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Baseline water quality of the Gold Coast Broadwater, southern Moreton Bay (Australia)

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Abstract

This study establishes baseline water quality characteristics for the Gold Coast Broadwater, southern Moreton Bay (Australia) utilising routinely monitored parameters between 2016 and 2021, across 18 sites. Combined site mean concentrations of NO_x-N, NH_3-N and total nitrogen were 11.4 ± 33.4 µg/L, 12.7 ± 27.2 µg/L, and 169 ± 109 µg/L, respectively, while PO_4-P and total phosphorous were 7.30 ± 5.10 µg/L and 21.7 ± 14.1 µg/L. Additionally, total suspended solids and turbidity combined site means were 6.6 ± 6.0 mg/L and 3.4 ± 2.9 NTU, respectively. During high rainfall periods nutrient concentrations increased by up to >200-, >150-, 15-, 12- and >12-fold for NO_x-N, NH_3-N, TN, PO_4-P and TP, respectively, compared to quiescent conditions. Furthermore, TSS and NTU values increased by up to 15- and 40-fold during periods of measured rainfall compared to quiescent conditions.

The Gold Coast Broadwater is a micro-tidal estuarine lagoon central to the Gold Coast City, which forms the southern part of the Ramsar internationally important wetland of Moreton Bay, Australia (Fig. 1). The Broadwater is protected from the Pacific Ocean by a barrier island system (North and South Stradbroke Islands), with tidal exchange occurring at the Gold Coast Seaway and Jumpinpin Bar entrances. Tides at these entrances are predominantly semi-diurnal characterised by an ebb dominance with ranges varying between 1–2 m (Mirfenderesk and Tomlinson, 2008).

The Broadwater is approximately 25 km in length (north–south) with depths ranging from exposed sand banks to deep channels (>8 m), with a large proportion of sediments predominantly composed of coarse quartz sands (Burton et al., 2005) and wetland and mangrove features within undeveloped areas. The ~64.0 km^2 catchment consists of a mix of rapidly expanding high-density urban features, forests, and cleared grazing and crop lands. The Nerang, Coomera, Pimpama and the Logan-Albert Rivers, in addition to several smaller creeks, drain the catchment with the run-off volume entering the Broadwater being of lesser magnitude than tidal inputs except during heavy rainfall (Moss and Cox, 1999). Additionally, under typical operating conditions, recycled water sourced from four sewage treatment plants is released during ebb tide conditions (based on predicted local tide times) from diffusers in the seaway in accordance with licence conditions, allowing the recycled water to be dispersed to the Pacific Ocean while limiting the amount returning into the Broadwater on the next flood tide (Stuart et al., 2009; Dunn et al., 2012a).

The region experiences regular summer storms, whilst tropical cyclones and east coast low pressure systems also influence the region by delivering high rainfall events. Mean annual rainfall for the region is 1284 mm with the greatest monthly mean rainfall occurring during the summer month of February (182.7 mm, BOM, 2021). Salinity and water temperature collected by Mirfenderesk and Tomlinson (2007) reflect a well flushed and dynamic system with no notable stratification during periods lacking rainfall. Under these quiescent conditions physicochemical parameters within the Broadwater are predominately tidally influenced (Dunn et al., 2003; 2012a; Moss and Cox, 1999).

The Broadwater has important biodiversity values, including populations of recreationally and commercially important fish and crustacean species, as well as sea turtles, dolphins, and dugongs. Seagrass meadows, saltmarshes, and mangroves provide vital feeding, spawning and nursery sites for species that live both in the Broadwater and in the adjoining offshore waters (Dunn et al., 2014). Furthermore, the Broadwater serves as an important migratory bird staging region that has led to areas being recognised under the Ramsar Wetlands Convention, in addition to Chinese-Australia (1974) and Japan-Australia (1986) Migratory Bird Agreements. Owing to high ecological, economic and cultural importance, in addition to community values, the Gold Coast Broadwater has been the focus of varying scientific and monitoring efforts concentrating on: bottom sediments (e.g. Burton et al., 2005; Dunn et al., 2007a; 2012b; Eyre et al., 2011), hydrological conditions (e.g. Mirfenderesk and Tomlinson, 2007; 2008; Davies et al., 2009), water quality (e.g. Moss and Cox, 1999; Dunn et al., 2007b; Waltham et al., 2014), biological-chemical indicators (e.g. Melville and Connolly, 2003; Kaminski et al., 2018), and microplastics (Sucharitakul et al., 2021).

Due to continued population growth within the catchment, the Broadwater will experience further capital urban expansion and essential infrastructure upgrades, which will require management in a way that supports growth whilst ensuring legislative and environmental obligations are met. The objective of this study was to establish system-wide baseline information on water quality parameters of the Gold Coast Broadwater over an extended period (2016–2021), thus enabling a means of evaluating any future changes against established baseline conditions.

The study included measurement of 14 parameters at 18 sample sites within the Gold Coast Broadwater (Fig. 1 and Table 1) between January 2016 and June 2021. Site locations were selected in order to capture influences of the Nerang River, Coomera River and Pimpama River catchments and selected smaller creeks, in addition to sites nearby entry points for oceanic exchange, and areas characterised by varying foreshore developments, to reflect differences in land and waterbody uses on water quality (Table 1). Parameters were measured at all sites fortnightly from 2016 to 2019 and then monthly from 2019 to 2021 (Table 1). Receiving catchment sites (Fig. 1 and Table 1) were sampled during the bottom of the ebb tide phase, whilst all remaining sites were sampled during the flood tide. All in situ monitoring of temperature, pH, dissolved oxygen and salinity was performed using a multi-parameter meter (ProDSS; YSI), calibrated <24 h prior to each sampling event, and sample collection for dissolved inorganic (NO_x-N, NH_3-N and PO_4-P) and total (nitrogen (TN) phosphorous (TP)) nutrient concentrations, chlorophyll *a*, enterococci, total suspended solids (TSS) concentrations, and turbidity (Table 2) was completed from a small research vessel (< 7.0 m length) at ~0.3 m depth. All data underwent quality control measures, and any errant data were removed from the reporting datasets. Although urbanised estuarine waters have the potential to be impaired by additional contaminants not measured during this study (e.g., trace metals, hydrocarbons and pesticides), water quality parameters outside of those previously listed were not investigated as part of this study.

Sample collection was made using a pole sampler and 4 x 1 L high density polyethylene (HDPE) wide mouth containers (Nalgene, Rochester, NY, USA). Thereafter, subsamples were filtered through polyethersulfone (PES) 0.45 µm filter membranes (Sartorius Stedim Biotech GnBH, Lower Saxony, Germany) and transferred to 30 mL sterilized polystyrene centrifuge tubes for the determination of the dissolved nutrient concentrations or directly transferred to tubes for total nutrient concentrations.

