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Journal of Marine Research, 57, 537–559, 1999

The effects of multiple trap spacing, baffles and brine volume on sediment trap collection efficiency

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ABSTRACT

The hydrodynamic effects on trapping efficiency of sediment trap cross-frame position, baffles and brine volume were evaluated in three short-term (<1 week) experiments in a temperate shallow marine environment (Evans Bay, Wellington Harbour, New Zealand). The effects of trap position and brine were further investigated during two open ocean, free-floating sediment trap deployments (1–2 days) near the Subtropical Front (STF), east of New Zealand. In the Evans Bay experiments (numbered I–III), cross-frames, each holding 12 cylindrical traps (inside diameter 9 cm, height 95 cm), were moored 3 meters above the seafloor in 15–18 m water depths at three randomly selected inner harbor sites. Triplicate subsamples from each cylinder were analyzed for total dry weight and mass fluxes calculated. The STF deployments utilized JGOFS MULTI-traps (inside diameter 7 cm, height 58 cm) attached to cross-frames moored at three depths (120, 300 and 550 m) on drifting arrays (Experiments IV and V). MULTI-trap samples were analyzed for total particulate mass, carbon and nitrogen. Results from Experiments I and V indicate that a spacing of about 3-trap diameters was sufficient to minimize inter-trap interactions and maintain trapping efficiency among traps suspended on a cross-frame at the same depth. Furthermore, baffles had no effect on trapping efficiency and an undetectable impact on zooplankton "swimmer" populations also collected in traps (Experiment II). In Experiment III, traps that were filled completely with high-density salt brine (50‰ excess NaCl) collected 2–3 times less material than traps with a basal brine height equivalent to 1- and 2.5-trap diameters. In contrast, high levels of inter-site variability confounded the STF MULTI-trap deployments during Experiment IV. However, variability in flux measurements from both Experiments III and IV increased 2 to 3-fold in brine-filled traps. Thus, the potential for brine-filled traps to undercollect material with higher levels of variability could possibly explain previously reported inaccuracies in the sediment trap method.

1. Introduction

Sediment trap studies in the 1970–1980's were concerned primarily with determining the most efficient sediment trap design. This research recognized that differences between trap shape and size could significantly affect trapping efficiency (e.g., Lau, 1979; Bloesch and Burns, 1980; Blomquist and Håkanson, 1981; Gardner, 1980a,b; Hawley, 1988; see summary by Bloesch, 1996). Subsequently, Butman (1986) and Butman *et al.* (1986) identified three dimensionless parameters that were critical to sediment trapping efficiency:

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trap Reynold's Number (R_t), the ratio of flow speed to particle fall velocity (R_v) and trap aspect ratio (AR). With respect to these parameters, these authors showed that trapping efficiency of unbaffled, straight-sided cylinders decreased over a range of increasing R_t and sinking speeds of particles, as was later validated in field tests by Baker *et al.* (1988). A controversial paper by Gust *et al.* (1996) has subsequently suggested that trapping efficiency increases with increasing R_t, contrary to the previous work of Gardner (1980a), Butman (1986) and Baker *et al.* (1988). Gardner *et al.* (1997) have recently refuted the experimental approach adopted by Gust *et al.* (1996).

