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## Short-Term Variability of Nutrients and Fecal Indicator Bacteria within the Gold Coast Seaway, Southern Moreton Bay (Australia)

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### ABSTRACT

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Significant urban development surrounding the Gold Coast Broadwater and upper catchment has resulted in concerns about degrading water quality of the estuarine system. The Gold Coast Seaway plays an important role in the exchange of estuarine and oceanic waters influencing the intertidal waters of the region. Water quality within the Gold Coast Seaway and the immediately adjacent Broadwater was investigated three times at three sample depths at 13 sample locations. Conductivity, temperature, and depth casts, total (nitrogen and phosphorus) and dissolved inorganic ( $\text{NO}_x$  and  $\text{NH}_4^+$ ) nutrients, and fecal indicator bacteria were measured at hourly intervals to compare the water quality under different tidal conditions at each location. Hydrological data were also collected. From these measurements, the intratidal variability of the Seaway waters was determined. Observed current velocities ranged from  $0.001$  to  $0.909 \text{ m s}^{-1}$  and  $0.018$  to  $1.8 \text{ m s}^{-1}$  during neap and spring tide periods, respectively. Physical parameters and nutrient concentrations demonstrated typical cyclic variations, with the influence of tidal and diurnal cycles apparent. Near minimum and maximum concentrations were generally observed at high and low water, respectively, indicating the influence of oceanic water during flood tides and catchment waters during ebb tides. Significant correlations were observed between surface water salinity values and total nitrogen and phosphorus concentrations. Fecal coliforms and *Enterococcus* spp. concentrations were low ( $<60$  colony-forming units per  $100 \text{ mL}^{-1}$ ), with no significant trends apparent between concentration and sample location, depth, or tidal phase.

**ADDITIONAL INDEX WORDS:** *Intratidal variability, water quality, hydrological conditions.*

### INTRODUCTION

Coastal environments are an important interface between land and the open ocean, providing habitats for numerous flora and fauna species, including migratory and indigenous birds and commercial and recreational fish (Stumpf and Haines, 1998). They also play a significant role in modifying the flow of matter and energy between terrestrial and open ocean environments (de la Paz, Gómez-Parra, and Forja, 2008), acting as a filter of contaminants and sediments and moder-

ating water quality (Faulkner, 2004), absorbing wave energy, and providing cultural and recreational benefits (Lee *et al.*, 2006). However, many coastal environments have been exposed to rapidly increasing human activities, ensuring ongoing impacts through changes in land use patterns. Coastal waters are the primary recipient of dissolved inorganic nutrients because of changes in land use patterns, including entry by point and diffuse sources of domestic and industrial waste and agricultural and urban drainage (Caraco and Cole, 1999; Downing *et al.*, 1999; Pereira-Filho *et al.*, 2001). Increased nutrient loadings potentially alter the trophic status, affecting dissolved oxygen concentrations (Parker and O'Reilly, 1991; Pennock, Sharp, and Schroeder, 1994), primary productivity (Nixon, 1982), species richness and abundance (Faulkner, 2004), and fishery yields (Cederwall and Elmgren, 1980).

Water quality sampling within dynamic coastal environments presents challenges from continual variations in freshwater inputs, tidal ranges, suspended sediment loads, and atmospheric conditions (Dittmar and Lara, 2001; Fettweis,

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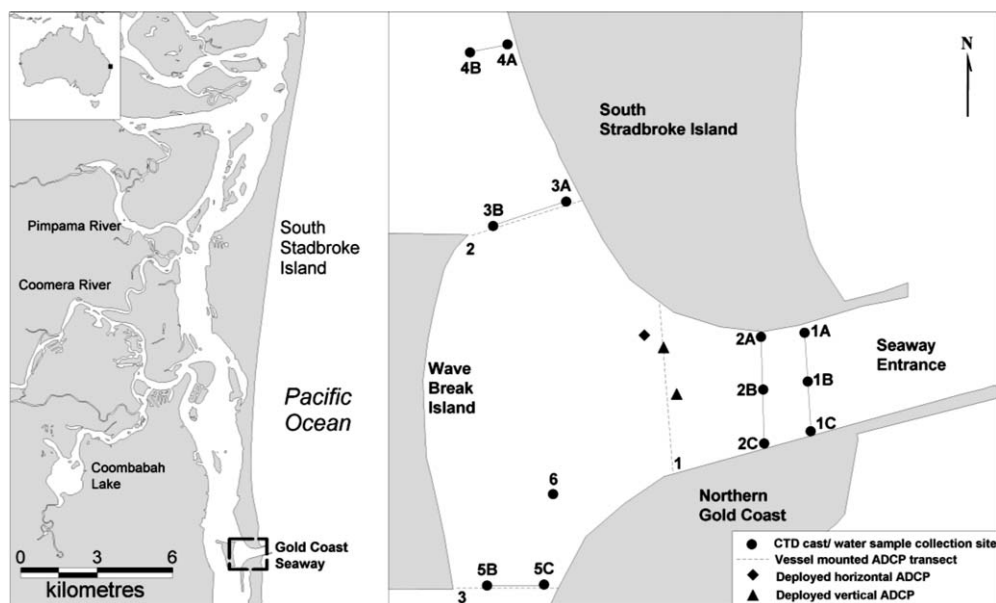


Figure 1. Sampling locations within the Gold Coast Seaway.