All sample containers were maintained on ice in the dark before being transported from the field to the laboratory for treatment and analysis according to standard methods (Table 2). Nutrient concentrations were determined by flow injection analysis (Lachat QuikChem 8500, Hach Co. Loveland, CO, USA). To ensure adequacy and integrity of measurement quality, certified reference material samples (WatR™ Pollution Simple Nutrients cat#584, ERA a Waters Company, Golden, CO, USA) and in-house seawater controls were employed as part of the study. Mean recoveries of all nutrients from the seawater certified reference material ranged between 96.7 ± 9.34% and 102 ± 6.65%. The instrument detection limits ([blank analysis] standard deviation × 3) were 1.62 ug/L for NOx-N and NH_3-N, 2.14 ug/L for TN, and 1.62 ug/L and 0.73 ug/L for PO_4-P and TP, respectively. Samples for chl *a* were filtered through PES 0.45 µm membranes (Sartorius Stedim Biotech GnBH, Lower Saxony, Germany) immediately upon return to the laboratory. Membranes were then stored frozen in the dark until they could be processed and the chl *a* concentrations measured using a UV/Vis spectrophotometer (Cary-60, Agilent Technologies, Santa Clara, CA, USA) according to APHA (2005) method APHA 10200 H (Table 2). TSS samples were also filtered through pre-weighed PES 0.45 µm filter membranes (Sartorius Stedim Biotech GnBH, Lower Saxony, Germany), before membranes were dried at 103–105°C in an oven and then cooled in a desiccator before weighing (Table 2). Turbidity was determined in accordance with standard nephelometric methods APHA 2130 B (APHA, 2005; Model TL2360, Hach Co. Loveland, CO, USA). Enterococci concentrations were measured immediately upon arrival at the laboratory using the membrane filtration mEI agar method according to the membrane filtration mEI agar method - US EPA1600 (US EPA, 2006) and are reported as colony-forming units per 100 mL (cfu/100 mL). Transparency depth was determined using a Secchi disk as per standard methods described in Department of Environment and Science (2018). All limits of reporting (LOR) are presented in Table 2, replacement values for parameters below the LOR were made at half the LOR.

Descriptive statistics including combined site ‘system-wide’ means, standard deviation and percent relative standard deviation (% RSD), and box and whisker plots presenting 5th, 25th, 50th, 75th, 95th percentiles and mean values of the combined site 2016–2021 datasets are presented. In addition, time-series plots of the 2016–2021 datasets including coincident rainfall observations are presented.

Table 3 presents the combined site summary statistics for all parameters measured during 2016–2021 at all 18 sample sites. Water temperatures ranged between 14.0°C and 30.1°C with a combined site mean of 22.9 ± 3.4°C, while salinity within the Broadwater ranged between 5.10 and 36.0 with a combined site mean of 32.7 ± 4.40. Mean salinity remained relatively constant across sample sites (Table S1), with the exception of periods of rainfall driven run-off. During rainfall events, salinities were reduced in comparison to quiescent dry conditions. Seasonal means of water temperature and salinity ranged from 18.7°C (winter) to 26.4°C (summer) and 31.2 (summer) to 34.0 (winter; Table S2), respectively, reflecting the increased temperatures and rainfall during summer (December–February) and minimal temperatures and rainfall during winter (June–August) within the region. The influence of rainfall driven run-off was dependent on the intensity and duration of the rainfall event, and typically decreased from the catchment receiving sites towards the Seaway entrance. Combined site pH and DO typically remained constant, varying from 7.3 to 9.1 with a mean of 8.1 ± 0.1, and 44% saturation to >120% saturation with a mean of 97 ± 8.0% saturation, respectively (Table 3 and Fig. 2). Despite the different local settings and hydraulic patterns at each site, variabilities of temperature, salinity, pH and DO ranged between 1.2%RSD and 15%RSD (Table 3). Such system-wide variability is low compared to many estuaries, particularly embayments and deeper drowned river valleys (Dyer, 1997). Temperature exhibited the greatest variability due to seasonally-influenced changes (Table S2) and sample time, whilst pH exhibited the lowest degree of variability reflective of most riverine (~7-7.6) and ocean (~8.2) water values. Temperature, salinity, pH and DO values are consistent with previous Broadwater investigations (Dunn et al., 2003; Macklin et al., 2014).

Concentrations of NO_x-N, NH_3-N and TN ranged from their respective LOR values up to 540 µg/L, 371 µg/L and 1,500 µg/L, respectively, with combined site mean concentrations of 11.4 ± 33.4 µg/L, 12.7 ± 27.2 µg/L and 169 ± 109 µg/L (Table 3 and Fig. 2). Additionally, PO_4-P and TP concentrations ranged from their LORs up to 58.0 µg/L and 210 µg/L, respectively. Mean PO_4-P and TP concentrations across all sites were 7.30 ± 5.10 µg/L and 21.7 ± 14.1 µg/L (Table 3 and Fig. 2). Concentrations were typical of those previously reported for Australian estuarine settings and Moreton Bay waters (Abal and Dennison, 1996; Dunn et al., 2012a; Moss and Cox, 1999; Richards et al., 2014; Looman et al., 2019). The variability of NO_x-N, NH_3-N, TN, PO_4-P and TP concentrations across all sample sites was characterized by measures of 293, 214, 64.5, 69.9 and 65.0% RSD, respectively (Table 3). This was despite the physicochemical parameters, which have an influence on nutrient concentrations, being much less variable.

Sites closest to catchment outputs typically exhibited higher maximum nutrient concentrations than those closer to the Seaway (Table S1), illustrating the dominant influence of catchment related influences on maximum nutrient concentrations observed within the Broadwater. Rainfall derived run-off has been shown to increase nutrient loads to the Broadwater via inputs from river and smaller creek inputs (Moss and Cox, 1999; Waltham et al., 2014). Mixed urban residential and commercial developments, and agricultural practices within the catchments and foreshores act as both point and diffuse nutrient sources (Waltham et al., 2014), particularly during high rainfall events. Nutrient concentrations appear to be strongly influenced by rainfall run-off from catchment sources as evidenced by the patterns of elevated concentrations coinciding with high rainfall events (Fig. 3 and 4). Between January 2016 and June 2021 seven high rainfall events (> 100 mm in 24 hrs) occurred, including rainfall associated with an east coast low pressure system and an ex-tropical cyclone (Debbie). During these high rainfall periods nutrient concentrations increased by up to >200-, >150- and 15- fold for NO_x-N, NH_3-N and TN, respectively (Fig. 3), and 12- and >12-fold for PO_4-P and TP (Fig. 4), with respect to quiescent conditions immediately prior to the rainfall. Such increases align with Dunn et al. (2013) who observed nutrient concentrations 5–25-fold greater than those of dry periods in a Broadwater tributary following a rainfall event. Reflective of the increased rainfall events during the summer and the coincident increased nutrient concentrations during rainfall events, nutrient concentrations typically demonstrated the greatest seasonal mean concentrations during summer (Table S2; e.g. 18.0 µg/L NO_x-N, 205 µg/L TN, and 26.0 µg/L TP). Large episodic event driven diffuse dissolved inorganic nitrogen loads entering the Broadwater can increase benthic and pelagic productivity, which may modify trophic states and ecosystem dynamics (Meyer-Reil and Köster, 2000; Ferguson and Eyre, 2010).

