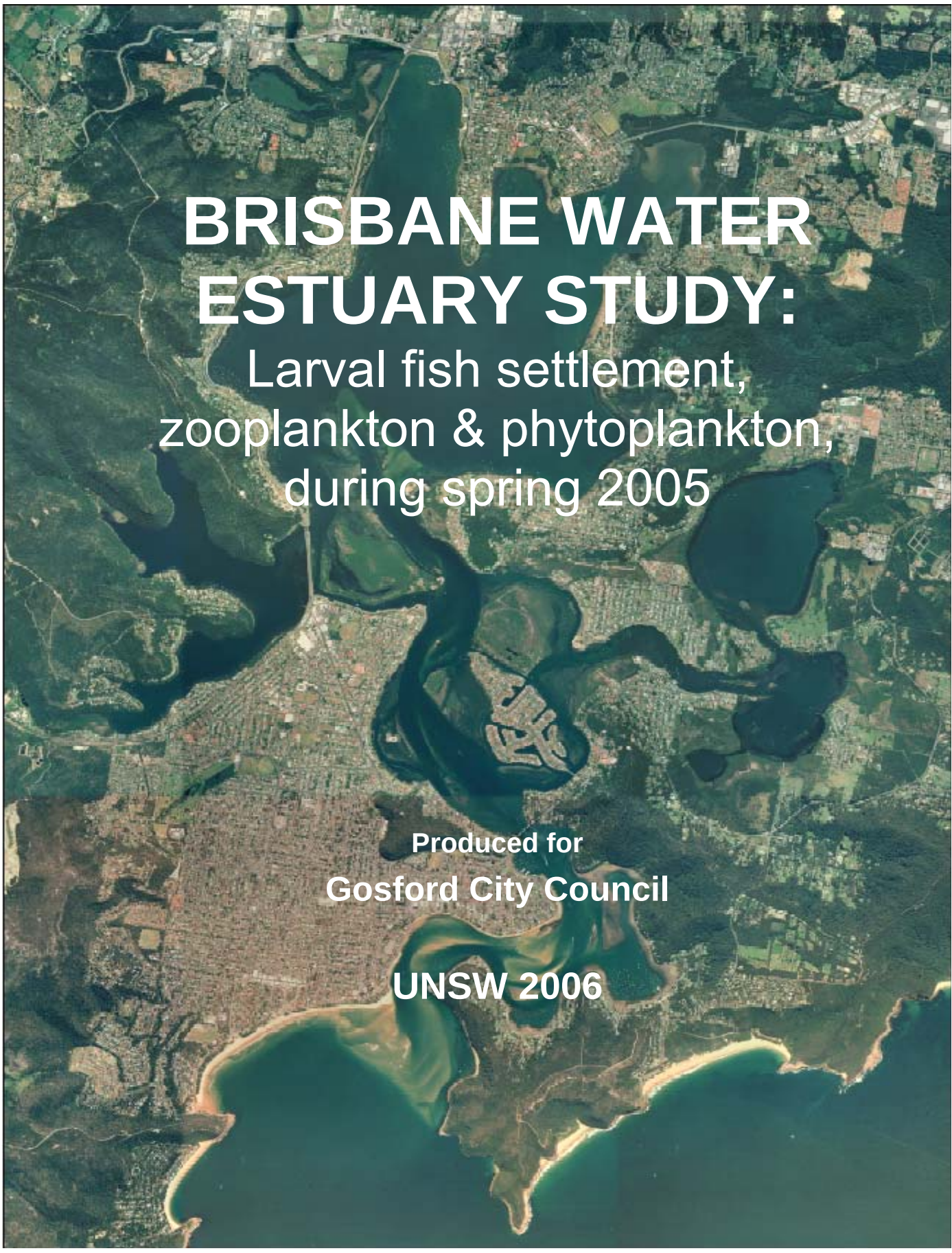

BRISBANE WATER ESTUARY STUDY:

Larval fish settlement, zooplankton & phytoplankton, during spring 2005

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REPORT TO GOSFORD CITY COUNCIL

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"Prediction of larval fish settlement 'hotspots' in relation to a current shear index, zooplankton biomass, and chlorophyll *a* distribution in Brisbane Water"

By

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PREFACE

This final report completes a study commissioned on 1 August 2005 by Dr Peter Freewater, Natural Resources Officer, Gosford City Council.

We wish to acknowledge the significant support of Dr Freewater, as well as the scientists of Cardno Lawson & Treloar, particularly Dr Doug Treloar, David Taylor, and Sean Garber. We also acknowledge the assistance of our volunteers Tom Mullaney, Jason Everett, Adrian Davis, Haysam El Hassan, Magdalena Sarnika, and Danielle Ord.

EXECUTIVE SUMMARY

The larval and juvenile fish fauna of seagrass beds within Brisbane Water entrance channel was diverse and similar in composition to other estuaries on the NSW coast during the spring recruitment period in late 2005. Relative abundance among the 30 taxa (species and families) differed across months, as seasonal spawning events in the open ocean dictated the larval fish entering the estuary. Average densities of larval and juvenile fish were lower than other NSW estuaries, possibly due to lower tidal volumes bringing fewer fish from the ocean, and more available seagrass to disperse (or "dilute") the fish. No 'hotspot' of high larval fish settlement was located, as numbers of larval and juvenile fish varied significantly among months and sites. The Maximum Shear Index (MSI) which has identified settlement hostpots in Lake Macquarie, failed to predict patterns of settlement in Brisbane Water. Other physical characteristics similarly failed to relate to settlement and it is likely that the highly variable fish abundances precluded any useful predictor. This is likely due to the continuous seagrass along the channel providing adequate habitat for fish entering the estuary. Larval fish entering the estuary have a great area of habitat to choose to settle into and are not forced into a single area to settle such as the Lake Macquarie channel. Consistent with this process we found the sparse seagrass beds near the channel entrance supported proportionally higher larval abundances of numerous coastal and estuarine-spawned fish species during some months.

Seagrass quality in the Brisbane Water channel was similar to that in the entrance channels of Lake Macquarie, Wallis Lake and Smiths Lake. Brisbane Water has a large area of seagrass which is generally in good condition to support a healthy ecosystem. Small patches of seagrass at Ettalong beach are identified as important habitat under threat from wave activity and human pressures, and should be targeted for protection and conservation.

Water quality in terms of plankton indicators in Brisbane Water from August to December 2005 was generally very good compared to ANZECC guidelines. During this time there was little substantial rainfall that can cause eutrophication. Indicators of eutrophication, including chlorophyll *a* biomass, were always less than 5 µg L-1. We deployed a new optical sensor of phytoplankton (the Fluoroprobe) that quantifies the concentration of 4 typical photosynthetic pigments, and find it to be well correlated with standard but more laborious extraction methods. Zooplankton abundance and size structure, another indicator of eutrophication, was similar to the Manning and Wallingat Rivers which receive agricultural nutrients. The

zooplankton size structure showed evidence of predation by fish in removing the larger particles.

We recommend users of Ettalong Beach be informed of the importance of seagrass beds as habitat for fish larvae (and invertebrates), and instructed not to tread on seagrass beds, where possible. The sparse seagrass habitat along Ettalong Beach should be monitored yearly for signs of degradation, either in the extent of bed coverage or density of shoots. The loss of these beds could reduce the survival of larval and juvenile stages of numerous estuarine fish species, particularly the iconic NSW state fish, the blue grouper. We also recommend further investigation of phytoplankton and zooplankton biomass after intense rain events, due to the similarity of Brisbane Water to other NSW estuaries vulnerable to eutrophication following rain.

INTRODUCTION

Seagrass beds are the major source of primary production within estuaries and form an integral part of the estuarine ecology (Howard & Edgar 1999). Seagrass provides habitat for a great abundance and diversity of fish (Beck *et al.* 2001), particularly larval and juvenile stages of larger species (Connolly *et al.* 1999). The structure of seagrass provides higher survival through refuge from predators and higher growth rates due to the abundance of food resources (Heck *et al.* 2003). Many commercial species on the NSW east coast spawn in the ocean and larvae settle into estuarine seagrass habitat when small and vulnerable to predators and starvation (Connolly *et al.*1999). Seagrass habitats within estuaries act as important nursery grounds providing recruits to the coastal adult populations.

Juvenile fish abundance in seagrass beds varies spatially (Bell *et al.* 1988, Jenkins & Wheatley 1998) and temporally (Smith & Sinerchia 2004, Upston & Booth 2003), making the identification of key areas a difficult task. Spatially consistent patterns of high juvenile abundance do however exist within estuarine environments (McNeill *et al.* 1992, Smith & Suthers 2000, Ford 2004). These areas may receive high numbers of initial settlers, or be advantageous for growth and survival, or a combination of both (Beck *et al.* 2001). The identification of such critical habitat of high juvenile abundance, and the physical and biological mechanisms behind them, are a necessary step toward the conservation of estuarine environments and fisheries management. One such 'recruitment hotspot' that was documented in the scientific literature is now covered by the Sydney Airport 3rd runway (McLean *et al.* 1992, Smith & Sinerchia 2004). Another recruitment hotspot was identified in Lake Macquarie and is now threatened by dredging activity (Ford 2004).

Three spatial models of the distributions of juvenile fish within estuaries exist, ranging from fine to large scale. Firstly, a more complex seagrass habitat has been seen to support higher abundances of fish (Bell 1986a, Leber 1985). Secondly, the geographical location of sites relative to larval source can influence settlement of larvae (Bell *et al.* 1988, Jenkins *et al.* 1998). Thirdly, dominant hydrological regimes within an estuary can advect particles to certain locations (Ford 2004, Jenkins *et al.* 1997).

A recent study conducted (Ford *et al.* submitted MS) found a site in the Lake Macquarie entrance channel which supports between 40-70% of the coastally spawned juveniles or larvae sampled over 4 months. Nine species of coastally spawned fish, most of commercial importance, were found in high abundances at this particular site, including blackfish, tarwhine, striped trumpeter, bream, blue wrasse, leatherjackets and mullet. Using

hydrographic models, the index of maximum shear index (MSI) proved to be a useful correlate:

MSI = (maximum velocity of channel - site velocity)/distance between.

This study investigates the spatial and temporal distribution of larval and juvenile fish among seagrass beds in Brisbane Water. It further attempts to assess larval distributions against seagrass quality, geographic position, and the maximum shear index of each site. Comparisons are also made between the abundances of larval (<20 mm) and juvenile (20-100 mm) fish to investigate the migration of individuals into the estuary with development. Fish abundances and estuary characteristics are lastly compared to similar estuaries on the NSW Central Coast.

Brisbane Water is an extensively modified and urbanised temperate estuary, located on the south-eastern Australian coast approximately 50 km north of Sydney (Fig. 1). Brisbane Water is a popular location for recreational boating and fishing, due to its sheltered environment and proximity to Sydney. The extent of residential development and the fact that crops, pastures, and plantations comprise 20% of the catchment area indicates the potential for run-off of significant quantities of nutrients during rain events. This, combined with the importance of this estuary to local and regional user groups, warrants investigation into the potential for harmful eutrophication.

The secondary aims of this study were to determine baseline levels of phytoplankton and zooplankton communities in Brisbane Water, as integrative measures of water quality. We wished to determine if excessive algal (phytoplankton) production occurs in Brisbane Water, identify which groups of phytoplankton contribute to the excessive production, and to identify areas most susceptible. We quantify chlorophyll *a*, a measure of phytoplankton biomass, using a standard electronic meter as well as with acetone extraction methods, and compare this with the precision of the Fluroprobe, an instrument capable of measuring the concentration of multiple groups of phytoplankton.

We determined zooplankton condition by means of an Optical Plankton Counter to determine the size frequency distribution (or 'size spectrum', Heath 1995; Moore & Suthers 2006), in comparison with other estuaries and the coastal ocean. Body size is an index of many complex biological rates and processes, including production and grazing of phytoplankton blooms. For the first time, the zooplankton size distributions among different

estuaries (Moore & Suthers 2006) were found to be correlated with the catchment use and water quality. We wished to compare those size spectra with those found in Brisbane Water.