Sas, and Monbaliu, 1998; Hyun *et al.*, 1999). Equilibrium conditions are unlikely to be approached, and as a result, determining the variability of key analytes (*i.e.*, trace metals and nutrients) might be more important than determining mean concentrations (Kramer, Brockman, and Warwick, 1994). This often requires use of sophisticated sampling strategies not usually feasible within the time and budget constraints of ongoing monitoring programs undertaken by local authorities. Synoptic sampling, wherein samples are collected simultaneously from multiple sample sites, is regarded as the best sampling strategy within such environments. However, this strategy usually requires a sampling team for each site and is only therefore possible for a limited number of sites (Kramer, Brockman, and Warwick, 1994).

The Gold Coast city located in southern Moreton Bay, southeast Queensland (Australia), is one of the fastest growing regions in the developed world. As a consequence, the region has experienced large-scale urban expansion, including extensive canal and golf course developments along the 250 km of the region's intertidal waterways and upstream freshwater environments. Many of these waterways flow into the Gold Coast Broadwater, a shallow inshore area that is separated from the Pacific Ocean by two barrier islands (South and North Stradbroke Islands). Changes in land use in the catchment inevitably will contribute to an increase in the run-off of nutrient and sediment loads entering the Broadwater. The southern connection between the Broadwater and the Pacific Ocean is through a man-made navigation channel, the Gold Coast Seaway. The Seaway plays an important role in the ecological health of the intertidal waters of the region, because it influences the exchange of oceanic waters, sediments, organic matter, nutrients, and trace metals between the Broadwater and the Pacific Ocean (Mirfenderesk and Tomlinson, 2008).

As a consequence of the ecological significance and potential for anthropogenic disturbances, processes and mechanisms occurring within the intertidal regions of the Broadwater and Seaway have been the focus of previous scientific efforts (*e.g.*, Ali, Lemckert, and Dunn, 2010; Dunn *et al.*, 2007a; 2007b, 2007c, 2008; Knight *et al.*, 2008; Warnken, Dunn, and Teasdale, 2004). To date, most studies within the Seaway have concentrated on physical and hydrological processes (*e.g.*, Mirfenderesk and Tomlinson, 2007, 2008; Sennes *et al.*, 2007), and as a result, the understanding of biological and chemical dynamics of the Seaway is still limited.

The objective of this study was to provide a comprehensive first account of the intratidal variability of water quality parameters, total (phosphorous [TP] and nitrogen [TN]) and dissolved inorganic ( $\text{NO}_x$  and  $\text{NH}_4^+$ ) nutrient concentrations and fecal indicator bacteria (fecal coliforms and *Enterococcus* spp.) concentrations within the Gold Coast Seaway and adjacent Broadwater. The baseline data collected provides an initial understanding of the system's behavior that will assist future management decisions in this and similar ecologically and economically important urbanized coastal systems. Furthermore, this study provides a database for comparison with future studies within the fast-growing urbanized region.

## METHODOLOGY

### Site Description

This study was undertaken within the Gold Coast Seaway (Figure 1). The Seaway is a 250-m-wide, man-made navigation channel averaging 11 m in water depth, connecting the Gold Coast Broadwater system to the Pacific Ocean. The Broadwater is a typically shallow lagoon system characterized by exposed sandbanks, mangrove islands, and seagrass beds, with

Table 1. Summary of sample trips, measured parameters, and sample locations.

Sample Trip	Date	Measured Parameters	Sample Intervals (relative to initial daily high water period)	Sample Location and Sample Depth
1	10 Feb 09	Hydrological parameters; salinity, temperature, and depth; NO <sub>x</sub> , TN, and TP; fecal coliforms and <i>Enterococcus</i> spp.	-1, +1, +2, +3, +5, +7	13 sites (three depths per site)
2	23 Mar 09	Hydrological parameters; salinity, temperature, and depth	-1, +1, +2, +3, +5, +7, +9, +10	13 (three depths per site)
3	22 Apr 09	NO <sub>x</sub> , NH <sub>4</sub> <sup>+</sup> , TN, and TP; fecal coliforms and <i>Enterococcus</i> spp.		

extensive residential canal and commercial developments on the western shores and a mean tidal range of 1.5 m (Moss and Cox, 1999). Tidal flows through the Seaway into the Broadwater range from 10 to 40 × 10<sup>6</sup> L (Moss and Cox, 1999), resulting in a very strong flushing effect within the shallow Broadwater. A detailed description of the tidal regime and hydrological characters of the Seaway is presented by Sennes *et al.* (2007) and Mirfenderesk and Tomlinson (2008). Freshwater primarily enters the Broadwater via the Nerang, Coomera (north and south arms), and Pimpama Rivers, which is of lesser magnitude than tidal inputs, except after periods of heavy rain (Moss and Cox, 1999). The Nerang, Coomera, and Pimpama River estuaries are approximately 21, 17, and 4 km in length, respectively. Historically, the region is characterized by approximately 120 days of rainfall per year, with a mean annual rainfall of 1400 mm. Episodically, large inputs of fresh water occur during periods of heavy rainfall, predominantly during summer (December–February). The summer period is characterized by 37 days of rainfall, which accounts for 30% of the annual regional rainfall.