Although increases in nutrient concentrations coincided with rainfall observations, the event-based increases were relatively short-lived owing to the hydrodynamic regime of the Broadwater and strong oceanic exchange (Mirfenderesk and Tomlinson, 2008; Dunn et al., 2012a). During quiescent periods, variations in nutrient concentrations were predominately tidally influenced (Moss and Cox, 1999; Dunn et al., 2012a). Though the rainfall events provided an opportunity to understand the magnitude of changes across a spectrum of conditions the relatively limited number of high rainfall instances during January 2016–June 2021 meant that such events had minimal influence on the 65-month combined site mean concentrations.

Chl *a* concentrations were also comparable with concentrations previously reported in southern Moreton Bay (Dunn et al., 2007c; Moss and Cox, 1999), ranging between 0.5 and 40 µg/L. The combined site mean of 2.1 ± 2.8 µg/L suggests a predominantly oligotrophic system (Tables 3 and S1). Limited instances of mesotrophic conditions (2–6 µg/L chl *a*, Håkanson and Bryhn, 2008) occurred based on the 95^{th} percentile concentration (Fig. 2). In addition, the variability of chl *a* concentrations was 133% RSD (Table 3). Concentrations of chl *a* tended to be elevated during the summer, with the greatest seasonal mean concentration observed during summer of 3.8 µg/L (Table S2), when air and water temperatures, and irradiance are maximal, whilst additionally coinciding with increased availability of nutrients during rainfall events. Temperature, salinity, and nutrients are all key influences on phytoplankton biomass (Cereja et al., 2021).

Enterococci concentrations exhibited the greatest degree of variability of all parameters with concentrations ranging from <1 up to 2000 CFU/100 mL, with an RSD of 541% (Table 3). The mean combined site enterococci concentration was 19.4 ± 105 CFU/100 mL, while the 95th percentile concentration did not exceed 90.0 CFU/100 mL (Fig. 2). Concentrations remained low and relatively constant across the Broadwater with the exception of the catchment recipient site of Loders Creek (Site 17) where the maximum concentrations were exclusively measured (Table S1). The creek has been modified to provide stormwater drainage relief with large sections consisting of concrete lined channels. Additional upstream features of the creek include urban and commercial developments, sporting and recreational parks, high density colonies of flying fox (*Pteropus* spp.) and roosting waterbirds, in addition to equine holding facilities, which may act as sources of enterococci (Garcia-Armisen and Servais, 2007). Mean seasonal enterococci concentrations ranged from 15 CFU/100 mL (summer and winter) to 29 CFU/100 mL (autumn).

TSS and turbidity varied from <2 mg/L to 67 mg/L and 0.2 to 40 NTU with combined site means of 6.6 ± 6.0 mg/L and 3.4 ± 2.9 NTU, respectively. Additionally, Secchi depth ranged between 0.2 m and 8.9 m with a combined site mean of 2.0 ± 1.2 m. Increases in TSS and turbidity throughout the Broadwater typically corresponded with periods of high rainfall (Fig. 5), due to the delivery of catchment-borne sediment and apparent increased pelagic productivity (phytoplankton), i.e. increased chl *a* concentrations, stimulated by the event-based nutrient inputs into the system. During rainfall run-off periods, elevated TSS and turbidity values typically occurred in the northern sample sites and trended to a reducing gradient towards the seaway in response to deposition and mixing influences. Similar to the influence of rainfall on nutrient concentrations, seasonal TSS and turbidity were greatest during periods of increased rainfall with summer mean concentrations of 8.4 mg/L and 4.3 NTU representing the maximum seasonal means throughout the study period, signifying increases of 100% and 87% from the winter mean to the summer mean, respectively (Table S2). Furthermore, the minimum and maximum seasonal mean Secchi disk depths were observed during summer and autumn (1.7 m) and winter (2.3 m), respectively. During high rainfall conditions, TSS and NTU values exhibited increases of up to 15- and 40-fold in comparison to prior quiescent conditions (Fig. 5), which is consistent with previous observations within a Broadwater tributary (Dunn et al., 2013). The delivery and deposition of sediments into the Broadwater increases turbidity and potentially impacts benthic and pelagic productivity (Ferguson and Eyre, 2010; Grinham et al., 2011). Insight into TSS and turbidity dynamics are important due to their critical roles in the function and health of estuaries, where they influence productivity, contaminant fluxes and fates, and light attenuation (Regnier and Wollast, 1993; Bilotta and Brazier, 2008).

This study investigated water quality parameters of the Gold Coast Broadwater, which is of particular interest due to its ecological, economic, and cultural importance coupled with continued urbanisation and population growth within the region. Using data collected fortnightly (2016–2019) then monthly (2019–2021) from 18 sites, between 2016 and 2021, this study establishes system-wide baseline information on water quality parameters of the Gold Coast Broadwater. The findings indicate parameter values within the estuary were typical of Australian estuarine settings and previously reported values for southern Moreton Bay, whilst also illustrating the influence of episodic rainfall driven run-off on water quality parameters. Continued monitoring of the Gold Coast Broadwater will be necessary to reliably identify future changes in water quality parameters associated with catchment development and climate-change induced influences. This study was undertaken to provide local authorities baseline data for detection and tracking of future changes in water quality parameters within the Gold Coast Broadwater. The findings of this research are important, particularly in light of increasing urban population growth, foreshore and catchment development, and the associated essential infrastructure upgrades and potential environmental changes. The findings of this study enable future comparisons of water quality parameters to assists future management decisions in this rapidly developing, yet ecologically and economically important waterbody.

