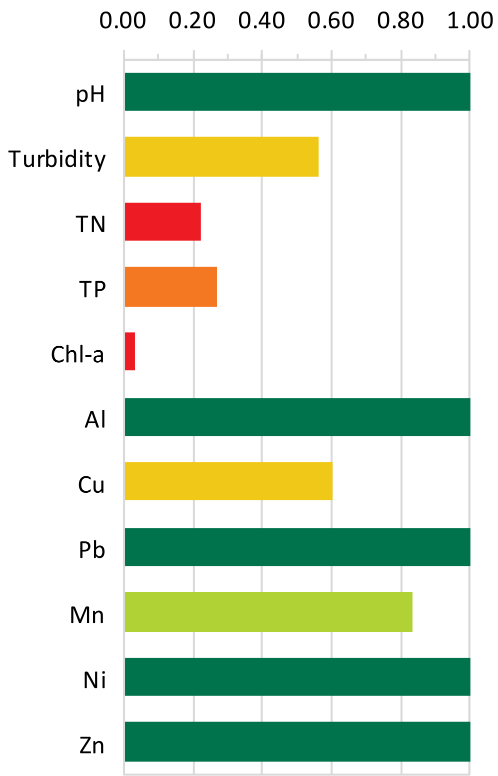


Figure A.15: 2018 Zone 4 measure scores.

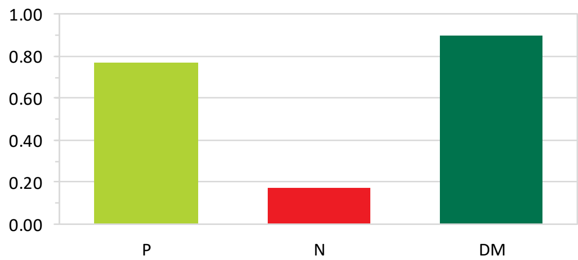


Figure A.14: 2018 Zone 4 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

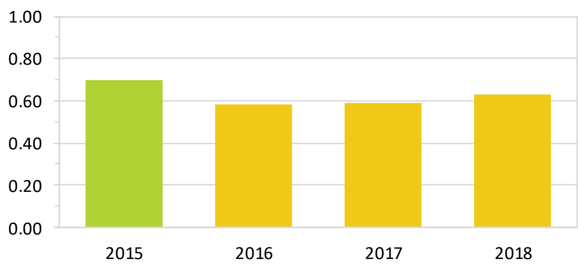


Figure A.16: Zone 4 overall water quality scores.

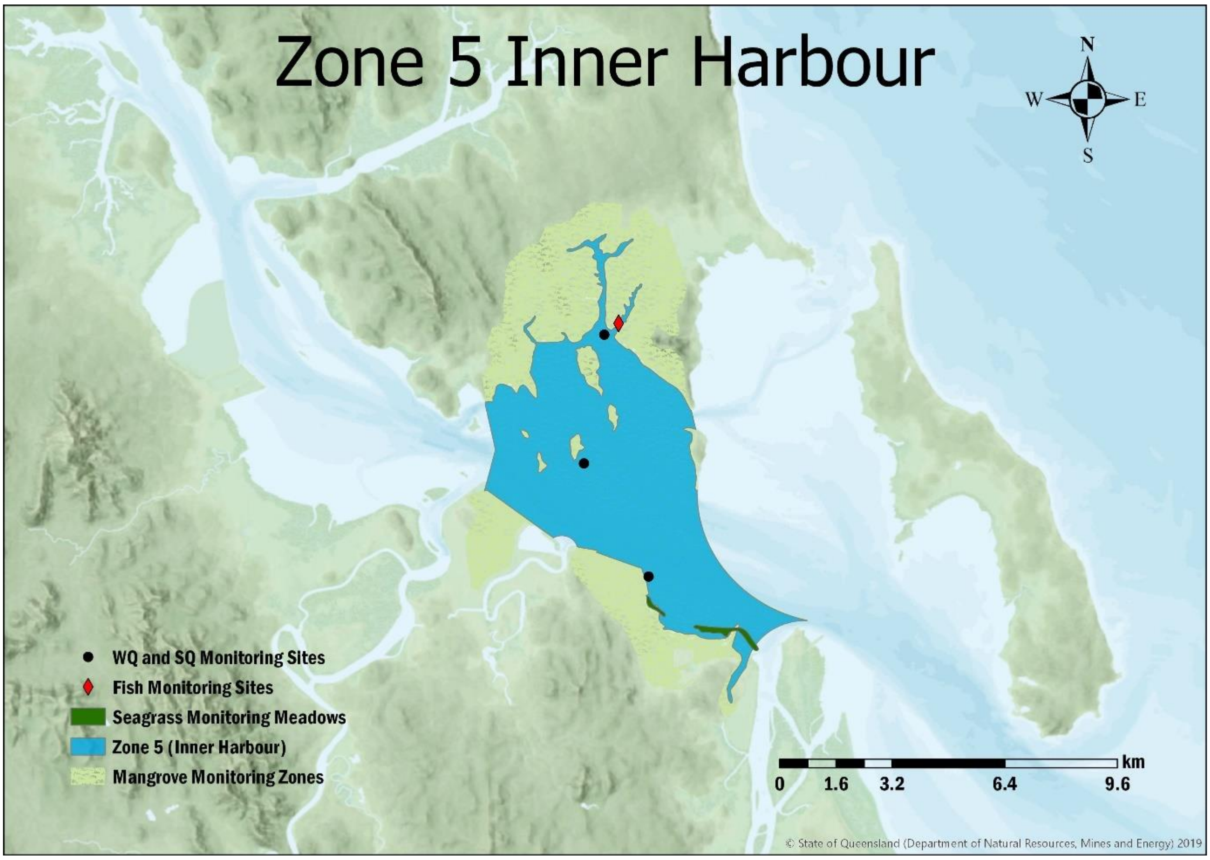


Figure A.17: Water and sediment quality sampling sites in Inner Harbour.

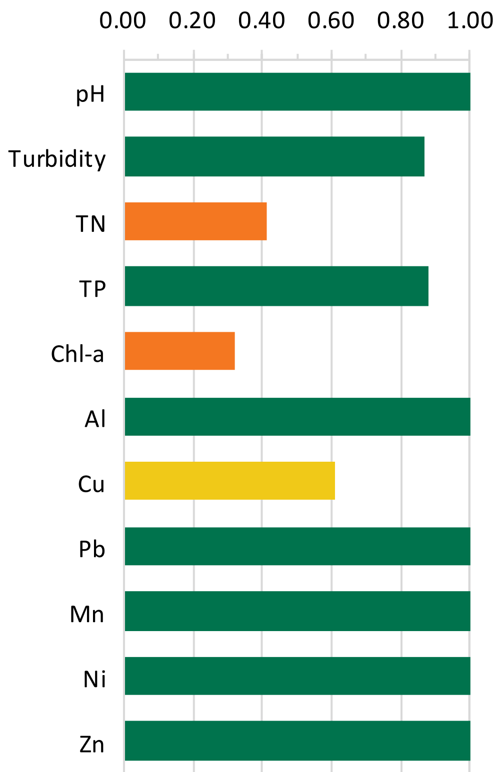


Figure A.19: 2018 Zone 5 measure scores.

