

Spatial and temporal variation in CDOM and trace elements in eastern Australian ports

**Implications for verifying ballast water exchange by
ships**

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1. Abstract

Prior to discharging ballast water in New Zealand, ships carrying overseas ballast are legally required to conduct mid-ocean ballast water exchange (BWE) in order to mitigate the spread of non-indigenous aquatic species. It has been proposed to verify that BWE was performed by measuring the concentrations of certain chemical tracers in ballast tanks, which should trace the removal of coastal water. Using three Australian ports as case studies (Port Botany, Port Curtis, and Port Phillip Bay), the spatial and temporal variability of chromophoric dissolved organic matter (CDOM) and three trace elements (Mn, Ba, and P), were measured to assess their utility as tracers of coastal (unexchanged) ballast water. In general, tracers showed greater spatial variation between and within ports, rather than temporal variation between seasons. CDOM fluorescence at $\lambda_{\text{ex}}/\lambda_{\text{em}} = 320/414$ nm (C2*) and 370/494 nm (C3*) and Mn concentrations were significantly higher in ports than in the adjacent Tasman Sea, except near port entrances and at a few sites in Port Botany. Barium concentrations were least useful as tracers of coastal sources, whereas elevated P easily discriminated water collected in Port Phillip Bay. The recommended approach for BWE verification of ballast water from eastern Australian ports involves two steps. The first is to test ballast water for salinity within the range 30 – 38, since salinities outside this range are incompatible with an oceanic source. The second is to test that CDOM concentrations significantly exceed the range of ocean concentrations. Both tests could potentially be performed using in situ instrumentation, allowing an instantaneous determination of compliance, however, regular intercalibration involving confirmatory laboratory tests would be essential.

Keywords: ballast water, CDOM, trace elements, biological invasions, ballast management

2. Introduction

The threat of marine biological invasions is now well recognized, resulting in international, national and local policies to reduce the risk of species transfer and their unwanted impacts (Ruiz et al. 2000, IMO 2004, MAF 2005, Minton et al. 2005, IMO 2006, MAF 2007). These include guidelines and regulations on the management of ships' ballast water.

The Import Health Standard for Ballast Water from All Countries promulgated under the New Zealand Biosecurity Act of 1993 requires that ships discharging ballast water from overseas perform mid-ocean ballast water exchange (BWE). Although alternative treatment is an option, and new treatment technologies are being actively developed world-wide, none are presently approved, and it appears that BWE will be used for years to come (Hunt et al. 2005). During BWE, the vessel replaces its original ballast water (taken on board while the vessel was in port or close to the coast) with water from the open ocean. Ballast exchange reduces the risk of species transfer in two ways: (1) replacing the majority of coastal organisms with oceanic species that are poorly adapted for survival in coastal environments (Minton et al. 2005), and in some cases (2) increasing the salinity level within the ballast tank to a level where many brackish- or fresh-water species cannot survive (Santagata et al. 2008). Currently there are no reliable methods for verifying BWE in vessels arriving to New Zealand or elsewhere. Salinity measurement can identify ballast water that originates from low salinity source ports, but many ports have high salinity water that is indistinguishable from the open-ocean. Thus, salinity does not provide an adequate indicator of BWE in ships carrying ballast water from high-salinity ports. This is particularly the case for many Australian ports, where the majority of ballast discharged in New Zealand is sourced and where salinities frequently exceed 34 psu (Veeh et al. 1995, Murphy et al. 2009, Doblin et al. submitted manuscript).

In 2005 – 2006, the Smithsonian Environmental Research Center investigated the utility of a suite of natural chemical tracers to verify ships' ballast water exchange between Australia and New Zealand (Murphy et al. 2009). That study included examination of the trace elements arsenic, barium, manganese, molybdenum, uranium and vanadium (As, Ba, Mn, Mo, P, U and V, respectively), chromophoric dissolved organic matter (CDOM) and radium isotopes (^{223}Ra and ^{224}Ra) inside ballast tanks and alongside ships as they travelled between Australia and New Zealand. Results were consistent with previous research showing that CDOM and barium concentrations were both reliable tracers of ballast exchange, behaving conservatively in ballast tanks and present in concentrations that decreased consistently with distance from shore (Murphy et al. 2004, Murphy et al. 2006, Murphy et al. 2008). Results for other trace elements were more variable; either (1) they were present in higher than expected concentrations following BWE than would be expected based upon conservative mixing (Mn), (2) they did not consistently show a decline in concentration after ballast water exchange (e.g. P, Mo, U, V), or (3) their concentrations did not vary predictably or sufficiently with distance from port (e.g. P, As, Mo, U, V) (Murphy et al. 2009). In the case of radium isotopes, sampling difficulties and time delays between sampling and analysis reduced the precision and accuracy of the results, and would make implementation of BWE verification using radium isotopes infeasible with current technology.

The goal of this study was to place the previous results into context by examining the spatial and temporal variation of a subset of ballast water verification tracers in several south-eastern Australian ports. Three ports in south-eastern Australia were selected for study: Port Curtis (Gladstone, QLD), Port Botany (NSW) and Port Phillip (encompassing the Port of Melbourne and Port of Geelong, Victoria). These ports were chosen on the basis that they are likely to be frequent sources of Australian ballast water being discharged in NZ, they encompass a wide geographic spread (latitude 23°, 34° and 38°S, respectively), and they vary considerably in

hydrological characteristics, representing a range of water residence time, freshwater inflows and seasonal runoff patterns.

In the case of Port Phillip, an additional concern was the high number of invasive species known to populate the Bay, many of which are believed to have been originally transported to the bay in ships' ballast (Murphy 1997, Campbell & Hewitt 1999). In 2005-6, over one fifth of the >700,000 tons of Australian ballast water discharged in New Zealand originated in Port Phillip Bay (MAF Biosecurity New Zealand Ballast Water Database, unpublished data). In recognition of the elevated biological risk associated with ballast water from this region, an annex to the mandatory BWE standards documented in the Import Health Standard for Ships' Ballast Water from All Countries (MAF 2005) prevents the issuance of BWE exemptions (granted on the basis of crew safety or vessel construction considerations) when the ballast water is derived from Port Phillip Bay.

The objectives of this study were threefold:

1. Characterise the spatial and temporal variation in chemical tracer concentrations in three south-eastern Australian ports;
2. Test whether chemical tracer concentrations in the ports are consistently different to those in the open-ocean, specifically in the Tasman Sea; and
3. Assess the extent to which chemical tracers could be used to verify BWE for ballast water sourced from each port.

3. Methods

Port surveys

The Port of Botany, Port Phillip Bay (including Ports of Melbourne and Geelong) and Port Curtis (Gladstone) were surveyed in 2007 and 2008, with the latter two ports visited in two different seasons. During each port survey, water was collected for analysis of CDOM and trace metals at 6 to 9 locations. Three sites were visited within each location (A, B, and C), encompassing a marine end-member collected near to the port entrance, sites near features such as shipping terminals, active berths and shipping channels, and an upstream location to represent the freshwater end-member. An overview of the surveys is provided in Table 1.

Table 1. Overview of Port Survey sampling events

Survey	Port	Vessel	Date	Season	No. Sites
NZ5	Port Botany	Clark Condor	18-Apr-07	Autumn	25
NZ6	Port Curtis	Mudskipper	21-Aug-07	Winter	9
NZ7	Port Phillip Bay	Pelagia / Platycat	24-Apr-07	Autumn	25
NZ8	Port Phillip Bay	Pelagia	25-Oct-07	Spring	25
NZ9	Port Curtis	Boomerang	03-Apr-08	Autumn	17

Botany Bay and Port Botany

Sampling of Botany Bay and Port Botany (survey NZ5) was conducted in autumn on April 18-19, 2007. Water samples were collected at twenty four sites throughout Botany Bay (Figure 1). Much of the southern boundary of Botany Bay was impossible to sample by boat due to shallowness, mangroves or abandoned oyster leases.

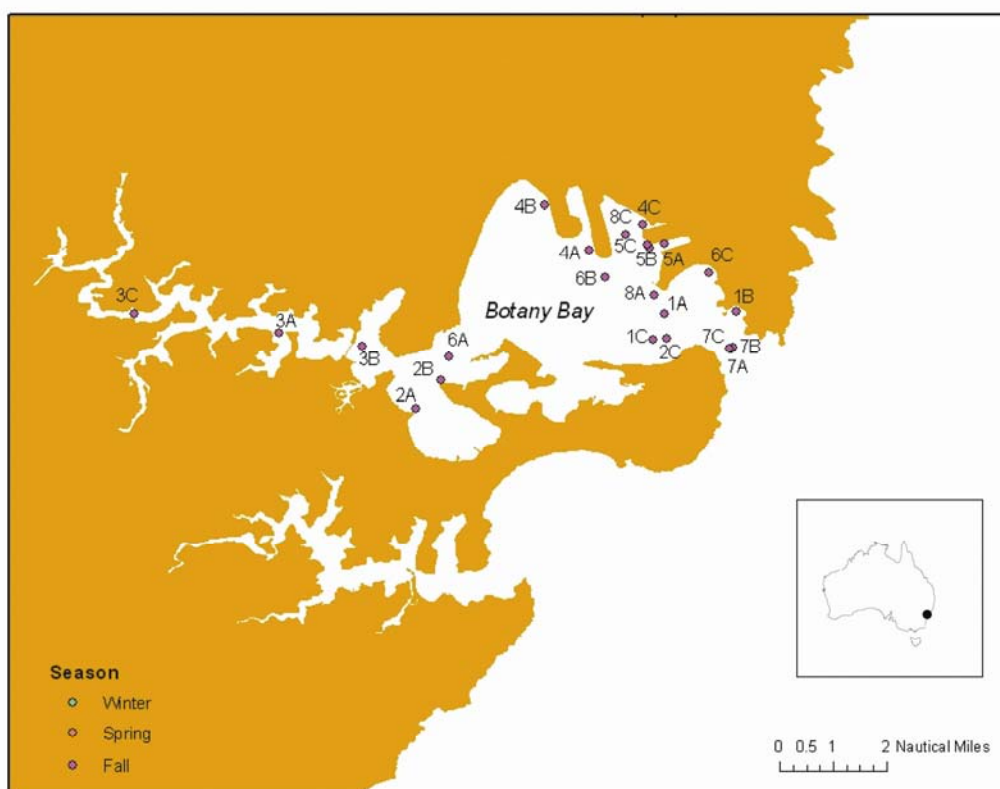


Figure 1. Sampling sites in Botany Bay during survey NZ5 (fall).

Table 2. Description of sites sampled in Botany Bay during NZ5

Site	Time	Latitude	Longitude	Depth (m)	Site type
1A	4/18/2007 15:10	-33.99193	151.21247	12.5	Shipping Channel
1B	4/18/2007 14:40	-33.99113	151.23463	6.3	Embayment
1C	4/18/2007 15:20	-34.00022	151.20860	12.3	Berth
2A	4/19/2007 9:12	-34.02187	151.13464	1.7	Shallow
2B	4/18/2007 10:40	-34.01309	151.14237	1.15	Shallow (oyster lease)
2C	4/19/2007 9:42	-33.99977	151.21301	10.7	Berth
3A	4/19/2007 14:25	-33.99776	151.09193	0.8	Georges River
3B	4/18/2007 17:01	-34.00215	151.11783	5.7	Georges River
3C	4/19/2007 14:06	-33.99195	151.04669	2.4	'Freshwater endmember' (Georges River)
4A	4/19/2007 12:55	-33.97179	151.18891	10.5	Shallow
4B	4/19/2007 13:10	-33.95781	151.17473	6.2	Shallow
4C	4/19/2007 12:00	-33.96375	151.20548	3.65	Shallow
5A	4/19/2007 11:30	-33.96982	151.21222	15.6	Berth
5B	4/19/2007 11:20	-33.97120	151.20777	21.4	Port entrance
5C	4/19/2007 11:43	-33.96995	151.20702	11	Berth
6A	4/18/2007 11:43	-34.00534	151.14506	3.2	Deep
6B	4/18/2007 16:02	-33.98060	151.19363	6	Deep
6C	4/19/2007 10:35	-33.97908	151.22622	4.7	Embayment
7A	4/18/2007 13:44	-34.00283	151.23340	18.7	Marine endmember
7B	4/19/2007 10:02	-34.00241	151.23364	20	Shipping Channel
7C	4/19/2007 13:30	-34.00306	151.23262	19.4	Shipping Channel
8A	4/18/2007 15:45	-33.98628	151.20907	12.6	Shipping Channel
8B	4/18/2007 16:25	-34.00545	151.18285	1.4	Shallow (oyster lease)
8C	4/19/2007 12:30	-33.96686	151.20022	6.9	Embayment
9A	4/19/2007 12:50	-33.97481	151.19377	1	Air blank (under airport runway)

Port Phillip Bay, Port of Geelong and Port Melbourne

The first of two field surveys of Port Phillip Bay (survey NZ7) was conducted in autumn (fall) on April 24-26, 2007. Samples were collected at twenty four sites encompassing the Port of Geelong (6 sites), the Port of Melbourne (9 sites) and the wider Bay region (9 sites; Figure 2). End-member samples were also collected from the Yarra River at Studley Park boathouse (above Dights Falls, the uppermost extent of the tidal excursion), which is the major source of freshwater to the Port of Melbourne (Harris et al. 1996). The second survey of Port Phillip Bay (survey NZ8) took place in spring on October 25 – 26, 2007. Sampling locations during the second survey were as close as possible to the sites visited in the first survey.

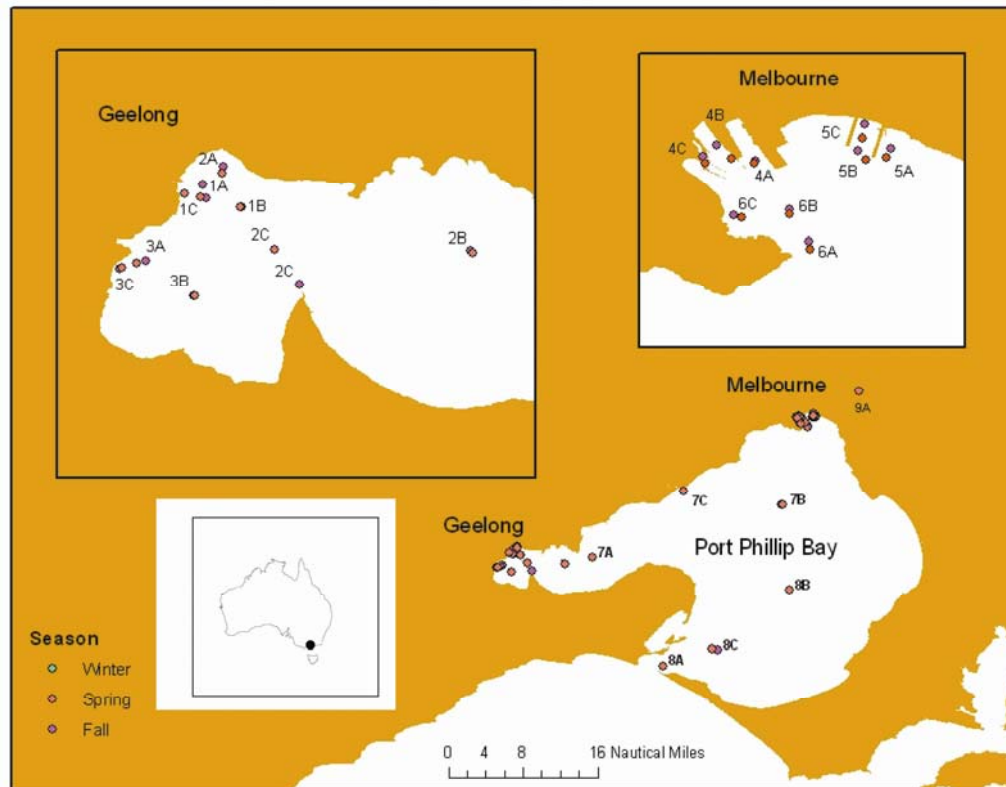


Figure 2: Sampling sites in Port Phillip Bay during surveys NZ7 (fall) and NZ8 (spring).