CRediT authorship contribution statement

Ryan J.K. Dunn: Conceptualization, Investigation, Writing - Original Draft, Vizualization. Nicholas J.C. Doriean: Conceptualization, Data curation, Investigation, Methodology, Writing - review & editing, Vizualization. William W. Bennett: Conceptualization, Investigation, Supervision, Writing - review & editing. David T. Welsh: Investigation, Supervision, Writing - review & editing. Jemma Purandare: Conceptualization, Investigation, Writing - review & editing. Rodger B. Tomlinson: Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables

Table 1. Coordinates and descriptions of the sample sites

Site	*Location (GDA1994)*		*Sampled*	*Sampling frequency*	*Depth (LAT) (m)*	*Site description*
	Easting	*Northing*				
1	542479.6401	6928572.5480	2016-2019	Fortnightly	4.0	Adjacent vessel anchorage, mangrove area
			2019-2021	Monthly		
2	538176.2635	6926797.4310	2016-2019	Fortnightly	3.5	Kangaroo Island, mangrove area (receiving catchment site)
			2019-2021	Monthly		
3	538793.8642	6922763.2740	2016-2019	Fortnightly	1.0	Pimpama River entrance, mangrove area (receiving catchment site)
			2019-2021	Monthly		
4	538812.7834	6921468.6980	2016-2019	Fortnightly	1.5	Coomera River north entrance, mangrove area (receiving catchment site)
			2019-2021	Monthly		
5	539070.5091	6916946.6800	2016-2019	Fortnightly	3.0	Paradise Point, Coomera River, Saltwater and Coombabah Creeks entrance, adjacent commercial and residential developments (receiving catchment site)
			2019-2021	Monthly		
6	539903.1956	6911023.5920	2016-2019	Fortnightly	1.0	Biggera Creek entrance, adjacent marina facility and urban inputs (receiving catchment site)
			2019-2021	Monthly		
7	540460.3548	6917263.0790	2016-2019	Fortnightly	1.5	Sovereign Islands, waterfront residential development
			2019-2021	Monthly		
8	540573.9804	6914912.4310	2016-2019	Fortnightly	1.5	Adjacent recreational campground facilities
			2019-2021	Monthly		
9	540833.6042	6912634.8950	2016-2019	Fortnightly	5.0	Crab Island, adjacent recreational campground facilities
			2019-2021	Monthly		
10	540341.7323	6910893.5000	2016-2019	Fortnightly	3.0	Adjacent Carters Bank (shallow sand bank)
11	541185.5284	6910758.3180	2016-2019	Fortnightly	5.0	South Stradbroke Island, north of Wavebreak Island
			2019-2021	Monthly		
12	541396.0013	6910234.5340	2016-2019	Fortnightly	7.0	Wavebreak Island north site, nearby sewage treatment plant outlet diffusers
			2019-2021	Monthly		
13	541351.3980	6909387.0730	2016-2019	Fortnightly	6.0	Wavebreak Island south site
			2019-2021	Monthly		
14	541218.4523	6908406.2140	2016-2019	Fortnightly	3.5	Nearby Marine Stadium (vessel anchorage)

15	541419.2178	6907190.4900	2016-2019 2019-2021	Fortnightly Monthly	5.0	Adjacent commercial development
16	541551.7127	6905683.4570	2016-2019 2019-2021	Fortnightly Monthly	4.5	Adjacent Broadwater Parklands and Southport Yacht Club marina (receiving catchment site)
17	540366.7334	6907672.6460	2016-2019 2019-2021	Fortnightly Monthly	1.0	Loders Creek entrance, commercial and residential development, mixed urban inputs (receiving catchment site)
18	541248.3080	6904983.0480	2016-2019	Fortnightly	2.5	Nerang River entrance, adjacent commercial and residential developments, mixed urban inputs (receiving catchment site)

LAT = lowest astronomical tide

Table 2. Parameters and nutrient forms, abbreviations, analytical methods, references and limits of reporting

Parameter	***Abbreviation***	***Method***	***Reference***	***LOR***
Temperature		Thermister	Camuffo (2019)	
Salinity		Determination from measured temperature and conductivity		
pH		Glass bulb combination electrode Ag/AgCl	Zhou (2008)	
Dissolved oxygen saturation	DO	Optical luminescence	Tai et al (2011)	
Oxidised nitrogen (nitrite+nitrate)	NO_x-N	Cadmium reduction flow injection (APHA 4500-NO_3^- I)	APHA (2005)	6.00 µg/L
Ammonia nitrogen	NH_3-N	Phenate method flow injection (APHA 4500-NH_3 H)	APHA (2005)	5.00 µg/L
Total nitrogen	TN	Persulfate oxidation (APHA 4500-P J)	APHA (2005)	50.0 µg/L
Orthophosphate	PO_4-P	Flow injection (APHA 4500-P G)	APHA (2005)	3.00 µg/L
Total phosphate	TP	Persulfate oxidation (APHA 4500-P J)	APHA (2005)	5.00 µg/L
Chlorophyll *a* biomass	chl *a*	Spectrophotometric (APHA 10200 H)	APHA (2005)	1 µg/L
Enterococci		Membrane filtration mEI agar (US EPA1600)	US EPA (2006)	1 CFU/100 mL
Total suspended solids	TSS	Gravimetric (APHA 2540 D)	APHA (2005)	2 mg/L
Turbidity		Nephelometric (APHA 2130 B)	APHA (2005)	
Secchi depth transparency	Secchi depth	Visual recognition	DES (2018)	

LOR = limit of reporting.

Table 3. Combined site summary statistics for all water quality parameters measured during 2016–2021 within the 18 sample sites of the Gold Coast Broadwater

Parameter	***Unit***	***n***	***Minimum***	***Maximum***	***Mean***	***Median***	***SD***	***%RSD***
Temperature	°C	1775	14.0	30.1	22.9	23.0	3.4	15
Salinity		1022	5.10	36.0	32.7	34.0	4.40	13.4
pH		1777	7.3	9.1	8.1	8.1	0.1	1.2
DO	% sat.	1770	44	>120	97	98	8.0	8.2
NO_x-N	µg/L	1795	*3.00*	540	11.4	3.00	33.4	293
NH_3-N	µg/L	1777	*2.50*	371	12.7	3.00	27.2	214
TN	µg/L	1790	*25.0*	1,500	169	150	109	64.5
PO_4-P	µg/L	1795	*1.50*	58.0	7.30	7.00	5.10	69.9
TP	µg/L	1791	*2.50*	210	21.7	19.0	14.1	65.0
chl *a*	µg/L	1795	*0.5*	40	2.1	2.0	2.8	133
Enterococci	CFU/100 mL	1615	*0.50*	2,000	19.4	1.00	105	541
TSS	mg/L	1794	*1.0*	67	6.6	5.0	6.0	91
Turbidity	NTU	1794	0.2	40	3.4	2.6	2.9	85
Secchi depth	m	1608	0.2	8.9	2.0	1.6	1.2	60

n = number of analyses; SD = standard deviation; %RSD = % relative standard deviation; % sat. = % saturation; italicized values = one half LOR

Figure Captions

Figure 1. Map of (A) Australia, illustrating the location of (B) southern Moreton Bay and (C) sampling sites of the Gold Coast Broadwater.

Figure 2. Box and whiskers plots of combined site (A) temperature, (B) salinity, (C) pH, (D) dissolved oxygen, (E) NO_x-N, (F) NH_3-N, (G) TN, (H) PO_4-P, (I) TP, (J) chl *a*, (K) enterococci and (L) turbidity datasets (2016–2021). Lower and upper whiskers represent 5^{th} and 95^{th} percentiles, lower-, mid- and upper-box borders represent 25^{th}, 50^{th} and 75^{th} percentiles, respectively, and + represents the mean value.

Figure 3. Individual sample site and combined site sample mean (A) NO_x-N, (B) NH_3-N and (C) TN datasets (2016–2021), and coincident rainfall observations at the Gold Coast Seaway station.