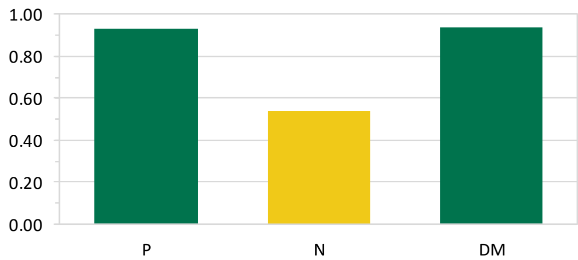


Figure A.18: 2018 Zone 5 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

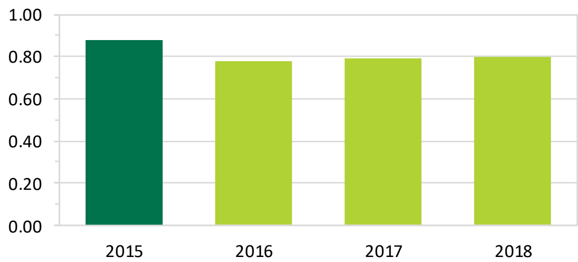


Figure A.20: Zone 5 overall water quality scores.

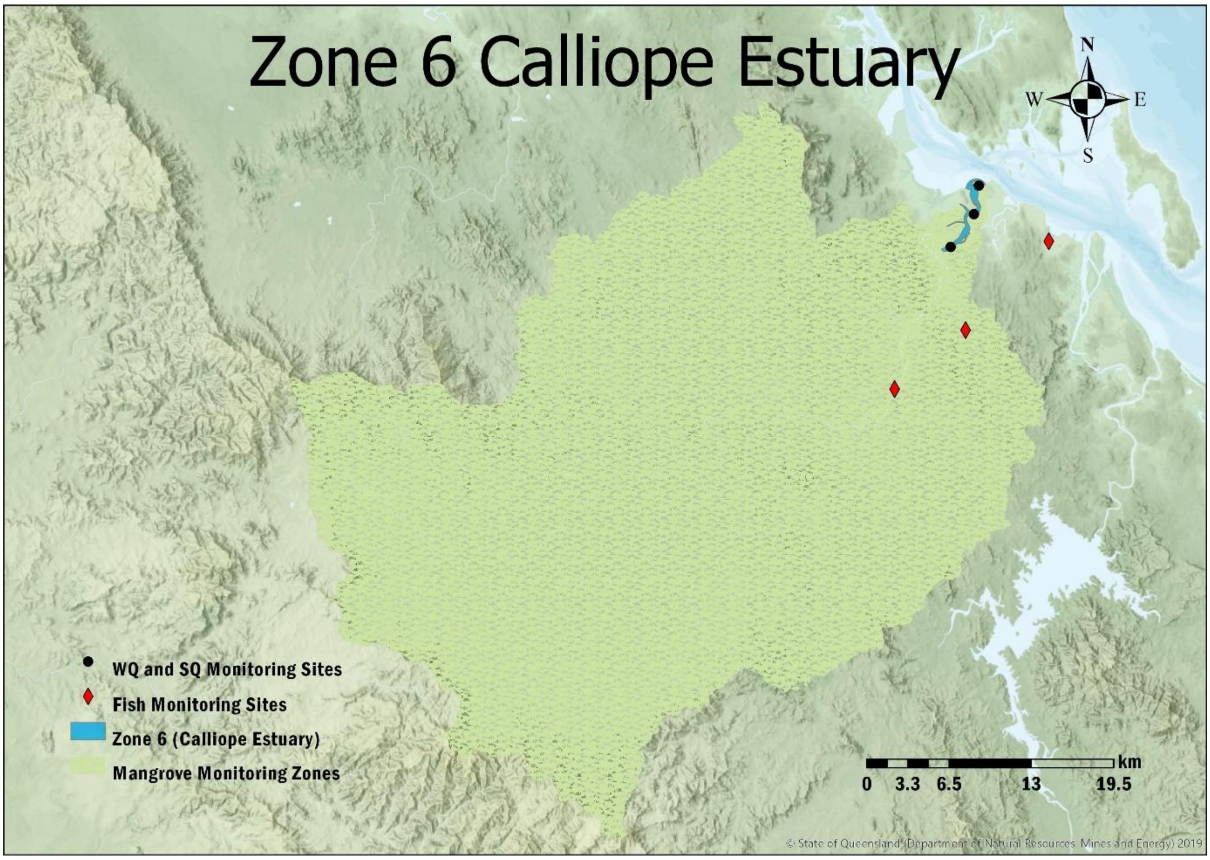


Figure A.21: Water and sediment quality sampling sites in Calliope Estuary.

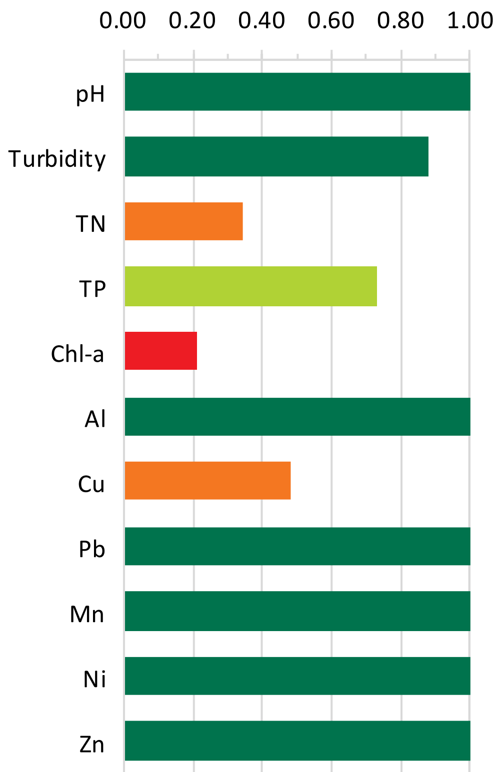


Figure A.23: 2018 Zone 6 measure scores.

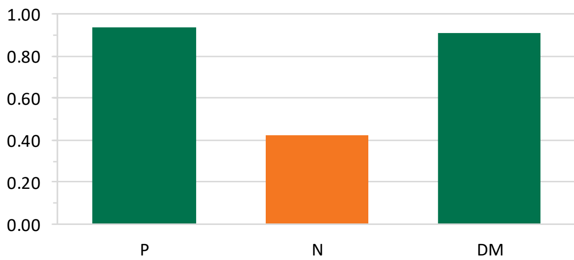


Figure A.22: 2018 Zone 6 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

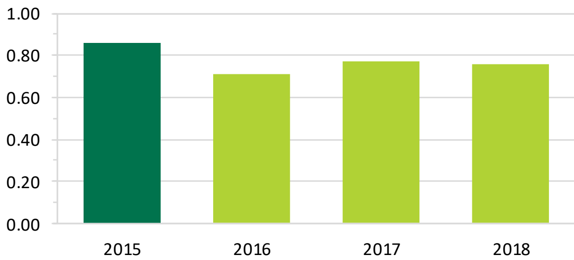


Figure A.24: Zone 6 overall water quality scores.