Table 3: Description of sites sampled in Port Phillip Bay during NZ7 and NZ8

Survey	Site	Time	Latitude	Longitude	Depth (m)	Site description
NZ7	1A	4/24/2007 10:02	-38.09131	144.39240	14	Berth
NZ7	1B	4/24/2007 10:50	-38.09455	144.40442	8	Shipping Channel
NZ7	1C	4/24/2007 10:15	-38.08652	144.39119	7	Berth
NZ7	2A	4/24/2007 10:30	-38.08020	144.39831	4	Tributary
NZ7	2B	4/24/2007 12:35	-38.10948	144.48381	7.5	Shipping Channel
NZ7	2C	4/24/2007 11:15	-38.12122	144.42460	1.3	Shallow
NZ7	3A	4/24/2007 9:25	-38.11293	144.37140	10	Berth
NZ7	3B	4/24/2007 8:55	-38.12501	144.38809	10	Embayment
NZ7	3C	4/24/2007 9:40	-38.11588	144.36230	7	Shallow
NZ7	7A	4/24/2007 9:40	-38.09842	144.53357	8	Berth
NZ7	8A	4/24/2007 10:28	-38.29292	144.65991	16.2	Marine endmember
NZ7	8C	4/24/2007 3:05	-38.26566	144.75768	2	Shallow
NZ7	4A	4/26/2007 2:02	-37.84803	144.90872	12	Berth
NZ7	4B	4/26/2007 1:45	-37.84502	144.90157	11	Berth
NZ7	4C	4/26/2007 1:27	-37.84708	144.89900	2	Boat ramp
NZ7	5A	4/26/2007 12:50	-37.84560	144.93364	10	Berth
NZ7	5B	4/26/2007 12:18	-37.84598	144.92755	6	Berth
NZ7	5C	4/26/2007 12:35	-37.84120	144.92868	2	Shallow
NZ7	6A	4/26/2007 11:20	-37.86276	144.91855	14	Berth
NZ7	6B	4/26/2007 11:46	-37.85683	144.91495	13	Port
NZ7	6C	4/26/2007 12:00	-37.85788	144.90477	1.4	Marina
NZ7	7B	4/26/2007 12:15	-38.00408	144.87268	18	Shipping Channel
NZ7	7C	4/26/2007 10:28	-37.97921	144.69659	2	Tributary, Werribee River
NZ7	8B	4/26/2007 9:13	-38.15681	144.88637	22.6	Shipping Channel
NZ7	9A	4/25/2007 16:00	-37.80029	145.00961	2	Yarra River endmember
NZ8	1A	10/25/2007 13:53	-38.09097	144.39030	13.7	Berth
NZ8	1B	10/25/2007 13:15	-38.09443	144.40410	8.6	Shipping Channel
NZ8	1C	10/25/2007 14:06	-38.08968	144.38468	7.7	Berth
NZ8	2A	10/25/2007 13:32	-38.08243	144.39793	6.3	Tributary
NZ8	2B	10/25/2007 12:02	-38.11002	144.48463	8.3	Shipping Channel
NZ8	2C	10/25/2007 12:58	-38.10883	144.41607	6	Shallow
NZ8	3A	10/25/2007 14:25	-38.11388	144.36823	13.5	Berth
NZ8	3B	10/25/2007 15:00	-38.12507	144.38835	8.7	Embayment
NZ8	3C	10/25/2007 14:40	-38.11537	144.36330	8.2	Shallow
NZ8	4A	10/26/2007 14:15	-37.84837	144.90853	8	Berth
NZ8	4B	10/26/2007 14:02	-37.84762	144.90430	14.8	Berth
NZ8	4C	10/26/2007 14:32	-37.84828	144.89942	2	Boat ramp
NZ8	5A	10/26/2007 12:30	-37.84727	144.93267	10.5	Berth
NZ8	5B	10/26/2007 12:47	-37.84763	144.92893	13	Berth
NZ8	5C	10/26/2007 12:57	-37.84383	144.92837	11.3	Shallow
NZ8	6A	10/26/2007 13:13	-37.86425	144.91862	14	Berth
NZ8	6B	10/26/2007 13:28	-37.85773	144.91503	15	Port
NZ8	6C	10/26/2007 13:45	-37.85840	144.90612	2.8	Marina
NZ8	7A	10/25/2007 11:42	-38.09838	144.53350	8.5	Berth
NZ8	7B	10/26/2007 11:53	-38.00408	144.87282	19.5	Shipping Channel
NZ8	7C	10/26/2007 10:59	-37.97900	144.69630	3	Tributary Werribee River
NZ8	8A	10/25/2007 9:15	-38.29290	144.65875	16.5	Marine endmember
NZ8	8B	10/25/2007 10:35	-38.15687	144.88625	23	Shipping Channel
NZ8	8C	10/25/2007 9:50	-38.26350	144.74687	7.9	Shallow
NZ8	9A	10/26/2007 16:45	-37.80017	145.00959	0.5	Yarra River endmember

Port Curtis / Gladstone

Two surveys were conducted in Port Curtis near Gladstone. Approximately half the sites were chosen to coincide with sites previously surveyed by the former Center for Research on Introduced Marine Pests (CRIMP) and the University of Central Queensland (UCQ) during the baseline surveys of introduced marine species in ports (Lewis et al. 2001). The remainder were selected principally to provide coverage of river and point sources to the port.

The first survey was conducted in winter on August 21 – 22, 2007, and a second partial survey was conducted in autumn on April 2-4, 2008, to replace CDOM and trace element samples that perished from the original survey (Figure 3). A subset of sites from the first survey were revisited during the second, allowing temporal changes to be examined in the study.

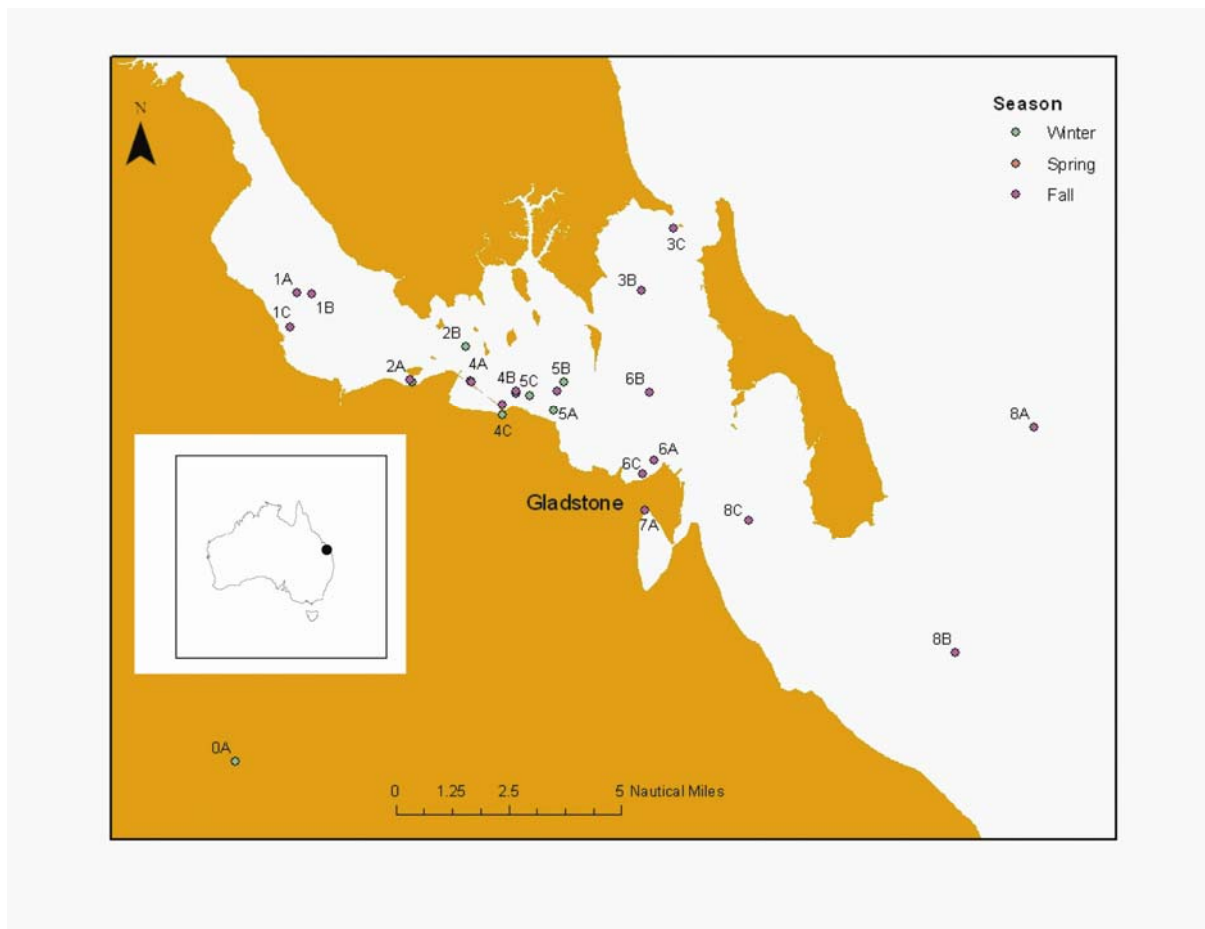


Figure 3: Sampling sites during the surveys of Port Curtis (NZ6 in winter and NZ9 in fall).

Table 4: Description of sites sampled in Port Curtis during NZ6 and NZ9

Survey	Site	Time	Latitude	Longitude	Depth (m)	Site description
NZ6	0	8/22/2007 12:30	-23.96320	151.15285	0.4	Freshwater endmember
NZ6	1A	8/21/2007 15:52	-23.78730	151.17585	13.5	Berth
NZ6	1B	8/21/2007 15:32	-23.79003	151.19330	7.8	Shipping Channel
NZ6	1C	8/21/2007 16:06	-23.80225	151.17245	1.5	Shallow
NZ6	2A	8/22/2007 8:15	-23.82262	151.21833	5.4	Calliope River entrance
NZ6	2B	8/21/2007 8:50	-23.80955	151.23827	13.4	Berth
NZ6	2C	8/21/2007 16:27	-23.81668	151.18602	1.5	Shallow
NZ6	3A	8/21/2007 15:04	-23.77977	151.26038	5.2	Shallow
NZ6	3B	8/21/2007 13:15	-23.79018	151.30152	4.7	Embayment
NZ6	3C	8/21/2007 14:40	-23.76640	151.31610	4.1	Shallow
NZ6	4A	8/22/2007 9:05	-23.82212	151.23982	4.7	Gladstone harbour
NZ6	4B	8/22/2007 9:23	-23.82682	151.25660	17.8	Berth
NZ6	4C	8/22/2007 10:36	-23.83465	151.25182	3.4	Marina
NZ6	5A	8/22/2007 10:20	-23.83310	151.27057	17.7	Berth
NZ6	5B	8/22/2007 9:55	-23.82270	151.27437	5.5	Shipping Channel
NZ6	5C	8/22/2007 9:37	-23.82758	151.26165	12.5	Berth
NZ6	6A	8/21/2007 12:08	-23.85080	151.30778	15.2	Berth
NZ6	6B	8/21/2007 12:45	-23.82562	151.30693	4.3	Shipping Channel
NZ6	6C	8/21/2007 12:28	-23.85270	151.31923	21.5	Berth
NZ6	7A	8/21/2007 11:43	-23.90192	151.30322	3	Tributary
NZ6	7B	8/21/2007 9:20	-23.85590	151.35230	6.6	Embayment*
NZ6	7C	8/21/2007 8:50	-23.83627	151.34903	1.4	Embayment
NZ6	8A	8/21/2007 10:05	-23.86925	151.46977	15	Marine endmember
						Anchorage
NZ6	8B	8/21/2007 10:40	-23.92163	151.41910	9.5	Shipping Channel
NZ6	8C	8/21/2007 11:16	-23.87385	151.34260	13.4	Shipping Channel
NZ6	9A	8/22/2007 0:00	-23.9632	151.15285	0.8	Air blank
NZ9	1A	4/3/2008 9:55	-23.78947	151.17580	7.5	Berth
NZ9	1C	4/3/2008 9:32	-23.80226	151.17319	1.7	Shallow
NZ9	13C	4/3/2008 10:14	-23.79023	151.18127	18	Berth
NZ9	2A	4/3/2008 8:45	-23.82177	151.21757	4.5	Calliope River entrance
NZ9	3B	4/3/2008 11:11	-23.78887	151.30338	4.6	Embayment
NZ9	3C	4/3/2008 11:43	-23.76577	151.31519	1.8	Shallow
NZ9	4A	4/3/2008 18:07	-23.82243	151.24036	8.5	Gladstone harbour
NZ9	4B	4/3/2008 17:33	-23.82593	151.25668	14	Berth
NZ9	4C	4/3/2008 17:50	-23.83092	151.25171	4.3	Marina
NZ9	5B	4/3/2008 17:14	-23.82587	151.27197	6.2	Shipping Channel
NZ9	6A	4/3/2008 15:52	-23.85147	151.30771	14	Berth
NZ9	6B	4/3/2008 16:26	-23.82625	151.30612	6.5	Shipping Channel
NZ9	6C	4/3/2008 15:30	-23.85682	151.30369	5.3	Berth
NZ9	7A	4/3/2008 15:00	-23.87033	151.30426	3	Tributary
NZ9	8A	4/3/2008 13:00	-23.83951	151.44810	17	Marine endmember
						Anchorage
NZ9	8B	4/3/2008 13:47	-23.92299	151.41931	9	Shipping Channel
NZ9	8C	4/3/2008 14:28	-23.87410	151.34271	10	Shipping Channel

Sample collection

Samples were collected by the authors using established methods (Murphy et al. 2003). Revisions to the protocol are maintained by the Smithsonian Environmental Research Center, and made available to the public via their website (www.serc.si.edu).

Physico-chemical parameters were measured in situ. Samples for laboratory analysis of trace element and CDOM analysis were collected using a peristaltic pump (Cole Parmer 7533-60 12vDC) fitted with rigid Teflon tubing and flexible Masterflex tubing and connected to a high-capacity inline 0.45µm capsule filter (GE Memtrex MP, 0.45 µm). The apparatus was flushed with at least 3 L of water prior to sampling at any site, and filters were changed 3-5 times during each survey depending on turbidity levels in the port. All tubing and filters were acid-washed before use.

Physico-chemical characteristics

Salinity, conductivity, temperature, and dissolved oxygen were measured using one or both of the following instruments (1) a YSI-85 owned by SERC, and (2) a YSI 650MDS datasonde and 65 probe owned by UTS. Instruments were calibrated with a NIST-traceable seawater conductivity standard (YSI 3169, 50 000 µScm⁻¹) or with a freshly-made solution of 36 ppt KCl prior to each cruise. In-situ pH was determined using a WTW pH sensor. Problems were detected with salinity measurements during some surveys, and data were subsequently cross-corrected against other data sources. For NZ6 in Port Curtis, laboratory tests on the YSI conducted soon after the survey indicated a 1.2 psu calibration offset. For the Port Phillip Bay surveys NZ7 and NZ8, data were crosschecked against hourly salinity measurements from Thompson's Bay, Central Bay and Long Reef collected by the Department of Sustainability and Environment (DSE) and indicated a 3.8 and 1.8 psu offset, respectively. No recalibration occurred between NZ5 and NZ7, therefore the offset calculated for NZ7 was adopted for NZ5 (Port Botany) as well. Based upon cross-calibrations, laboratory tests and post-event instrument calibrations, we made the following adjustments to the salinity data collected on these surveys: NZ5: -3.8 psu (UTS-YSI); NZ6: +1.2 psu (SERC-YSI); NZ7: -3.8 psu (UTS-YSI); NZ8: +0.6 psu (SERC-YSI), -1.8 psu (UTS-YSI); NZ9: 0 psu (SERC-YSI). The corrected data for all surveys are considered accurate to ± 1 psu.

Table 5: Sampling design (samples collected per site) during port surveys.

Tracer	Port Surveys
CDOM	3 reps @ 5 m, or @ 1 m off the seafloor in shallow sites
Trace elements in seawater	3 reps @ 5 m, or @ 1 m off the seafloor in shallow sites
Trace elements in air	3 samples per port
pH	2 reps @ 5 m, or @ 1 m off the seafloor in shallow sites
Temperature (°C)	Measured every 1 m to 5 m depth (deep sites) or to 0.5 m off seafloor
Salinity (psu)	Measured every 1 m to 5 m depth (deep sites) or to 0.5 m off seafloor
Conductivity (mScm ⁻¹)	Measured every 1 m to 5 m depth (deep sites) or to 0.5 m off seafloor
Dissolved Oxygen (mgL ⁻¹)	Measured every 1 m to 5 m depth (deep sites) or to 0.5 m off seafloor
Bottom depth (m)	1 reading at start of sampling
GPS/time	1 reading at start and end of sampling

Trace element and CDOM protocols

Filtered water was collected in acid-cleaned 50 ml plastic centrifuge tubes for trace element analyses, or ashed amber glass bottles for CDOM analyses.

At each site, triplicate samples of CDOM and trace elements were collected, and in-situ profiles of physico-chemical characteristics recorded (Table 5). Air blanks for determining trace element baselines were also collected at locations where aerosol input was thought to be significant, such as the Sydney Airport runway approach. All air blanks showed very low concentrations of trace elements.

Following collection, samples were stored on the boat in a cooler, then refrigerated and ultimately frozen at -20 °C before being shipped to the US for analysis. Analysis occurred within 6 weeks of sample collection for CDOM and within 8 months of sample collection for trace elements. Previous studies in both laboratories have found no significant effects on data quality by storing samples for this length of time.

Sample analysis

Samples were shipped by international express post to our collaborating specialist laboratory at Rutgers, New Jersey (trace elements) and to SERC (CDOM). Several samples, usually CDOM samples in glass bottles, broke in transit. In most cases, however, all three replicates were analysed. On cruises NZ6, NZ8 and NZ9, typically two of three trace element replicates were analysed from each site, with the third replicate retained as a backup in case that confirmation of the data from the first two replicates was required. Across the entire study, 271 CDOM samples and 243 trace element samples from Australian ports were analysed.

Trace elements

Trace element samples were analysed at Rutgers Inorganic Analytical Laboratory, Institute of Marine and Coastal Sciences, Rutgers the State University of New Jersey. Samples were analysed on a sector field inductively coupled plasma mass spectrometer (ICP-MS) with high-resolution capability (ELEMENT, Finnigan MAT, Bremen, Germany). Total dissolved concentrations of seven trace elements (arsenic [As], barium [Ba], manganese [Mn], molybdenum [Mo], phosphorus [P], uranium [U] and vanadium [V]) were determined according to published methods (Field et al. 2007).

Samples were analysed in four batches between September 10, 2007 and April 23, 2008. In general, the coefficients of variation (SD/mean) for replicate samples collected from each site were small (2 – 8%), indicating that measurements were precise despite small sample sizes (Table 6). A small proportion of samples (2.9%) were identified as severe outliers relative to their replicates and deleted from the dataset. An additional 2.6% of samples produced inconsistent data (i.e. showed higher or lower levels relative to their replicates) for 2 or fewer elements, usually Mo and P. For these samples, data for the inconsistent elements were removed but data for the remaining elements were retained.

CDOM

CDOM analysis was performed by excitation-emission matrix spectroscopy (EEMS) at the Smithsonian Environmental Research Center, USA, using a JY Horiba Spex Fluorolog-3 (Edison, New Jersey, USA). Samples were analysed in a 1-cm quartz cell maintained at 20° C with a temperature-controlled cell holder and processed in ratio mode with a 0.5 second integration time and a 5 nm bandwidth for both excitation and emission. The experimental wavelength range was 220-455 nm in 5-nm intervals on excitation and 290-700 nanometres (nm) in 4-nm intervals on emission.