Figure 4. Individual sample site and combined site sample mean (A) PO_4-P and (B) TP datasets (2016–2021), and coincident rainfall observations at the Gold Coast Seaway station.

Figure 5. Individual sample site and combined site sample mean (A) TSS, (B) turbidity and (C) Secchi depth datasets (2016–2021), and coincident rainfall observations at the Gold Coast Seaway station.

Figures

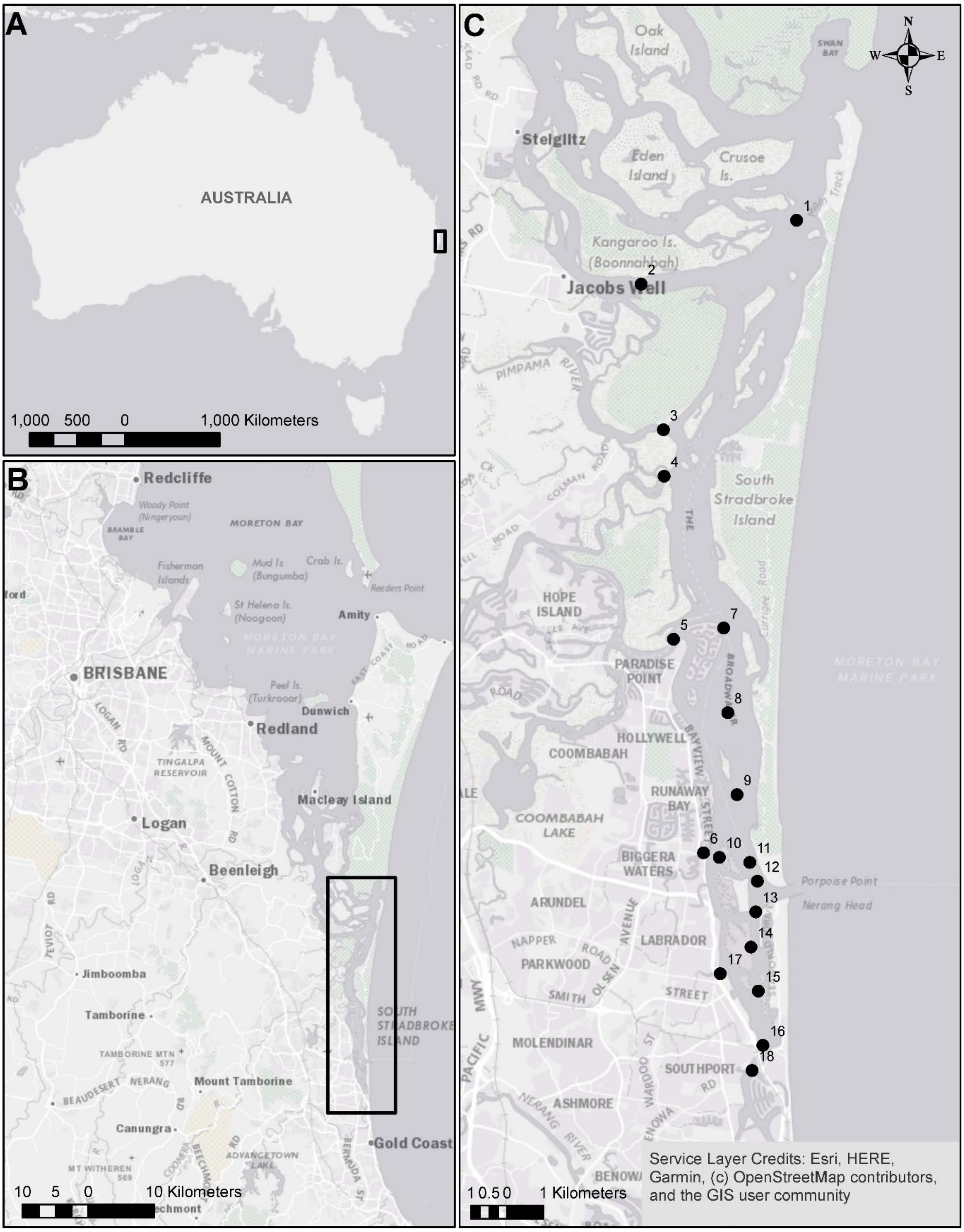
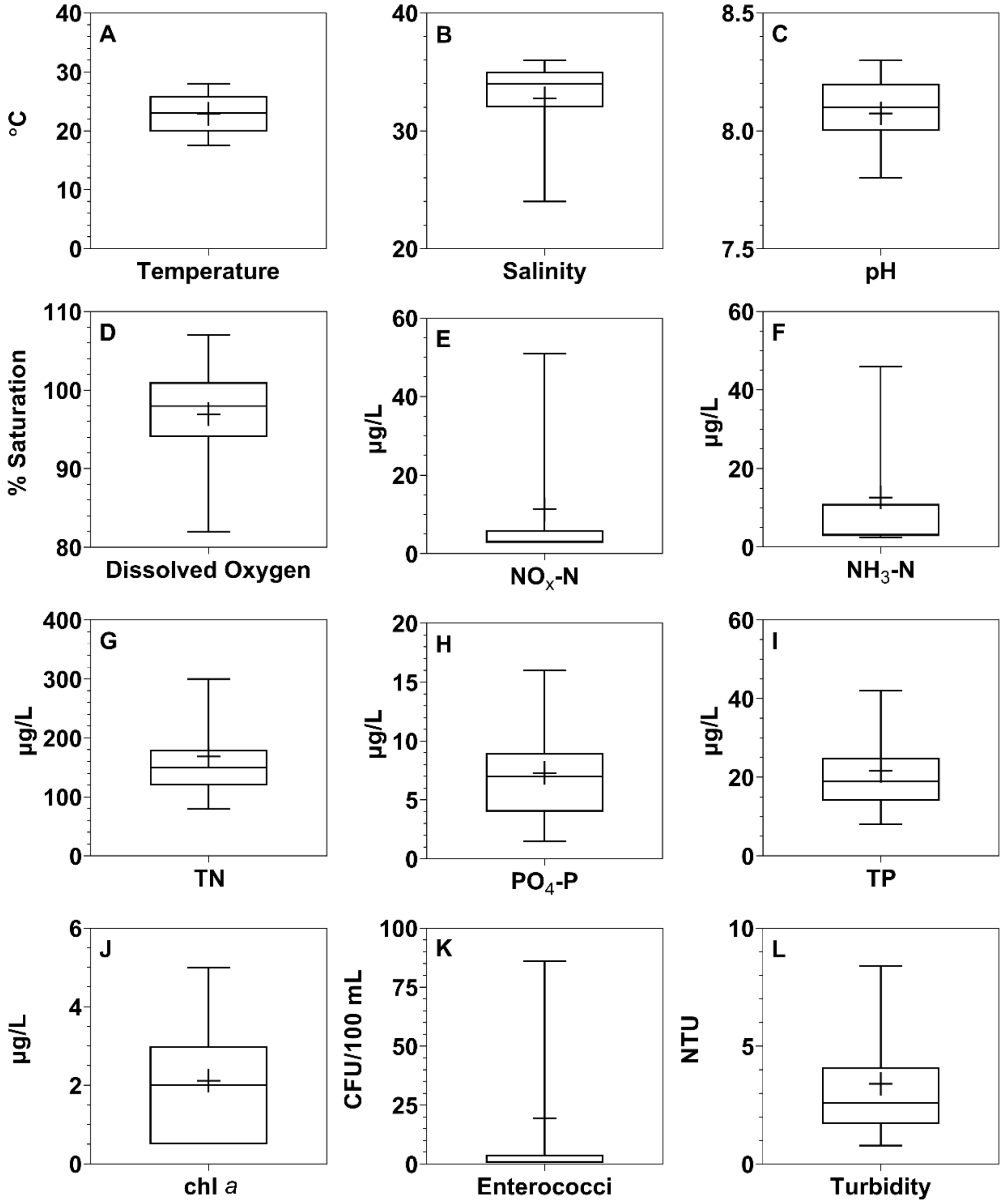