In modern sediment trap studies, many of the earlier findings have been followed in the design of traps and subsequent application of trapping experiments in marine environments ranging from harbors, fjords, shallow enclosed seas and open oceanic regimes. For example, at two Joint Global Ocean Flux Study (JGOFS) time-series stations in the equatorial central Pacific and western Atlantic oceans, free-floating arrays with multiple cylindrical sediment traps (MULTI-traps, e.g., Knauer *et al.,* 1979; Martin *et al.,* 1987, 1993) have been deployed on a monthly basis over the past 8 years and have received substantial scientific attention (e.g., Lohrenz *et al.,* 1992; Michaels *et al.,* 1994; Karl *et al.,* 1996). Attempts to independently calibrate these traps using mass balance modeling of ^{234}Th:^{238}U disequilibria in the upper water column (<200 m), however, have led to suggestions that traps may underestimate actual sinking fluxes by as much as 80% (e.g., Buesseler, 1991; Buesseler *et al.,* 1992, 1994; Michaels *et al.,* 1994). Most recently, Murnane *et al.* (1996, p. 239) have proposed that a "33% trapping efficiency scenario produces results that are consistent with the water column ^{234}Th budget," rather than a 100% efficiency scenario that sediment trap enthusiasts would anticipate. Furthermore, Michaels *et al.* (1994) proposed that a three-fold imbalance in the carbon budget modeled near the JGOFS Bermuda time-series site (BATS) could be attributed almost entirely to inaccuracies in the export flux measured using free-floating sediment traps.

The underlying causes of such significant differences between two independent measurements of vertical particulate flux from the upper ocean (e.g., thorium disequilibria modeling and sediment traps) needs to be explored further. It is pertinent, therefore, to re-investigate some fundamental hydrodynamic questions regarding *how* traps work, particularly as many factors remain to be addressed (e.g., U. S. GOFS Report 10, 1989; JGOFS Report 29, 1994; Gardner, 1997). Specifically, the effects of inter-trap hydrodynamic interactions, baffles and brine volume have not been evaluated adequately under field conditions. This situation is despite the pervasive use in many sediment trap studies of multiple trap arrays, baffled obstructions, and high-density brine solutions (e.g., Knauer *et al.,* 1979; Martin *et al.,* 1987, 1993; Lohrenz *et al.,* 1992; Lee *et al.,* 1992; Michaels *et al.,* 1994; Karl *et al.,* 1996). The effect of these factors on trapping efficiency is evaluated in this paper.

2. Methods

Two contrasting field situations were utilized in the present study. The first used high aspect ratio ($AR = 10.6$), cylindrical traps that were bottom moored in a shallow water, harbor environment, while the second approach tested aspects of trapping efficiency using JGOFS MULTI-traps ($AR = 8.3$) deployed on free-floating arrays in the open ocean. The data were analyzed statistically using a General Linear Model (GLM) Analysis of Variance (ANOVA) and a multiple comparison *a posteriori* procedure (Tukey test). The computer program employed for all statistical analyses was NCSS (Version 6.0).

a. Bottom moored sediment trap experiments in Wellington Harbour (Experiments I–III)

A series of three experiments were conducted in the shallow (<20 m) inner harbor waters of Evans Bay, Wellington Harbour (41°18.25′S 178°48.44′E) between 1994 and 1995. Wellington Harbour is a semi-enclosed, 85 km^2 embayment at the southern end of North Island, New Zealand (Fig. 1). Evans Bay is a 1–2 km wide major arm of the harbor, oriented roughly north-south, parallel to the present harbor entrance to Cook Strait (Fig. 1B). In Wellington Harbour, tidal streams are weak (<2 cm s^{-1}; Heath, 1977; Abraham, 1997). Consequently, flows within the harbor are predominantly meteorologically forced (Brodie, 1958; Heath, 1977; Abraham, 1997). For example, Abraham (1997) observed wind-driven flows of up to 30 cm s^{-1} associated with winds of over 10 m s^{-1}. Near-bottom currents generally lag wind events by 14 hours (M. Hadfield, pers. comm., 1996). Sandy muds and mud, grading to muddy sand on the western flank of Evans Bay (Lewis and Carter, 1976), dominate sediments in Wellington Harbour and Evans Bay. These sediments are derived mainly from freshwater sources by tidal dispersion (Brodie, 1958).