Fluorescence EEMs were corrected for instrument and lamp variability and normalized to quinine sulfate fluorescence intensity as previously described (Coble, Mopper & Schultz, 1993, method 1) using an in-house program written for Matlab (Ver. 7). One source of measurement error is the inner filter effect, where reabsorption of emitted radiation in concentrated samples causes a reduction in emitted light per molecule in solution, reducing the measured intensity of light. In the Tampa Bay estuary, Boehme (J. Boehme, unpublished data) found the fluorescence intensity corresponding to the onset of inner filter effects was around 16-20 QSE, which roughly corresponded to $A_{300} < 0.02$. Samples from this study were relatively dilute with 350/450 ($\lambda_{ex}/\lambda_{em}$) intensities below 9 QSE at 94% of sites sampled. The only sites where intensities exceeded 16 QSE were low-salinity end-member sites distant from the ports. Inner filter effects may have resulted in a slight underestimation of intensities at these end-member sites, but is unlikely to have had a significant effect upon determined concentrations at sites within the ports.

Table 6: Average coefficients of variation (CV = SD/mean) for replicate samples analysed from each port survey. The CV indicates precision of the sampling + analytical process. The average number of samples analysed per site is indicated for trace elements (NTE) and CDOM (NCDOM).

	N _{TE}	N _{CDOM}	Ba	P	Mn	Mo	C2*	C3*
NZ5	2.8	2.8	1.9%	8.2%	3.1%	4.2%	8.4%	8.3%
NZ6	2.0	2.9	2.1%	2.6%	2.4%	4.7%	2.8%	2.6%
NZ7	2.8	2.7	2.9%	11.9%	4.5%	3.1%	12.7%	13.6%
NZ8	1.9	2.6	3.0%	4.5%	4.1%	4.8%	1.9%	1.8%
NZ9	2.0	2.4	4.6%	6.0%	6.1%	4.4%	2.6%	2.4%

4. Results

Conservative tracers: Salinity and Mo¹

Salinity at all ports was generally ≥ 32 psu, with sites closest to port entrances (i.e. sites 8A-C at Port Curtis, Port Phillip Bay and site 7A-C in Port Botany) generally having highest salinities and those closest to the freshwater 'end-member' having lowest (Figure 4). Salinity data as presented have been adjusted as discussed in Section 2.3. The results indicate that salinities at the majority of sites within the ports surveyed fell within the range of 33-38 psu. Between repeat surveys, salinity varied by < 5 psu ($< 15\%$) in Port Curtis and < 1 psu ($< 3\%$) in Port Phillip Bay. Within any single survey, the total salinity range was small – typically less than 2 psu, excluding freshwater end-members.

The trace element Molybdenum was relatively constant between sites within the same survey, and only showed significant seasonal differences between surveys in Port Melbourne/Geelong with average (\pm SD) values in April 2007 (NZ7) being $\sim 15\%$ lower than survey NZ8 in October 2007 ($11.9 \pm 0.4 \mu\text{g L}^{-1}$ compared to $9.9 \pm 0.8 \mu\text{g L}^{-1}$) (Figure 5).

Results for U, V and As were similar to results for Mo. They are not discussed further here, but data for these elements are summarized in the Appendices for completeness.

¹ The concentration of the trace element molybdenum is conservative in the ocean (Palmer and Edmond 1993; Sohrin et al 1998), meaning that it is a passive tracer of seawater and typically behaves in the same way as salinity. It has therefore been grouped together with salinity in the results section.

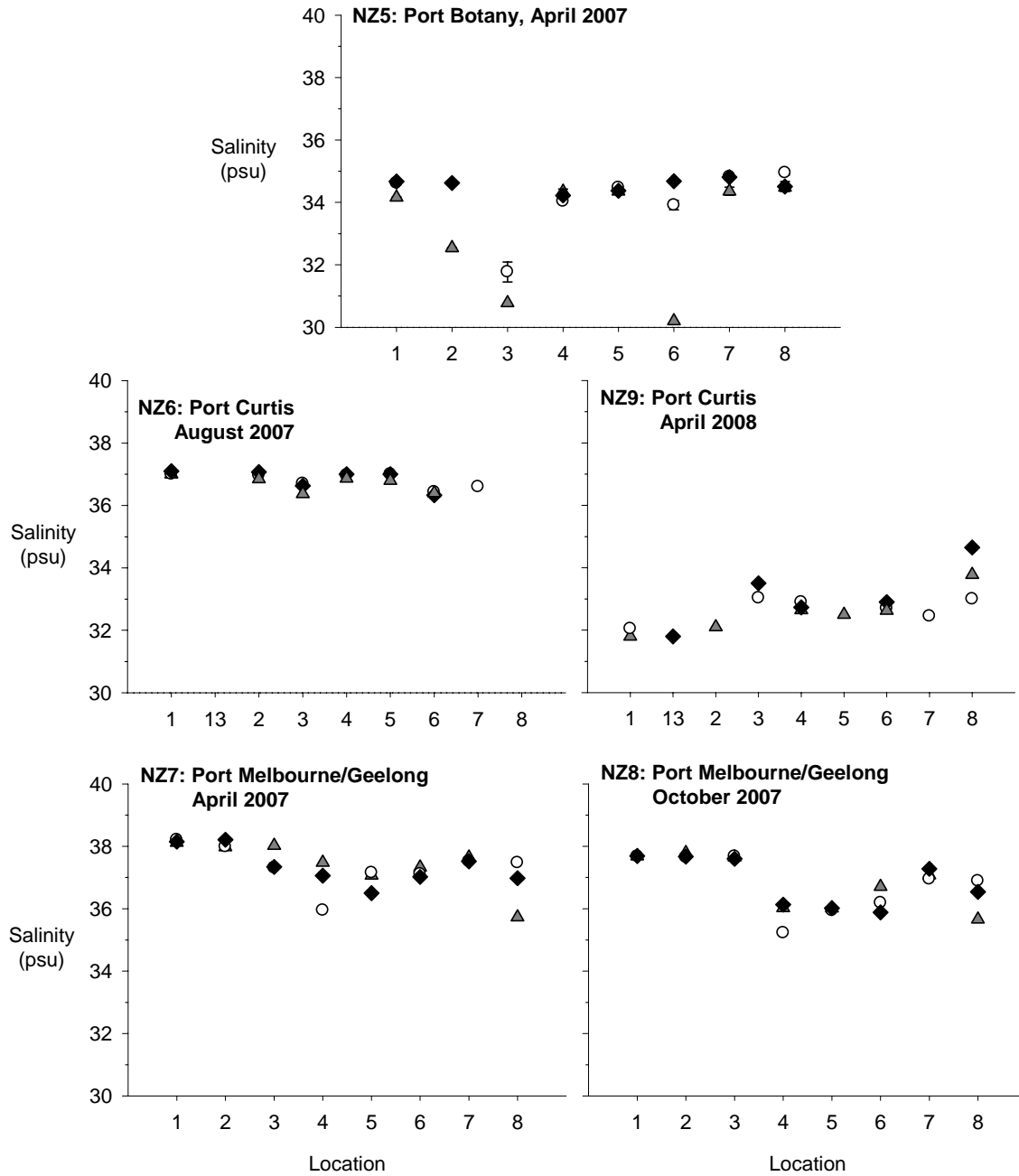


Figure 4: Salinity distribution (corrected data) during the five port surveys. Data are means at average depth sampled. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

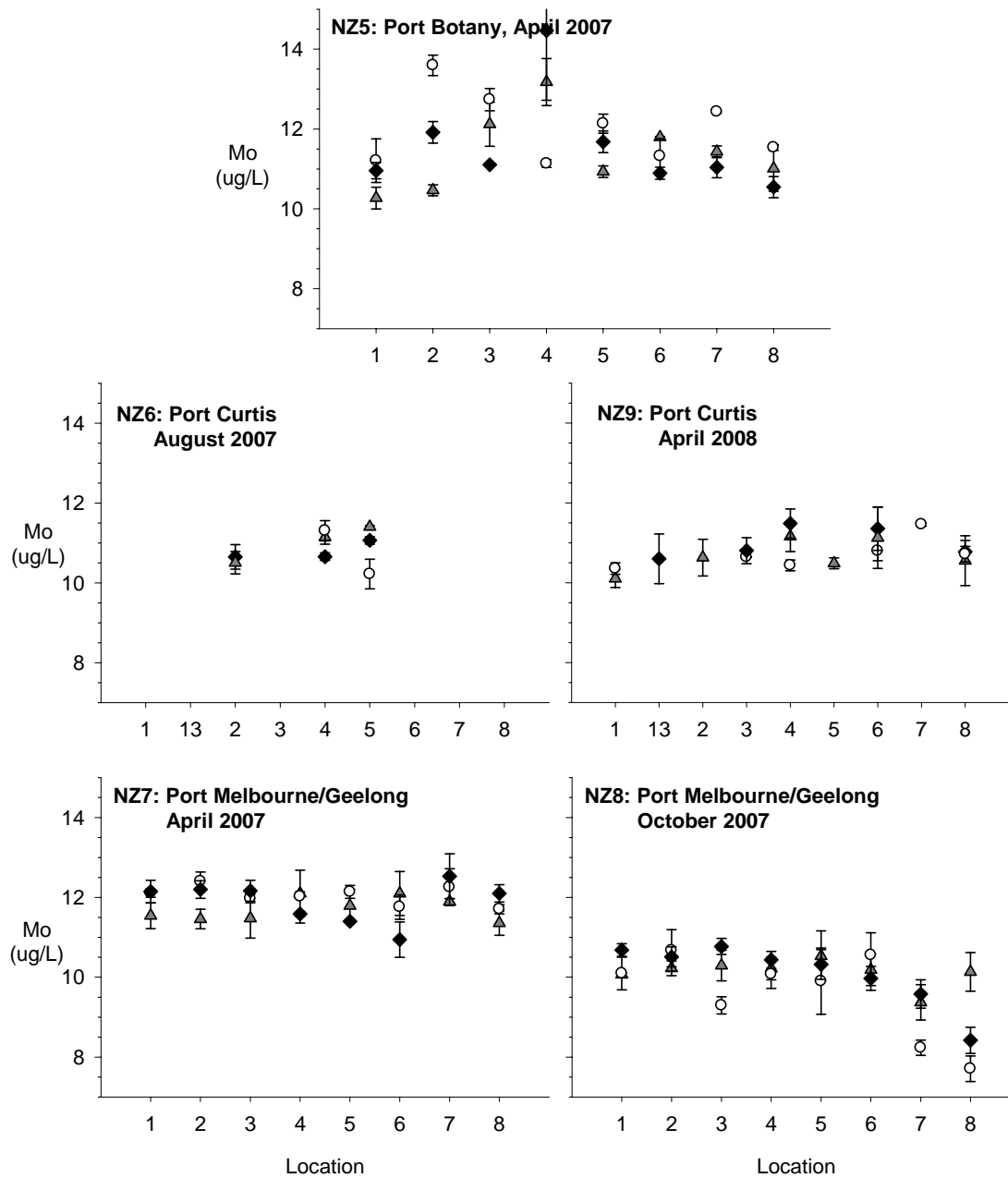


Figure 5: Molybdenum distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

CDOM

CDOM C2* (320/414) and C3* (320/494) showed similar trends (Figure 6 - 8), with C3* values generally ~47 - 60% lower than C2*. As expected, CDOM values were lowest at sites close to port entrances and increased at sites adjacent to freshwater inputs. CDOM showed stronger differences between sites for NZ5 and NZ9 compared to salinity, with values varying by as much as 8 QSE (Figure 6). Interestingly, CDOM values were least variable in Port Phillip Bay (C2* of 4.5 ± 1.3 QSE in April 2007 and 4.7 ± 1.4 QSE in October 2007) compared to 3.8 ± 3.6 QSE in Port Botany and 8.1 ± 2.9 QSE in Port Curtis.

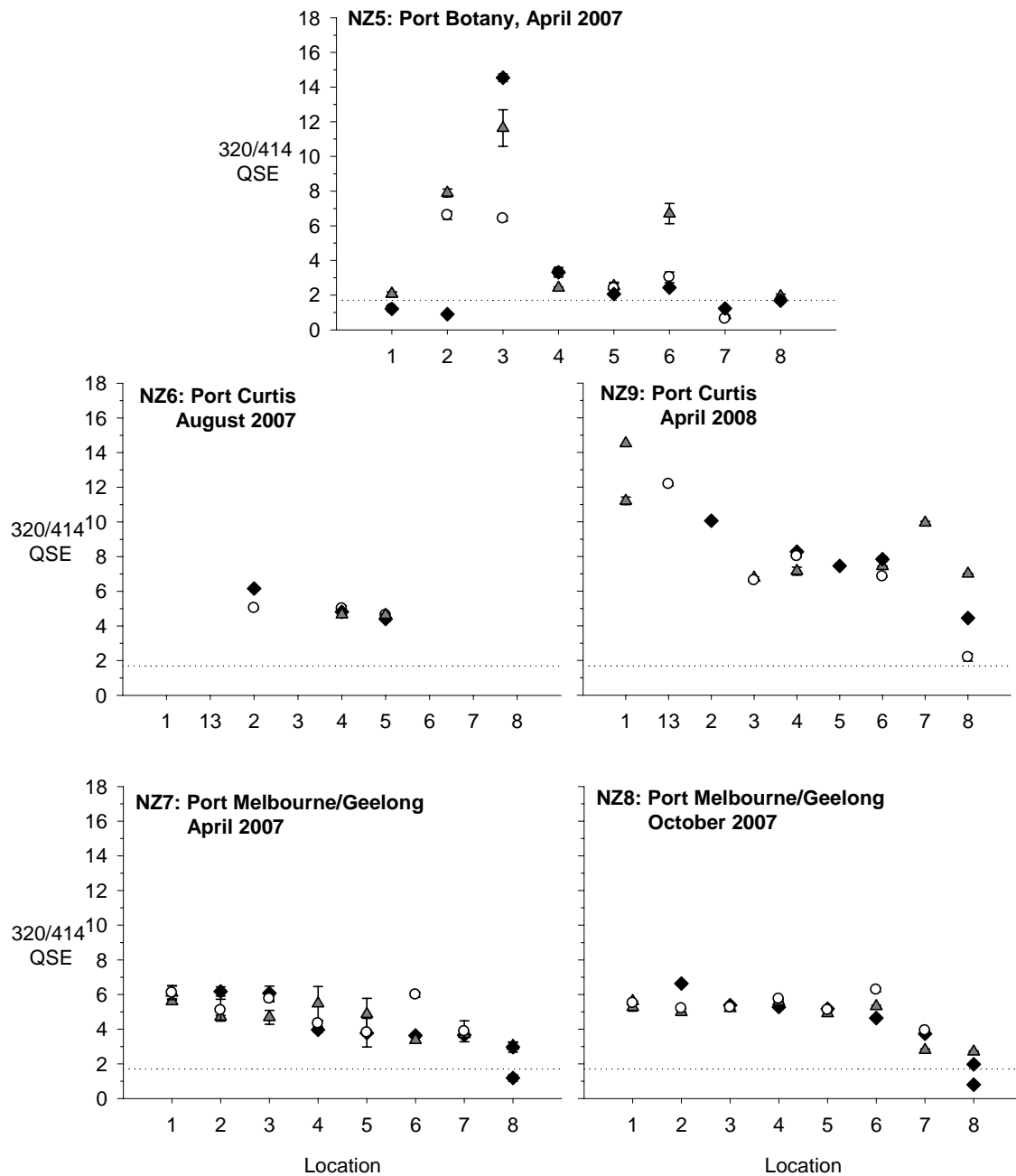


Figure 6: CDOM (C2*) distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

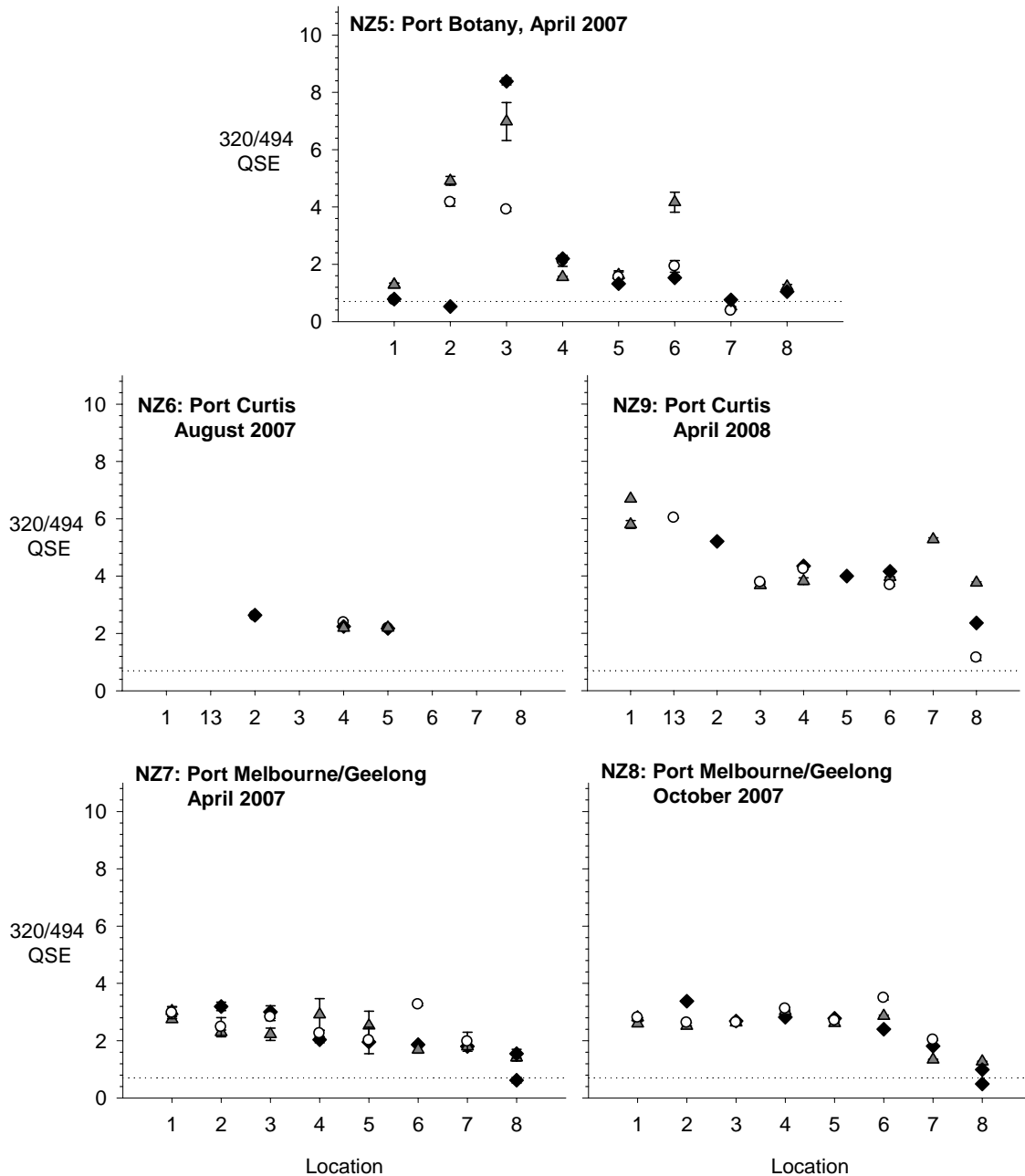


Figure 7: CDOM (C3*) distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

Trace elements

Barium

Barium concentrations were similar in Port Curtis and Port Phillip Bay, averaging between 7 and 9 $\mu\text{g L}^{-1}$. In Port Botany, Ba concentrations were low at deeper sites near berths (5 – 6 $\mu\text{g L}^{-1}$) and high in the Georges River (15.9 $\mu\text{g L}^{-1}$ at site 3) (Figure 8). Like CDOM, Barium concentrations in Port Phillip Bay and Port Curtis were quite similar between seasons, with values decreasing closest to the port entrances.