Figure 1.



A
°C
Temperature
B
Salinity
C
pH
D
% Saturation
Dissolved Oxygen
E
µg/L
NO_x-N
F
µg/L
NH_3-N
G
µg/L
TN
H
µg/L
PO_4-P
I
µg/L
TP
J
µg/L
chl *a*
K
CFU/100 mL
Enterococci
L
NTU
Turbidity

Figure 2.

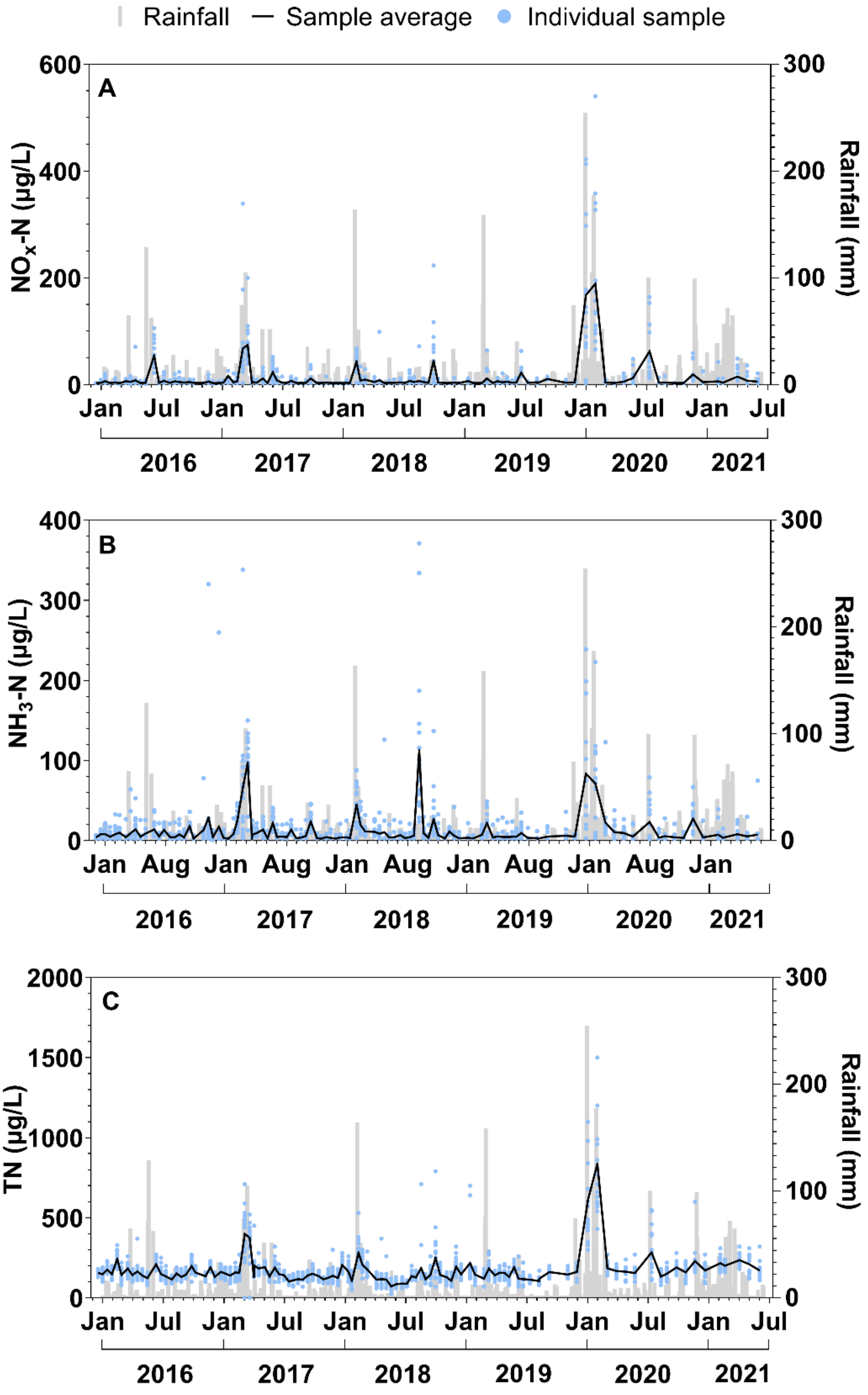

Rainfall
Sample average
Individual sample
A
NOx-N (µg/L)
Rainfall (mm)
B
NH3-N (µg/L)
Rainfall (mm)
C
TN (µg/L)
Rainfall (mm)
Jan
Jul
Aug
2016
2017
2018
2019
2020
2021

Figure 3.