METHODS

Brisbane Water forms the northern tidal arm of the Broken Bay estuary located 50 km north of Sydney. It is a tidally dominated shallow inlet characterised by a permanently open narrow entrance (150 m) and a dominant tidal channel which separates into a number of basins 6-8 km inland. Tides are semi-diurnal with a range of around 1 m. This study focuses on the tidally dominated region between the entrance and the basins, referred to as the Entrance Reach and Woy Woy Reach (Gosford Council 2000). Abundant seagrass is found along the fringes of the tidal channel and is dominated by the species *Zostera capricorni* (eelgrass), and also includes *Posidonia australis* (strapweed) and *Halophila ovalis* (paddleweed).

Fish Sampling. Eight sampling sites were selected in seagrass within the tidal dominated region of Brisbane Water (Fig 1). Sites were chosen within seagrass beds for optimal sampling depth, the absence of obstructions such as oyster leases, and to represent a good distribution from the entrance along the main channel. Two replicate beach seine hauls were done over seagrass at each site with a 2 mm square mesh beach seine so that approximately 25 m^2 was sampled. Fish larger than 20 mm in length were identified, counted and returned to the water along with sygnathids, gobiids, molluscs, and crustaceans. All other fish were euthanized with 1% benzocaine solution and preserved with 5% formalin.

Fish were sampled during the day on a low tide for two separate days during the new moon. This corresponded to a night-time flood tide which is associated with higher abundances of larval fish entering an estuary (Forward *et al.* 1999, Trnski 2001). Samples were taken on 5th and 8th August, 5th and 7th September, 2nd and 4th November and 5th and 7th December 2005. The basic sampling design was therefore Month (4 levels, fixed), Day (2, nested), Site (8, fixed), however this was modified for specific tests, for example – when very few newly settled fish were caught (see Analyses).

To monitor the estuary for any related oceanographic events such as cool upwelling, a water temperature (ºC) logger (Onset Computer Corporation) was attached to a channel marker 0.5 m below the low-water mark at the commencement of sampling on 06/08/2005, and removed in May 2006. The channel marker (starboard-hand marker, #153) was located

approximately 7 km from the estuary entrance at the opening of the broadwater, near Saratoga Island (adjacent to larval fish site BG, Fig.1), and temperature was logged every 2 hours.

Site Properties. Three environmental variables were calculated for each site representing biological, geographical, and hydrological influences. Seagrass density was measured for each tow to represent cover and structure provided for refuge for juvenile fish. A Perspex quadrat 35 cm x 35 cm was haphazardly thrown twice at each site on each tow and the proportion of seagrass to bare sand used to calculate density. Distance to the ocean was calculated using bathymetry maps and followed the path of the deepest channel from seagrass bed to entrance. The maximum shear index (MSI) indicates the change in velocity between the seagrass bed and channel relative to the distance between them. This value in $ms^{-1}m^{-1}$ is calculated using the maximum velocities on the flood tide and investigates the connectivity between channels as a larval supply and seagrass beds as retentions zones for larvae. Hydrological data was obtained using hydrological models supplied by Cardno Lawson and Treloar Pty Ltd. Particle tracking was conducted using these models to determine movement of passive particles entering the estuary. Particles were released at the entrance at the beginning, the middle and end of the flood tide and tracked over four full tidal periods.

Analyses of Larval Abundance. Due to the paucity of larval-juvenile fish found in Brisbane Water and the many zeros, the 2 replicate days of each month were pooled. This pooling was checked by comparing data from the two days of sampling within each the new moon period were compared using two-tailed paired t-tests. Results showed that no significant difference exists between the two days in any month ($t = 0.6$ for Aug, 0.4 for Sep, 0.1 for Nov, 0.2 for Dec) and hence the data was pooled to give 4 replicates per site per month.

In addition to the divisions of larval (<20mm) and juveniles (20-100mm), fish were also separated into two categories: coastally spawned (CS) species and lagoon spawned (LS) species (Table 1). This separation indicates the source of the larvae and hence the different conditions associated with their transport and settlement. Four abundance counts were calculated for each site ; Coastally Spawned (CS) larvae (<20mm), CS juveniles (20mm-100mm), total larvae, and total juveniles. These abundances were then divided by the areas of seagrass sampled to provide a number of fish per m^2. The species *Ambassis jacksoniensis* was not used in these calculations as it's schooling behaviour significantly affects variance. Two-way ANOVAs were used to compare the abundance counts (per m^{-2}) between sites and months. The variance in all cases was found to be heterogeneous due to the high frequency of

zero counts. A transformation of ln(x+1) was applied and reduced heterogeneity but the Cochrans test was still significant. We continued with the ANOVA but reduced $P<0.01$ to reduce the effect of a Type I error.

In order to remove the effect of high monthly variation and non-homogeneity of the data, abundances (per m^{-2}) for each site were converted to a proportion of the total number m^{-2} sampled during that month. Proportions were compared among sites for each month using one-way ANOVA. Site proportions were further compared to the MSI, the seagrass density and the distance to the ocean using correlation statistics. Proportions of CS larvae were compared to proportions of CS juveniles at each site using correlation statistics.

Phytoplankton and Zooplankton Sampling Plankton was collected during the four collection dates in August (phytoplankton only), September, November, December, 2005. Six primary sites were chosen to represent a range of distances from the estuary entrance at Broken Bay. Site 1 was located in the main channel, approximately 0.5 km from the entrance, whilst Sites 5 and 6 were located approximately 12 km from the entrance, near the northern limit of the broadwater (Fig 1). Sites 2, 3, and 4 were located between these distances. In addition to the primary sites, two extra phyto-only sites were chosen for investigation of catchment run-off; Punt Bridge, located at the entrance to Erina Creek (Site 7), and Fagan's Bay, located north of Point Claire (Site 8, Fig 1). All sites were sampled during a single ebb-tide on one day. Sampling began when first ebb-flow was detected at Fagan's Bay at the top of the estuary, and progressed toward sites closer to the mouth, finishing at Site 1. Sampling all 8 sites took approximately 5 hours to complete. Two replicate 2 L surface water samples were taken for extraction of chlorophyll *a* at each of the six primary sites on each cruise. Water samples were taken using 'dark' bottles and were stored in the shade until processing.

In situ concentrations (μgL^{-1}) of four phytoplankton groups, Chlorophyceae (green algae), Cyanophyceae (cyanobacteria), Bacillariophyceae (diatoms) and Dinophyceae, (dinoflagellates), and Cryptophyceae (small flagellates) were measured at all sites on each occasion using a calibrated FluoroProbe (bbe Moldaenke; after Beutler *et al*. 2002). Light-emitting diodes on the FluoroProbe emit pulsed light at five frequencies; 450 nm, 525 nm, 570 nm, 590 nm, and 610 nm. The probe then determines the concentration of each phytoplankton group based on the intensity of the fluorescence excitation spectrum specific to each group. Measurements are recorded at 1 s intervals. The classes Bacillariophyceae and Dinophyceae cannot be differentiated based on their excitation spectra, therefore results for these classes are grouped together (diatom/dinoflagellate group). At each site, two replicate

vertical profiles were made by lowering the FluoroProbe from the surface to within 0.5 m of the bottom at approximately 0.1 ms^{-1}. Only one vertical profile was made at sites 1 to 6 and no measurements were taken at sites 7 and 8 during August due to time constraints.

For comparison with surface water samples, *in situ* chlorophyll *a* concentrations (μgL^{-1}) were measured at all sites during the November and December cruises using a calibrated Datasonde 4a probe (Hydrolab). Two replicate vertical profiles were made by lowering the probe from the surface to within 0.5 m of the bottom, recording the chlorophyll *a* concentration at 0.5 m increments.

Zooplankton was collected with a 20 cm diameter, 100 µm mesh net, towed in a slight arc near the surface at ~1 ms^{-1} for approximately 5 minutes. The net was un-metered but flow was estimated during the tow by engine speed, boat speed and the passage of flotsam past the boat. Plankton was preserved in 5% solution of formalin in seawater.

Laboratory Procedure for Phytoplankton and Zooplankton 2 mL of super-saturated $MgCO_3$ solution was added to each surface water sample which was then filtered through a 0.2 µm glass fibre filter under low vacuum. Filters were then folded, blotted dry, wrapped in aluminium foil, and stored at -20 °C until analysis. Chlorophyll *a* concentration (μgL^{-1}) was determined for each filter using the methods outlined in Lorenzen (1967) and Jeffrey & Humphrey (1975).

Zooplankton was rinsed of formalin solution with a 100 µm sieve and slowly introduced into the header tank of a laboratory based optical plankton counter (OPC-2L), keeping the particle count rate <20 counts per second. The OPC counts and estimates the size of any optically refractive particle as they enter a 2 x 2 cm sampling tunnel and interrupt a coherent light beam (4 x 20 mm; light emitting diode, LED, array). A photodiode receiver records the change in light intensity (mV), calibrated as digital size-intervals between 1 and 4096 mV that correspond to sizes between 75 and 9000 µm equivalent spherical diameter (esd; Herman 1988, Sprules *et al.* 1992, Beaulieu *et al.* 1999). We re-classified the 4096 digital size-classes to 64 size-bins based on the integer value of the square root of the digital size-class (due to initial size classification by particle projected area). In practice the sampling resolution is restricted to between digital size-classes 7 and 442 (bins 3–21, 250–2500 µm esd, Table 2).

The OPC particle counts were converted to biomass ($mg\ m^{-3}$) by multiplying its abundance by its volume using its geometric mean esd (mm, Table 2). This biomass calculation assumes that the volume of particles is adequately represented by a sphere, and

that the volume has a specific gravity of 1. Data were normalised (dividing the biomass by the size interval), and the average normalized biomass size spectrum (NBSS) for each depth interval was calculated. The normalised data enables the slope and intercept to be compared to other studies, independently of the size ranges chosen. We then determined the NBSS slope and intercept using least squares regression (model-1).

Plankton analyses Two-factor ANOVAs were used to compare phytoplankton concentrations (μgL^{-1}) among the six primary sites and four months for; a) chlorophyll *a* (extraction values), b) diatoms/dinoflagellates (FluoroProbe measurements), c) green algae (FluoroProbe measurements), and d) slopes and intercepts of the NBSS. For green algae and diatom/dinoflagellate measurements, no vertical pattern of concentration was found, therefore data from all depths were pooled to generate means. Punt Bridge and Fagan's Bay sites were not included in the green algae and diatom analyses due to the lack of measurements during the first cruise. The Tukey post-hoc test was used to determine which sites in each month had significantly different concentrations from each other.

Concentrations (μgL^{-1}) of diatoms/dinoflagellates, green algae, and chlorophyll *a* (Datasonde 4a probe measurements) were compared with chlorophyll *a* extractions (μgL^{-1}) using linear regression.

RESULTS

Fish species abundance A total of 3295 fish, representing over 32 species from 21 families, were collected in Brisbane Water over the spring months of 2005 (Table 1). 1681 fish were grouped as new settled or "larval" (<20mm) and 1614 as juvenile (20-100mm). The most abundant species was *Ambassis jacksoniensis* (Port Jackson glassfish - 23% of all individuals), followed by Sygnathidae (pipefish and seahorses - 20%), Gobiidae (gobies - 18%), *Centropogon australis* (fortesque – 15%) and *Pelates sexlineatus* (six-lined trumpeter – 8%). 51% of individuals were classified as coastally spawned, 49% as lagoon spawned and <0.1% unknown. 13% were considered to be either commercially or recreationally important species.

Temporal variation in fish species The species composition of larval fish differed distinctly among months. Relative abundances of coastally spawned species varied greatly among months, while relative abundances of lagoon spawned species were more consistent. Juvenile species composition remained relatively consistent and was dominated by lagoon spawned Gobiidae and Sygnathidae (Table 1).

Temporal and spatial distribution of larval and juvenile fish. No consistent pattern of larval or juvenile fish abundance was evident either among sites or among months (Fig 2). Abundances were generally highest in the month of December, with notably high abundances at the BA and BB sites, and lowest in August. No site showed consistent abundances across months for larval fish, although juvenile fish numbers showed some consistency at the BC, BD and BE sites. The two-way ANOVAs conducted among site and month showed a significant interaction term which influenced all further results (Table 3).

Proportion comparisons, carried out to remove the effect of month, showed a similar lack of consistency in abundance among sites (Fig. 3). No site of consistently high CS larval settlement was identified. Despite high larval proportions at the BE site in August and the BB site in December, the dominance at these sites did not extend to the other months. Neither the proportions of larval or juvenile fish differed significantly among sites (Table 3).