Manganese

Manganese concentrations were highly variable between sites during all surveys (Figure 9). Like Barium, Mn concentrations were generally lowest at port entrances, where they often approached oceanic concentrations (Tables 7 and 8). Interestingly, Mn distributions varied considerably between the two Port Phillip Bay surveys (5.2 \pm 2.4 $\mu\text{g L}^{-1}$ in April 2007 and 3.4 \pm 1.4 $\mu\text{g L}^{-1}$ in October 2007).

Phosphorus

Total phosphorus concentrations were significantly different between ports (Figure 10), with Port Curtis having generally low levels (6.8 \pm 1.0 and 6.9 \pm 1.3 $\mu\text{g L}^{-1}$ in October 2007 and April 2008, respectively). Port Botany had intermediate P concentrations (17.0 \pm 4.2 $\mu\text{g L}^{-1}$) but Port Phillip Bay had by far the highest concentrations (>60 $\mu\text{g L}^{-1}$), even at sites close to the Bay entrance.

A summary of minimum and maximum concentrations for all tracers is found in Table 7.

Table 7: Minimum and maximum tracer concentrations in SE Australian ports determined in this study. Site numbers are indicated in square brackets. Measurement units are QSE (CDOM), $\mu\text{g L}^{-1}$ (trace elements) and psu (salinity).

Tracer	Botany Bay	Gladstone	Port Phillip Bay
C2*	0.6 [7B] - 14.5 [3C]	2.2 [8A] - 14.5 [1A]	0.8 [8A] - 6.6 [2A]
C3*	0.4 [7B] - 8.4 [3C]	1.1 [8A] - 6.7 [1A]	0.5 [8A] - 3.5 [6C]
Ba	4.8 [8C] - 15.9 [3C]	4.9 [8A] - 11.7 [13C]	5.5 [8A] - 11.1 [2A]
Mn	0.2 [7B] - 5.3 [3A]	0.3 [8B] - 6.0 [7A]	0.1 [8A] - 8.3 [6C]
P	10.7 [1C] - 28.1 [3C]	4.1 [8A] - 9.0 [8C]	8.9 [8A] - 93.2 [6A]
Salinity	28.4 [3C] - 35.0 [8B]	31.8 [1A] - 37.1 [2B]	35.2 [4B] - 38.2 [2C]
Relevant sites for ballast uptake	5A 5B 4C 5C 2C 1C berth 1A 7A 7B 7C channel	1A 13C 4A 5A 6A 6C berth 6B 8B 8C channel 8A anchorage	5A B C; 4B, 4A, 6C, 6A, Melb. berths 1C 1A 3A 3C 7A Geelong berths 2B 7B 8B 8A channel

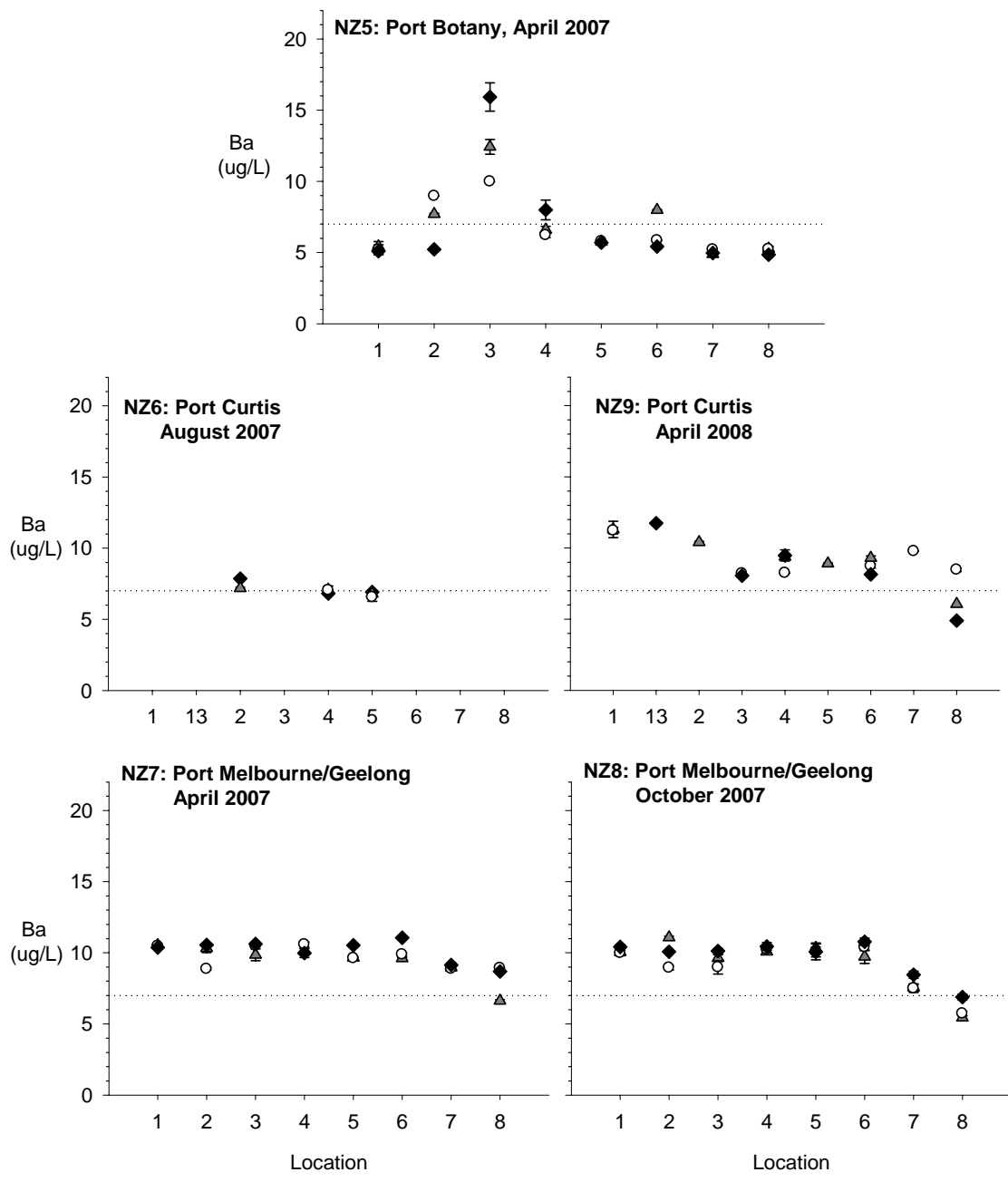


Figure 8: Barium distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

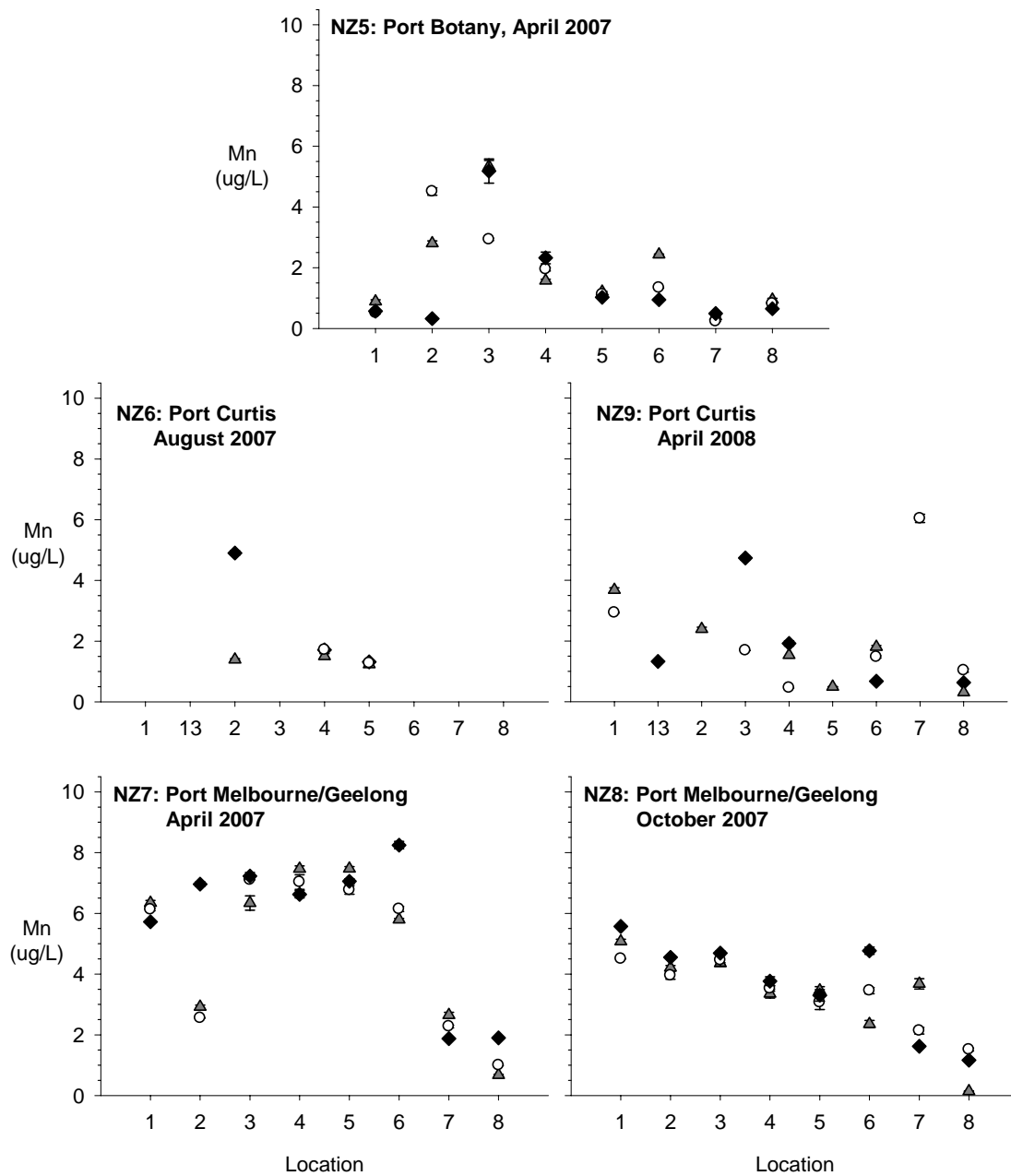


Figure 9: Manganese distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

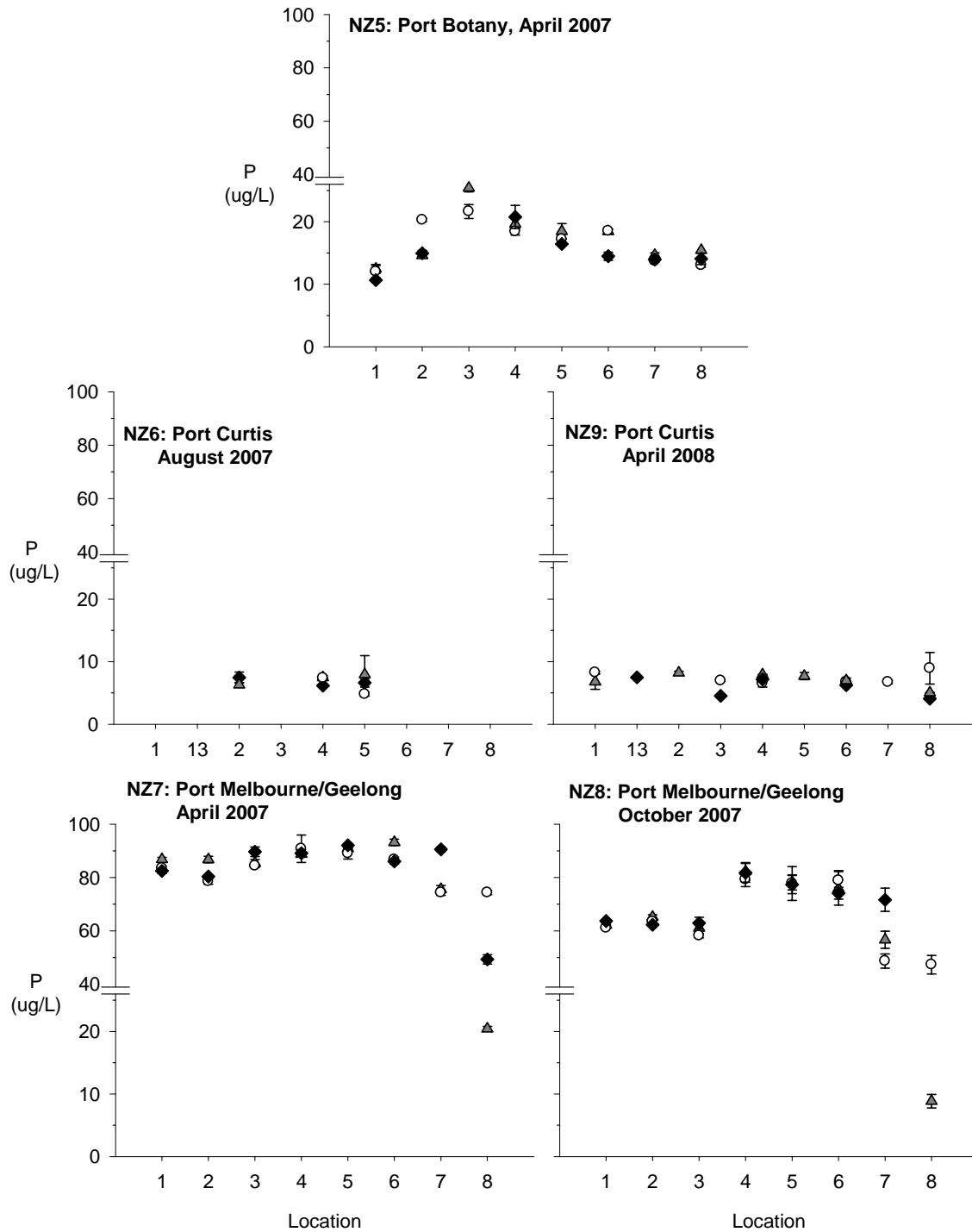


Figure 10: Phosphorus distribution during the five port surveys. Data are means \pm SD for duplicate samples. Symbols indicate locations within sites (A: triangles, B: circles, C: diamonds).

5. Discussion

Differences between chemical tracer concentrations in ports and the open-ocean

It can be seen from Figure 4 that salinity at most sites in all ports was similar to (within 10% of) background levels in the Tasman Sea (Table 8). This is consistent with the earlier study of Murphy et al. (2007; in preparation) who found initial salinities in ballast water tanks departing the Port of Geelong to have been indistinguishable from sites sampled more than 100 nautical miles offshore. These data indicate that most port water from southeast Australia could not be reliably discriminated from the Tasman Sea based on salinity. In addition to ports exhibiting lowered salinity due to freshwater inputs, some Australian ports are locally or seasonally hypersaline (more salty than the ocean), for example, Port Adelaide (de Silva Samarasinghe & Lennon 1987, Veeh et al. 1995), and in recent years, Port Phillip Bay (Longmore 2007). For this reason, salinity screening is still of value, whether or not the ballast water is likely to have originated from Australia. Ballast water salinities below ~31 psu or in excess of ~38 psu should be considered suspicious, because such salinities are generally inconsistent with seawater derived from the open oceans.

Molybdenum did not offer any greater resolution than salinity, with Mo exhibiting a small range within and between ports. This result is consistent with previous findings in the northern hemisphere (Murphy et al. 2008). Also, in four ballast water exchange experiments conducted between Australia and New Zealand by Murphy et al. (2007; in preparation), Mo concentrations in ballast tanks after BWE were not significantly different from initial concentrations, mirroring the salinity results and suggesting this element would be an ineffective stand-alone tracer of ballast water exchange.

In contrast, average C2* and C3* CDOM concentrations in port were up to an order higher than average Tasman Sea levels (Table 8), with only a handful of sites located closest to port entrances approaching concentrations in the open ocean (Figure 6 - 8). Interestingly, there were several sites (1B, 1C, 2B) near deepwater oil-terminal berths in Botany Bay that had very low levels of CDOM, suggesting ballast water from this port would be most difficult to distinguish from the Tasman Sea.