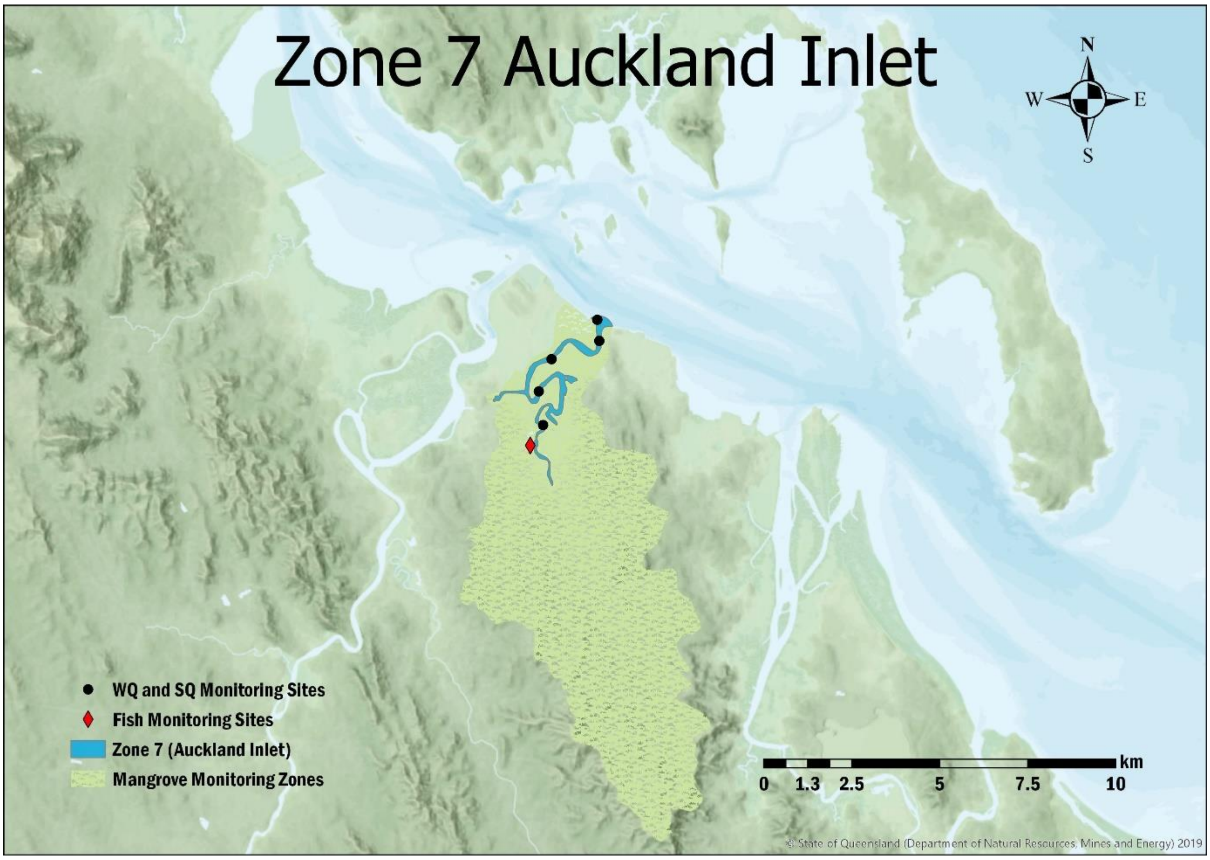


Figure A.25: Water and sediment quality sampling sites in Auckland Inlet.

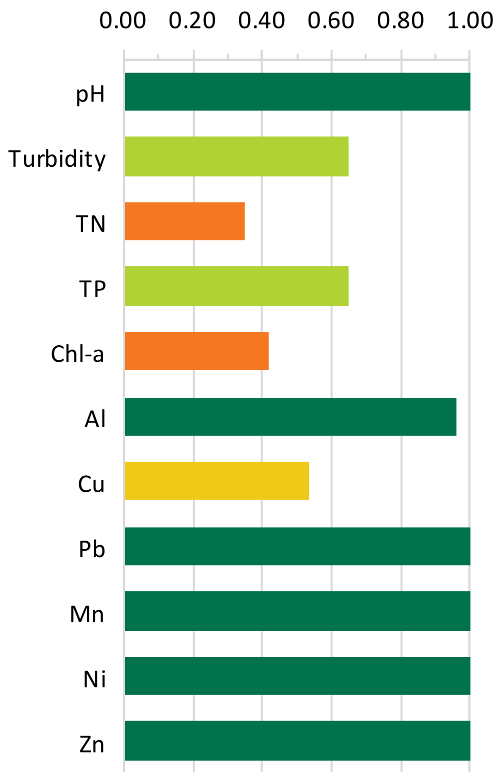


Figure A.27: 2018 Zone 7 measure scores.

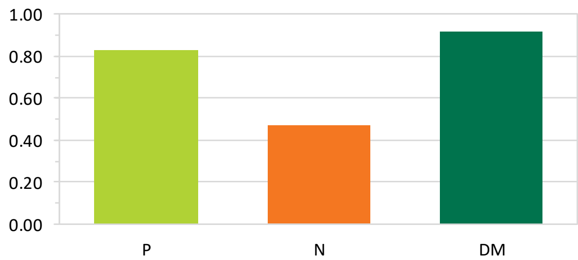


Figure A.26: 2018 Zone 7 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

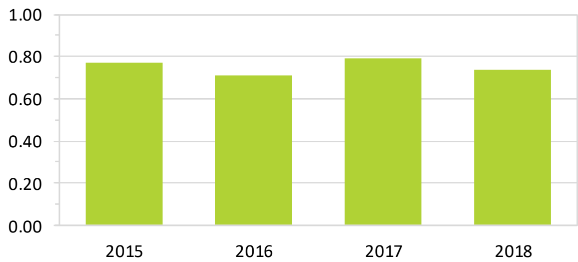


Figure A.28: Zone 7 overall water quality scores.