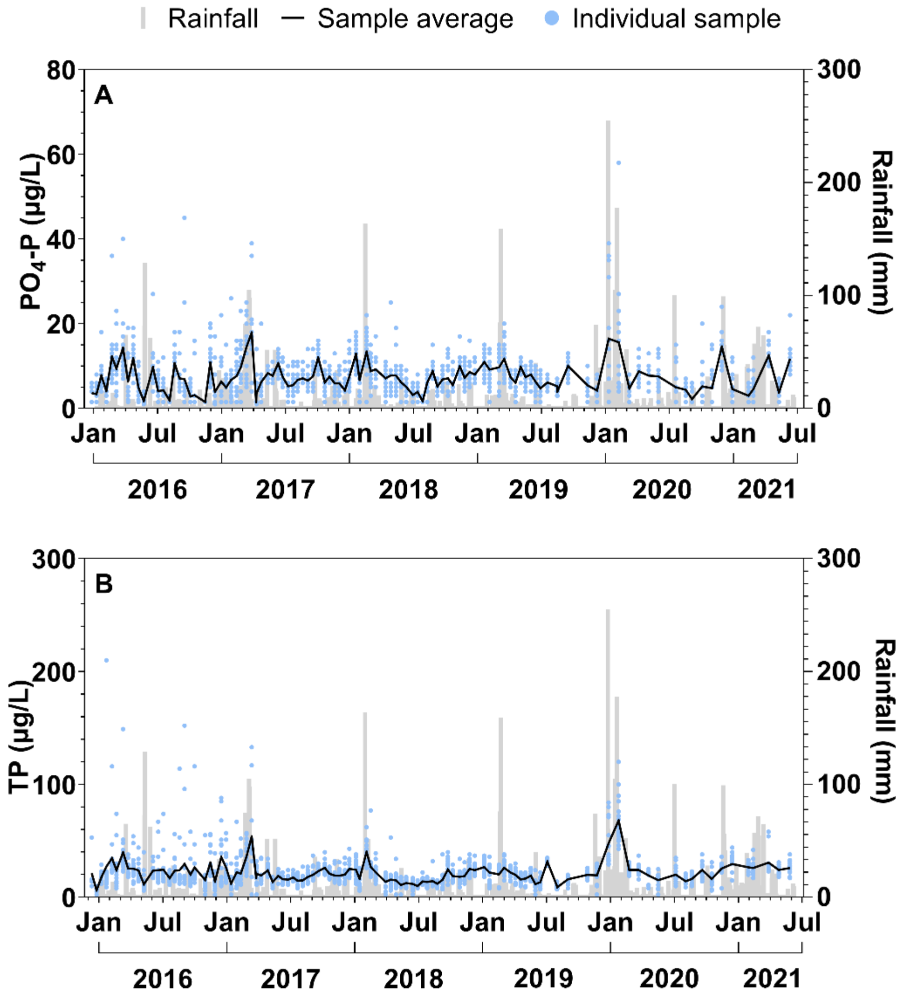

Rainfall
Sample average
Individual sample
A
PO_4-P (µg/L)
Rainfall (mm)
0
20
40
60
80
0
100
200
300
Jan
Jul
2016
2017
2018
2019
2020
2021
B
TP (µg/L)
Rainfall (mm)
0
100
200
300

Figure 4.

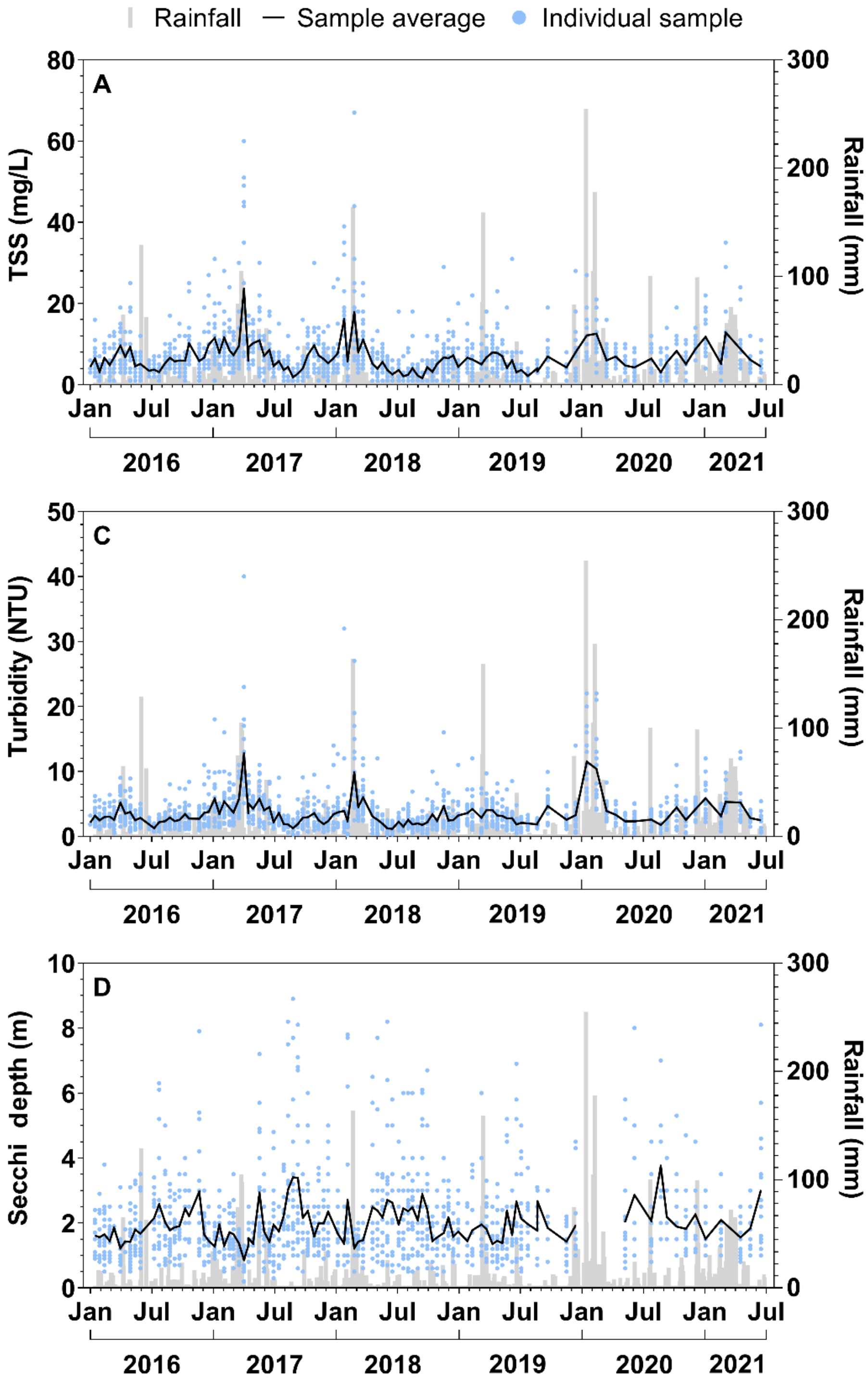

Rainfall
Sample average
Individual sample
A
TSS (mg/L)
Rainfall (mm)
C
Turbidity (NTU)
D
Secchi depth (m)
Jan Jul Jan Jul Jan Jul Jan Jul Jan Jul Jan Jul
2016 2017 2018 2019 2020 2021

Figure 5.