Barium concentrations were also above Tasman Sea background levels on average (Table 8) and at most sites in Port Curtis and Port Phillip Bay (Figure 9). However, Ba concentrations at most sites in Botany Bay, and at sites close to all port entrances, were similar to the open ocean. Manganese performed better than barium, showing consistently higher concentrations at port sites than in the Tasman Sea in almost all cases. Only at sites closest to the port entrance were Mn concentrations similar to in the open ocean (Figure 9, Table 8).

Phosphorus showed an interesting result. Even though it is biologically active, being taken up and released by micro organisms on short time scales, concentrations were nearly an order of magnitude higher in Port Phillip Bay than in the Tasman Sea, the only exception being at the heads (site 8A) in October 2007. The high P measured in these surveys is consistent with long-term monitoring studies in the Bay (Harris et al. 1996), which indicate high P year-round. Many sites in Port Botany also had higher P concentrations than the Tasman Sea. Conversely, Port Curtis P concentrations were below typical Tasman Sea levels.

Table 8: Background tracer levels in the Tasman Sea (>100 nmi from land) determined in previous studies for CDOM (QSE units), trace elements ($\mu\text{g L}^{-1}$) and salinity (psu), compared to results from ports in this study. Data are means \pm SD or measurement range. Data sources are [a] Murphy et al., in preparation; [b] Murphy et al., 2007.

Tracer	Tasman Sea	NZ5	NZ6	NZ7	NZ8	NZ9
		Port Botany	Port Curtis	Port Phillip Bay	Port Phillip Bay	Port Curtis
C2*	0.57 \pm 0.15 ^a	3.8 \pm 3.6	4.9 \pm 0.5	4.5 \pm 1.3	4.7 \pm 1.4	8.1 \pm 2.9
C3*	0.35 \pm 0.08 ^a	2.3 \pm 2.1	2.3 \pm 0.2	2.3 \pm 0.7	2.4 \pm 0.7	4.2 \pm 1.3
Ba	4.85 \pm 0.78 ^a	6.8 \pm 2.7	7 \pm 0.4	9.8 \pm 1	9.3 \pm 1.6	9 \pm 1.8
Mn	0.5 \pm 0.29 ^a	1.7 \pm 1.5	1.9 \pm 1.2	5.2 \pm 2.4	3.4 \pm 1.4	1.9 \pm 1.6
P	12.1 \pm 3.0 ^a	17 \pm 4.2	6.8 \pm 1	81.2 \pm 15.9	63.8 \pm 16.9	6.9 \pm 1.3
Salinity	34.8 \pm 0.8 ^{a,b}	33.8 \pm 0.7	36.8 \pm 0.09	37.4 \pm 0.3	36.8 \pm 0.2	32.7 \pm 0.1

In general, most tracers showed greater spatial rather than temporal variability, with greater variation between ports or between sites within the same port, rather than between surveys (e.g., phosphorus in Port Phillip Bay; Figure 10). This is a desired outcome given that high temporal variability could make thresholds for BWE verification seasonally dependent.

Port Phillip Bay stood out as having relatively consistent CDOM (C2* and C3*) and Ba concentrations between surveys (April and October 2007). The relatively long water residence time in the Bay (\sim a year; Harris et al. 1996) may be an important determinant of tracer variability, and is in marked contrast to more rapid flushing rates in the relatively open waters of Port Botany and Port Curtis. In general, it can be expected that ports experiencing greater exchange with coastal waters and lower freshwater inflows will have contracted gradients in terrestrial tracer concentrations of all types, making them potentially more difficult to identify as coastal sources than enclosed ports or bays.

Ballast water exchange verification between eastern Australia and New Zealand

This study demonstrates that salinity is an insensitive tracer of BWE exchange between eastern Australian ports and New Zealand. All of the ports investigated had relatively high salinity at sites close to berths, indicative of minimal freshwater influence and relatively high rates of evaporation. Although there was usually a clear decrease in salinity at sites located in estuaries (e.g. Georges River, Botany Bay; NZ5) compared to those at the port entrance (marine endmembers), they were heavily influenced by tidal flows, particularly in view of our shallow (typically 5 m) sampling depth. Despite its low resolution as a tracer of Australian port water, salinity-based screening of BWE is still recommended for all ships arriving to New Zealand for the following reason. Salinity can be measured quickly and easily and in some cases will be the only verification tool required, since low (< 30 psu) or excessively high (>40 psu) salinity is an unambiguous indicator of coastal sources. If a ballast tank is found to contain low-salinity seawater, this result precludes the need for any further tests. Only when salinity lies in an ambiguous range (\geq 30 – 40 psu) are further tests necessary.

Greater resolution for verifying BWE was found in the other tracers, particularly CDOM and manganese: C2*, C3* and Mn could be used to discriminate water taken up as ballast at all sites except for those at the entrance to each port, with some exceptions in Port Botany. Compared to previous studies, barium was somewhat less successful than Mn at distinguishing port water from the ocean, mainly due to the relatively low Ba concentrations in Port Botany and Port Curtis.

Overall, seawater from Port Botany/Botany Bay was the hardest to distinguish from Tasman Sea samples. This was due to low tracer concentrations at sites upstream of shipping berths and at the port entrance. At sites nearest the shipping berths, concentrations of CDOM, Ba and Mn were not significantly elevated above Tasman Sea concentrations. In contrast, P concentrations were somewhat elevated at the berths, with total dissolved P concentrations in Port Botany on average $17 \pm 4.2 \mu\text{g L}^{-1}$ compared to $12.1 \pm 3.0 \mu\text{g L}^{-1}$ in the Tasman Sea. Further examination of these data are underway to determine whether P might be used in combination with CDOM to identify ballast water sourced from this port.

Port Phillip Bay was clearly the port which could be most easily distinguished from open ocean seawater, with CDOM, Mn, P and Ba all present in high concentrations relative to the open ocean. CDOM concentrations in Port Phillip Bay near shipping berths were on average ~ 3 x higher than concentrations in the Tasman Sea, making CDOM a powerful tracer of seawater sourced from this port. P could also be used as a stand-alone indicator of ballast water from Geelong and Melbourne, with concentrations in the Bay near shipping berths typically ~ 4 x higher than concentrations in the Tasman Sea. Long-term phosphate records in Port Phillip Bay indicate that high P levels are a predictable occurrence (Harris et al. 1996, Longmore 2007), suggesting it may be worth exploring options for P testing of ballast water in New Zealand to target ballast water from this high-risk region. A large number of laboratories specializing in water quality applications are capable of measuring phosphorus in seawater at low ppb ($\mu\text{g L}^{-1}$) levels, including MAFRI in Victoria, which routinely monitors phosphorus in Port Phillip Bay. Although there are already instruments on the market for measuring phosphorus *in situ* (in the form of phosphate, which is typically the main component of total dissolved phosphorus in the ocean), these are typically designed for higher concentration applications (e.g. wastewater and river water) and are currently unsuited to ballast water testing.

Ballast sourced at Port Curtis would also be relatively easy to distinguish from the Tasman Sea using CDOM, which is present in concentrations 3 – 6x higher than in the Tasman Sea. Trace elements offer lower sensitivity in this port, with Ba approximately 1.2 - 2x higher, Mn approximately 0 - 10x higher and P exhibiting similar concentrations as in the Tasman Sea.

While this study did not measure tracer levels beyond port or bay limits, previous research has shown that once a ship departs port, ambient tracer levels can drop to near-oceanic levels within a few miles of the Australian coast (Murphy et al. 2007). As a result, some ships that exchange ballast water outside of port limits but near the Australian coastline will appear to be carrying oceanic ballast water in their ballast tanks. As yet, there is no known way to identify these ships using the tracer suite currently under examination. However, this may not present a severe problem given that BWE of a single pair of tanks can take 1 - 8 hours depending on the method used, during which the ship will generally be moving away from the coast at >12 knots. Thus if any BWE is initiated any time after leaving port, most water sourced during BWE is likely to have been drawn at distances greater than just a few miles from shore.

Table 9 shows univariate threshold levels for identifying exchanged ballast water in the Pacific, Atlantic and Tasman Sea, compiled from a series of studies. It is clear that in some cases, the thresholds are lower than the concentrations measured at various port sites during this study. This suggests that when implementing these thresholds, some ballast water sourced from eastern Australian ports will appear to have come from the open ocean. It should be noted, however, that the thresholds in Table 9 were developed for ballast water, not ports, and are therefore elevated relative to actual ocean concentrations in order to take into account

the presence of residual coastal signals in ballast tanks (since ships are required to exchange only 95% of the original coastal water). Also, in the case of Mn and P, it has been found to be the case that these elements often have slightly higher concentrations in ballast tanks than in the ports where the ballast water was loaded (Murphy et al. 2008). Consequently, while it is likely that BWE verification could fail to detect some coastal ballast water from some ports at some times of year, in the majority of cases, these criteria are likely to be successful.

Implementation

While these results are promising, we caution regulators and the shipping industry against the use of a single criterion to verify BWE. Instead, we recommend a tiered approach, in which one would first test ballast water for salinity below 30 psu or above 40 psu, indicating an unambiguous coastal source and second, test whether CDOM concentrations exceed oceanic concentrations. If there were still uncertainty regarding compliance following these tests, a final test could be performed for Ba, Mn or P. Of these, P is likely to be most useful if the ballast water originated from Port Phillip Bay or Botany Bay. Mn typically offered greater sensitivity than Ba in the ports examined during this study, however, the greater spatial and temporal variability of Mn observed at a number of sites suggests that Mn determinations may be more sensitive on average but less consistent in general than Ba.

A tiered approach is also appropriate considering operational practice, whereby ships may not take on all their ballast while berthed. During previous studies, the authors have observed ships topping up ballast in the shipping channel, either to save time or due to draft restrictions at the dock. This practice could dilute tracer signals, effectively reducing their power to verify BWE. In addition, this study shows that tracer concentrations at sites where ships are typically ballasting are intermediate (i.e. lie within the range, rather than at the end of the range; Table 7), indicating that tracer concentrations need to be sufficiently different from ocean water to verify BWE, because their signal could be diluted through water mixing within the port.

Table 9: Potential univariate threshold levels for BWE verification using CDOM (QSE units), trace elements (μgL^{-1}) identified in previous studies. Ballast water with values above these thresholds retains significant coastal influences. Salinities are assumed to exceed 30 psu. Data sources are [a] Murphy et al. 2004; [b] Murphy et al. 2006; [c] Murphy et al. 2008; [d] Murphy et al., in preparation.

Tracer	Pacific	Atlantic	Tasman Sea
C2*	1.7 ^b		1.75 ^d
C3*	0.7 ^b		1.0 ^d
Ba	-	7 ^{a, c}	6.9 ^d
Mn	1 ^c	2 ^c	2.6 ^d
P	-	-	-

6. Conclusions

The results of this study demonstrate considerable utility of CDOM and trace elements as tools to verify ballast exchange between eastern Australian ports and New Zealand.

We recommend a general approach to BWE verification in New Zealand using salinity + CDOM that would allow sensitive screening of Australian ballast water as well as ballast water from other parts of the world. For maximum resolution, the combination of tracers used to verify BWE would best be tailored to each port, however, since ballast water histories can be complex and incompletely (or incorrectly) recorded in ships' logs, a general method is likely to be more useful in practice. For the ports examined in this study, CDOM was the most useful tracer overall. Identification of coastal water from Port Curtis required only CDOM measurement. Identification of coastal water from Port Phillip Bay required CDOM or P as stand-alone tracers. For Port Botany, CDOM and P would probably work best if considered in combination, although further examination of the data from Port Botany are needed in order to finalize the recommendations for this port.

Operationally, the approach for BWE verification of ballast water from eastern Australian ports should involve at least two steps. The first is to test ballast water for salinity 30 – 38, since ballast water with salinity outside this range is almost certainly not oceanic. Most Australian ballast water will pass this test whether derived from a port or elsewhere, however, some ships arriving from Australia will have loaded ballast in other countries where low salinities are more prevalent (e.g. many ports in Asia). The second is to test that CDOM concentrations significantly exceed the range of ocean concentrations. Both tests could potentially be performed using *in situ* instrumentation, allowing an instantaneous determination of compliance. Additional tests, required only if greater certainty is desired, include the analysis of trace element samples, and/or a paper audit of ships records of ballast water handling, similar to the Newcastle Verification Method implemented by AQIS. In the case of trace elements, the objective is to ensure that the concentrations of trace elements exceed oceanic concentrations, subject to the types of inter-port variability that have been described in this report. In the case of the Newcastle method, the objective is to ensure that ships engine logs and power records support the ship's claims about the location and extent of BWE performed.

Given the promising results of this study in relation to CDOM, it is recommended that MAF Biosecurity New Zealand consider pursuing the *in situ* measurement of CDOM for verifying BWE in ships arriving to New Zealand. Threshold concentrations applicable to *in situ* CDOM instruments are still in development, consequently, it is critical that for the time being, *in situ* measurements are cross-checked with discrete laboratory measurements of C2* and C3* following the methods used here. We also recommend a similar approach for other tracers, i.e. that *in situ* measurements be regularly calibrated against independently determined tracer levels in the laboratory. Such procedures are critical to the success of all monitoring programs and should be included in any best-practice methods of BWE verification.

7. Acknowledgements

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Sites maps included in this report were prepared by Monaca Noble.

8. References

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Appendix A: CDOM concentrations (QSE, mean \pm SD) at fixed wavelength pairs ($\lambda_{ex}/\lambda_{em}$) by site and sampling depth (D) during surveys of Botany Bay, Port Phillip Bay and Port Curtis. C2* and C3* correspond to $\lambda_{ex}/\lambda_{em}$ of 320/414 and 370/494, respectively.

Event	Location	Site	Depth	250/450	350/450	320/414	370/494
NZ5	1	A	5	5.58 + 0.62	1.77 + 0.15	2.07 + 0.2	1.28 + 0.11
NZ5	1	B	5	3.13 + 0.16	1.05 + 0.08	1.2 + 0.09	0.75 + 0.04
NZ5	1	C	5	3.3 + 0.11	1.07 + 0.03	1.21 + 0.03	0.79 + 0.01
NZ5	2	A	1	21.86 + 0.84	6.73 + 0.33	7.9 + 0.39	4.91 + 0.26
NZ5	2	B	1	17.81 + 0.58	5.62 + 0.24	6.61 + 0.33	4.16 + 0.18
NZ5	2	C	5	2.15 + 0.13	0.76 + 0.03	0.9 + 0.03	0.52 + 0.02
NZ5	3	A	0.5	31 + 5.13	9.66 + 1.54	11.63 + 1.82	6.98 + 1.15
NZ5	3	B	5	17.97 + 0.23	5.34 + 0.16	6.42 + 0.21	3.91 + 0.09
NZ5	3	C	1.5	38.5 + 0.91	11.85 + 0.3	14.54 + 0.38	8.38 + 0.21
NZ5	4	A	5	6.76 + 0.2	2.09 + 0.08	2.41 + 0.11	1.55 + 0.06
NZ5	4	B	5	9.27 + 1.31	2.86 + 0.42	3.32 + 0.49	2.11 + 0.32
NZ5	4	C	2.5	9.43 + 1.07	2.94 + 0.37	3.31 + 0.3	2.2 + 0.19
NZ5	5	A	5	6.99 + 0.91	2.17 + 0.34	2.52 + 0.41	1.62 + 0.26
NZ5	5	B	5	6.88 + 1.28	2.07 + 0.4	2.4 + 0.48	1.55 + 0.32
NZ5	5	C	5	5.75 + 0.49	1.78 + 0.12	2.06 + 0.12	1.32 + 0.09
NZ5	6	A	2.5	18.78 + 2.19	5.65 + 0.84	6.7 + 1.01	4.16 + 0.61
NZ5	6	B	5	8.21 + 1.54	2.58 + 0.46	3.03 + 0.53	1.92 + 0.35
NZ5	6	C	3.5	6.8 + 0.53	2.08 + 0.17	2.43 + 0.19	1.53 + 0.13
NZ5	7	A	5	2.23 + 0.08	0.75 + 0.05	0.83 + 0.03	0.52 + 0.02
NZ5	7	B	5	1.68 + 0.1	0.6 + 0.12	0.63 + 0.05	0.38 + 0.03
NZ5	7	C	5	3.31 + 0.15	1.05 + 0.02	1.23 + 0.03	0.76 + 0.02
NZ5	8	A	5	5.38 + 0.74	1.64 + 0.18	1.93 + 0.22	1.22 + 0.13
NZ5	8	C	5	4.78 + 0.22	1.45 + 0.07	1.68 + 0.07	1.04 + 0.05
NZ6	0		0.2	38.59 + 0.4	11.47 + 0.02	15.35 + 0.05	8.04 + 0.12
NZ6	2	A	3	12.56 + 0.21	3.67 + 0.08	5.02 + 0.12	2.6 + 0.04
NZ6	2	B	5	13.63 + 0.11	3.79 + 0.04	6.16 + 0.05	2.64 + 0.01
NZ6	4	A	4	12.04 + 0.54	3.39 + 0.18	5 + 0.31	2.38 + 0.15
NZ6	4	B	5	11.38 + 0.12	3.22 + 0	4.81 + 0.04	2.24 + 0
NZ6	4	C	2	11.29 + 0.11	3.1 + 0.07	4.66 + 0.08	2.2 + 0.04
NZ6	5	A	5	11.08 + 0.27	3.08 + 0.07	4.62 + 0.12	2.18 + 0.06
NZ6	5	B	4.5	10.87 + 0.44	3.05 + 0.18	4.41 + 0.24	2.18 + 0.14
NZ6	5	C	5	11.12 + 0.24	3.11 + 0.08	4.63 + 0.12	2.2 + 0.04
NZ7	1	A	5	15.69 + 2.13	4.55 + 0.51	6.1 + 0.73	3.03 + 0.28
NZ7	1	B	5	13.97 + 0.71	4.14 + 0.19	5.61 + 0.26	2.75 + 0.15
NZ7	1	C	5	15.4 + 1.75	4.46 + 0.51	6.1 + 0.68	2.97 + 0.35
NZ7	2	A	4	15.03 + 1.26	4.74 + 0.36	6.18 + 0.46	3.2 + 0.26
NZ7	2	B	5	11.79 + 0.31	3.46 + 0.13	4.71 + 0.15	2.3 + 0.12
NZ7	2	C	0.5	13.24 + 2.52	3.77 + 0.83	5.1 + 1.1	2.47 + 0.57
NZ7	3	A	5	15.26 + 1.04	4.52 + 0.55	6.07 + 0.72	3 + 0.38
NZ7	3	B	5	12.19 + 1.01	3.42 + 0.44	4.69 + 0.56	2.23 + 0.3
NZ7	3	C	5	15.01 + 0.72	4.26 + 0.28	5.75 + 0.31	2.82 + 0.21
NZ7	4	A	5	10.56 + 0.57	3.02 + 0.23	3.97 + 0.26	2.04 + 0.18
NZ7	4	B	5	14.26 + 4.29	4.27 + 1.38	5.48 + 1.71	2.92 + 0.96
NZ7	4	C	1	11.9 + 1.17	3.34 + 0.25	4.33 + 0.32	2.25 + 0.19
NZ7	5	A	5	10.04 + 0.27	2.88 + 0.11	3.78 + 0.12	1.96 + 0.09
NZ7	5	B	5	12.74 + 2.43	3.73 + 1.03	4.87 + 1.29	2.53 + 0.71
NZ7	5	C	1	10.74 + 3.42	2.95 + 0.95	3.81 + 1.17	2.01 + 0.65
NZ7	6	A	5	10.3 + 1.27	2.79 + 0.15	3.64 + 0.23	1.87 + 0.12