Three separate experiments were undertaken in Evans Bay (Fig. 1B and C) to investigate the effects of multiple trap spacings (Experiment I), baffles (Experiment II) and brine volume (Experiment III) on trapping efficiency. The NZOI-NIWA traps comprised 95-cm high, polycarbonate cylindrical traps, with an inside diameter (D_i) of 9 cm and an aspect ratio of 10.6 without brine (Fig. 1D). The upper opening of each trap was 0.0064 m^2. Removable baffles were made of polyvinyl chloride tubing with a D_i of 2 cm and a length of 9.5 cm (i.e., baffle length was equivalent to outside trap diameter, e.g., Knauer *et al.,* 1979). Baffles were inserted into the openings of twelve cylindrical traps that were attached to four arms of a stainless steel cross-frame at spacings of at least $3D_i$ (i.e., 30 cm).

In each experiment, a single sediment trap cross-frame, holding twelve cylindrical traps, was bottom moored at depths of 3 m above the seafloor (Fig. 1D) at three randomly chosen sites in water depths ranging from 15–18 m (Fig. 1C). Each mooring was held taut using 50 kg anchors with 40 kg of buoyancy provided by two Viny buoys. Traps and baffles were washed using 1 M HCl, rinsed with distilled water and capped with plastic bags, prior to deployment. Brine solutions were prepared 1–2 days in advance from Evans Bay seawater that was pressure-filtered through 1.0 and 0.45 μm membrane filters. The seawater was then mixed with 50 g ANALAR NaCl and 100 ml formalin for every liter of dyed filtered seawater to produce a 50‰ excess brine solution (e.g., Karl *et al.,* 1990). Traps were deployed and recovered from a small boat, with traps opened and closed by SCUBA divers using plastic bags. Spatial relationships between individual trap moorings were determined using measured ground-lines connected to a central permanent NZOI-NIWA equipment