## Study Design

Physicochemical parameters were monitored and chemical and microbiological water samples were simultaneously collected at 13 sample locations along six transects within the Gold Coast Seaway (Figure 1) from four research vessels. Sample depths at each location included: surface (approximately 0.5 m from surface waters), middle (mid-water column depth), and bottom (~0.5–1 m from bottom sediments). Sampling was completed during summer (February) and autumn (March and April) 2009 (Table 1).

Conductivity, temperature, and depth (CTD) casts were conducted at each sample point during water sample collection. Water samples were collected for the determination of nutrient and microbiological parameters, at 1- or 2-hour intervals or at both times for typically 10 hours at all sample locations (Table 1). Each sampling event commenced immediately before morning high-water periods. Additionally, hydrological parameters were measured continuously between February and June 2009 with the use of stationary acoustic Doppler current profilers (ADCPs) and continuously during each sample event with vessel-mounted ADCPs.

Vessel-mounted depth sounders were used to determine water depth at time of sampling, allowing surface, middle, and bottom sample depth determination. Visual observations of the

water column characteristics were also recorded during each sample event.

## Water Sample Collection and Analysis

Water samples for the determination of TN, TP, NO<sub>x</sub> (ΣNO<sub>3</sub><sup>-</sup> + NO<sub>2</sub><sup>-</sup>), NH<sub>4</sub><sup>+</sup>, fecal coliforms, and *Enterococcus* spp. concentrations were collected with the use of a horizontal Van Dorn sampler. The contents of the sampler was transferred to an acid-washed (10% HCl) and water-rinsed (Milli-Q element water; 18 MΩ cm, Millipore Pty. Ltd.) container, from which 10-mL subsamples were collected for the determination of total nutrient concentrations. Subsamples were directly transferred by acid- and water-washed (10% HCl) and sample-rinsed 50-mL syringes into 10-mL sterilized polystyrene centrifuge tubes for the determination of TN and TP concentrations. Additional 10-mL subsamples were filtered through GF/F membranes (25 mm diameter, Whatman, Floram Park, New Jersey) and transferred into sterilized polystyrene centrifuge tubes with and without the addition of 200 μL of 2 M HCl for the determination of NH<sub>4</sub><sup>+</sup> and NO<sub>x</sub> concentrations, respectively. Additionally, 250 mL subsamples were collected and transferred to sterilized polystyrene screw-cap containers for the determination of fecal coliforms and *Enterococcus* spp. concentrations.

All water samples were immediately stored at <4 °C in the dark before being transported from the field. Nutrient samples were stored frozen (-20 °C within 4 h of collection) awaiting analysis. Biological samples were analyzed immediately on arrival to the laboratory (within 4 h of collection).

All inorganic nutrient concentrations were determined by an automated colorimetric nutrient analyzer (EasyChem Plus Random Access analyzer, Systea Analytical Technologies, Anagni, Italy) on the basis of standard colorimetric methodologies (APHA, AWWA, and WPCF, 2005). TN and TP samples were digested (potassium persulfate/sodium hydroxide; 2 × 45 min; 120 °C) before analysis. Limit of detection concentrations ([blank analysis] standard deviation × 3) were 2.01, 0.701, 0.133, and 0.229 μg L<sup>-1</sup> for TN, TP, NO<sub>x</sub>, and NH<sub>4</sub><sup>+</sup>, respectively.

Fecal coliform concentrations were determined according to a membrane filtration method (4276.5; Australian/New Zealand Standards, 2007). Similarly, *Enterococcus* spp. concentrations were also determined after sample filtration and incubation (method 9222-D; APHA, AWWA, and WPCF, 2005). Microbial results are reported as colony-forming units per 100 mL (cfu [100 mL]<sup>-1</sup>).

## Conductivity, Temperature, and Depth (CTD) Profiles

Vertical profiles were obtained with the use of weighted YSI (Letchworth, UK) 6600 multiparameter Sonde or RBR (Ottawa, Canada) XR CTD data loggers. Weights were added to each instrument to reduce horizontal drift. Casts were made at each sample site in parallel with the collection of the water samples at a rate of 1 m per 5 seconds for the first meter and 1 m per 3 seconds for the remaining depth. Instruments were configured to collect data at 2-second intervals. Conductivity data are reported as salinity. Data were converted to salinity by YSI EcoWatch (Version 3.18.00) and RBR Software (Version 6.05), respectively, applying the UNESCO practical salinity scale.