Event	Location	Site	Depth	250/450	350/450	320/414	370/494
NZ7	6	B	5	9.82 + 0.25	2.54 + 0.25	3.38 + 0.25	1.69 + 0.17
NZ7	6	C	0.5	16.83 + 1.75	4.71 + 0.15	5.99 + 0.24	3.26 + 0.08
NZ7	7	A	5	9.74 + 0.84	2.71 + 0.1	3.66 + 0.16	1.8 + 0.03
NZ7	7	B	5	9.8 + 0.93	2.75 + 0.18	3.72 + 0.27	1.8 + 0.08
NZ7	7	C	1	10.21 + 2.65	2.91 + 0.83	3.88 + 1.05	1.97 + 0.57
NZ7	8	A	5	3.5 + 0.56	0.93 + 0.25	1.19 + 0.34	0.62 + 0.17
NZ7	8	B	5	8.01 + 0.63	2.19 + 0.25	3.04 + 0.32	1.42 + 0.21
NZ7	8	C	1	7.88 + 1.24	2.24 + 0.42	2.97 + 0.51	1.55 + 0.26
NZ7	9	A	1	121.85 + 0	43.83 + 0	52.31 + 0	30.63 + 0
NZ8	1	A	5	14.53 + 0.08	4.2 + 0.03	5.62 + 0.03	2.81 + 0.02
NZ8	1	B	5	13.63 + 0.75	3.93 + 0.29	5.27 + 0.4	2.6 + 0.11
NZ8	1	C	5	14.54 + 0.15	4.17 + 0.03	5.5 + 0.07	2.8 + 0.01
NZ8	2	A	5	16.79 + 0	5 + 0	6.63 + 0	3.38 + 0
NZ8	2	B	5.5	13.06 + 0.31	3.73 + 0.03	4.98 + 0.03	2.52 + 0.01
NZ8	2	C	4	13.63 + 0.17	3.87 + 0.04	5.19 + 0.04	2.63 + 0.01
NZ8	3	A	5	14.11 + 0.25	4.06 + 0.11	5.39 + 0.09	2.69 + 0.04
NZ8	3	B	5	13.76 + 0.27	3.9 + 0.02	5.21 + 0.02	2.64 + 0.03
NZ8	3	C	5	13.96 + 0.35	3.89 + 0.14	5.25 + 0.15	2.64 + 0.11
NZ8	4	A	5	14.03 + 0.36	4.1 + 0.08	5.28 + 0.08	2.82 + 0.04
NZ8	4	B	5	14.73 + 0.13	4.4 + 0.05	5.6 + 0.02	3.03 + 0.02
NZ8	4	C	1	15.09 + 0.23	4.52 + 0.09	5.75 + 0.07	3.12 + 0.08
NZ8	5	A	5	13.99 + 0.21	4.07 + 0.03	5.18 + 0.05	2.78 + 0.01
NZ8	5	B	5	13.19 + 0.44	3.83 + 0.18	4.91 + 0.21	2.62 + 0.08
NZ8	5	C	5	13.47 + 0.66	3.93 + 0.19	5.11 + 0.2	2.71 + 0.11
NZ8	6	A	5	12.39 + 0	3.53 + 0	4.64 + 0	2.4 + 0
NZ8	6	B	5	14.33 + 0.45	4.14 + 0.06	5.32 + 0.1	2.86 + 0.06
NZ8	6	C	1	16.88 + 0.48	5.01 + 0.11	6.27 + 0.18	3.49 + 0.11
NZ8	7	A	5	9.93 + 0.07	2.71 + 0.04	3.73 + 0.03	1.81 + 0.02
NZ8	7	B	5	7.77 + 0.05	1.99 + 0.02	2.79 + 0.09	1.34 + 0.01
NZ8	7	C	1.5	10.79 + 0.45	2.97 + 0.04	3.92 + 0.04	2.03 + 0.04
NZ8	8	A	5	2.42 + 0.09	0.72 + 0.02	0.8 + 0.01	0.49 + 0.01
NZ8	8	B	5	7.37 + 0.26	1.91 + 0.02	2.71 + 0.07	1.27 + 0.02
NZ8	8	C	5	5.62 + 0	1.47 + 0	1.98 + 0	0.99 + 0
NZ8	9	A	0.1	81.18 + 0.43	31.61 + 0.19	34.93 + 0.15	22 + 0.06
NZ9	1	A	4.5	33.16 + 0	9.61 + 0	14.52 + 0	6.69 + 0
NZ9	1	C	1	27.55 + 1.07	8.27 + 0.35	11.21 + 0.37	5.8 + 0.24
NZ9	13	C	4	29.37 + 0.51	8.66 + 0.03	12.17 + 0.14	6.03 + 0
NZ9	2	A	2	24.8 + 0.11	7.46 + 0.05	10.06 + 0.15	5.21 + 0.03
NZ9	3	B	3.5	17.77 + 0.35	5.27 + 0.1	6.77 + 0.1	3.68 + 0.07
NZ9	3	C	1	17.69 + 0.06	5.34 + 0.03	6.62 + 0.03	3.78 + 0.03
NZ9	4	A	4.5	20.82 + 0.34	6.19 + 0.02	8.27 + 0.09	4.35 + 0.05
NZ9	4	B	5	18.55 + 0.56	5.4 + 0.23	7.15 + 0.33	3.82 + 0.16
NZ9	4	C	3	20.35 + 0.27	6.05 + 0.09	8.01 + 0.1	4.24 + 0.03
NZ9	5	B	5	19.09 + 0.04	5.68 + 0.09	7.45 + 0.03	4 + 0
NZ9	6	A	5	18.97 + 0.37	5.64 + 0.02	7.44 + 0.01	3.96 + 0
NZ9	6	B	5	17.37 + 0.32	5.25 + 0.1	6.84 + 0.06	3.67 + 0.05
NZ9	6	C	4	19.85 + 0.46	5.94 + 0.18	7.84 + 0.25	4.16 + 0.13
NZ9	7	A	1	25.49 + 0.45	7.48 + 0.12	9.94 + 0.14	5.28 + 0.09
NZ9	8	A	5	5.58 + 0.51	1.67 + 0.26	2.18 + 0.38	1.15 + 0.17
NZ9	8	B	5	11.44 + 0.27	3.4 + 0.07	4.45 + 0.1	2.36 + 0.07
NZ9	8	C	4	17.81 + 0.28	5.38 + 0.06	7.01 + 0.01	3.76 + 0.04

Appendix B: Ba, Mn and P concentrations (μgL^{-1} , mean \pm SD) by site and sampling depth during surveys of Botany Bay, Port Phillip Bay and Port Curtis.

Survey	Location	Site	Depth, m	Ba	Mn	P
NZ5	1	A	5	5.43 \pm 0.59	0.89 \pm 0.1	12.44 \pm 1.24
NZ5	1	B	5	5.19 \pm 0.61	0.51 \pm 0.06	12.01 \pm 1.7
NZ5	1	C	5	5.1 \pm 0.39	0.57 \pm 0.06	10.67 \pm 0.47
NZ5	2	A	1	7.7 \pm 0.09	2.81 \pm 0.11	14.6 \pm 0.33
NZ5	2	B	1	8.97 \pm 0.01	4.51 \pm 0.17	20.27 \pm 0.38
NZ5	2	C	5	5.22 \pm 0.08	0.32 \pm 0.04	14.95 \pm 0.78
NZ5	3	A	0.5	12.42 \pm 0.89	5.34 \pm 0.33	25.4 \pm 1.06
NZ5	3	B	5	9.98 \pm 0.03	2.93 \pm 0.06	21.63 \pm 1.56
NZ5	3	C	1.5	15.92 \pm 1.72	5.18 \pm 0.7	28.1 \pm 2.75
NZ5	4	A	5	6.6 \pm 0.41	1.57 \pm 0.08	19.64 \pm 1.59
NZ5	4	B	5	6.21 \pm 0.27	1.95 \pm 0.09	18.44 \pm 0.96
NZ5	4	C	2.5	7.99 \pm 1.19	2.32 \pm 0.33	20.77 \pm 3.19
NZ5	5	A	5	5.75 \pm 0.13	1.21 \pm 0.03	18.48 \pm 2.07
NZ5	5	B	5	5.78 \pm 0.15	1.12 \pm 0.03	17.21 \pm 0.07
NZ5	5	C	5	5.7 \pm 0.08	1.02 \pm 0.01	16.45 \pm 0.12
NZ5	6	A	2.5	7.98 \pm 0.06	2.43 \pm 0.03	18.45 \pm 0.49
NZ5	6	B	5	5.84 \pm 0.05	1.34 \pm 0.04	18.52 \pm 0.58
NZ5	6	C	3.5	5.42 \pm 0.27	0.95 \pm 0.02	14.49 \pm 1.11
NZ5	7	A	5	4.89 \pm 0.05	0.4 \pm 0.02	14.65 \pm 0.67
NZ5	7	B	5	5.2 \pm 0.11	0.23 \pm 0.01	13.72 \pm 0.23
NZ5	7	C	5	4.96 \pm 0.05	0.49 \pm 0.01	13.95 \pm 0.49
NZ5	8	A	5	5.27 \pm 0.3	0.94 \pm 0.08	15.45 \pm 0
NZ5	8	B	0.5	5.23 \pm 0.28	0.81 \pm 0.07	13.04 \pm 0.58
NZ5	8	C	5	4.85 \pm 0.23	0.65 \pm 0.03	14.07 \pm 1.31
NZ5	9	A	air	0.03 \pm 0	0 \pm 0.01	0.08 \pm 0.13
NZ6	0		0.2	53.94 \pm 3.33	21.39 \pm 1.77	9.33 \pm 1.08
NZ6	2	A	4	7.86 \pm 0.18	4.9 \pm 0.14	7.48 \pm 0.41
NZ6	2	B	5	7.19 \pm 0.07	1.39 \pm 0.01	6.31 \pm 0.23
NZ6	4	A	4	6.81 \pm 0.12	1.71 \pm 0.01	6.17 \pm 0.16
NZ6	4	B	5	7.07 \pm 0.37	1.51 \pm 0.12	7.47 \pm 0.01
NZ6	4	C	2	7.04 \pm 0	1.71 \pm 0.08	7.39 \pm 0.56
NZ6	5	A	5	6.92 \pm 0.03	1.32 \pm 0.05	6.62 \pm 0.94
NZ6	5	B	4.5	6.8 \pm 0.15	1.24 \pm 0.08	7.97 \pm 4.24
NZ6	5	C	5	6.56 \pm 0.42	1.28 \pm 0.06	4.81 \pm 0.42
NZ7	1	A	5	10.53 \pm 0.19	6.34 \pm 0.14	86.77 \pm 1.4
NZ7	1	B	5	10.46 \pm 0.17	6.13 \pm 0.07	83.5 \pm 1.49
NZ7	1	C	5	10.38 \pm 0.09	5.72 \pm 0.02	82.46 \pm 1.6
NZ7	2	A	4	10.33 \pm 0.55	2.92 \pm 0.1	86.76 \pm 2.1
NZ7	2	B	5	8.87 \pm 0.14	2.55 \pm 0.02	78.61 \pm 1.9
NZ7	2	C	0.5	10.55 \pm 0.11	6.96 \pm 0.12	80.4 \pm 0.15
NZ7	3	A	5	9.86 \pm 0.72	6.34 \pm 0.41	85.42 \pm 2.33
NZ7	3	B	5	10.48 \pm 0.11	7.1 \pm 0.03	84.34 \pm 1.02
NZ7	3	C	5	10.62 \pm 0.18	7.23 \pm 0.19	89.67 \pm 3.11
NZ7	4	A	5	10.2 \pm 0.18	7.47 \pm 0.17	88.78 \pm 1.26
NZ7	4	B	5	10.59 \pm 0.25	7.03 \pm 0.34	90.78 \pm 7.3
NZ7	4	C	1	9.98 \pm 0.55	6.63 \pm 0.21	89.12 \pm 2.3
NZ7	5	A	5	9.65 \pm 0.06	7.47 \pm 0.12	90.87 \pm 0.35
NZ7	5	B	5	9.62 \pm 0.21	6.77 \pm 0.24	89.03 \pm 3.64
NZ7	5	C	1	10.53 \pm 0.17	7.06 \pm 0.15	92.08 \pm 1.3

Survey	Location	Site	Depth, m	Ba	Mn	P
NZ7	6	A	5	9.61 ± 0.1	5.8 ± 0.06	93.22 ± 2.07
NZ7	6	B	5	9.88 ± 0.21	6.14 ± 0.14	86.74 ± 1.58
NZ7	6	C	0.5	11.06 ± 0.13	8.25 ± 0.21	86.04 ± 1.63
NZ7	7	A	5	8.97 ± 0.19	2.65 ± 0.13	75.59 ± 2.02
NZ7	7	B	5	8.87 ± 0.26	2.27 ± 0.08	74.33 ± 1.77
NZ7	7	C	1	9.14 ± 0.23	1.88 ± 0.05	90.58 ± 1.34
NZ7	8	A	5	6.63 ± 0.11	0.68 ± 0.04	20.44 ± 0.51
NZ7	8	B	5	8.93 ± 0.04	1 ± 0.02	74.36 ± 1.09
NZ7	8	C	1	8.69 ± 0.09	1.9 ± 0	49.34 ± 2.47
NZ7	9	A	1	26.61 ± 0.38	14.78 ± 0.06	19.71 ± 1.57
NZ8	1	A	5	10.06 ± 0.18	5.08 ± 0.11	62.19 ± 0.12
NZ8	1	B	5	9.95 ± 0.14	4.5 ± 0.01	61.14 ± 0.24
NZ8	1	C	5	10.42 ± 0.15	5.57 ± 0.09	63.7 ± 0.02
NZ8	2	A	5	11.08 ± 0.17	4.21 ± 0.07	65.17 ± 0.35
NZ8	2	B	5.5	8.95 ± 0.22	3.96 ± 0.18	63.45 ± 1.77
NZ8	2	C	4	10.07 ± 0.02	4.55 ± 0.07	62.31 ± 0.54
NZ8	3	A	5	9.63 ± 0.34	4.36 ± 0.04	61.1 ± 1.51
NZ8	3	B	5	8.98 ± 0.65	4.46 ± 0.28	58.21 ± 1.1
NZ8	3	C	5	10.12 ± 0	4.69 ± 0	62.92 ± 0
NZ8	4	A	5	10.07 ± 0.04	3.32 ± 0.14	81.6 ± 2.84
NZ8	4	B	5	10.16 ± 0.36	3.49 ± 0.15	78.28 ± 4.31
NZ8	4	C	1	10.33 ± 0.5	3.7 ± 0.3	80.38 ± 5.95
NZ8	5	A	5	10.22 ± 0.48	3.5 ± 0.16	77.42 ± 3.29
NZ8	5	B	5	10.06 ± 0	3.07 ± 0	77.8 ± 0
NZ8	5	C	5	9.89 ± 0.73	3.21 ± 0.39	75.8 ± 6.59
NZ8	6	A	5	9.73 ± 0	2.36 ± 0	75.94 ± 0
NZ8	6	B	5	10.32 ± 0.29	3.42 ± 0.14	77.68 ± 5.15
NZ8	6	C	1	10.68 ± 0.44	4.72 ± 0.21	73.23 ± 3.71
NZ8	7	A	5	7.49 ± 0.26	3.64 ± 0.17	55.81 ± 3.67
NZ8	7	B	5	7.49 ± 0.03	2.14 ± 0.01	48.4 ± 1.27
NZ8	7	C	1.5	8.39 ± 0.31	1.61 ± 0.04	70.52 ± 4.89
NZ8	8	A	5	5.42 ± 0.13	0.14 ± 0.01	8.68 ± 0.77
NZ8	8	B	5	5.69 ± 0.14	1.5 ± 0.05	46.65 ± 2.93
NZ8	8	C	5	6.88 ± 0.05	1.15 ± 0.05	32.94 ± 1.77
NZ8	9	A	0.1	19.2 ± 1.03	14.03 ± 1.01	6.98 ± 0.91
NZ9	1	A	4.5	11.3 ± 0.81	3.68 ± 0.1	6.79 ± 1.68
NZ9	1	C	1	11.22 ± 0.33	2.93 ± 0.03	8.27 ± 0.27
NZ9	13	C	4	11.74 ± 0.19	1.33 ± 0.01	7.51 ± 0.02
NZ9	2	A	2	10.4 ± 0.1	2.4 ± 0.08	8.21 ± 0.4
NZ9	3	B	3.5	8.2 ± 0.06	1.69 ± 0.01	6.96 ± 0.18
NZ9	3	C	1	8.06 ± 0.17	4.74 ± 0.11	4.54 ± 0.17
NZ9	4	A	4.5	9.38 ± 0.14	1.54 ± 0	7.95 ± 0.08
NZ9	4	B	5	8.25 ± 0.04	0.46 ± 0.02	6.55 ± 0.86
NZ9	4	C	3	9.48 ± 0.56	1.92 ± 0.13	7.18 ± 0.57
NZ9	5	B	5	8.91 ± 0.08	0.49 ± 0.01	7.71 ± 0.81
NZ9	6	A	5	8.73 ± 0.2	1.48 ± 0.05	6.78 ± 0.16
NZ9	6	B	5	8.15 ± 0.01	0.68 ± 0.01	6.25 ± 0.14
NZ9	6	C	4	9.3 ± 0.21	1.81 ± 0.06	6.98 ± 0.62
NZ9	7	A	1	9.78 ± 0.01	6.04 ± 0.19	6.75 ± 0.39
NZ9	8	A	5	4.9 ± 0.06	0.63 ± 0.06	4.1 ± 0.3
NZ9	8	B	5	6.06 ± 0	0.31 ± 0	5.06 ± 0.05
NZ9	8	C	4	8.47 ± 0.16	1.03 ± 0.08	8.96 ± 3.57

Appendix C: As, Mo, U and V concentrations (μgL^{-1} , mean \pm SD) by site and sampling depth during surveys of Botany Bay, Port Phillip Bay and Port Curtis.