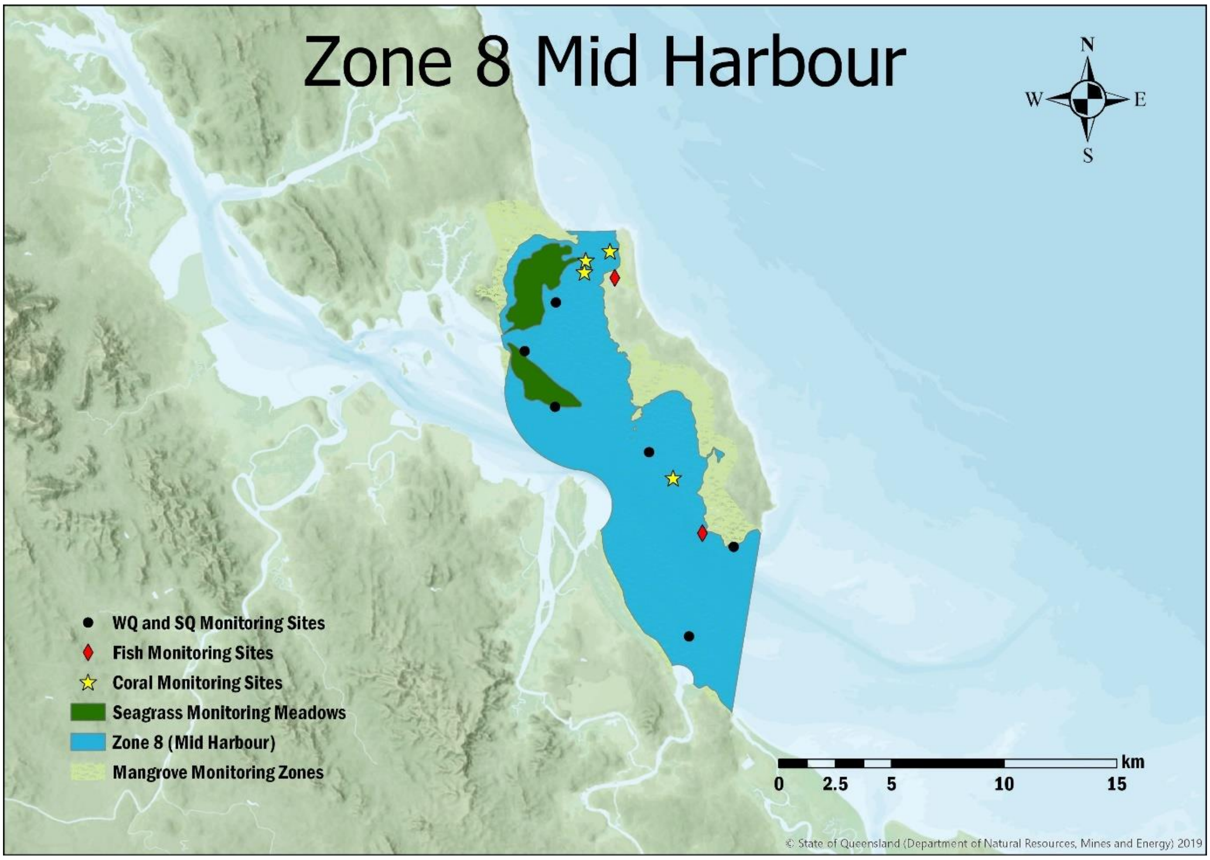


Figure A.29: Water and sediment quality sampling sites in Mid Harbour.

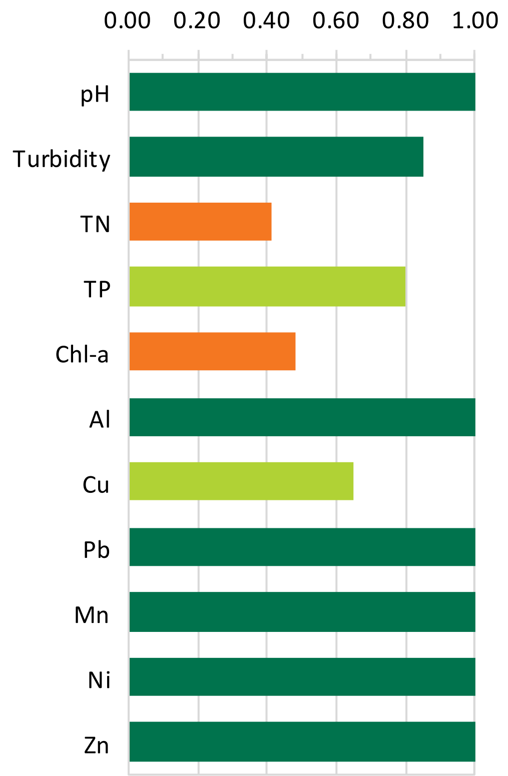


Figure A.31: 2018 Zone 8 measure scores.

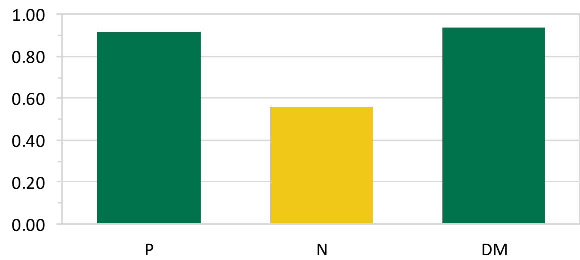


Figure A.30: 2018 Zone 8 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

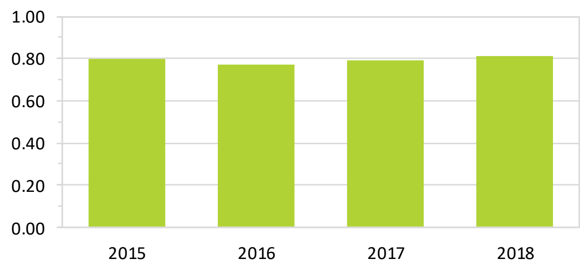


Figure A.32: Zone 8 overall water quality scores.