Species-specific patterns of abundance. Two of the three most abundant CS species ("larvae" or newly settled), *C. australis* and *Achoerodus viridis*, showed a strong response with distance from the channel entrance (Fig. 4). Abundances of both species were much greater in the three

sites closest to the entrance. *P. sexlineatus* and Monocanthidae showed a more uniform distribution with elevated abundances at mid-distance sites. The lagoon spawned Gobiidae and Sygnathidae showed no discernable pattern.

None of the three site properties showed a significant relationship with CS larval proportion (Fig 5). The proportion of CS larvae showed a correlation of 0.68 with the proportion of CS juveniles (Fig 6). The proportion of CS larvae showed no relationship with the proportion of CS Juveniles of the following month.

Particle tracking showed that a passive particle entering Brisbane Water channel entrance on the beginning of the flood tide can be advected almost into Brisbane Water broadwater on a single flood tide (Fig 7). A particle entering the channel mouth during mid-flood tide will be advected only half-way along the entrance channel.

From August to December, water temperatures ranged from 12 to 29 ºC with a gradual increase in temperature (Fig 8), and no apparent relation to larval fish settlement.

Phytoplankton Concentration Phytoplankton concentrations were generally low throughout the study. Green algae and diatoms/dinoflagellates were the most concentrated groups, with negligible concentrations of cyanobacteria and small flagellates found (greatest value less than 0.2 and 0.6 (μgL^{-1}), respectively).The greatest chlorophyll *a* and diatom/dinoflagellate concentrations of 3.5 and 4.5 μgL^{-1}, respectively, were found at Site 1 during August (Fig. 9, Fig. 10).

There was no consistent spatial pattern of extracted chlorophyll *a* concentrations across all months (Fig. 9, ANOVA interaction term, df = 15, $F = 16.9$, $p < 0.001$). Within each month, chlorophyll *a* concentration appeared to be greatest at Site 1, however the difference was not significant for September or December (Fig 9). A secondary peak in concentration was evident at Sites 3 and 4 in September, November, and December, however the difference was not significant in September. This secondary peak occurred at Sites 5 and 6 in August. Chlorophyll *a* concentrations also appeared to increase slightly with month at Sites 2 to 6, except during August when concentrations were generally higher than those in September.

Diatom/dinoflagellate concentrations (from Fluoroprobe) showed a similar pattern and magnitude to chlorophyll *a* concentrations, with significant interaction among sites and months (Fig. 10, ANOVA, interaction term, df = 15, $F = 126.4$, $p < 0.001$). Highest diatom/dinoflagellate concentrations were found at Site 1 in August and November, Site 4 in December, and Sites 5 and 6 in September, although differences were not significant in

September (Fig. 10). Secondary peaks in concentration occurred at Sites 3 and 4 in November and December, and Sites 5 and 6 in August and September. A slight increase in diatom/dinoflagellate concentration with month was evident at Sites 2 to 5, again with the exclusion of August.

The Fluoroprobe's green algae concentrations showed similar patterns to chlorophyll *a* and diatom/dinoflagellate concentrations, with a significant interaction among sites and months (ANOVA, interaction term, df = 15, $F = 54.8$, $p < 0.001$), however concentrations at Site 1 were approximately half those of the other two groups (Fig. 11).

Concentrations of both diatoms/dinoflagellates and green algae at Punt Bridge and Fagan's Bay were similar to those found at other sites throughout the study duration (Figs. 10, 11).

Diatom/dinoflagellate concentrations (FlouroProbe measurements) were highly correlated to extracted chlorophyll *a* (Fig 12, $R^2 = 0.93$, $p < 0.001$). The regression line slope of 1.2 indicates diatom/dinoflagellate concentrations were slightly higher than those suggested by chlorophyll *a* concentrations. Green algae concentrations (FluoroProbe measurements) were significantly related to chlorophyll *a* concentrations (extraction values), however only 55% of the variance in green algae concentrations was explained by chlorophyll *a* concentrations (Fig 13, $R^2 = 0.55$, $p < 0.001$). A regression line slope of 0.8 indicates green algae concentrations were slightly lower than those suggested by chlorophyll *a* concentrations. Chlorophyll *a* concentrations measured using the Datasonde 4a probe were 1.6 times higher than those determined using extraction methods (Fig 14, $R^2 = 0.68$, $p = 0.001$).

Zooplankton Biomass The zooplankton NBSSs near the entrance to the estuary (Site 1) were typically around -1, while further into the estuary they were often considerably steeper (Fig 15). The spectra showed evidence of removal of the larger zooplankton, rather than enhanced production of the smaller zooplankton.

The slopes of the zooplankton NBSS showed significant differences among months and sites (P=0.001, Fig. 16), with no consistent trend from site 1 to 6, or from September to December.

DISCUSSION

Temporal and spatial abundance of fish within Brisbane Water

No consistent patterns of larval or juvenile fish abundances were evident within Brisbane Water. High monthly variation was detected in both species composition and overall numbers, similar to neighbouring estuaries on the NSW east coast (Ford 2004). In general, the abundances of lagoon spawned species remained more consistent among months and sites than coastally spawned species. Coastally spawned (CS) abundances in Brisbane Water are driven by larval supply to the estuary, tied to spawning events in the coastal ocean and favourable hydrodynamics advecting larvae into the estuary (Brown *et al.* 2004, Churchill *et al.* 1999, Fowler *et al.* 2001). Monthly pulses of recruitment were evident for a number of CS species, a process well documented in NSW estuaries (Gillanders 1997, Pollock *et al.* 1983, Smith & Sinerchia 2004). The most prominent of these events were the abundance of newly settled "larval" *Rhabdosargus sarba* and *Achoerodus viridis* in September, *Centropogon australis* and *A. viridis* in November, and *C. australis* in December.

The three properties measured to represent biological, geographical and hydrodynamic features of each site showed no relationship to the distributions of coastally spawned larval fish. The high variability of abundances (and proportions) at any given site over the four months provided a wide scatter of data and hence it is doubtful whether any significant relationship with a site property could have been found.

The lack of response to seagrass density is not surprising considering results of studies in similar estuaries (Bell *et al.* 1988, Ford 2004). Microhabitat quality is likely to play a role in where fish reside within a seagrass bed (Bell *et al.* 1986a), however it is often the presence of structure, rather than the quality of habitat which determines fish presence on a wider scale (Bell *et al*. 1987, Jenkins & Wheatley 1998).

The index of MSI, which has shown to be a good indicator of high CS larval settlement in Lake Macquarie (Ford 2004), was not applicable to the sites sampled in Brisbane Water. The explanation for this likely lies in the physical attributes of the estuary itself. Settlement patterns of coastally spawned estuarine fish have been shown to be driven by larval supply dictated by tidal currents (Bell *et al.* 1988, Hamer & Jenkins 1996, Jenkins *et al.* 1997). The Brisbane Water entrance has a single dominant channel which carries the majority of the tidal flow through into Brisbane water proper. Seagrass is abundant on both sides of the channel throughout most of the distance. The single channel carrying the vast majority of the tidal volume, and hence the majority of fish from the ocean, therefore passes

directly by a large area of seagrass habitat. As settlement is driven by larval supply, fish entering the estuary therefore have many possible settling points along the channel, which included the eight sites sampled in this study. The Lake Macquarie hotspot was the result of a dominant channel, with little seagrass on the fringes, directing flow toward the closest seagrass patch to the channel's end. Due to the numerous settling points along the main channel, a settlement hotspot for CS larval fish is unlikely to occur in the Brisbane entrance channel.

The results of the particle tracking model suggest that fish entering on the middle of the flood tide, when the greatest volume is entering the estuary, will be advected only half-way up the channel length. The closest sites to this area showed no higher settlement of CS larvae than other sites, however the closest site sampled was at least 500 m away from the suggested deposition point, due to the difficulty of access and lack of seagrass close to the channel. This area warrants further investigation and could have higher abundances of recently settled CS larval fish.

There were however significant species specific responses to distance from the ocean. The sites closest to the mouth, BA, BB and BC were shown to be the main habitat for larval and juvenile stages of the CS species *A. viridis* and *C. australis.* Furthermore, these three sites which have low seagrass density and are very patchy in nature, supported proportionally high numbers of lagoon spawned gobies, pipefish, and pygmy squid. The importance of seagrass habitat near to the entrance has previously been noted in Lake Macquarie (Hannan & Williams 1998) and Port Phillip Bay (Jenkins *et al.* 1996). If fish settle indiscriminately into the first seagrass bed they encounter, as proposed by Bell *et al.* (1986a), these seagrass beds provide an important first settlement point for coastally spawned fish. The sites BA and BB, located on Ettalong beach, are in areas of high wave activity and high levels of human disturbance through boating and swimming. As staging areas for newly arrived larval fish, and also as isolated bastions of habitat within a high energy environment, sites within Ettalong beach are very important for the ecology of Brisbane Water. Furthermore, these sites may act as a refuge for fish carried towards the mouth on the ebb tide. Similarly sites BC and BE, both smaller seagrass patches close to the main channel, act as staging areas as coastally spawned fish move into the estuary.

There is evidence that CS larval fish do not use the channel fringe seagrass solely as staging grounds for further movement up the estuary. The correlation between CS larvae and juveniles in each catch suggest some fish remain in the seagrass after settlement. This pattern however is not repeated when comparing CS larvae to the CS juveniles of the next sampling

month. Therefore the 'settle and stay' hypothesis documented in nearby Broken Bay (Bell *et al.* 1988) may not be applicable on monthly time scales within Brisbane Water. Within the month it is likely that most juveniles have moved further into the estuary and the low-energy seagrass environment of the broadwater and tributaries, similar to that seen in Lake Macquarie (Hannan & Williams 1998).

Comparison to NSW Central Coast estuaries

Similar studies of the seagrass fish fauna (<20mm) were previously conducted in three NSW Central Coast estuaries (Ford *et al.* submitted MS). Lake Macquarie, Smiths Lake, and Wallis Lake were sampled in the winter of 2003 using the same techniques and equipment as this study. As defined by Roy *et al.* (2001), Brisbane Water, Lake Macquarie and Wallis Lake are all Type III (5) estuaries – Wave Dominated Barrier Estuaries, characterised by highly modified permanently open entrances and high energy marine tidal deltas. Smiths Lake is classified as a type IV (8) Intermittent Saline Coastal Lagoon and is regularly closed from the ocean for over 18 months at a time. A comparison of the fish collected reveals similar species/groups and 27 of the 32 species found in Brisbane Water were also present in at least one other estuary. On average less fish were caught in Brisbane Water per m^2 of habitat than the other estuaries (Table 4). This difference can be attributed to two factors – firstly the volume of water, and hence the relative number of fish, entering Brisbane Water is much less than Wallis Lake and Lake Macquarie. Secondly, the amount of seagrass along the main tidal channel available for settlement is much higher in Brisbane Water than in Smiths Lake, where settlement occurs primarily to small seagrass patches near the entrance. Brisbane Water therefore has fewer coastally spawned fish entering the estuary than larger barrier estuaries, and fish are more evenly distributed through the larger area of seagrass in the entrance region.

Phytoplankton.

The low phytoplankton concentrations found throughout the study suggest the water quality of Brisbane Water is good, with no direct management response to reduce nutrient loads required at this time. No measured chlorophyll *a* value exceeded the suggested trigger value for south-eastern Australian estuaries of 4 μgL^{-1} (ANZECC, 2000), however one diatom/dinoflagellate value of 4.5 μgL^{-1} was recorded near the estuary mouth in August. ANZECC trigger values are based on slightly to moderately disturbed ecosystems, and as Brisbane Water is classified as an extensively modified estuary (Coastal CRC, undated) where trigger values can be relaxed to a degree (ANZECC, 2000), the recommendation of no direct

action can be made. Furthermore, the two extra sites chosen because of their potential for run-off induced algal blooms showed similar concentrations of green algae and diatoms to other sites throughout the study, although this could not be tested statistically. Caution should be exercised, however, as rainfall during late 2005 was low, sampling periods did not immediately follow intense rainfall events, when run-off and salinity stratification would be greatest, and sampling ceased before the highest summer water temperatures were reached. The phytoplankton concentrations found in this study should therefore be considered baseline data indicative of conditions during periods of low freshwater input and low to moderate water temperatures.