Survey	Location	Site	Depth, m	As	Mo	U	V
NZ5	1	A	5	1.51 \pm 0.25	10.27 \pm 0.47	3.16 \pm 0.35	1.58 \pm 0.15
NZ5	1	B	5	1.68 \pm 0.3	11.21 \pm 0.95	3.55 \pm 0.44	1.77 \pm 0.24
NZ5	1	C	5	1.47 \pm 0.37	10.96 \pm 0.35	3.46 \pm 0.25	1.7 \pm 0.13
NZ5	2	A	1	1.25 \pm 0.3	10.47 \pm 0.19	2.99 \pm 0.01	1.38 \pm 0.06
NZ5	2	B	1	2 \pm 0.26	13.6 \pm 0.36	3.82 \pm 0.02	1.92 \pm 0.08
NZ5	2	C	5	1.94 \pm 0.11	11.92 \pm 0.47	3.54 \pm 0.03	1.82 \pm 0.06
NZ5	3	A	0.5	1.45 \pm 0.19	12.12 \pm 0.96	3.48 \pm 0.26	1.59 \pm 0.09
NZ5	3	B	5	1.76 \pm 0.24	12.74 \pm 0.39	3.76 \pm 0.08	1.76 \pm 0.03
NZ5	3	C	1.5	1.65 \pm 0.36	11.11 \pm 0.02	3.29 \pm 0.49	1.52 \pm 0.21
NZ5	4	A	5	1.97 \pm 0.03	13.18 \pm 1.02	3.73 \pm 0.2	1.99 \pm 0.08
NZ5	4	B	5	1.8 \pm 0.11	11.14 \pm 0.13	3.44 \pm 0.12	1.82 \pm 0.06
NZ5	4	C	2.5	2.09 \pm 0.39	14.46 \pm 3.03	4.26 \pm 0.74	2.28 \pm 0.39
NZ5	5	A	5	1.89 \pm 0.29	10.93 \pm 0.25	3.29 \pm 0.12	1.7 \pm 0.05
NZ5	5	B	5	2.05 \pm 0.08	12.13 \pm 0.41	3.46 \pm 0.12	1.73 \pm 0.03
NZ5	5	C	5	1.89 \pm 0.11	11.68 \pm 0.47	3.32 \pm 0.09	1.7 \pm 0.04
NZ5	6	A	2.5	1.9 \pm 0.02	11.8 \pm 0.02	3.41 \pm 0.02	1.58 \pm 0.05
NZ5	6	B	5	1.96 \pm 0.05	11.32 \pm 0.75	3.36 \pm 0.06	1.59 \pm 0.03
NZ5	6	C	3.5	1.85 \pm 0.12	10.89 \pm 0.26	3.34 \pm 0.14	1.58 \pm 0.08
NZ5	7	A	5	2 \pm 0.06	11.43 \pm 0.25	3.48 \pm 0.02	1.72 \pm 0.01
NZ5	7	B	5	2.12 \pm 0.1	12.43 \pm 0.04	3.75 \pm 0.06	1.76 \pm 0.01
NZ5	7	C	5	1.98 \pm 0.07	11.04 \pm 0.45	3.33 \pm 0.04	1.62 \pm 0.03
NZ5	8	A	5	2.32 \pm 0.49	11.01 \pm 0.99	3.23 \pm 0.19	1.59 \pm 0.13
NZ5	8	B	0.5	1.93 \pm 0.08	11.54 \pm 0.12	3.43 \pm 0.27	1.68 \pm 0.12
NZ5	8	C	5	1.79 \pm 0.16	10.55 \pm 0.37	3.06 \pm 0.21	1.47 \pm 0.04
NZ5	9	A	air	-0.01 \pm 0.01	0.12 \pm 0.1	0 \pm 0.01	-0.01 \pm 0.01
NZ6	0		0.2	0.7 \pm 0.1	7.64 \pm 0.98	2.28 \pm 0.21	2.16 \pm 0.23
NZ6	2	A	4	0.88 \pm 0.05	10.65 \pm 0.15	3.31 \pm 0.09	1.3 \pm 0.01
NZ6	2	B	5	0.89 \pm 0.07	10.51 \pm 0.07	3.33 \pm 0.03	1.33 \pm 0.01
NZ6	4	A	4	0.67 \pm 0.08	10.66 \pm 0.13	3.21 \pm 0.13	1.28 \pm 0.01
NZ6	4	B	5	0.8 \pm 0.18	11.15 \pm 0.25	3.41 \pm 0.3	1.36 \pm 0.04
NZ6	4	C	2	0.97 \pm 0.06	11.31 \pm 0.36	3.29 \pm 0.09	1.36 \pm 0.01
NZ6	5	A	5	0.93 \pm 0.03	11.07 \pm 0.13	3.36 \pm 0.03	1.34 \pm 0.01
NZ6	5	B	4.5	0.86 \pm 0.07	11.41 \pm 0.05	3.39 \pm 0.19	1.32 \pm 0.01
NZ6	5	C	5	0.69 \pm 0.01	10.22 \pm 0.52	3.24 \pm 0.29	1.21 \pm 0.08
NZ7	1	A	5	3.56 \pm 0.04	11.54 \pm 0.56	3.6 \pm 0.02	2.25 \pm 0.06
NZ7	1	B	5	3.43 \pm 0.25	12.11 \pm 0.18	3.57 \pm 0.05	2.25 \pm 0.02
NZ7	1	C	5	3.2 \pm 0.05	12.15 \pm 0.49	3.62 \pm 0.09	2.19 \pm 0.05
NZ7	2	A	4	3.02 \pm 0.04	11.46 \pm 0.42	3.52 \pm 0.14	1.97 \pm 0.06
NZ7	2	B	5	3.09 \pm 0.13	12.4 \pm 0.4	3.58 \pm 0.03	2.22 \pm 0.02
NZ7	2	C	0.5	3.16 \pm 0.21	12.2 \pm 0.38	3.53 \pm 0.04	2.18 \pm 0.08
NZ7	3	A	5	3.33 \pm 0.22	11.48 \pm 0.86	3.36 \pm 0.24	2.1 \pm 0.16
NZ7	3	B	5	3.32 \pm 0.11	11.97 \pm 0.18	3.54 \pm 0.06	2.23 \pm 0.01
NZ7	3	C	5	3.44 \pm 0.16	12.16 \pm 0.46	3.62 \pm 0.04	2.22 \pm 0.05
NZ7	4	A	5	3.09 \pm 0.07	12.1 \pm 0.07	3.56 \pm 0.09	2.35 \pm 0.06
NZ7	4	B	5	3.16 \pm 0.04	12.02 \pm 0.93	3.5 \pm 0.01	2.29 \pm 0.03
NZ7	4	C	1	3.14 \pm 0.22	11.58 \pm 0.11	3.3 \pm 0.09	2.25 \pm 0.11
NZ7	5	A	5	2.87 \pm 0.1	11.79 \pm 0.71	3.38 \pm 0.06	2.36 \pm 0.02
NZ7	5	B	5	3.03 \pm 0.06	12.14 \pm 0.28	3.37 \pm 0.14	2.36 \pm 0.11
NZ7	5	C	1	2.94 \pm 0.12	11.4 \pm 0.07	3.16 \pm 0.05	2.2 \pm 0.08

Survey	Location	Site	Depth, m	As	Mo	U	V
NZ7	6	A	5	2.93 ± 0.13	12.1 ± 0.95	3.47 ± 0.06	2.37 ± 0.03
NZ7	6	B	5	2.96 ± 0.13	11.76 ± 0.53	3.46 ± 0.09	2.28 ± 0.05
NZ7	6	C	0.5	2.81 ± 0.18	10.94 ± 0.77	3.35 ± 0.11	2.38 ± 0.07
NZ7	7	A	5	2.77 ± 0.07	11.9 ± 0.11	3.4 ± 0.08	2.48 ± 0.08
NZ7	7	B	5	2.92 ± 0.14	12.26 ± 0.8	3.55 ± 0.11	2.32 ± 0.05
NZ7	7	C	1	3.03 ± 0.17	12.53 ± 0.79	3.57 ± 0.01	2.4 ± 0.02
NZ7	8	A	5	1.97 ± 0.17	11.36 ± 0.43	3.45 ± 0.05	1.7 ± 0.04
NZ7	8	B	5	2.92 ± 0.29	11.71 ± 0.16	3.62 ± 0.01	2.31 ± 0.06
NZ7	8	C	1	2.68 ± 0.05	12.1 ± 0.38	3.61 ± 0.07	2.28 ± 0.09
NZ7	9	A	1	0.57 ± 0.05	0.59 ± 0.14	0.05 ± 0.02	0.76 ± 0.04
NZ8	1	A	5	1.87 ± 0.08	10.07 ± 0.06	3.37 ± 0.04	1.89 ± 0.01
NZ8	1	B	5	1.74 ± 0.34	9.9 ± 0.84	3.41 ± 0.04	1.82 ± 0.01
NZ8	1	C	5	2.26 ± 0.26	10.68 ± 0.24	3.48 ± 0.08	1.91 ± 0.04
NZ8	2	A	5	2.18 ± 0.05	10.23 ± 0.3	3.56 ± 0.04	1.95 ± 0.02
NZ8	2	B	5.5	1.95 ± 0.38	10.67 ± 0.74	3.5 ± 0.01	1.95 ± 0.07
NZ8	2	C	4	1.95 ± 0.34	10.51 ± 0.35	3.58 ± 0.16	1.88 ± 0.07
NZ8	3	A	5	1.61 ± 0.1	10.3 ± 0.54	3.44 ± 0	1.81 ± 0.11
NZ8	3	B	5	1.51 ± 0.09	9.3 ± 0.3	3.06 ± 0.2	1.66 ± 0.08
NZ8	3	C	5	2.19 ± 0	10.77 ± 0	3.63 ± 0	1.87 ± 0
NZ8	4	A	5	2.11 ± 0.25	10.11 ± 0.47	3.39 ± 0.01	1.93 ± 0.08
NZ8	4	B	5	1.94 ± 0.22	9.96 ± 0.48	3.34 ± 0.15	1.93 ± 0.11
NZ8	4	C	1	2.03 ± 0.65	10.36 ± 0.31	3.38 ± 0.16	1.92 ± 0.1
NZ8	5	A	5	1.87 ± 0.52	10.32 ± 0.92	3.43 ± 0.15	1.96 ± 0.07
NZ8	5	B	5	2.51 ± 0	9.9 ± 0	3.38 ± 0	1.94 ± 0
NZ8	5	C	5	1.93 ± 0.62	10.14 ± 0.75	3.37 ± 0.27	1.91 ± 0.14
NZ8	6	A	5	2.16 ± 0	10.19 ± 0	3.4 ± 0	1.94 ± 0
NZ8	6	B	5	2.22 ± 0.39	10.37 ± 0.78	3.39 ± 0.12	1.95 ± 0.11
NZ8	6	C	1	2.08 ± 0.45	9.84 ± 0.55	3.25 ± 0.19	1.78 ± 0.09
NZ8	7	A	5	1.84 ± 0.43	9.31 ± 0.28	3.42 ± 0.11	1.81 ± 0.12
NZ8	7	B	5	1.89 ± 0.26	8.2 ± 0.15	3.43 ± 0.05	1.7 ± 0.02
NZ8	7	C	1.5	1.82 ± 0.63	9.41 ± 0.71	3.37 ± 0.12	1.74 ± 0.12
NZ8	8	A	5	1.47 ± 0.2	9.97 ± 0.68	3.25 ± 0.14	1.33 ± 0.08
NZ8	8	B	5	1.95 ± 0.27	7.78 ± 0.3	3.36 ± 0.03	1.71 ± 0.02
NZ8	8	C	5	1.69 ± 0.55	8.47 ± 0.2	3.23 ± 0.12	1.56 ± 0.08
NZ8	9	A	0.1	0.27 ± 0.01	0.12 ± 0.01	0.03 ± 0	0.39 ± 0.02
NZ9	1	A	4.5	0.96 ± 0.31	10.11 ± 0.32	2.52 ± 0.08	1.9 ± 0.1
NZ9	1	C	1	1.16 ± 0.04	10.36 ± 0.21	2.71 ± 0.09	1.92 ± 0.01
NZ9	13	C	4	1.28 ± 0.24	10.6 ± 0.88	2.88 ± 0.02	1.9 ± 0
NZ9	2	A	2	1.27 ± 0.08	10.63 ± 0.65	2.76 ± 0.05	1.84 ± 0.03
NZ9	3	B	3.5	1.24 ± 0.07	10.64 ± 0.01	2.89 ± 0.01	1.78 ± 0.01
NZ9	3	C	1	1.4 ± 0.21	10.81 ± 0.46	3.1 ± 0.02	1.85 ± 0.01
NZ9	4	A	4.5	1.31 ± 0.24	11.16 ± 0.54	2.98 ± 0.13	1.79 ± 0.04
NZ9	4	B	5	1.38 ± 0.04	10.44 ± 0.19	2.91 ± 0.01	1.71 ± 0.04
NZ9	4	C	3	1.35 ± 0.25	11.49 ± 0.52	3.07 ± 0.17	1.92 ± 0.13
NZ9	5	B	5	1.35 ± 0.14	10.49 ± 0.19	2.95 ± 0.01	1.78 ± 0.02
NZ9	6	A	5	1.4 ± 0.01	10.8 ± 0.35	2.97 ± 0.07	1.78 ± 0.01
NZ9	6	B	5	1.4 ± 0.1	11.36 ± 0.77	2.97 ± 0.04	1.77 ± 0.02
NZ9	6	C	4	1.38 ± 0.08	11.13 ± 1.08	3.05 ± 0.09	1.84 ± 0.06
NZ9	7	A	1	1.42 ± 0.14	11.46 ± 0.06	3.08 ± 0	2.19 ± 0.07
NZ9	8	A	5	1.72 ± 0.03	10.78 ± 0.4	3.32 ± 0.08	1.55 ± 0.04
NZ9	8	B	5	1.45 ± 0.08	10.56 ± 0.88	3.17 ± 0	1.58 ± 0.04
NZ9	8	C	4	1.34 ± 0.14	10.72 ± 0.28	3.11 ± 0.03	1.75 ± 0.02

Appendix D: Raw (unadjusted) physico-chemical data (Sal: salinity, Con: conductivity, Temp: temperature, dO: dissolved oxygen) by site and average sampling depth (d) during surveys of Botany Bay, Port Phillip Bay and Port Curtis.