## Hydrodynamic and Atmospheric Conditions

Hydrodynamic data (current speed and direction) were measured with the use of stationary and vessel-mounted ADCPs. Current velocities were measured with a vessel-mounted ADCP (Sontek) along transects (Figure 1) during each sample day for typically 12 hours. Vertical velocity data were measured at 5-second intervals. Three stationary ADCPs were also intermittently deployed (Figure 1) from February to June 2009. A horizontally mounted ADCP (Sontek SL500) was attached to a channel marker (Figure 1) at a depth of approximately 4 m below the water surface placed in a direction of 212° (from north) from 25 February to 11 June. Velocity profiles were collected at intervals of 20 (25 February 2009 to 19 March 2009) and 10 minutes (19 March 2009 to 11 June 2009) for a sample period of 120 seconds. Seabed (vertically) mounted ADCPs (Sontek XR, San Diego, California, and Flowquest, San Diego, California) were configured to sample vertical velocity profiles for 6-minute and 10-second periods at 30-minute intervals during each deployment period. Data were averaged across the width and height of each cell. All instruments were deployed intermittently between 1 February and 11 June.

## Meteorological Measurements

Meteorological data were obtained from the Australian Bureau of Meteorology weather stations located at Hinze Dam (~20 km from the Seaway), at Coomera (~6 km from the Seaway), and immediately at the Gold Coast Seaway. Rainfall recorded at Hinze Dam and Coomera are representative of the Nerang and northern Gold Coast catchments, respectively.

## Statistical Analysis

Descriptive statistics, t test analyses, analysis of variance (ANOVA), and Pearson correlations were used to explore data sets and identify relationships between hydrodynamic conditions, physical variables, water column nutrients, and bacterial concentrations, respectively, with SPSS for Windows (version 11.5.0, SPSS Inc., Chicago, Illinois). A criteria of  $p < 0.05$  was used to determine statistical significance at the 0.05 level (two-tailed). In all instances, data did not require transformation. Descriptive statistics included the determination of the minimum, maximum, mean, standard deviation, and percent relative standard deviation (% *rsd*) of individual data sets.

Nutrient and microbiological concentrations were compared with the Broadwater subregion values within the Queensland Water Quality Guidelines (QWQG) (QEPA, 2006) and the Australian and New Zealand Environmental Conservation Council (ANZECC, 2000) Water Quality Guidelines.

## RESULTS AND DISCUSSION

### Meteorological Conditions and Visual Observations

No rainfall was recorded during any sampling trip; however, rainfall events in the surrounding catchments were recorded within a 7-day period before trips 1 and 2. Subsequently, all sampling was considered as a representation of “dry” conditions. Wind speed and direction varied between and during each sampling trip, with increased mean speeds occurring in the afternoon period (~30 km h<sup>-1</sup>). Air temperatures ranged between 18.2 and 31.4 °C at the Seaway. Water clarity decreased during periods coinciding with maximum wind speeds and flood tide periods. Consistent increases in turbidity at the Seaway during low water have previously been documented (Moss and Cox, 1999). During each sample trip, water clarity was greatest during periods of high water, particularly during the morning period when wind speeds were largely reduced. Alternatively, water clarity was greatly reduced either side of low water as a result of observed increased suspended particulate matter (SPM) loadings. This period coincided with increased wind speeds during the afternoon. The influence of propeller wash scouring surface sediments and acting as a source of suspended sediments (Beachler and Hill, 2003; Schoellhammer, 1996; Smart *et al.*, 1985) should not be discounted within the major navigational channel between the Gold Coast Broadwater and Pacific Ocean. The resuspension of sediments and increased SPM concentrations within coastal systems has been documented and affect the physical conditions of the system and the associated organisms within (Harvey and Caton, 2003; van Rijn, 1993). Periodic increases of sediment resuspension could represent a source of increased nutrient flux (Morin and Morse, 1999; Simon, 1989).

### Hydrodynamic Conditions

Observed current velocities ranged from 0.001 to 0.909 m s<sup>-1</sup> and 0.018 to 1.82 m s<sup>-1</sup> during the neap and spring tide periods, respectively. Maximum currents were recorded by the horizontally deployed ADCP (Figure 2). Measured current velocities were generally uniform throughout the water column with respect to depth and indicated a typically sustained reduction in magnitude at a distance of 41.5–51.5 m from the ADCP. This identified zone of reduced current speed is supported by data collected from the vertically mounted ADCPs (individual data not shown). Typically, tidal flow at tidal entrances is characterized by asymmetry, with higher peak current velocities and shorter durations of flow during flood tides (Braddock, Lee, and Tomlinson, 2000; Tomlinson 1990); however, no clear pattern of tidal asymmetry was observed during the monitoring period. Dominant flow directions during the flood and ebb tide periods ranged from 260° to 290° and 100° to 110°, respectively. At the southern ADCP, flow reversal during flood-to-ebb and ebb-to-