Average phytoplankton concentrations found in Brisbane Water were similar to baseline conditions determined for other NSW estuaries. Chlorophyll *a* concentrations of 5.5, 5.4, and 3.9 μgL^{-1}, were found in the mid-north coast Manning, Wallamba, and Wallingat Rivers, respectively, under normal low flow conditions during the period 2001 to 2003 (Moore et al. 2005). Following medium to large (approx. 60 and 200 mm of rain) rain events, these estuaries experienced algal blooms in mid to upstream sections with chlorophyll *a* concentrations reaching two orders of magnitude higher than baseline values. This indicates the potential for algal blooms following rain events in Brisbane Water, especially considering Brisbane Water catchment is more urbanised than Manning, Wallamba, and Wallingat River catchments, and has a similar percentage of catchment land devoted to agriculture compared to Wallingat River (20%). Further investigation into phytoplankton concentrations in Brisbane Water immediately following medium level rain events is warranted.

The Datasonde 4a probe overvalued chlorophyll *a* concentrations by 1.6 times the actual value (determined using extraction of water samples) during the December sampling period, despite being calibrated using wet samples taken in the previous sampling period in Brisbane Water. Further experiments are required to determine the exact nature of the probe error associated with chlorophyll *a* measurement. Diatom/dinoflagellate concentrations measured with the FluoroProbe (which was previously untested in Australia) were closely related to chlorophyll *a* concentrations determined using traditional extraction techniques (Fig 5, $R^2 = 0.93$), however only 55% of the variance in green algae concentrations was explained by chlorophyll *a* concentrations (Fig 6, $R^2 = 0.55$). The latter result suggests either the FluoroProbe calibration for green algae requires modification for temperate Australian conditions, or chlorophyll *a* concentration, as determined by extraction methods, is not a suitable proxy for green algae concentration. Despite this, these results show the FluoroProbe is a useful tool for use in temperate Australian estuaries.

The zooplankton NBSS shows evidence of planktivory, presumably by small fish removing the larger copepods. Consistent with the findings for phytoplankton abundance, there is no evidence of eutrophication and bottom-up enhancement of zooplankton production. The zooplankton NBSS in Brisbane Water is similar to estuaries such as the Manning River and Wallamba River which have significant eutrophication problems, particularly after rain (Fig 17). As drought persisted during most of the study period, it would be useful to repeat aspects of this water quality study in response to significant rainfall. The phytoplankton and zooplankton measurements here provide a useful benchmark of water quality, to determine any investment in run-off mitigation.

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Table 1. Total abundances and percentage composition of newly settled fish "larval" (< 20 mm length) and juvenile (20 – 100 mm length) fish caught in Brisbane Water, 2005.

Spawning type (either coastal or lagoon) taken from Hannan & Williams (1998) and Neira *et al.* (1998)

SPECIES	COMMON NAME	# Larvals	%	# Juveniles	%	Spawning	Commercial
Ambassis jacksoniensis	port jackson glassfish	734	43.7	29	3.1	Coastal	No
Centropogon australis	fortesque	323	19.2	172	18.1	Coastal*	No
Gobiidae	gobies	168	10.0	416	43.9	Lagoon	No
Pelates sexlineatus	six-lined trumpeter	161	9.6	91	9.6	Coastal	No
Achoerodus viridis	eastern blue groper	80	4.8	30	3.2	Coastal*	Yes
Meuschenia spp.	six-spine, yellow fin leatherjackets	60	3.6	-	-	Coastal*	Yes
Girella tricuspidata	luderick	25	1.5	8	0.8	Coastal*	Yes
Rhabdosargus sarba	tarwhine	22	1.3	2	0.2	Coastal*	Yes
Scobanichthys granulatus	rough leatherjacket	22	1.3	-	-	Coastal*	Yes
Microcanthus strigatus	stripey	20	1.2	0	0.0	Coastal	No
Pagrus auratus	snapper	13	0.8	1	0.1	Coastal*	Yes
Brachaluteres jacksoniensis	pygmy leatherjacket	11	0.7	0	0.0	Unkown	No
Atypicthys strigatus	australian mado	7	0.4	0	0.0	Coastal	No
Enoplosus armatus	old wife	7	0.4	5	0.5	Coastal	No
Acanthopagrus australis	yellow-finned bream	6	0.4	7	0.7	Coastal*	Yes
Monocanthidae (unidentified)	leatherjacket	6	0.4	135	14.2	Coastal*	Yes
Liza argentea	flat-tail mullet	6	0.4	0	0.0	Coastal*	Yes
Sillago ciliata	sand whiting	2	0.1	1	0.1	Coastal	Yes
Siphamia cephalotes	little siphonfish	1	0.1	2	0.2	Lagoon	No
Sillago maculata	trumpeter whiting	1	0.1	0	0.0	Lagoon	Yes
Labridae (unidentified)	wrasse	1	0.1	0	0.0	Coastal	No
Ambassis marianus	ramsay's glassfish	1	0.1	0	0.0	Lagoon	No
Atherinadae	hardyheads	0	0.0	18	1.9	Lagoon	No
Tetradontidae	pufferfish	0	0.0	12	1.3	Lagoon	No
Upeneus tragula	bar-tail goatfish	0	0.0	10	1.1	Lagoon	No
Blenniidae	blennie	0	0.0	4	0.4	Lagoon	No
Cristiceps spp.	triple fin	0	0.0	1	0.1	Lagoon	No
Cheilodactylus fuscus	red morwong	0	0.0	1	0.1	Coastal	Yes
Cnidoglanis macrocephala	estuary catfish	0	0.0	1	0.1	Lagoon	No
Pseudorhombus spp.	flounder	0	0.0	2	0.2	Unknown	Yes
Unidentified/Damaged		4	0.2	0	0.0		
Total Coastally Spawned		1495		482			
TOTAL FISH		1681		948			
Other							
Idiosepius Notoides	southern pigmy squid			291		Lagoon	No
Sygnathidae	pipefish			662		Lagoon	No
Hiippocampus whitei	white's seahorse			4		Lagoon	No
Sepiidae	cuttlefish			1		Unknown	No

* marks species used in the Coastally Spawned (CS) group to evaluate settlement patterns

Table 2. Zooplankton size classes counted by the Optical Plankton Counter (OPC), corresponding geometric mean equivalent spherical diameter (esd, after Suthers *et al.* 2006), and the calculated biomass of a particle in each class. The dominant taxa are summarised from Rissik *et al.* (1997) from the south Coral Sea.

esd (μm)	Biomass (mg)	Dominant taxa
318	0.017	Invertebrate eggs
425	0.040	Copepods, larvae of mysids, cirripedes, bryozoans
535	0.080	Mysids, copepods, cirripede, bryozoan larvae
648	0.143	Copepods, ostracods
764	0.234	Copepods, ostracods
883	0.361	Copepods, ostracods, mysids
1003	0.528	Copepods, mysids, ostracods
1125	0.746	Copepods, mysids
1249	1.020	Copepods, mysids, chaetognaths
1375	1.361	Copepods, chaetognaths, mysids, hyperids
1502	1.774	Copepods, chaetognaths, hyperids, mysids
1631	2.272	Copepods, hyperids, mysids
1761	2.859	Copepods, mysids, chaetognaths
1893	3.552	Copepods, chaetognaths, hyperids
2025	4.348	Copepods, mysids, fish eggs, *Lucifer*
2159	5.269	Mysids, *Lucifer*
2293	6.313	Fish eggs, mysids, *Lucifer*
2429	7.504	Fish eggs, mysids, *Lucifer*
2566	8.846	Fish eggs, mysids, *Lucifer*

Table 3. Two-factor ANOVAs of abundances (m^{-2}) and one-factor ANOVAs of monthly proportions among sites of a) coastally spawned larval (< 20 mm length) fish, b) coastally spawned juvenile (20 – 100 mm length) fish, c) total larval fish, d) total juvenile fish, among months (4 levels) and sites (8 levels) in Brisbane Water, 2005.

Two-way ANOVAs of abundance (m^{-2})

a) CS Larvae

Source	SS	df	MS	F-ratio	P
MONTH	1.402	3	0.467	16.253	0.000
SITE	0.579	7	0.083	2.878	0.009
MONTH*SITE	2.019	21	0.096	3.344	0.000
Error	2.76	96	0.029		

b) CS Juvenile

MONTH	0.263	3	0.088	6.879	0.000
SITE	0.334	7	0.048	3.74	0.001
MONTH*SITE	0.732	21	0.035	2.732	0.000
Error	1.225	96	0.013		

c) Total Larvae

MONTH	1.821	3	0.607	12.7	0.000
SITE	1.011	7	0.144	3.021	0.007
MONTH*SITE	2.418	21	0.115	2.408	0.002
Error	4.589	96	0.048		

d) Total Juvenile

MONTH	0.806	3	0.269	4.93	0.003
SITE	1.334	7	0.191	3.495	0.002
MONTH*SITE	5.34	21	0.254	4.664	0.000
Error	5.234	96	0.055		

One-way ANOVAs of Proportions

a) CS Larvae

Source	SS	df	MS	F-ratio	P
SITE	0.092	7	0.013	0.782	0.609
Error	0.403	24	0.017		

b) CS Juvenile

SITE	0.155	7	0.022	1.478	0.222
Error	0.359	24	0.015		

c) Total Larvae

SITE	0.143	7	0.02	1.341	0.275
Error	0.365	24	0.015		

d) Total Juvenile

SITE	0.049	7	0.007	0.729	0.649
Error	0.229	24	0.01		

Table 4. Comparison of larval fish abundances (m^{-2}) and seagrass areas (m^{-2}) sampled among estuaries on the NSW coast. (CS = coastally spawned larvae).

ESTUARY	Sampling Dates	Total Larval Fish	Total CS Larvae	Seagrass area sampled m^2	Larval Fish m^{-2}	CS Larval m^{-2}
Brisbane Water	Aug-05 Sep-05 Nov-05 Dec-05	1635	722	3071	0.5	0.2
Lake Macquarie	Aug-03 Sep-03	3050	1856	563	5.4	3.3
Wallis Lake	Jul-03 Aug-03	1837	419	1024	1.8	0.4
Smiths Lake	Jul-03 Aug-03	2374	819	405	5.9	2.0

Note: counts do not include Sygnathidae and Gobiidae

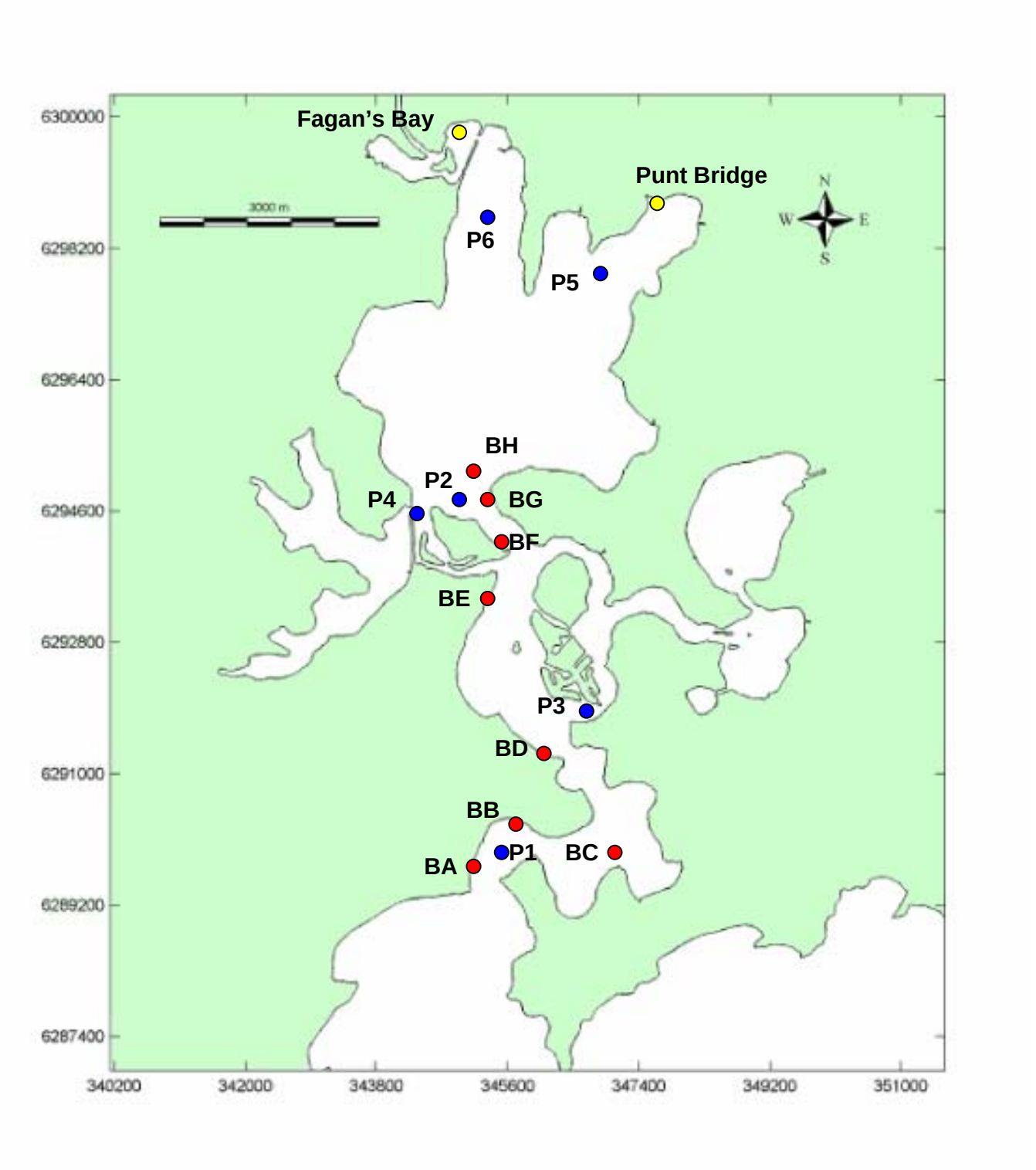

Figure 1. Location of larval fish sampling sites (red dots; BA to BH), phytoplankton/zooplankton primary sites (blue dots; P1 to P6), and phytoplankton run-off sites (yellow dots; Fagan's Bay and Punt Bridge) in Brisbane Water estuary, 2005.