Survey	Location	Site	d (m)	Con (mScm ⁻¹)		Sal (psu)		Temp (°C)		dO (mgL)		dO (%)	
				mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
NZ5	1	A	2.8	53.55	0.08	37.96	0.02	21.88	0.11				
NZ5	1	B	2.8	54.42	0.32	38.42	0.06	22.14	0.22				
NZ5	1	C	2.8	54.55	0.19	38.47	0.05	22.21	0.14				
NZ5	2	A	0.5	51.26	0.06	36.34	0.01	21.63	0.06				
NZ5	2	B	1.0			33.50		22.60					
NZ5	2	C	2.8	53.48	0.33	38.42	0.02	21.29	0.31				
NZ5	3	A	0.0	49.62		34.58		22.18					
NZ5	3	B	2.8	50.80	0.43	35.57	0.32	22.12	0.02				
NZ5	3	C	1.7	46.37	0.07	32.16	0.06	22.04	0.04				
NZ5	4	A	2.8	53.54	0.03	38.15	0.08	21.65	0.10				
NZ5	4	B	2.8	53.16	0.04	37.84	0.05	21.65	0.02				
NZ5	4	C	2.8	53.25	0.13	38.02	0.02	21.53	0.09				
NZ5	5	A	2.8	53.46	0.09	38.16	0.05	21.55	0.08				
NZ5	5	B	2.8	53.47	0.07	38.27	0.03	21.46	0.03				
NZ5	5	C	2.8	53.50	0.14	38.17	0.07	21.51	0.10				
NZ5	6	A	1.8					22.60	0.14				
NZ5	6	A	2.5			34.00	1.41						
NZ5	6	B	2.8	53.28	0.09	37.71	0.15	21.89	0.09				
NZ5	6	C	2.5	53.73	0.12	38.48	0.03	21.46	0.07				
NZ5	7	A	2.7	53.99	0.23	38.16	0.13						
NZ5	7	A	3.0					22.03	0.12				
NZ5	7	B	2.8	54.27	0.20	38.62	0.02	21.77	0.14				
NZ5	7	C	2.8	54.08	0.08	38.61	0.04	21.63	0.12				
NZ5	8	A	2.8	53.98	0.08	38.28	0.06	21.93	0.10				
NZ5	8	B	0.3	55.02	0.08	38.75	0.07	22.27	0.08				
NZ5	8	C	2.8	53.57	0.05	38.31	0.16	21.49	0.15				
NZ6	0	C	0.2	51.57	0.52	33.70		21.17	0.04	6.15		101.00	
NZ6	1	A	2.7	54.63	0.61	35.80	0.00	21.04	0.07	6.17	0.04	88.78	
NZ6	1	B	2.7	54.58	0.60	35.80	0.00	21.10	0.18	6.51	0.12	93.20	
NZ6	1	C	0.5	54.76	0.64								
NZ6	1	C	0.8			35.90	0.00						
NZ6	1	C	1.0					20.38	0.02			93.10	
NZ6	1	C	1.5							6.75	0.08		
NZ6	2	A	2.3	54.65	0.63	35.77	0.15	25.10	0.16	5.76	0.02	91.02	
NZ6	2	B	2.7	54.65	0.46	35.87	0.06	21.54	0.61	6.22	0.13	90.90	
NZ6	2	C	0.8	54.55	0.77	35.65	0.21	20.36	0.05	6.87	0.17	96.50	
NZ6	3	A	1.5	54.22	0.59	35.50	0.00	20.35	0.16	6.68	0.18	93.78	
NZ6	3	B	2.8	54.00	0.52	35.43	0.05	19.66	0.15	6.75	0.10	94.20	
NZ6	3	C	2.0	53.79	0.61	35.17	0.06	20.47	0.40	6.68	0.07	94.92	
NZ6	4	A	2.7	54.49	0.57	35.77	0.06	20.96	0.04	6.22	0.10	90.63	
NZ6	4	B	2.7	54.51	0.56	35.80	0.00	20.96	0.04	6.60	0.00	93.26	
NZ6	4	C	2.0	54.45	0.70	35.67	0.23	20.93	0.04	6.50	0.00	92.57	
NZ6	5	A	2.7	54.53	0.58	35.80	0.00	20.86	0.05	6.57	0.03	94.57	
NZ6	5	B	2.0							6.37	0.15		
NZ6	5	B	2.3	54.54	0.57			20.51	0.11			91.80	
NZ6	5	B	2.7			35.80	0.10						
NZ6	5	C	2.0							6.57	0.06		
NZ6	5	C	2.3	54.43	0.69			20.86	0.06			92.35	
NZ6	5	C	2.7			35.60	0.10						
NZ6	6	A	2.0							6.61	0.19		

Survey	Location	Site	d (m)	Con (mScm ⁻¹)		Sal (psu)		Temp (°C)		dO (mgL)		dO (%)	
				mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
NZ6	6	A	2.3	54.02	0.71							92.25	
NZ6	6	A	2.7			35.23	0.25	20.41	0.07				
NZ6	6	B	2.0	53.82	0.82	35.13	0.12	20.43	0.04	6.70	0.10	93.52	
NZ6	6	C	2.2					20.26	0.05				
NZ6	6	C	2.7	53.87	0.79	35.20	0.20			6.62	0.07		
NZ6	6	C	3.0									92.92	
NZ6	7	A	0.7			35.40							
NZ6	7	A	1.0	54.76	0.71							93.28	
NZ6	7	A	1.1					19.98	0.02				
NZ6	7	B	2.0									95.88	
NZ6	7	B	2.1					20.03	0.08				
NZ6	7	B	2.8	54.17	0.01								
NZ6	7	C	0.8	53.96	0.01			18.78	0.00			91.30	
NZ6	8	A	2.7	53.71	0.01			19.80	0.01			93.47	
NZ6	8	B	2.7	54.21	0.00			20.09	0.03			98.87	
NZ6	8	C	3.8	54.38	0.01							104.00	
NZ6	8	C	3.9					20.02	0.01				
NZ7	1	A	2.8	53.50	0.01	41.92	0.02	17.69	0.01				
NZ7	1	B	2.8	53.48	0.02	42.01	0.00	17.58	0.02				
NZ7	1	C	2.8	53.48	0.06	41.95	0.01	17.65	0.02				
NZ7	2	A	2.5	52.14	0.05	41.78	0.49	16.44	0.06				
NZ7	2	B	2.8	53.62	0.02	41.79	0.03	17.91	0.04				
NZ7	2	C	0.5	53.37		42.01		17.50					
NZ7	3	A	2.8	53.52	0.05	41.82	0.03	17.80	0.01				
NZ7	3	B	2.7	52.75	0.16	41.11	0.17	17.80	0.02				
NZ7	3	C	2.8	52.36	0.77	41.14	0.39	17.44	0.30				
NZ7	4	A	3.3	53.16	0.03	41.28	0.04	18.01	0.01				
NZ7	4	B	3.3	51.67	0.97	39.75	1.10	18.38	0.15				
NZ7	4	C	1.5	53.66	0.50	40.86	0.08	18.88	0.32				
NZ7	5	A	3.3	52.84	0.40	40.87	0.39	18.13	0.06				
NZ7	5	B	3.3	52.88	0.46	40.95	0.43	18.12	0.06				
NZ7	5	C	1.5	52.09	0.01	40.30	0.04	18.09	0.04				
NZ7	6	A	3.3	53.18	0.17	41.13	0.36	18.20	0.36				
NZ7	6	B	3.3	53.02	0.30	40.91	0.36	18.27	0.13				
NZ7	6	C	0.8	53.65	0.35	40.82	0.26	18.90	0.01				
NZ7	7	A	2.8	53.12	0.06	41.45	0.04	17.82	0.01				
NZ7	7	B	3.3	53.40	0.00	41.32	0.00	18.19	0.01				
NZ7	7	C	1.2	52.63	0.06	41.32	0.02	17.55	0.04				
NZ7	8	A	2.8	51.11	0.03	39.53	0.05	17.98	0.02				
NZ7	8	B	3.3	53.39	0.04	41.27	0.03	18.22	0.01				
NZ7	8	C	1.1			40.09	1.39						
NZ7	8		1.2	53.36	0.06			18.68	0.02				
NZ7	9	A	0.7			0.43	0.49						
NZ7	9	A	0.8	0.26	0.00			16.99	0.07				
NZ8	1	A	2.8	48.02	1.63	38.34	1.43	16.39	0.04	7.67	0.44		
NZ8	1	B	2.8	47.57	1.58	38.33	1.42	15.96	0.05	7.77	0.39		
NZ8	1	C	2.8	48.12	1.62	38.34	1.44	16.46	0.06	7.48	0.42		
NZ8	2	A	2.8	48.81	1.67	38.44	1.46	17.01	0.02	7.79	0.65		
NZ8	2	B	2.8	47.96	1.59	38.30	1.39	16.37	0.05	7.82	0.58		
NZ8	2	C	2.8	47.65	1.60	38.32	1.41	16.04	0.05	8.02	0.70		
NZ8	3	A	2.8	47.82	1.63	38.30	1.42	16.25	0.05	7.57	0.50		
NZ8	3	B	3.0	47.75	1.66	38.33	1.46	16.14	0.05	7.64	0.22		
NZ8	3	C	3.0	47.92	1.66	38.25	1.48	16.34	0.05	7.47	0.29		

Survey	Location	Site	d (m)	Con (mScm ⁻¹)		Sal (psu)		Temp (°C)		dO (mgL)		dO (%)	
				mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
NZ8	4	A	3.2	45.92	1.65	36.68	1.47	16.13	0.09	7.02	0.19		
NZ8	4	B	3.2	44.95	1.87	35.88	1.63	16.03	0.09	7.06	0.18		
NZ8	4	C	1.5	53.25	2.02	36.78	1.54	22.94	0.10	6.70	0.18		
NZ8	5	A	3.2	45.67	1.64	36.67	1.40	15.92	0.16	7.42	0.38		
NZ8	5	B	3.2	45.77	1.72	36.59	1.43	16.09	0.19	7.24	0.21		
NZ8	5	C	3.2	45.65	1.81	36.67	1.52	15.97	0.29	7.15	0.23		
NZ8	6	A	3.2	46.36	1.56	37.36	1.24	16.00	0.06	7.07	0.22		
NZ8	6	B	3.0	46.20	1.58	36.84	1.44	16.19	0.10	7.20	0.27		
NZ8	6	C	1.5	45.63	1.60	36.53	1.42	16.00	0.09	6.70	0.19		
NZ8	7	A	3.0	46.82	1.83	37.73	1.65	15.88	0.04	8.08	0.86		
NZ8	7	B	3.2	45.63	1.46	37.60	1.35	14.90	0.01	7.89	0.08		
NZ8	7	C	1.8	47.35	1.48	37.93	1.34	16.14	0.04	7.52	0.32		
NZ8	8	A	3.0	49.12	4.33	36.31	1.40	14.48	0.02	8.18	0.60		
NZ8	8	B	3.0	45.59	1.50	37.54	1.39	14.92	0.04	8.22	0.83		
NZ8	8	C	3.0	45.60	1.52	37.19	1.41	15.30	0.02	7.98	0.54		
NZ8	9	A	0.1	0.14	0.02	0.09	0.01	18.35	0.08	8.28	0.60		
NZ9	1	A	2.3	48.49	0.01	31.80	0.00	24.78	0.05	5.57	0.05		
NZ9	1	C	0.8	48.82	0.11	32.05	0.07	24.75	0.21	4.96	0.48		
NZ9	13	C	1.3	48.83	0.03	31.80	0.00	25.13	0.06	5.86	0.02		
NZ9	2	A	1.5	48.95	0.25	32.10	0.17	24.83	0.06	5.89	0.08		
NZ9	3	B	1.9	50.45	0.44	33.03	0.05	25.10	0.45	4.64	0.48		
NZ9	3	C	1.1	50.40	0.10	33.50	0.00	24.47	0.06	5.98	0.09		
NZ9	4	A	2.6	50.20	0.08	32.65	0.06	25.38	0.05	5.88	0.04		
NZ9	4	B	2.8	50.23	0.05	32.90	0.00	25.00	0.08	5.63	0.11		
NZ9	4	C	2.0	50.40	0.00	32.73	0.06	25.37	0.06	5.54	0.07		
NZ9	5	B	2.8	49.78	0.05	32.50	0.00	25.13	0.05	5.71	0.02		
NZ9	6	A	2.8	50.15	0.06	32.70	0.08	25.30	0.00	5.49	0.04		
NZ9	6	B	2.6	50.25	0.06	32.90	0.00	25.03	0.05	5.84	0.03		
NZ9	6	C	2.5	50.03	0.17	32.63	0.05	25.23	0.05	5.54	0.02		
NZ9	7	A	1.6	50.00	0.00	32.45	0.06	25.40	0.08	5.73	0.15		
NZ9	8	A	2.8	52.43	0.25	34.65	0.06	24.88	0.29	5.74	0.07		
NZ9	8	B	2.8	51.43	0.10	33.78	0.21	25.00	0.22	5.74	0.06		
NZ9	8	C	2.5	50.60	0.22	33.00	0.00	25.33	0.05	5.56	0.06		

Appendix E: Baseline corrections applied to raw salinity data, as determined via cross calibration (see section 2.3).

Survey	SERC-YSI	UTS-YSI
NZ5	-	-3.8
NZ6	1.2	-
NZ7	-	-3.8
NZ8	0.6	-1.8
NZ9	0	-

Appendix F: pH by site and sampling depth (d) during surveys of Botany Bay, Port Phillip Bay and Port Curtis.

Survey	Location	Site	d	mean	SD	Survey	Location	Site	d	mean	SD
NZ5	1	A	5.0	8.20							
NZ5	1	B	5.0	8.18	0.06						
NZ5	1	C	5.0	8.25	0.01						
NZ5	2	A	1.0	8.11	0.01						
NZ5	2	B	1.0	7.89	0.12						
NZ5	2	C	5.0	8.30	0.02						
NZ5	3	A	0.0	8.02	0.01						
NZ5	3	B	5.0	8.10	0.01						
NZ5	3	C	2.0	8.06	0.04						
NZ5	4	A	5.0	8.27							
NZ5	4	B	5.0	8.25	0.01						
NZ5	4	C	5.0	8.30	0.01						
NZ5	5	A	5.0	8.31	0.01						
NZ5	5	B	5.0	8.37	0.01						
NZ5	5	C	5.0	8.31	0.01						
NZ5	6	A	2.5	8.04	0.04						
NZ5	6	B	5.0	8.19	0.00						
NZ5	6	C	4.0	8.14							
NZ5	7	A	5.0	8.19							
NZ5	7	B	5.0	8.32	0.01						
NZ5	7	C	5.0	8.32	0.01						
NZ5	8	A	5.0	8.20							
NZ5	8	B	0.5	8.23							
NZ5	8	C	5.0	8.27	0.01						
NZ6	0	C	0.2	7.97	0.01	NZ7	0	C			
NZ6	1	A	3.6	8.02	0.09	NZ7	1	A	5.0	8.20	0.01
NZ6	1	B	3.6	8.04	0.09	NZ7	1	B	5.0	8.18	0.06
NZ6	1	C	0.9	8.06	0.10	NZ7	1	C	5.0	8.25	0.00
NZ6	2	A	3.0	7.92	0.06	NZ7	2	A	4.0	8.13	0.01
NZ6	2	B	3.6	7.96	0.04	NZ7	2	B	5.0	8.25	0.01
NZ6	2	C	0.9	8.10	0.11	NZ7	2	C	0.5	8.24	0.01
NZ6	3	A	1.8	8.12	0.09	NZ7	3	A	5.0	8.20	
NZ6	3	B	3.5	8.10	0.08	NZ7	3	B	5.0	8.21	0.00
NZ6	3	C	2.4	8.14	0.09	NZ7	3	C	5.0	8.20	0.00
NZ6	4	A	3.2	7.99	0.04	NZ7	4	A	5.0	8.15	0.01
NZ6	4	B	3.6	7.99	0.05	NZ7	4	B	5.0	8.18	0.00
NZ6	4	C	2.0	8.00	0.02	NZ7	4	C	1.0	8.21	0.01
NZ6	5	A	3.3	8.01	0.03	NZ7	5	A	5.0	8.04	0.03
NZ6	5	B	3.4	8.02	0.04	NZ7	5	B	5.0	8.14	0.01
NZ6	5	C	3.6	7.99	0.03	NZ7	5	C	1.0	8.05	0.01
NZ6	6	A	3.6	8.03	0.01	NZ7	6	A	5.0	8.19	0.03
NZ6	6	B	2.4	8.10	0.08	NZ7	6	B	5.0	8.14	0.03
NZ6	6	C	3.6	8.05	0.01	NZ7	6	C	0.5	8.14	0.02
NZ6	7	A	1.5	7.94	0.03	NZ7	7	A	5.0	8.22	0.00
NZ6	7	B	3.1	8.12	0.10	NZ7	7	B	5.0	8.20	0.02
NZ6	7	C	0.9	8.14	0.13	NZ7	7	C	1.0	8.15	0.01
NZ6	8	A	5.0	8.26	0.12	NZ7	8	A	5.0	8.21	0.01
NZ6	8	B	5.0	8.21	0.11	NZ7	8	B	5.0	8.14	0.01
NZ6	8	C	4.3	8.09	0.08	NZ7	8	C	1.0	8.13	0.04
NZ6	9	A				NZ7	9	A	0.5	7.15	0.01

Survey	Location	Site	d	mean	SD	Survey	Location	Site	d	mean	SD
NZ8	1	A	3.5	8.22	0.21	NZ9	1	A	1.8	8.11	0.02
NZ8	1	B	3.5	8.22	0.19	NZ9	1	C	0.9	8.14	0.04
NZ8	1	C	3.5	8.21	0.21	NZ9	13	C	1.3	8.10	0.02
NZ8	2	A	3.2	8.21	0.18	NZ9	2	A	2.0	8.13	0.04
NZ8	2	B	3.5	8.21	0.20	NZ9	2	B			
NZ8	2	C	3.5	8.23	0.20	NZ9	2	C			
NZ8	3	A	3.5	8.21	0.21	NZ9	3	A			
NZ8	3	B	3.8	8.23	0.23	NZ9	3	B	2.4	8.16	0.05
NZ8	3	C	3.8	8.23	0.22	NZ9	3	C	1.1	8.27	0.04
NZ8	4	A	3.9	8.07	0.04	NZ9	4	A	3.3	8.15	0.07
NZ8	4	B	3.9	8.07	0.04	NZ9	4	B	3.2	8.15	0.06
NZ8	4	C	1.3	8.04	0.04	NZ9	4	C	2.3	8.14	0.07
NZ8	5	A	3.6	8.09	0.03	NZ9	5	A			
NZ8	5	B	3.9	8.09	0.04	NZ9	5	B	3.2	8.15	0.07
NZ8	5	C	3.9	8.09	0.04	NZ9	5	C			
NZ8	6	A	3.9	8.09	0.05	NZ9	6	A	3.5	8.09	0.03
NZ8	6	B	3.8	8.09	0.04	NZ9	6	B	3.4	8.15	0.07
NZ8	6	C	3.3	8.07	0.05	NZ9	6	C	3.3	8.09	0.03
NZ8	7	A	3.8	8.21	0.23	NZ9	7	A	1.4	8.06	0.02
NZ8	7	B	3.2	8.06	0.01	NZ9	7	B			
NZ8	7	C	3.1	8.12	0.07	NZ9	7	C			
NZ8	8	A	3.8	8.17	0.24	NZ9	8	A			
NZ8	8	B	3.8	8.22	0.21	NZ9	8	A	3.5	8.19	0.09
NZ8	8	C	3.8	8.22	0.21	NZ9	8	B	3.5	8.04	0.16
NZ8	9	A	0.1	7.74	1.09	NZ9	8	C	3.0	8.14	0.08