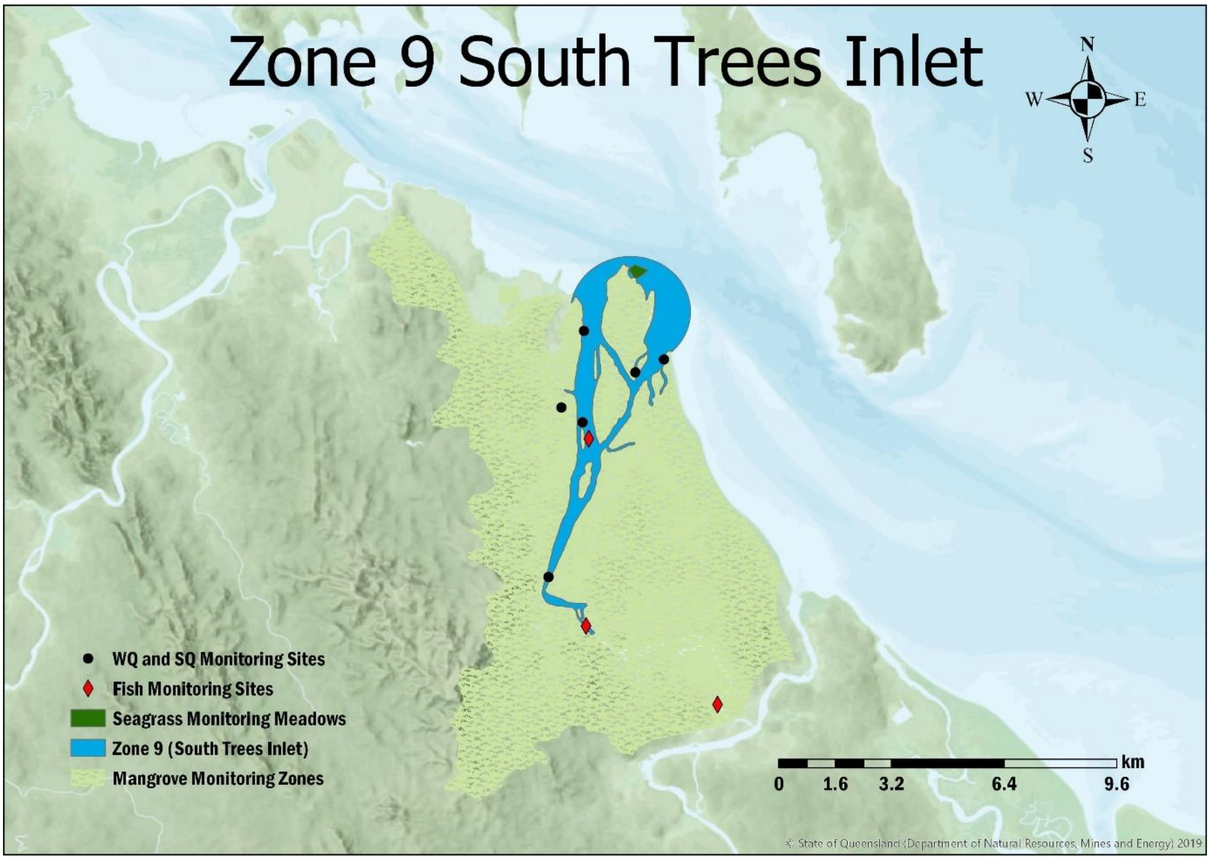


Figure A.33: Water and sediment quality sampling sites in South Trees Inlet.

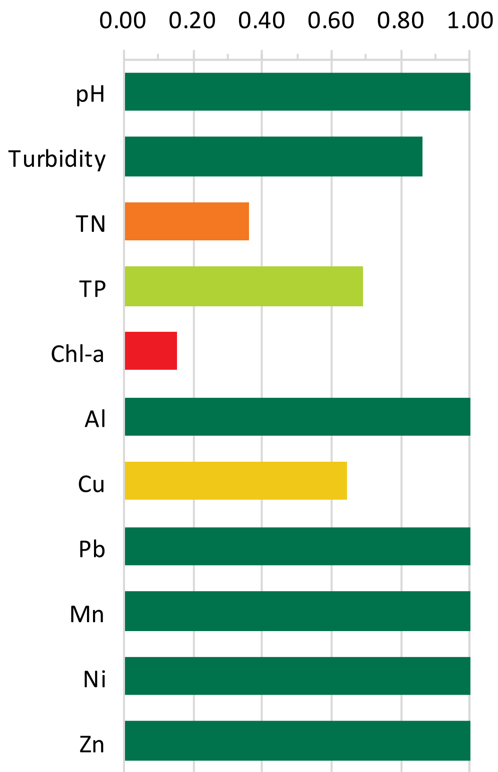


Figure A.35: 2018 Zone 9 measure scores.

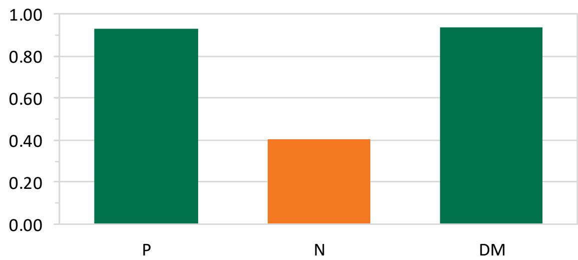


Figure A.34: 2018 Zone 9 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

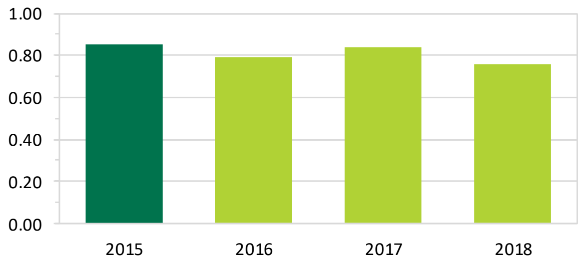


Figure A.36: Zone 9 overall water quality scores.

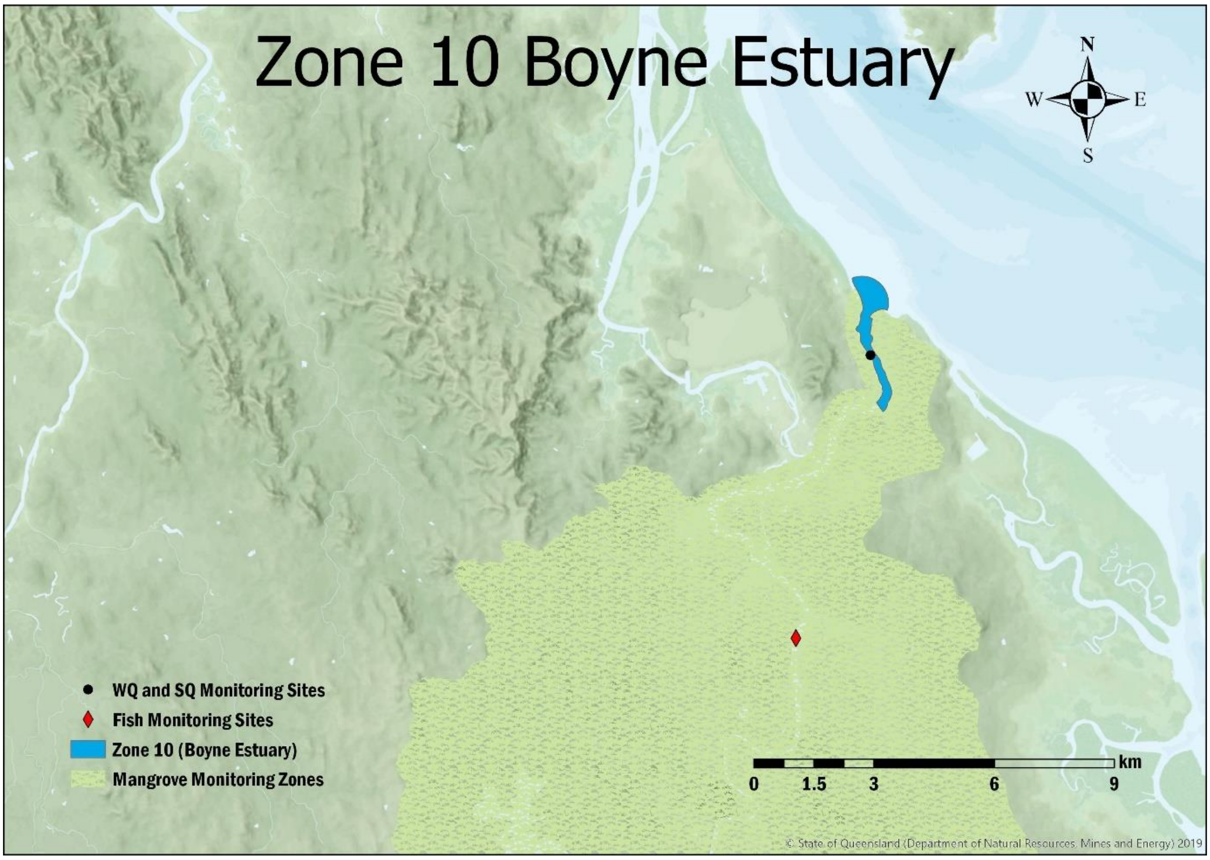


Figure A.37: Water and sediment quality sampling sites in Boyne Estuary.