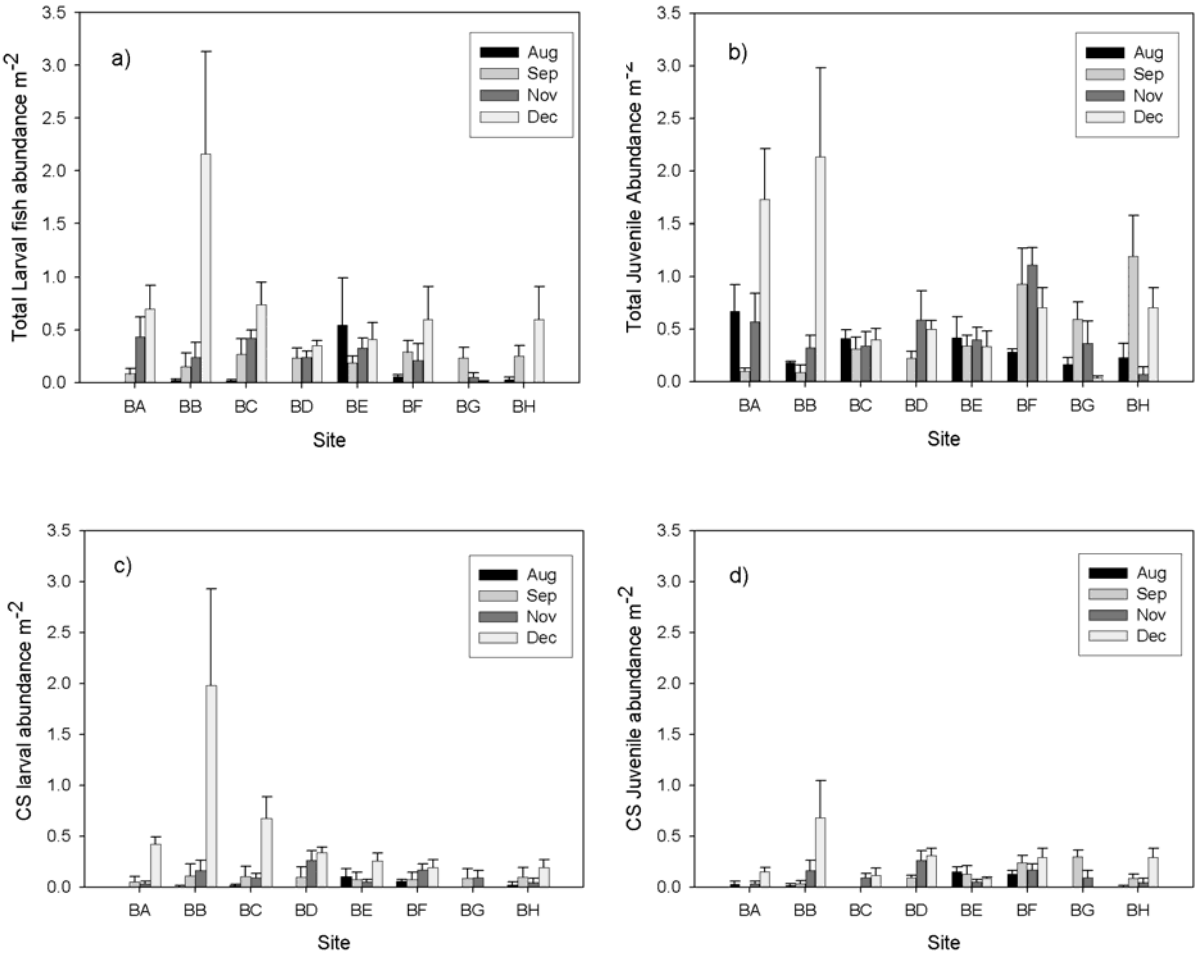

Figure 2. Site and monthly abundances (m^{-2}) of: a) total larval (<20mm length) fish, b) total juvenile (20-100mm length) fish, c) coastally spawned (CS) larval fish, and d) CS juvenile fish in Brisbane Water, 2005. Bars indicate standard errors. See Table 3 for ANOVA.

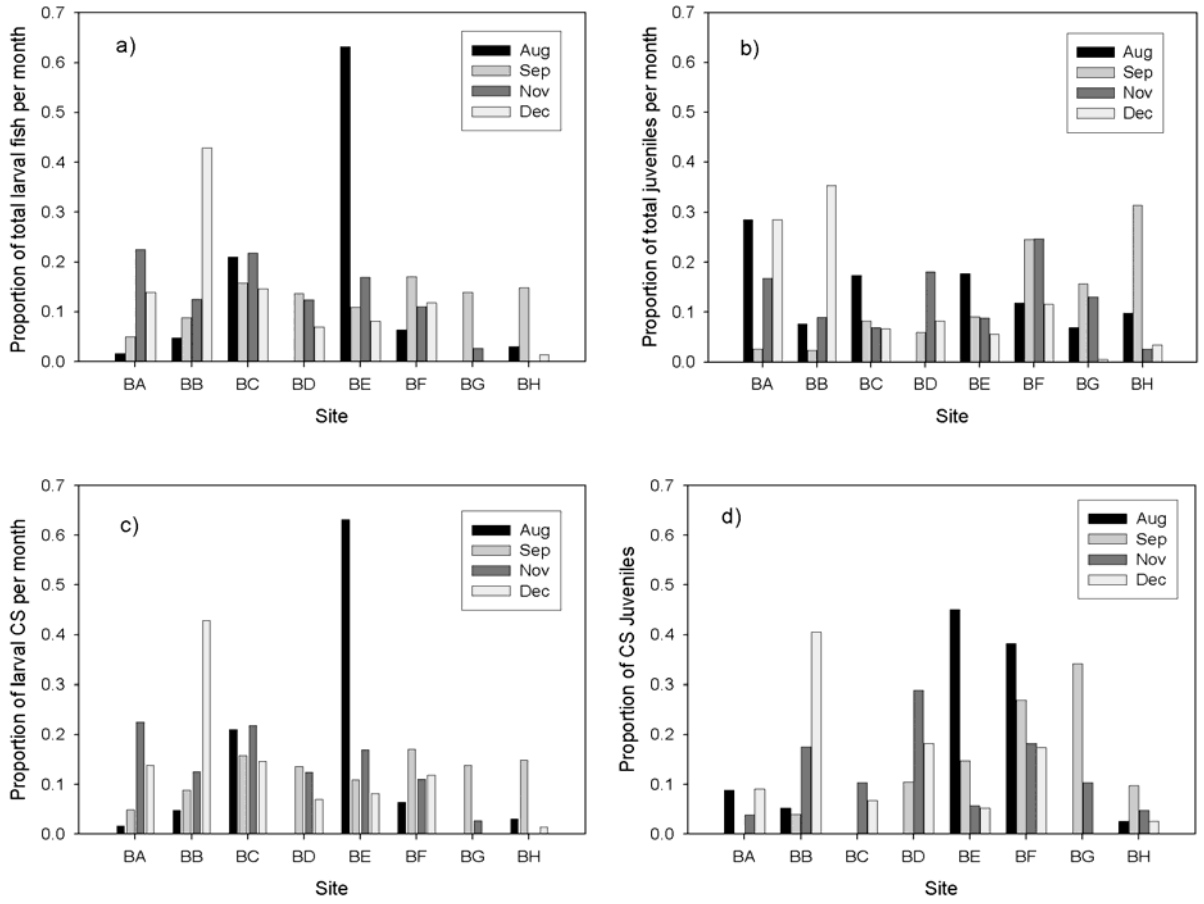

Figure 3. Proportions by site and month of: a) total larval (<20mm length) fish, b) total juvenile (20-100mm length) fish, c) coastally spawned (CS) larval fish, and d) CS juvenile fish in Brisbane Water, 2005. See Table 3 for ANOVA.

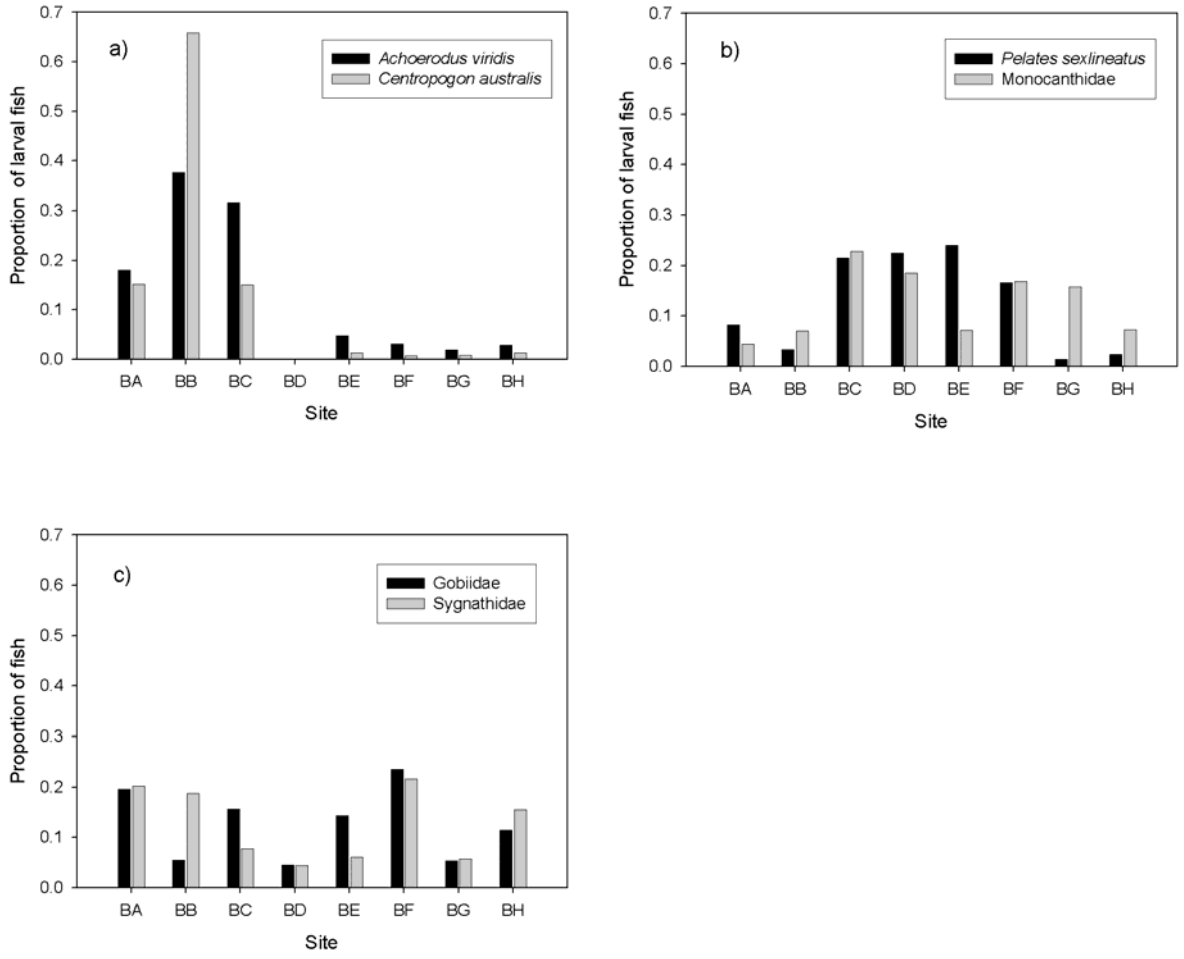

Figure 4. Proportions of fish caught by site across all months for; a) "larval" or newly settled *Achoerodus viridis* and *Centropogon australis*, b) "larval" or newly settled *Pelates sexlineatus* and monocanthids, and c) larval and juvenile gobiids and sygnathids.