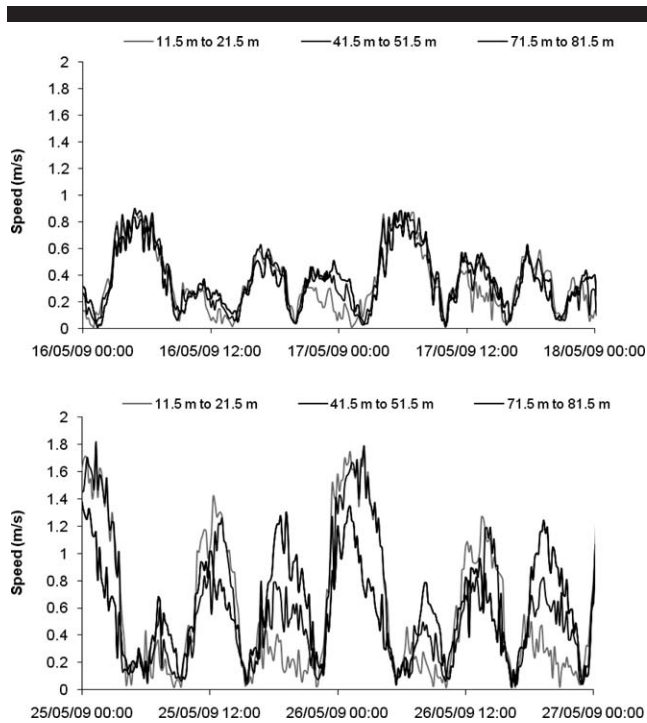


Figure 2. Snapshot of current speed measured at select distances from the horizontal ADCP during a neap tide period (top) and spring tide period (bottom).

flood tidal phase changes were identified typically to occur 1 h before the corresponding flow reversal observed at the northern vertically and horizontally deployed ADCP, presumably as a result of the identified zone of reduced current velocities occurring approximately 50 m from the northern seaway. Flow rates ranged approximately between  $-3800$  and  $4000 \text{ m}^3 \text{ s}^{-1}$  between ebb and flood tides, respectively. Maximum flow rates were observed during the flood tide period along the Seaway entrance (transect 1, Figure 1). Flow rates were significantly greater ( $p < 0.001$ ,  $\alpha = 0.05$ ) across the northern channel (transect 2,  $2183 \pm 1092 \text{ m}^3 \text{ s}^{-1}$ ) compared with the southern channel (transect 3,  $1534 \pm 746.0 \text{ m}^3 \text{ s}^{-1}$ ) supporting previous findings of Mirfenderesk and Tomlinson (2007). Seasonal variability of flow volumes with respect to the magnitude of mean flow is to be expected within the system. This current study does not take into account such seasonal events, including periods of heavy rainfall, in which case flow values would be expected to increase significantly.

### Physical Variables

Depth-averaged salinity and temperature values showed characteristic cyclic variations, with the influence of tidal and diurnal irradiance cycles apparent (Figure 3). Variability was characterized by % *rsd* measures of 3.98 and 6.21 for salinity and temperature, respectively. Salinity values ranged from 25.1 to 35.6 and were significantly greater ( $p < 0.001$ ,  $\alpha = 0.05$ ) during high-water periods ( $34.87 \pm 0.64$ ) coinciding with the increased flux of oceanic waters through the Seaway. The low water mean salinity value was  $33.54 \pm 1.33$ . Although no

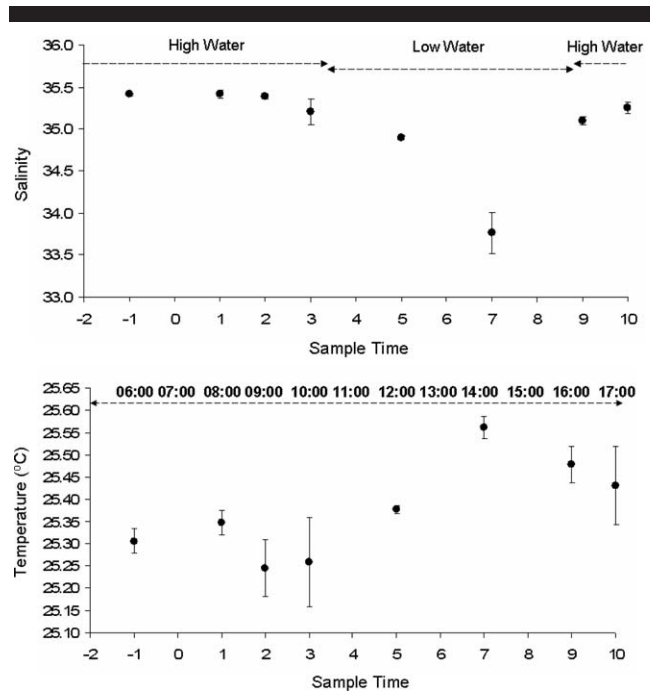


Figure 3. Depth-averaged time series plot of mean  $\pm$  standard deviation (a) salinity and (b) temperature values recorded at sample location 2B during sample trip 2 (sample time 0 indicates the initial high water period).