Supplementary Tables

Table S1. Site specific mean and maximum or minimum values measured during 2016–2021 within the Broadwater

Site		*Temp*	*Sal*	*pH*	*DO*	*NO_x-N*	*NH_3-N*	*TN*	*PO_4-P*	*TP*	*chl a*	*Enterococci*	*TSS*	*Turbidity*	*Secchi depth*	
		°C			*% sat.*			*µg/L*			*µg/L*	*CFU/ 100 mL*	*mg/L*	*NTU*	*m*	
1	Mean	22.4	34.1	8.12	99.5	10.0	10.0	158	7.00	23.0	2.4	1.41	9.4	4.9	Mean	1.0
	Max.	28.9	36.0	8.30	115	358	371	1,200	27.0	100	20	40.0	44	22	Min.	0.5
2	Mean	22.8	33.5	8.07	97.8	11.0	11.0	184	10.0	29.0	2.7	5.31	11	5.9	Mean	1.4
	Max.	29.5	36.0	8.30	109	540	334	1,500	58.0	210	10	120	39	21	Min.	0.5
3	Mean	22.6	31.7	7.91	88.4	19.0	21.0	228	8.00	24.0	2.5	5.61	8.8	4.7	Mean	1.5
	Max.	29.5	36.0	8.20	103	422	338	1,200	25.0	96.0	20	320	67	27	Min.	0.5
4	Mean	22.7	33.1	7.98	90.5	10.0	14.0	182	9.00	25.0	1.9	2.00	9.2	4.6	Mean	1.0
	Max.	29.3	36.0	8.30	119	175	135	860	40.0	149	30	15	28	14	Min.	0.3
5	Mean	22.9	31.6	8.01	94.4	14.0	15.0	187	8.00	23.0	2.5	4.20	7.4	4.0	Mean	1.7
	Max.	29.6	36.0	8.30	103	340	260	990	23.0	72.0	10	91.0	35	32	Min.	0.5
6	Mean	22.8	32.5	8.04	93.7	10.0	15.0	184	8.00	23.0	2.3	44.27	7.3	3.9	Mean	1.3
	Max.	29.3	36.0	8.30	113	171	126	600	36.0	74.0	10	440	31	17	Min.	0.5
7	Mean	23.2	32.3	8.16	97.2	12.0	11.0	182	8.00	23.0	3.0	4.74	7.8	4.2	Mean	1.7
	Max.	29.9	36.0	9.10	110	327	150	960	20.0	76.0	30	190	44	40	Min.	0.2
8	Mean	23.2	33.2	8.10	103	8.00	10.0	167	7.00	23.0	2.8	1.49	8.3	4.3	Mean	1.6
	Max.	30.1	36.0	8.50	134	195	320	770	22.0	88.0	40	22	45	15	Min.	0.5
9	Mean	22.9	33.6	8.12	101	8.00	7.00	152	6.00	20.0	2.5	1.25	5.7	3.1	Mean	2.1
	Max.	29.5	36.0	8.40	110	157	95.0	710	36.0	133	40	22.0	51	23	Min.	0.5
10	Mean	23.4	34.4	8.18	110	5.00	7.00	128	5.00	17.0	1.6	1.46	5.0	2.4	Mean	1.5
	Max.	28.8	36.0	8.80	180	61.0	86.0	330	15.0	85.0	8.0	17.0	24	12	Min.	0.6
11	Mean	22.8	33.9	8.14	100	9.00	7.00	141	6.00	18.0	2.5	1.47	5.1	2.6	Mean	2.8
	Max.	29.6	36.0	8.40	114	133	93.0	630	20.0	77.0	40	17.0	60	17	Min.	0.7

12	Mean	22.9	34.0	8.15	100	9.00	8.00	140	5.00	17.0	2.2	1.13	4.7	2.3	Mean	3.4
	Max.	29.6	36.0	8.40	111	136	88.0	600	16.0	68.0	30	16.0	49	13	Min.	0.6
13	Mean	22.9	33.7	8.16	101	10.0	9.00	138	5.00	16.0	2.3	1.47	3.6	1.8	Mean	3.7
	Max.	28.6	36.0	8.50	112	110	146	710	27.0	116	40	30.0	13	7.4	Min.	1.3
14	Mean	23.2	33.5	8.16	101	8.00	9.00	132	6.00	18.0	1.6	2.43	3.3	1.6	Mean	2.3
	Max.	28.9	36.0	8.40	114	65.0	95.0	510	39.0	117	10	38.0	15	9.1	Min.	0.5
15	Mean	22.7	32.1	7.97	97.6	13.0	13.0	154	6.00	18.0	1.9	16.1	4.0	1.9	Mean	2.0
	Max.	27.8	36.0	8.30	104	297	199	840	35.0	71.0	10	620	24	14	Min.	0.7
16	Mean	22.7	31.0	7.96	82.0	24.0	29.0	223	11.0	28.0	1.7	249	5.8	3.4	Mean	1.4
	Max.	28.5	35.0	8.30	99.0	413	123	1100	45.0	152	20	2,000	32	20	Min.	0.8
17	Mean	22.9	30.5	8.07	95.9	15.0	14.0	172	8.00	22.0	2.1	15.8	4.4	2.2	Mean	2.6
	Max.	28.9	36.0	8.40	103	319	184	980	39.0	84.0	10	180	12	16	Min.	1.0
18	Mean	23.0	31.5	8.05	96.6	10.0	14.0	162	8.00	21.0	1.9	11.4	4.6	2.0	Mean	2.4
	Max.	28.4	35.0	8.20	106	93.0	107	640	23.0	57.0	20	120	18	9.0	Min.	1.0

Max. = Maximum; Min. = Minimum

Table S2. Seasonal mean and maximum or minimum values measured during 2016–2021 within the Broadwater

Season		***Temp***	***Sal***	***pH***	***DO***	***NO_x-N***	***NH_3-N***	***TN***	***PO_4-P***	***TP***	***chl a***	***Enterococci***	***TSS***	***Turbidity***	***Secchi depth***	
		°C			***% sat.***			***µg/L***			***µg/L***	***CFU/ 100 mL***	***mg/L***	***NTU***	***m***	
Summer	Mean	26.4	31.2	8.05	96.4	18.0	14.0	205	8.00	26.0	3.8	15	8.4	4.3	Mean	1.7
(Dec–Feb)	Max.	28.4	36.0	9.10	134	339	338	710	40.0	149	10	2,000	60	40	Min.	0.2
Autumn	Mean	23.8	32.5	8.07	94.9	11.0	16.0	182	9.00	24.0	2.2	29	7.7	4.1	Mean	1.7
(Mar–May)	Max.	27.4	36.0	8.50	141	223	371	790	45.0	152	10	1,600	30	16	Min.	0.4
Winter	Mean	18.7	34.0	8.12	98.0	10.0	7.00	135	6.00	17.0	1.1	15	4.2	2.3	Mean	2.3
(Jun–Aug)	Max.	30.1	36.0	8.30	156	540	320	1,500	58.0	210	40	620	67	32	Min.	0.5
Spring	Mean	22.7	33.5	8.06	98.6	6.00	13.0	151	6.00	20.0	2.1	20	5.7	2.8	Mean	2.1
(Sep–Nov)	Max.	22.4	36.0	8.90	180	164	79.0	550	27.0	74.0	5.0	1,000	31	9.0	Min.	0.3

Max. = Maximum; Min. = Minimum