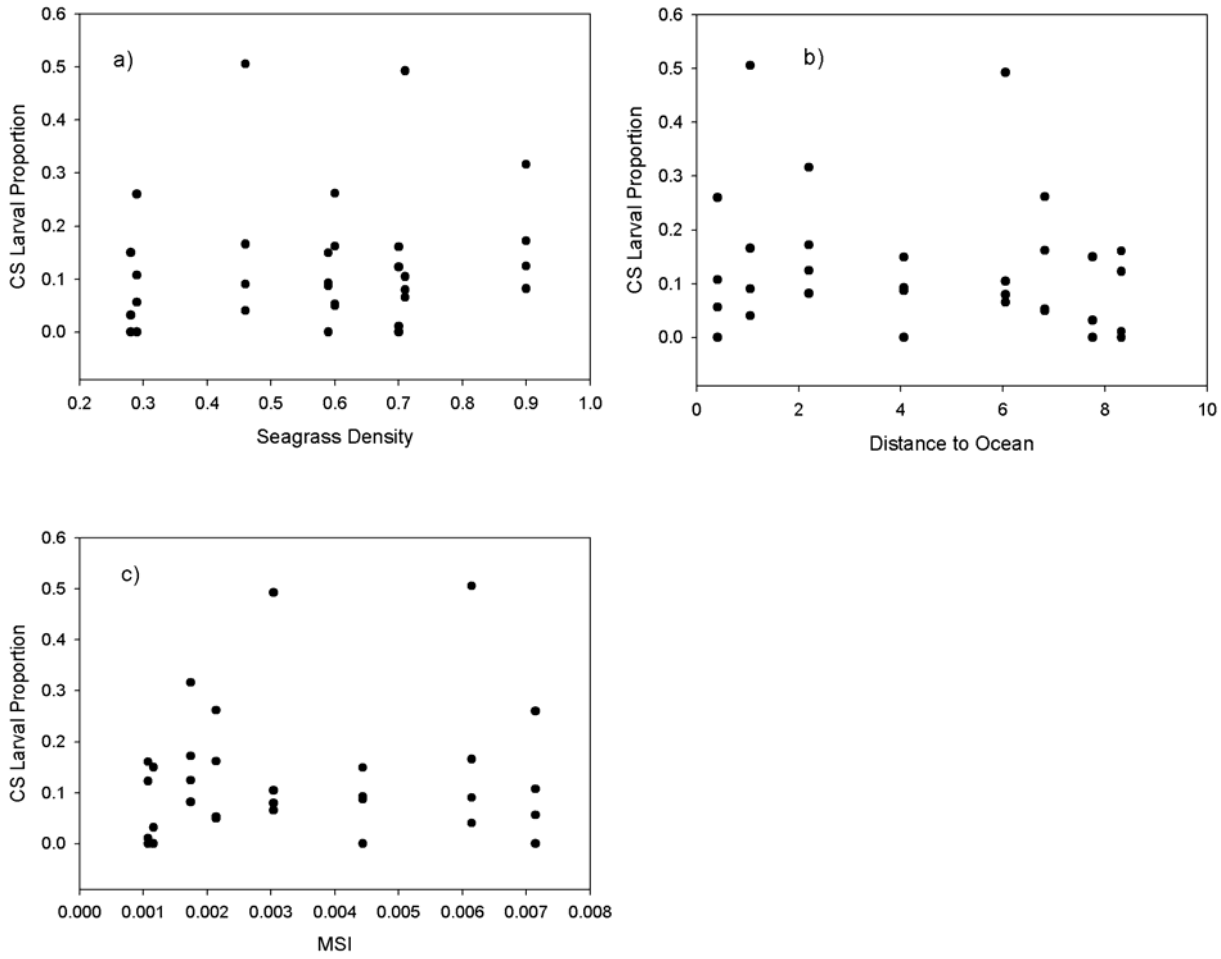

Figure 5. Scatterplots of coastally spawned (CS) larval proportion on; a) seagrass density (proportion of cover to bare sand), b) distance to ocean (km), and c) maximum shear index ($ms^{-1}m^{-1}$).

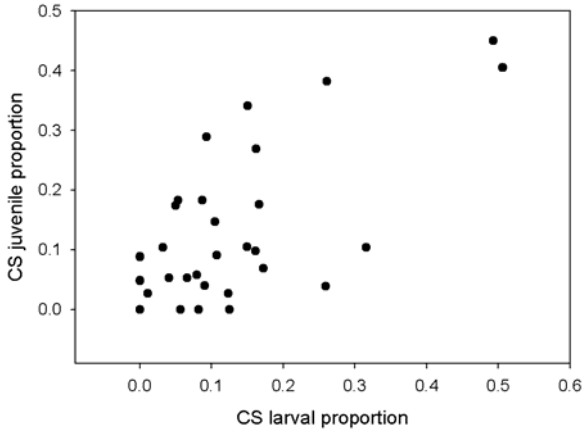

Figure 6. Scatterplot of coastally spawned (CS) juvenile fish proportion on CS larval fish proportion. Pearson's Correlation Coefficent = 0.68

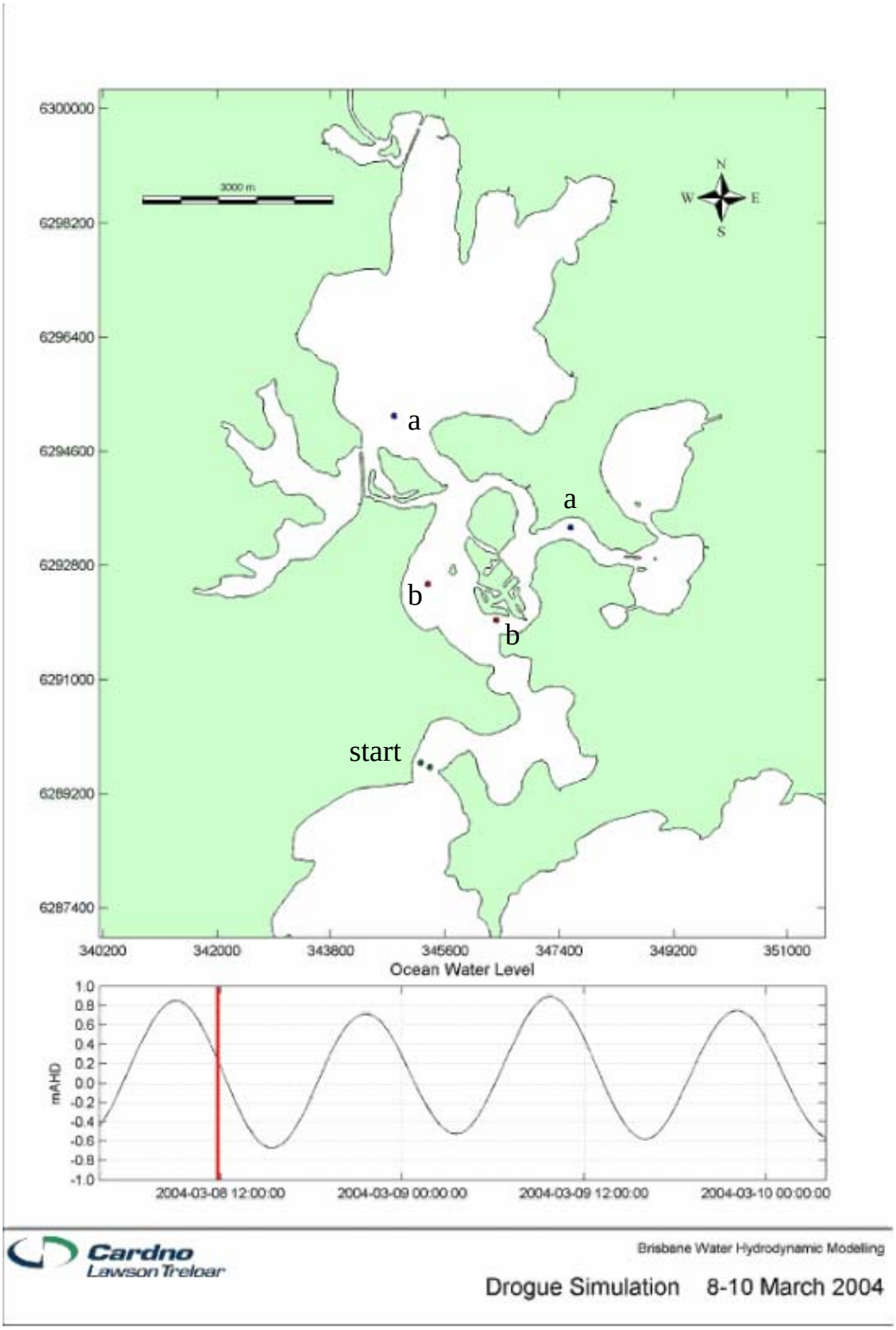

Figure 7. Still-shot of the particle-tracking hydrodynamic model of Brisbane Water estuary showing the position reached at high tide by particles released at the channel entrance at; a) the start of the flood-tide (2 particles, dark blue dots), and b) mid flood tide (2 particles, red dots).

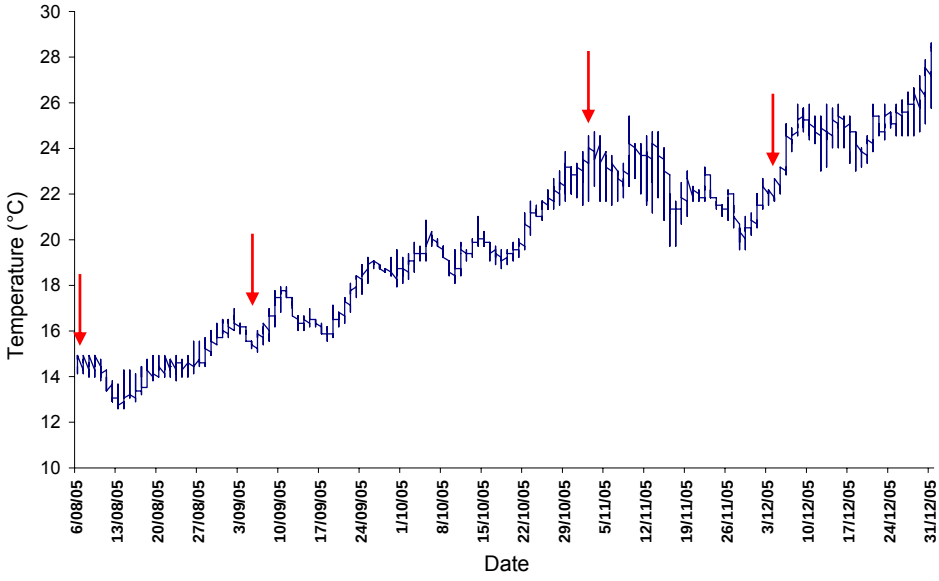

Figure 8. Water temperature recorded every 2 hours by a temperature logger deployed near the entrance to the broadwater in Brisbane Water. Red arrows indicate commencement date of the four sampling periods during August, September, November, and December, 2005.