significant difference was observed between sample sites, surface water salinity values were typically lower at sites 1 and 2 during the ebb tide periods, presumably as a result of the release of recycled waters from diffusers situated along the northern seaway (Kirkpatrick and Hughes, 2009; Moss and Cox, 1999; Stuart *et al.*, 2009). The Coombabah waste water treatment plant releases excess recycled water from the northern Seaway wall through a diffuser system, which releases approximately 110 ML of recycled water per day (Stuart *et al.*, 2009). Under typical operating conditions, recycled water is released on the ebb tide (on the basis of predicted local tide times) at the Seaway entrance, allowing the recycled water to be dispersed to the Pacific Ocean while limiting the amount of excess recycled water returning into the Seaway (and Broadwater) on the next flood tide (Stuart *et al.*, 2009). In addition to spatial salinity profiles, depth salinity profiles also indicated no significant difference between sample depths, demonstrating a well-mixed semidiurnal tidal system. Water temperature varied according to water column depth and time of day, with temperatures ranging from 22.1 to 30.5 °C. Elevated water temperatures coincided with increases in air temperatures observed during the afternoon period (+7, +9, and +10 hour samplings), and maximum water temperatures typically decreased during the flood tide periods (Figure 3).

### Total and Dissolved Inorganic Nutrients

Combined sample trip depth-averaged percentile and mean concentrations for each transect are shown in Table 2. No significant differences were observed with changes in sample

Table 2. Combined sample depth-averaged nutrient concentrations for sample transect ( $\mu\text{g L}^{-1}$ ).

Site	Percentile			Mean	SD	% rsd
	20	50	80			
Total nitrogen (limit of detection = 2.01)						
1	173	254	383	280	125	44.8
2	206	315	450	338	150	44.4
3	208	296	473	337	142	42.0
4	237	339	505	362	152	42.0
5	211	284	425	316	122	38.7
6	313	389	462	370	88.8	24.0
	130	150	190	Broadwater subregional guideline values		
Total phosphate (limit of detection = 0.701)						
1	7.09	16.4	30.5	20.3	15.6	76.8
2	8.61	19.9	33.1	24.3	19.8	81.5
3	6.92	14.5	25.0	16.7	13.0	77.7
4	5.94	14.9	24.7	16.1	11.2	69.7
5	4.78	14.7	23.8	15.6	11.6	74.6
6	4.15	6.69	19.2	13.3	11.6	87.3
	14	17	22	Broadwater subregional guideline values		
Nitrite + nitrate (limit of detection = 0.133)						
1	4.30	9.28	16.7	13.5	16.4	121
2	4.17	9.27	18.7	16.2	24.9	154
3	4.20	8.09	12.0	8.31	4.73	57.3
4	3.73	8.44	12.5	10.0	10.3	102
5	4.64	8.87	12.9	10.9	11.7	108
6	2.81	8.74	11.2	8.25	4.95	59.9
	2	2	4	Broadwater subregional guideline values		
Ammonium (limit of detection = 0.229)						
1	3.98	10.0	17.9	11.3	7.53	66.7
2	5.28	10.3	17.4	11.5	7.75	67.2
3	5.04	10.6	15.9	11.6	7.34	63.5
4	6.10	11.5	17.7	12.2	6.90	56.5
5	6.81	12.0	18.7	12.9	6.90	53.5
6	4.05	8.36	11.1	12.6	8.81	69.9
	2	4	8	Broadwater subregional guideline values		

SD = standard deviation; % rsd = relative standard deviation.

location and water depth. Total nitrogen and phosphate concentrations ranged from 12.4 to 845  $\mu\text{g L}^{-1}$  and 0.743 to 110  $\mu\text{g L}^{-1}$ , with a mean concentration of  $326 \pm 141 \mu\text{g L}^{-1}$  and  $18.9 \pm 15.4 \mu\text{g L}^{-1}$ , respectively (Figure 4). Depth-averaged TN concentration exceeded the Broadwater QWQG concentrations (190  $\mu\text{g L}^{-1}$ ; Table 2). The 80th percentile TP concentrations exceeded the Broadwater QWQG concentration (22  $\mu\text{g L}^{-1}$ ). Mean Seaway  $\text{NO}_x$  concentration was  $12.2 \pm 16.3 \mu\text{g L}^{-1}$  and exceeded the Broadwater QWQG (4  $\mu\text{g L}^{-1}$ ). Ammonium concentrations ranged between 0.03 and 46.1  $\mu\text{g L}^{-1}$ , with a mean concentration of  $11.7 \pm 7.32 \mu\text{g L}^{-1}$ , which also exceeded the Broadwater QWQG values. The variability of TN, TP,  $\text{NO}_x$ , and  $\text{NH}_4^+$  concentrations across all sample sites was characterized by measures of 43.1, 81.6, 134, and 62.3% rsd, respectively. Nutrient concentrations were typical of concentrations reported in Australian and local coastal waters (Abal and Dennison, 1996; Cox and Moss, 1999; Dunn *et al.*, 2007a; Moss and Cox, 1999) and specifically compare well to concentrations previously reported within the Seaway during “dry” sample periods by Moss and Cox (1999).