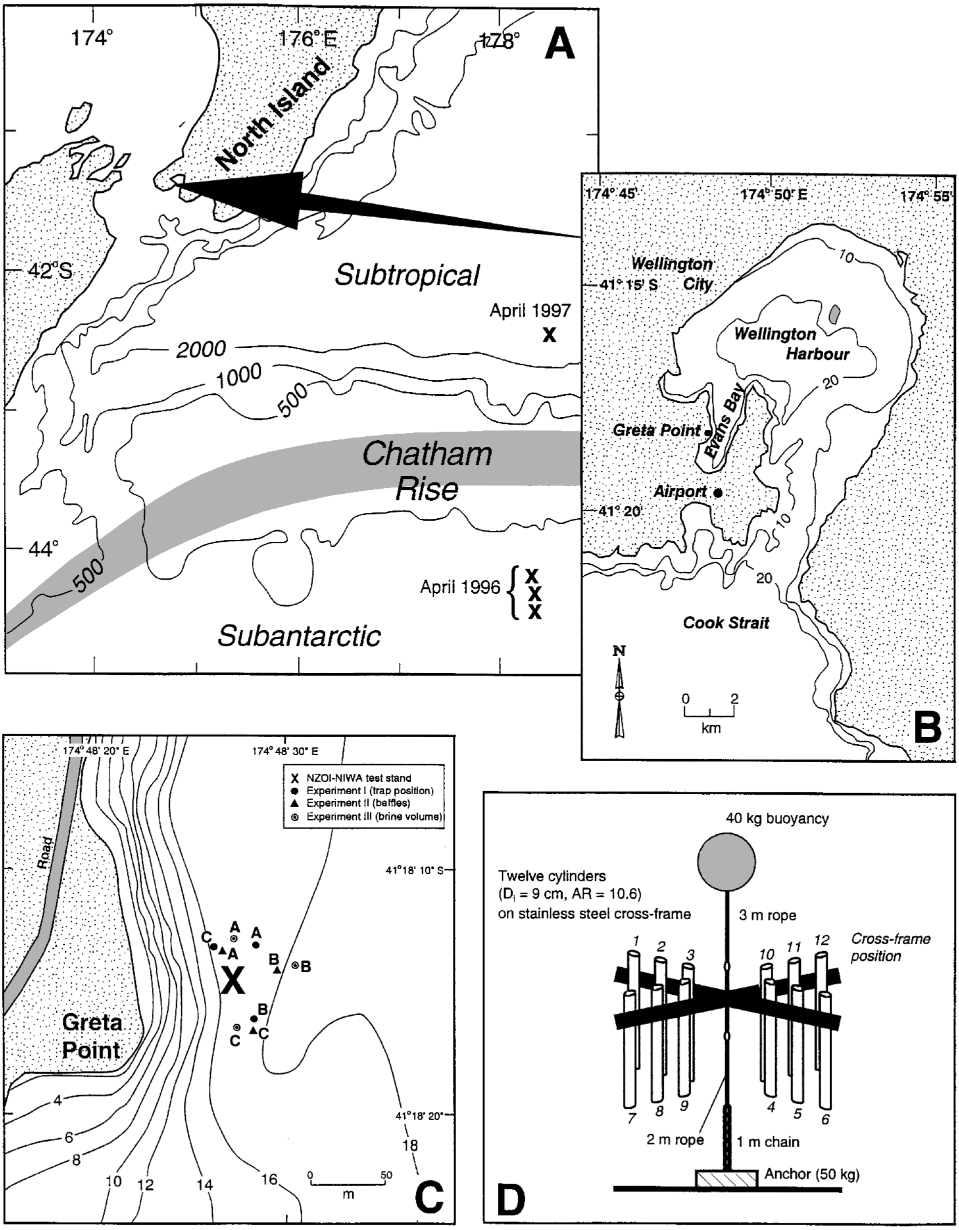

Figure 1. Location of study sites near Chatham Rise (A) and in Evans Bay, Wellington Harbour, New Zealand (B). Free-floating MULTI-trap deployments in austral autumn 1996 and 1997 were conducted in deep water (>500 m) away from the Subtropical Front, which is depicted as the shaded area across the crest of Chatham Rise (A). Locations of bottom moored sediment trap arrays used in the three Evans Bay experiments in 1994 and 1995 are shown in C. Note that sites A, B and C were at different locations in each of the three experiments. A diagram of the mooring configuration used in the Evans Bay experiments is also shown (D). All bathymetric contours are in meters.

test-stand offshore from Greta Point from which an Aanderaa current meter was attached (Fig. 1C).

Upon recovery, after deployments ranging from 1–6 days, seawater overlying the basal brine was siphoned off and trap contents were pre-screened through a 200 µm mesh to remove large zooplankton "swimmers" (e.g., Karl *et al.,* 1990). The trap solution was then poured into a 10 l Nalgene container, homogenized well by shaking and aliquots removed into measuring cylinders. Material collected on the 200 µm mesh was transferred to a plastic flask, 30 cm^3 of 2% sodium metahexaphosphate added and the sample shaken on a mechanical shaker for 15 min to breakdown organic material. This solution was then recombined with the originally sieved trap contents by being passed back through the 200 µm mesh; the final >200 µm fraction was preserved in 2.5% pH-buffered formalin and stored in a refrigerator. Three aliquots of about 100-ml trap solution from each cylinder were then filtered through pre-weighed, 25-mm diameter, 0.2 µm Nuclepore filters. Average mass fluxes for each cylinder were calculated gravimetrically based on the methods and equations in Karl *et al.* (1990) with filtered samples washed with 1 M isotonic ammonium formate to remove sea-salts, oven-dried (60°C for 2 hours) and re-weighed to constant dry weight.

Ambient current flow characteristics over the course of the Evans Bay experiments were measured using an Aanderaa rotary current meter, except during the first experiment when the current meter failed. The current meter was moored 3 m above the seafloor on the permanent equipment test-stand located in Evans Bay (Fig. 1C). Estimates of maximum trap Reynolds numbers experienced during each experiment were calculated using these current meter measurements and trap geometry.

b. Floating sediment trap experiments in Chatham Rise region (Experiments IV and V)

In 1996 and 1997, two investigations were undertaken in an open ocean environment using free-floating sediment trap arrays deployed near the Chatham Rise (Fig. 1A). A major oceanic frontal zone, the Subtropical Front, lies along Chatham Rise to the east of New Zealand (Heath, 1985). Here, warm (summer >15°C, winter >10°C), highly saline (35.7–35.8‰), nutrient-depleted subtropical waters to the north are mixed with cold (summer <15°C, winter <10°C), less saline (~34.5‰), nutrient-rich subantarctic waters to the south. The STF is characterized by strong latitudinal gradients of sea-surface temperature and salinity of up to 4°C and 0.9‰, respectively, over one degree of latitude (Heath, 1985).