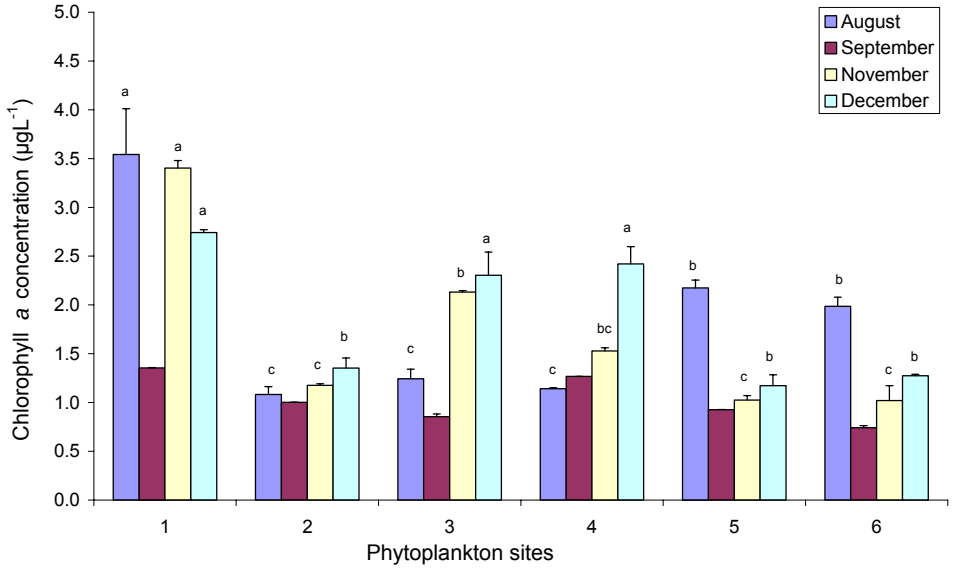

Figure 9. Concentration of chlorophyll *a* (µgL^{-1}) at the six primary sites in Brisbane Water during August, September, November, December, 2005, as determined by extraction. Site 1 is closest to the estuary mouth, Site 6 is located furthest away from the mouth. Bars indicate standard error. Lower-case letters indicate significant differences among sites. Sites with similar concentrations within a particular month share a letter.

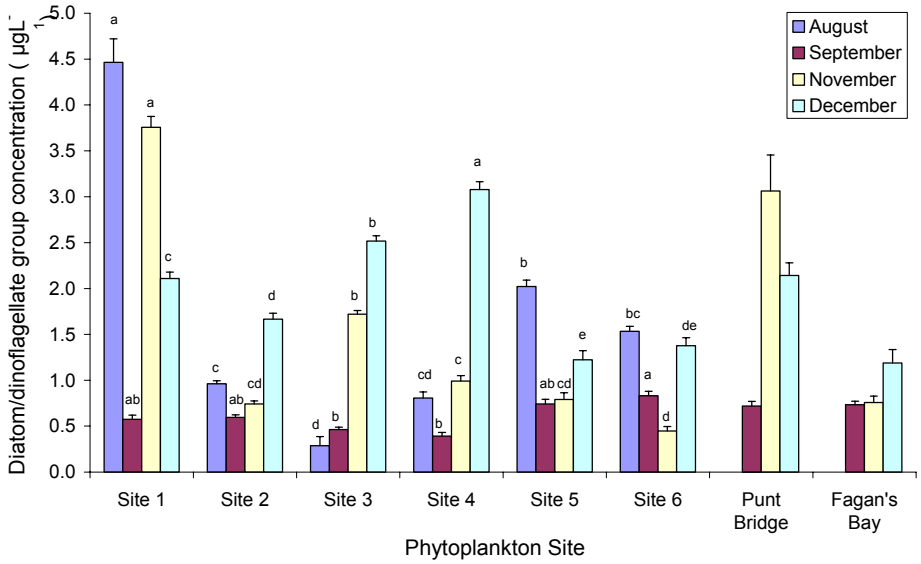

Figure 10. Concentration of diatoms/dinoflagellates (µgL^{-1}) at all sites in Brisbane Water during August, September, November, December, 2005, measured using the Fluoroprobe. Site 1 is closest to the estuary mouth, Fagan's Bay is located furthest away from the mouth. Bars indicate standard error. Lower-case letters indicate significant differences among sites. Sites with similar concentrations within a particular month share a letter.

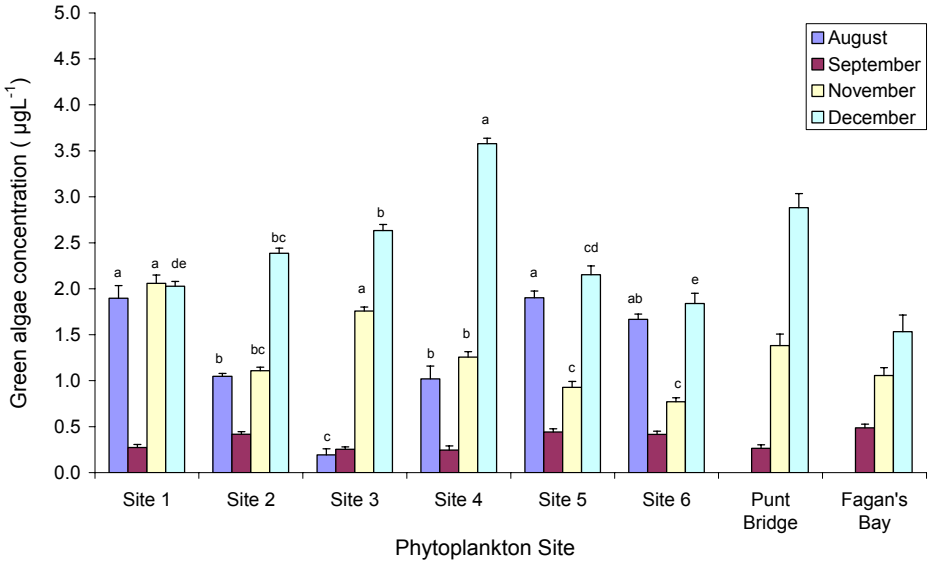

Figure 11. Concentration of green algae (μgL^{-1}) at all sites in Brisbane Water during August, September, November, December, 2005, measured using the Fluoroprobe. Site 1 is closest to the estuary mouth, Fagan's Bay is located furthest away from the mouth. Bars indicate standard error. Lower-case letters indicate significant differences among sites. Sites with similar concentrations within a particular month share a letter.

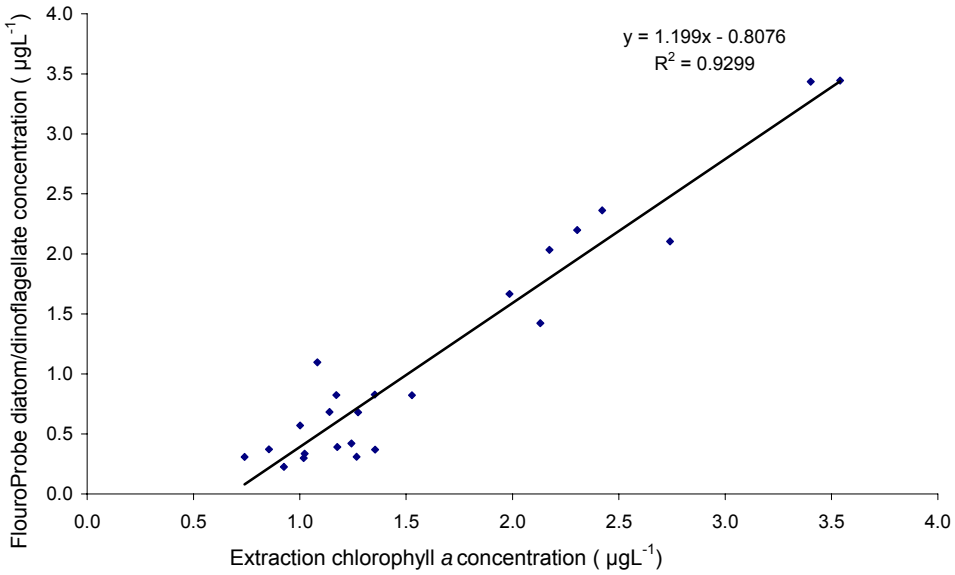

Figure 12. Linear regression comparing diatom/dinoflagellate concentrations (μgL^{-1}) measured using the FluoroProbe (bbe Moldaenke) with chlorophyll *a* concentrations (μgL^{-1}) determined using extraction at the same sites in Brisbane Water, 2005. Data are mean values taken from all sampling periods.

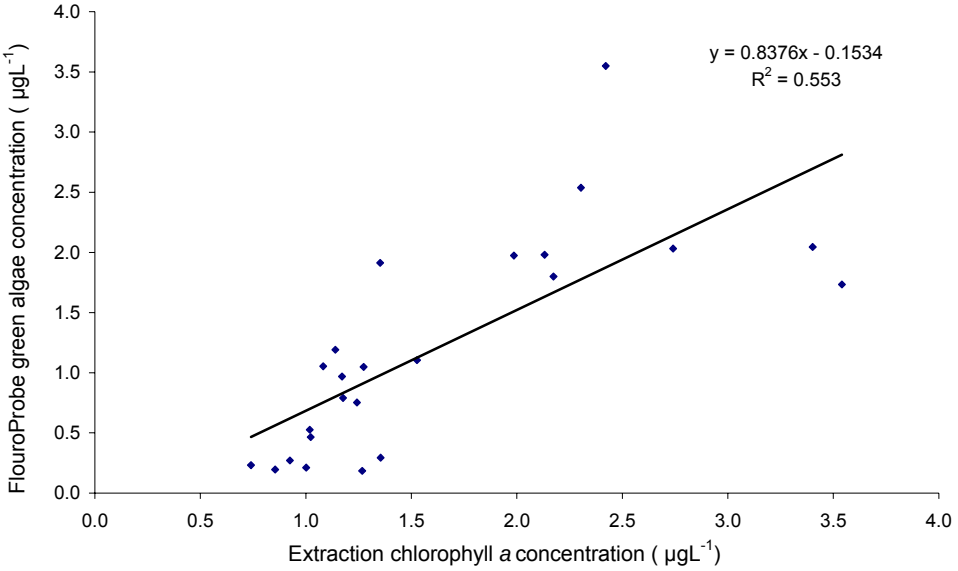

Figure 13. Linear regression comparing green algae concentrations (µgL^{-1}) measured using the FluoroProbe (bbe Moldaenke) with chlorophyll *a* concentrations (µgL^{-1}) determined using extraction at the same sites in Brisbane Water, 2005. Data are mean values taken from all sampling periods.

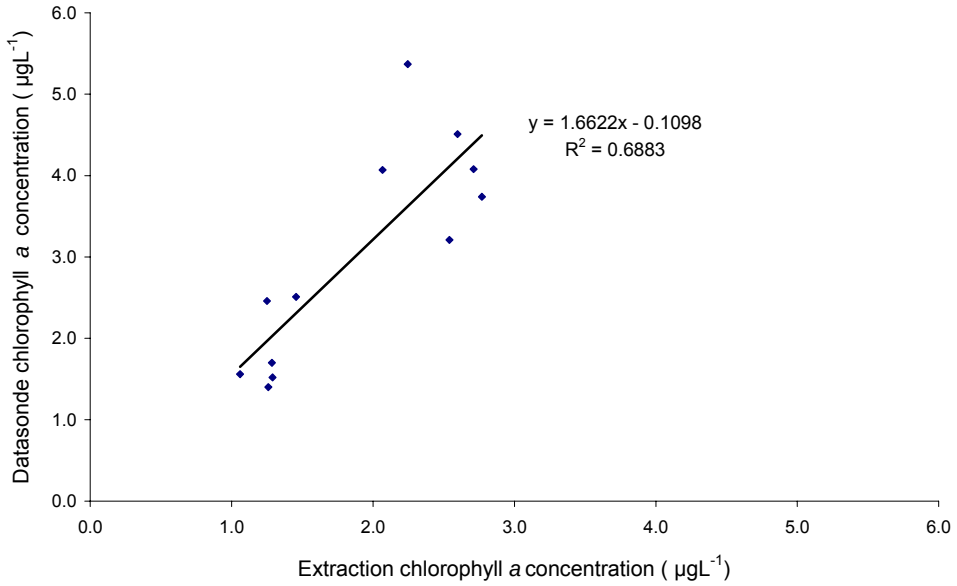

Figure 14. Linear regression comparing chlorophyll *a* concentrations (µgL^{-1}) measured using the Datasonde 4a probe (Hydrolab) with chlorophyll *a* concentrations (µgL^{-1}) from extraction at the same sites during December, 2005, in Brisbane Water. Data are values from individual replicates.