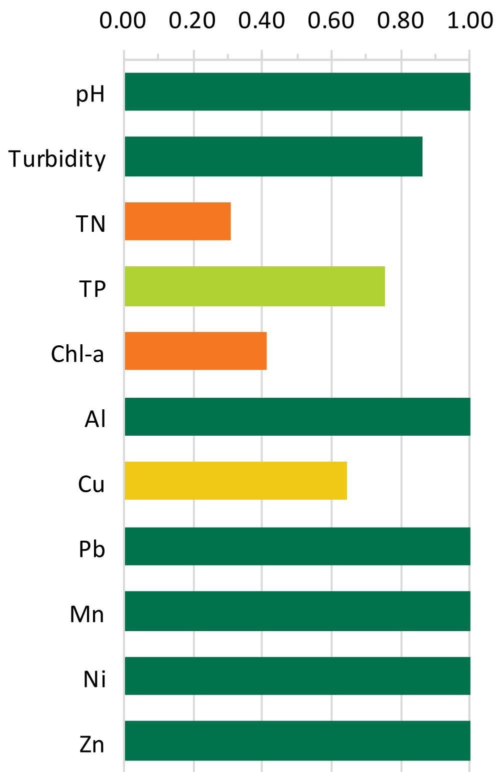


Figure A.39: 2018 Zone 10 measure scores.

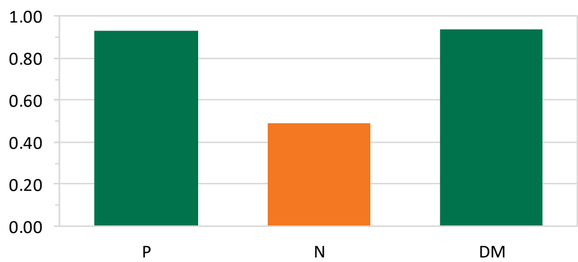


Figure A.38: 2018 Zone 10 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

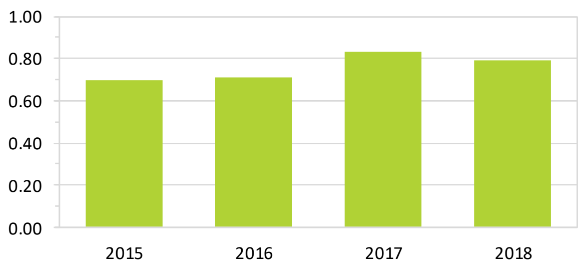


Figure A.40: Zone 10 overall water quality scores.

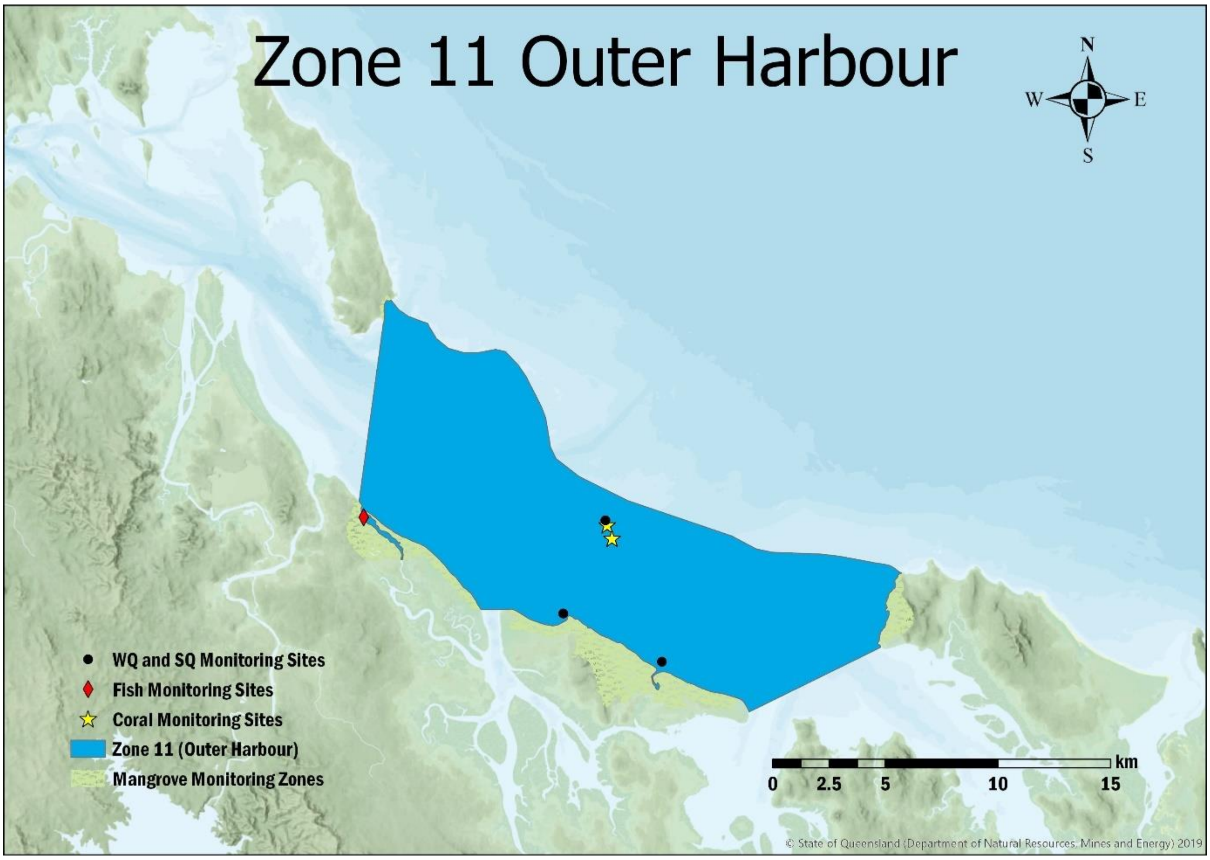


Figure A.41: Water and sediment quality sampling sites in Outer Harbour.