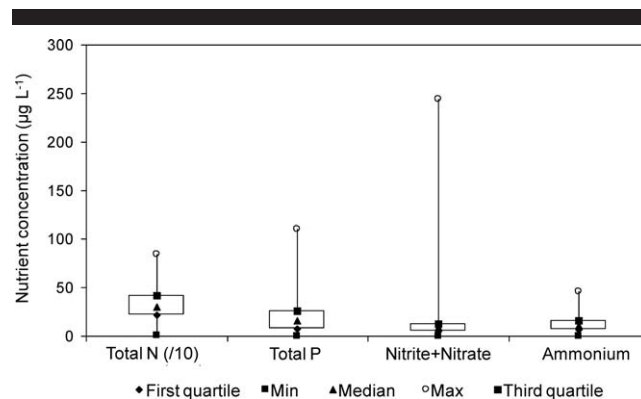


Figure 4. Combined mean total and dissolved inorganic nutrient concentration box plot representation.

Filterable and total dissolved inorganic nutrient concentrations demonstrated significant differences between sample times during sample trips ( $p < 0.05$ ,  $\alpha = 0.05$ ). Concentrations typically demonstrated a pattern with respect to the high and low tide phases with near minimum and maximum concentrations observed during high and low water, respectively (Figure 5). This pattern is presumably a result of mixing of the enclosed coastal waters of the Broadwater and the waters of the adjacent Pacific Ocean. Water quality in the Broadwater is influenced by flushing of oceanic waters during flood tides and by water quality in the two urbanized tributaries, the Nerang and Coomera Rivers, which provide nutrient sources and freshwater inflow into the Broadwater during ebb tides. Rainfall events have been shown to increase the influx of trace metals, nutrients, and suspended sediment concentrations into intertidal waters connected to the Broadwater (Dunn *et al.*, 2007c; Teasdale *et al.*, 2009; Tomlinson *et al.*, 2005, 2006).

Additionally, elevated nutrient concentrations appeared to coincide with observed periods of increased SPM, which have previously been shown to constitute a source of nutrients (Gao, Li, and Ding, 2008; Rocha, Cabeçadas, and Brogueira, 1995; Valdes and Real, 1998). The pattern of nutrient concentrations in the Broadwater and ocean could be expected to be altered by

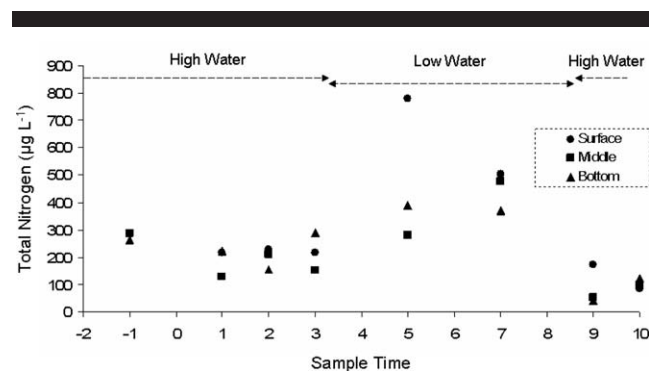


Figure 5. Time series plot of mean  $\pm$  standard deviation total nitrogen concentration for surface, middle, and bottom waters recorded at sample location 2B during sample trip 2 (sample time 0 indicates the initial high water period).

the release of recycled water at the Seaway (Moss and Cox, 1999). If the release of recycled waters significantly increased nutrient concentrations during the release period (ebb tides), this would be expected in the vicinity of the release plume (sites 2A, 1A). However, significant increases in concentrations were not consistent within the expected plume vicinity during release for each sampling trip. Furthermore, during the release phase, waters from the upper tributaries are being exported from the Broadwater, making the assessment of the relative contributions of catchment inputs and nutrients sourced from the released recycled waters difficult.

This study does not aim to quantify the influence of surrounding catchments or the release of recycled water within the Seaway but, rather, acknowledge their potential influence on the observed variability within the system. Investigations relating to the capacity of the Broadwater to assimilate a greater quantity of recycled water and the optimization of the release system have previously been undertaken (Rasch, Davies, and Chiffings 2007; Stuart *et al.*, 2009).