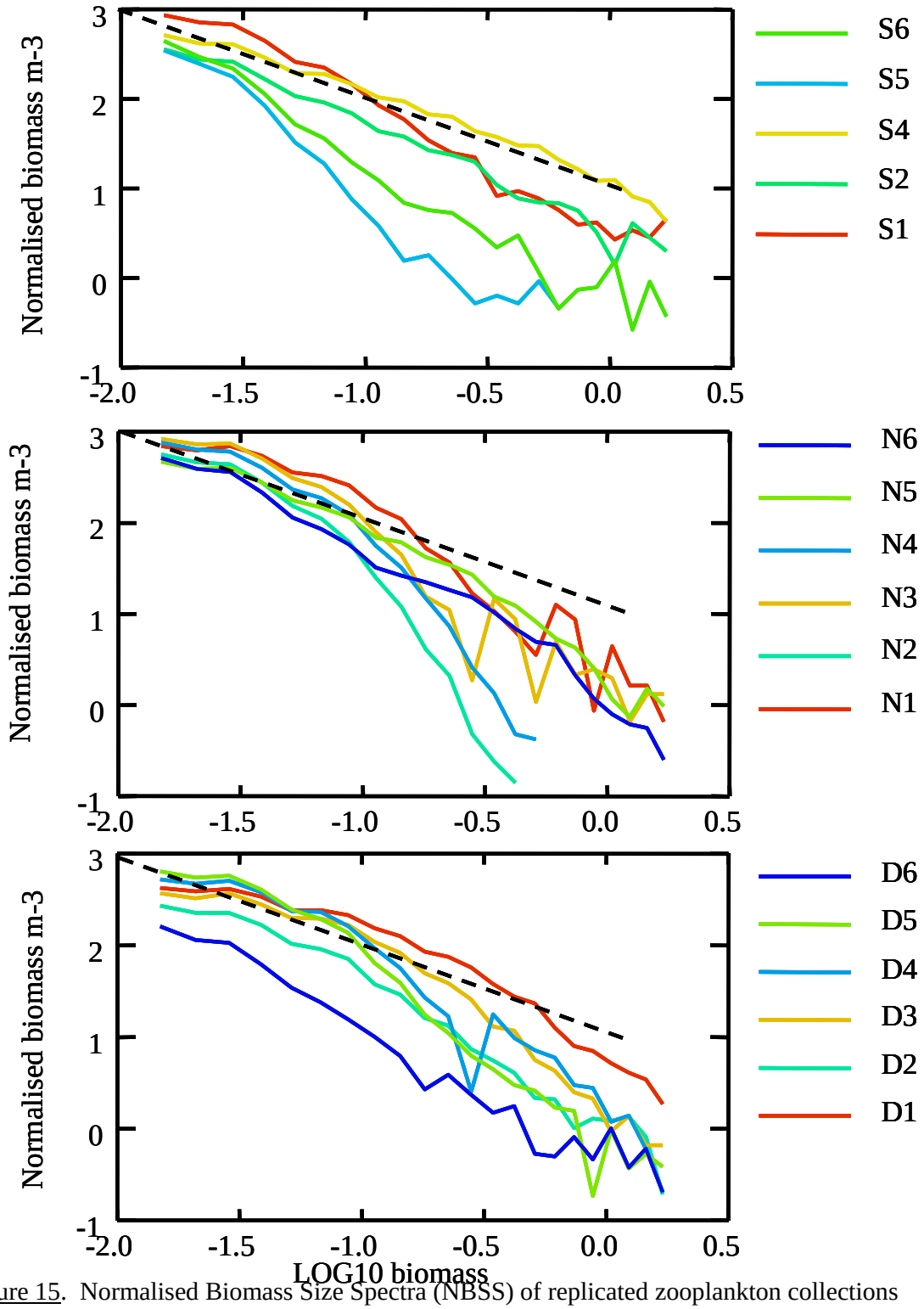

Figure 15. Normalised Biomass Size Spectra (NBSS) of replicated zooplankton collections during September (S), November (N) and December (D) at sites 1 to 6 in Brisbane Water, 2005, determined using a laboratory-based Optical Plankton Counter (OPC). Site 1 is near the entrance, Site 6 is near Gosford (Fig. 1) The mid point esd ranges from 306 to 1482 µm. The dashed line shows the -1 slope for comparison.

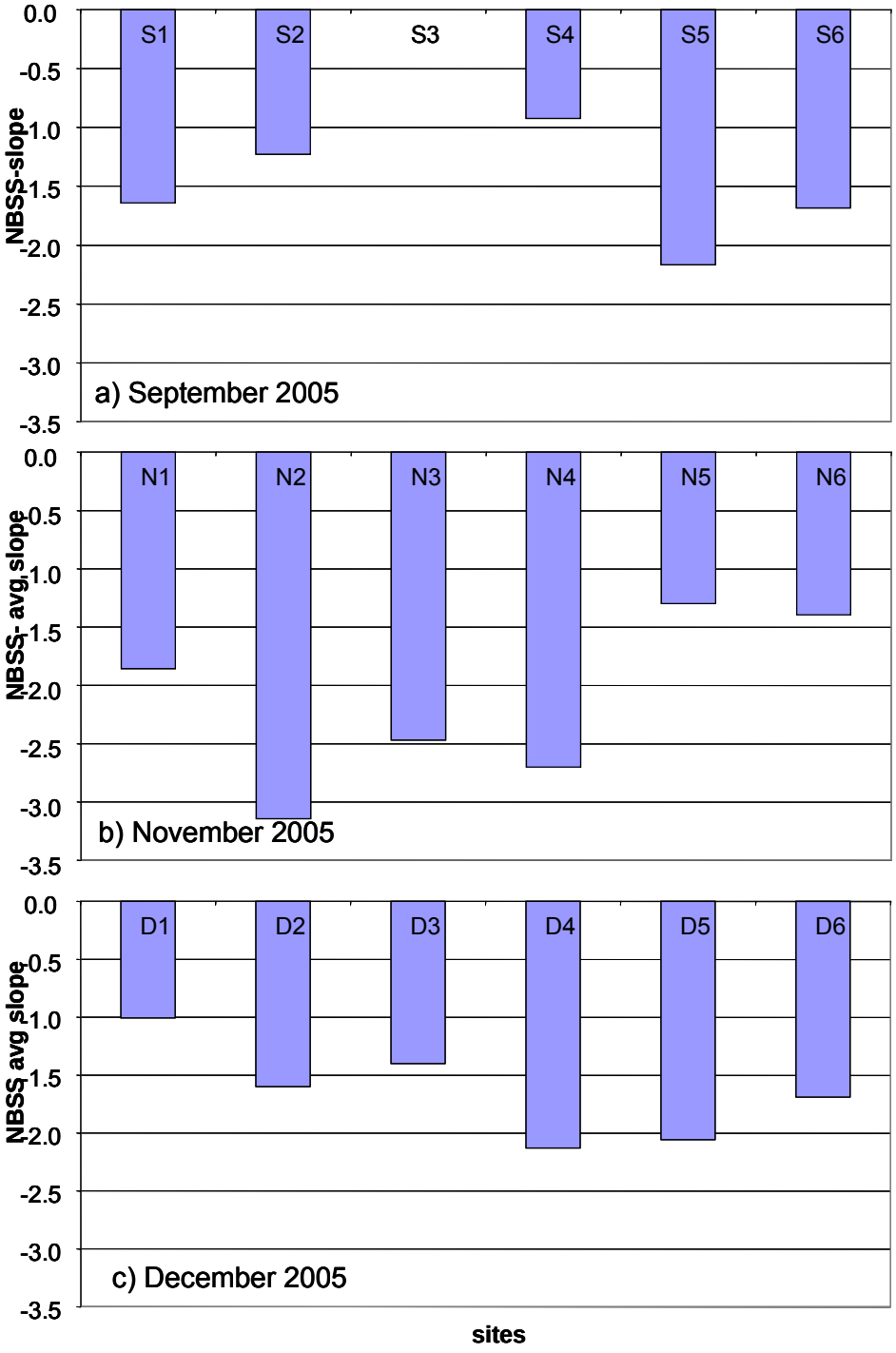

Figure 16. The average slopes of the normalised biomass size spectrum (NBSS) of zooplankton determined using a laboratory-based Optical Plankton Counter (OPC), between 380 to 992 µm esd size bins only, collected at 6 sites during the ebb tide at Brisbane water, 2005. SE for comparison is 0.31.

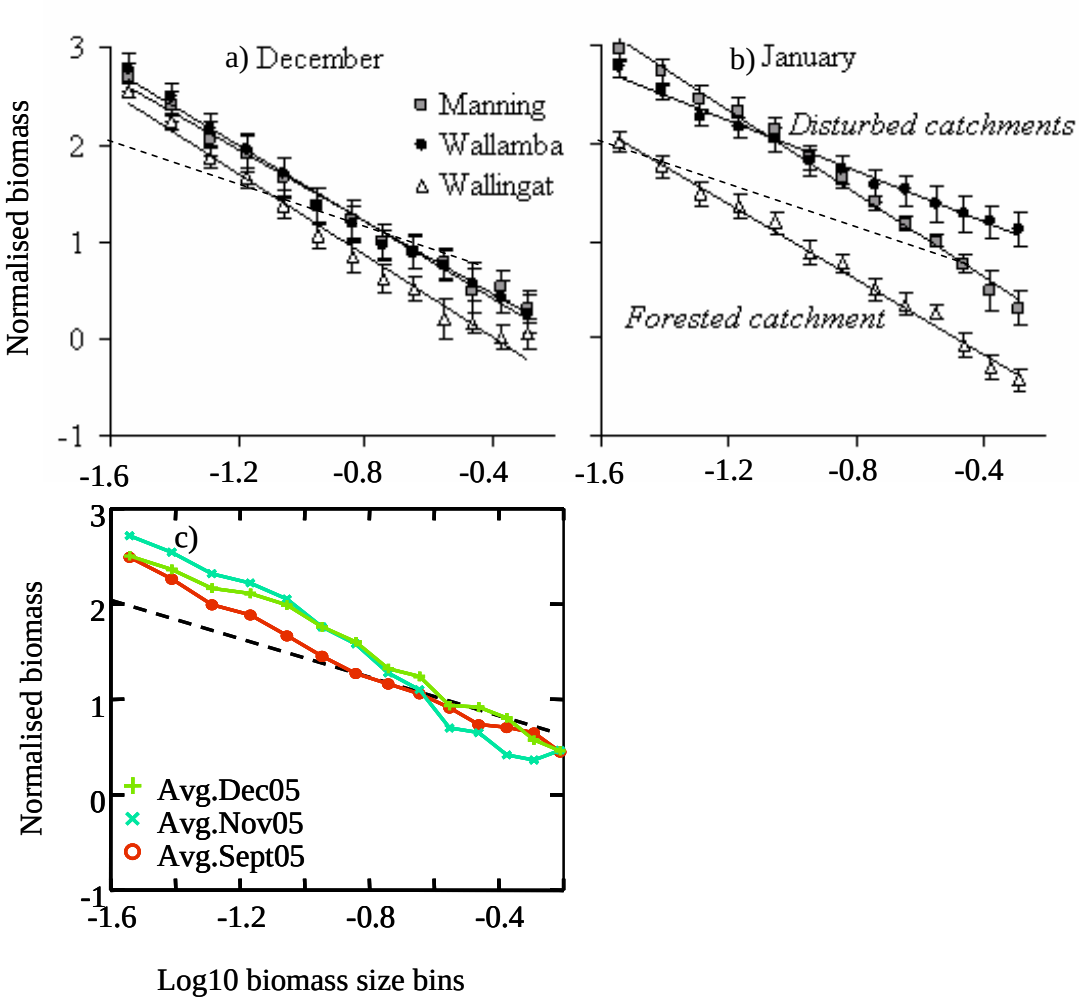

Figure 17. Average normalised biomass size spectra (NBSS) from sites within the Manning River, Wallamba and Wallingat Rivers in a) December 2003 after heavy rain, b) January 2004 (both a) and b) from Moore and Suthers, 2006), and c) in Brisbane Water in September, November and December 2005. The dashed line shows the -1 slope. Bottom-up processes (nutrient enrichment) are indicated when the NBSS slope rises above the -1 slope at the small particles (left hand) side of the spectrum, while top-down (zooplankton predation by fish) is implied when the NBSS falls below the -1 slope at the larger particles (right hand) end of the spectrum.