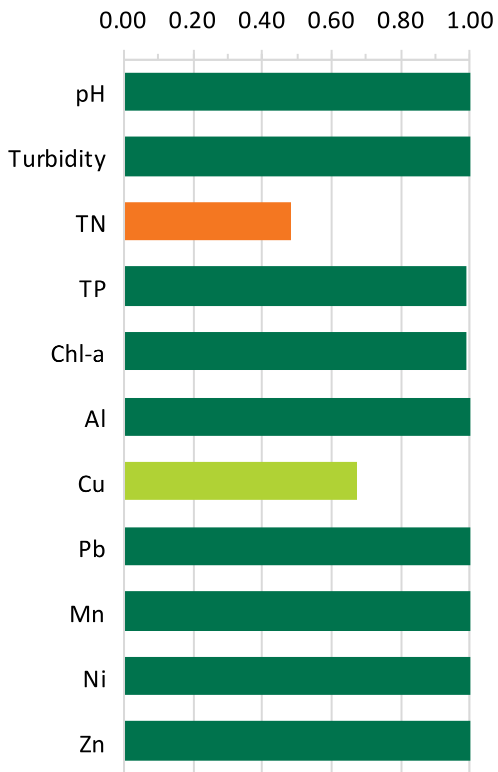


Figure A.43: 2018 Zone 11 measure scores.

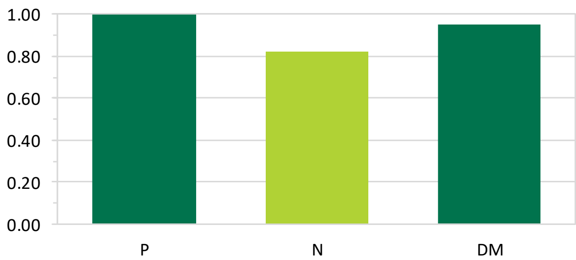


Figure A.42: 2018 Zone 11 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

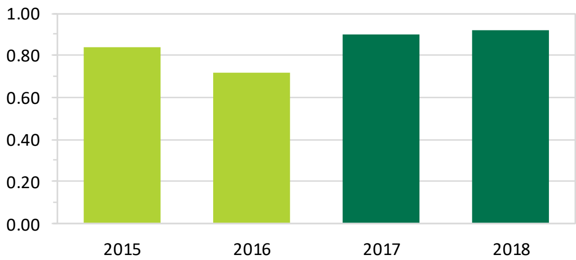


Figure A.44: Zone 11 overall water quality scores.

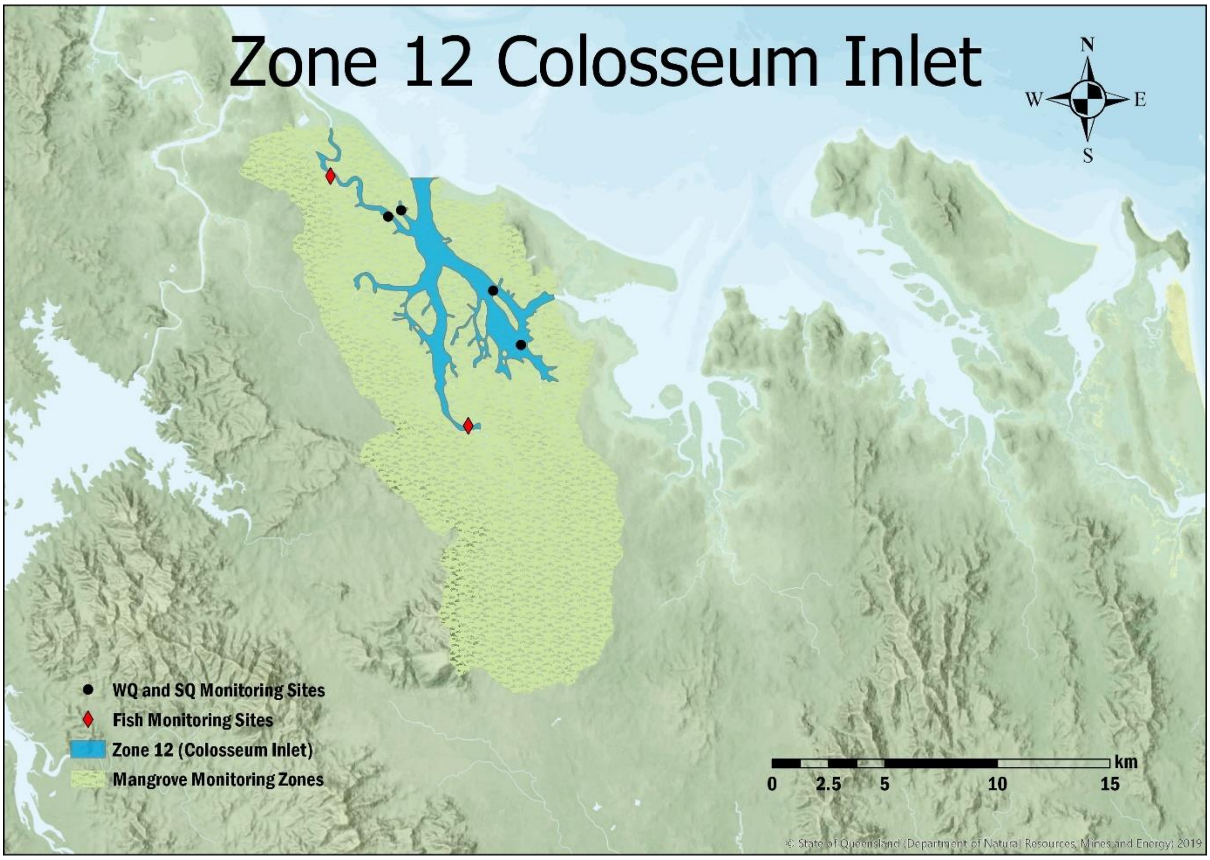


Figure A.45: Water and sediment quality sampling sites in Colosseum Inlet.

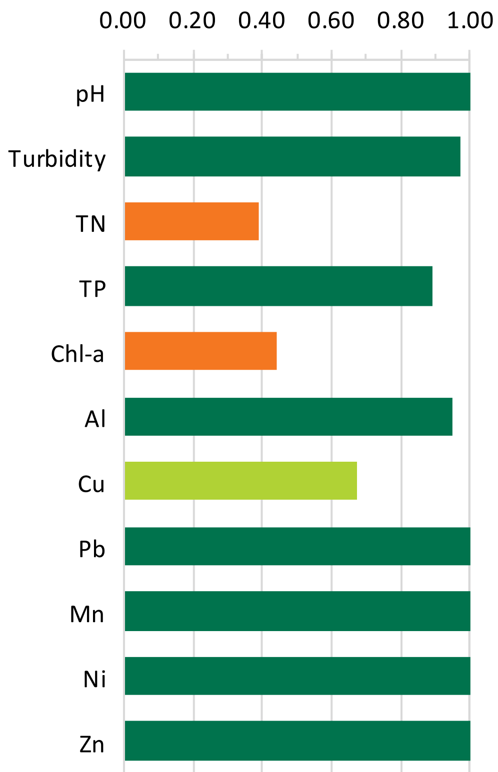


Figure A.47: 2018 Zone 12 measure scores.