Earlier comparisons of water quality within the Seaway suggest that run-off from the Nerang River catchment entering the Broadwater during rainfall events has a greater effect on nutrient concentrations than the release of recycled waters within the Seaway (Moss and Cox, 1999). Teasdale *et al.* (2009) demonstrated that rainfall (>65 mm over 24 h) had a significant influence on nutrient (total dissolved nitrogen, NO<sub>x</sub>, NH<sub>4</sub><sup>+</sup>, total dissolved phosphorous, and PO<sub>4</sub><sup>3-</sup>) concentrations in the Saltwater Creek estuary within the Broadwater, increasing concentrations by up to >500% compared with dry periods.

During this study, significant correlations were observed between surface water salinity values and TN ( $r = -0.325$ ,  $p < 0.001$ ,  $\alpha = 0.05$ ) and TP ( $r = -0.364$ ,  $p < 0.001$ ,  $\alpha = 0.05$ ) concentrations during sampling performed during “dry” conditions.

Nutrient data collected provides a snapshot of the conditions throughout the sampling period and does not necessarily reflect the long-term trends in water quality or conditions during rainfall periods that were not encountered during the study. During heavy rainfall events, industrial and commercial developments, waterfront housing, and impervious surfaces within the catchment and foreshores act as point and diffuse nutrient sources. Elevated TN and TP concentrations during low water also coincided with observed increased suspended sediment loads within the sampled waters.

### Fecal Indicator Bacteria

Concentrations of fecal indicator bacteria were relatively low and ranged from 0 to 52 cfu (100 mL)<sup>-1</sup> for fecal coliform and 0 to 58 cfu (100 mL)<sup>-1</sup> for *Enterococcus* spp. (Table 3). Mean fecal coliform and *Enterococcus* spp. concentrations were all well below water quality guideline values of 150 cfu (100 mL)<sup>-1</sup> and 35 cfu (100 mL)<sup>-1</sup>, respectively (ANZECC, 2000). No significant difference was observed between sample locations or sample depths, with variability ranging from 71 to 136% rsd and 71 to 203% rsd for fecal coliforms and *Enterococcus* spp., respectively. No trends were apparent with respect to concentration and sample time during each sample trip. Furthermore, no

Table 3. Combined depth-averaged microbiological concentrations for each sample transect from sample trips 1, 2, and 3.

Site	Minimum	Maximum	Mean	SD	% rsd
Fecal coliforms (cfu [100 mL] <sup>-1</sup> )					
1	0.0	52	7.2	9.8	136
2	0.0	45	9.1	8.9	98.1
3	1.0	23	5.0	4.1	80.3
4	0.0	36	5.3	5.6	104
5	0.0	46	10	9.8	97.0
6	0.0	12	5.2	3.7	71.2
<i>Enterococci</i> spp. (cfu [100 mL] <sup>-1</sup> )					
1	0.0	58	3.4	6.9	203
2	0.0	36	3.1	4.6	149
3	0.0	7	2.3	1.7	71.0
4	0.0	10	2.2	1.8	82.9
5	0.0	32	4.1	5.4	130
6	0.0	14	3.5	4.5	128

SD = standard deviation; % rsd = relative standard deviation.

significant correlation was observed between microbiological concentrations and salinity. No significant trends were observed between microbiological concentrations and the release of recycled water during ebb tide cycles within the Seaway.

### CONCLUSION

The results of this study illustrate the dynamic and well-mixed environment of the Seaway channel and adjacent Broadwater. The Broadwater was strongly influenced by tidal flow during the sample period, with maximum flow velocities recorded of 1.82 m s<sup>-1</sup>. The Broadwater also exhibits the typical characteristics of a shallow estuary, including a phase lag between the tide level and the flow reversal. Salinity, temperature, and depth data collected over the sampling period also reflected a well-mixed, dynamic system, with no notable stratification within the Seaway channel. Physical parameters and nutrient concentrations within the Seaway typically demonstrated cyclic variations, with the influence of tidal and diurnal irradiance cycles apparent. No trends were observed relative to fecal indicator bacteria concentrations within the Seaway during the study. Parameter variability ranged from 3.98 to 203% rsd, with salinity and *Enterococcus* spp. concentrations characterized by the smallest and largest intratidal variability, respectively. Mean total and dissolved inorganic nutrient concentrations typically demonstrated an increasing pattern with respect to the high and low tide phases, with near minimum and maximum concentrations observed during high and low water, respectively. Nutrient concentrations exceeded Broadwater QWQG values. Fecal coliforms and *Enterococcus* spp. concentrations were low, with no significant trends apparent between concentration and sample location, depth, or tidal phase.

This study provides the first comprehensive account of the intratidal variability of water quality parameters, total and dissolved inorganic nutrient concentrations, and fecal indicator bacteria concentrations within the sampled waters. Data collected during this study provide a snapshot of the conditions throughout the sampling period but do not necessarily reflect the long-term trends in water quality or conditions during



heavy rainfall periods, which were not encountered during the study. Future assessments of riverine influences are required to provide an understanding of intertidal and event-specific variations of the physicochemical and biogeochemical processes in the ecologically significant region of the Gold Coast Seaway, which is an important link between the Gold Coast Broadwater and the Pacific Ocean.

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