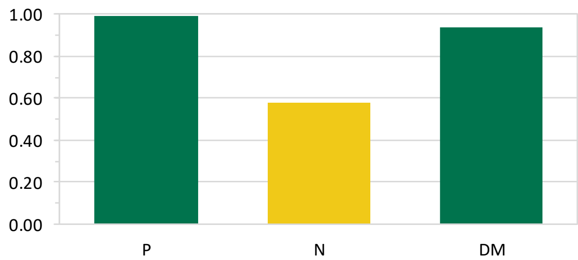


Figure A.46: 2018 Zone 12 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

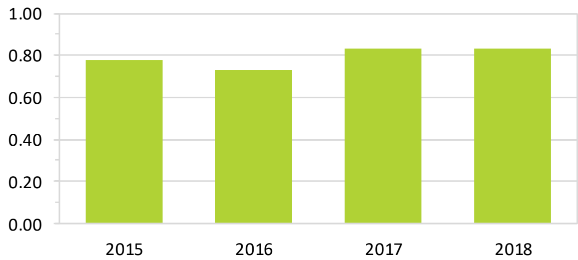


Figure A.48: Zone 12 overall water quality scores.

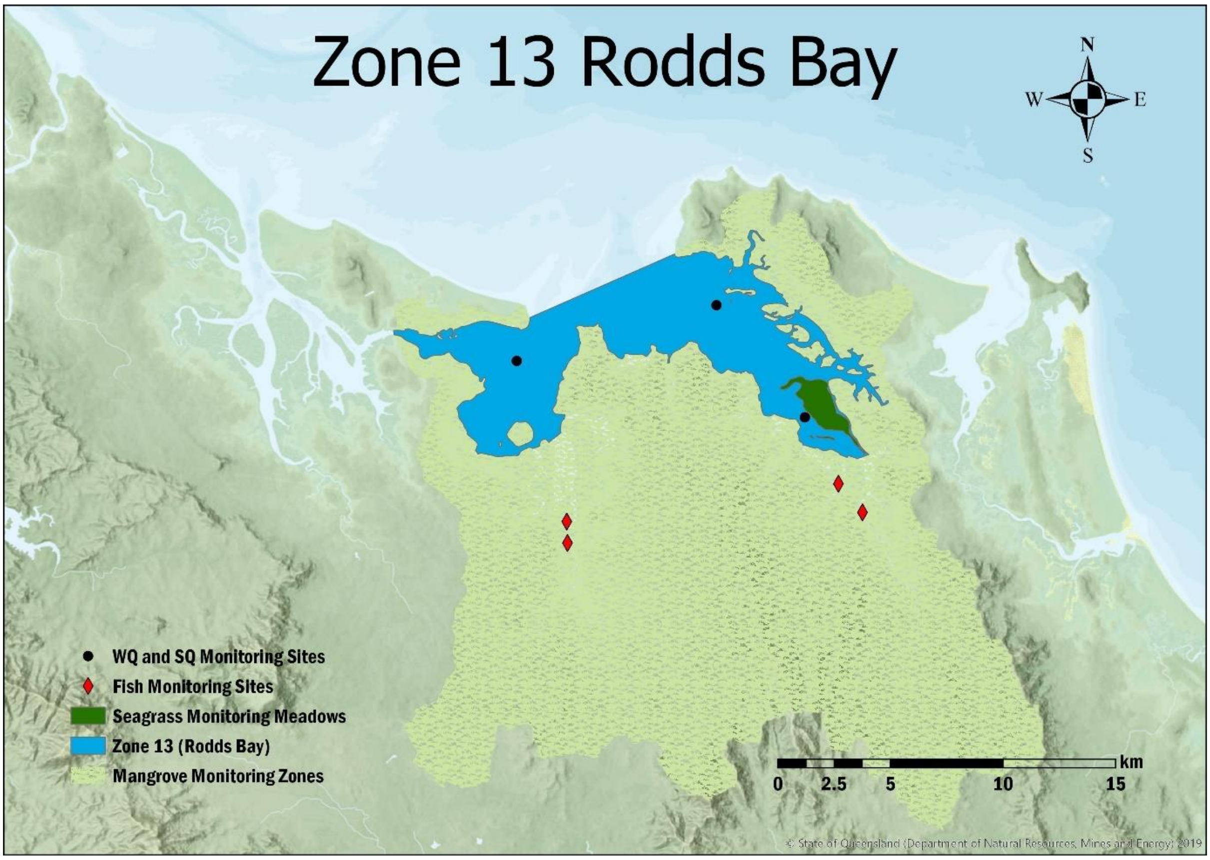


Figure A.49: Water and sediment quality sampling sites in The Narrows.

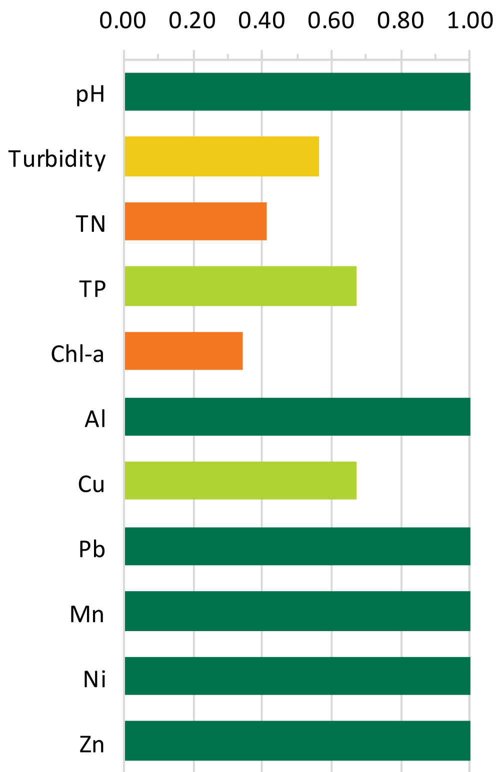


Figure A.51: 2018 Zone 13 measure scores.

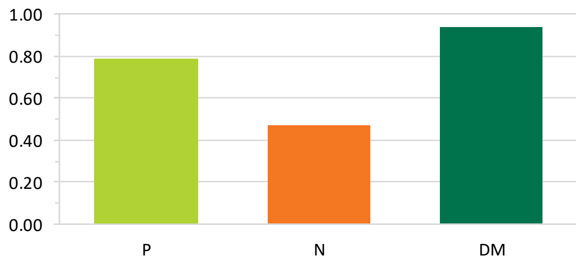


Figure A.50: 2018 Zone 13 sub-indicator scores for Physicochemical (P), Nutrients (N) and Dissolved Metals (DM).

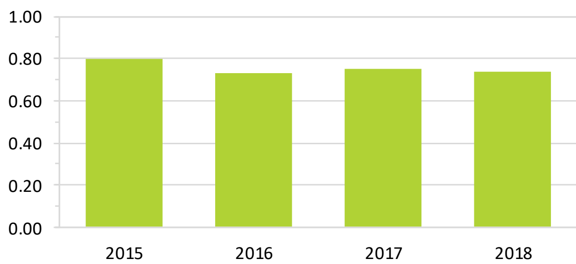


Figure A.52: Zone 13 overall water quality scores.