The Chatham Rise deployments were undertaken using cylindrical MULTI-traps after completion of the Evans Bay experiments. Individual, baffled MULTI-traps have a D_i of 7 cm and an aspect ratio (without brine) of 8.3. For the Chatham Rise experiments, cross-frames, each holding twelve traps with inter-trap spacings of 14–16 cm, were deployed on the same mooring line at three depths (120, 300 and 550 m) at each free-floating station. Mooring designs were similar to those employed during other JGOFS studies (e.g., Lohrenz *et al.,* 1992; Martin *et al.,* 1993; Karl *et al.,* 1996). Traps were cleaned and prepared in an identical manner to those used in the Evans Bay experiments. Trap spacings on the MULTI-trap cross-frames are $<3\text{-}D_i$, compared to the NZOI-NIWA trap configuration of $>3\text{-}D_i$.

Deployments at three stations were conducted for 48 hours in subantarctic waters, south of Chatham Rise, in austral autumn (April) 1996 (Fig. 1A) to investigate brine volume effects on trapping efficiency. The stations were placed initially 5 nautical miles (9 km) apart since Chiswell (1994) observed no coherence in physical parameters between current meter moorings deployed 7 nautical miles (13 km) apart on Chatham Rise. A single array was deployed for 24 hours in subtropical waters, north of Chatham Rise, in April 1997 (Fig. 1A) to determine whether inter-trap hydrodynamics on the MULTI-trap cross-frames affected the collection rate of sinking particulate matter.

In the first Chatham Rise experiment (Experiment IV), investigating brine volume effects, five of twelve traps on each cross-frame were completely filled with a 50‰ excess NaCl, 1% formalin brine (e.g., Karl *et al.,* 1990). Five other traps had a basal 1-diameter (D) brine volume added. Upon recovery, trap samples were processed in an identical manner to trap samples in Wellington Harbour, except that due to the substantially lower amount of organic material in the Chatham Rise samples, >200 µm particles were not treated with sodium metahexaphosphate. Known aliquots of about 150–200 ml were taken from each brine-filled cylinder for mass flux analyses that were determined by weighing the desalted, filtered samples to constant dry weight, as described above. Total particulate carbon and nitrogen fluxes were determined from samples filtered onto pre-combusted (450°C for 4 hours), GF/F filters using a Perkin-Elmer 2400 CHN analyzer (Nodder, 1997). For traps with 1-D brine volume, approximately 200 ml of trap solution was filtered, compared with 450–500 ml for traps filled completely with brine. All fluxes were blank-corrected (e.g., Nodder and Alexander, 1998). Particulate fluxes for each sample depth were averaged across the three stations.

In the second Chatham Rise experiment (Experiment V), similar procedures were undertaken as outlined above, with total particulate mass, carbon and nitrogen fluxes determined from twelve traps at each sample depth. Each trap was deployed with a 1-D thick, NaCl-formalin basal brine, as described above. All fluxes were blank-corrected, except for mass flux samples.

3. Results

a. *Experiments I and V: inter-trap interactions*

At each of the three mooring sites in Wellington Harbour, there were no significant differences in trapping efficiency due to cross-frame position for the NZOI-NIWA trap configuration (*d.f.* = 2; $F = 2.90$; $P = 0.167$; power = 0.096) (Fig. 2). ANOVA tests detected, however, a significant "site" effect with fluxes measured at sites A and B statistically different to those measured at site C (*d.f.* = 2; $F = 16.50$; $P = 0.00$). A mean

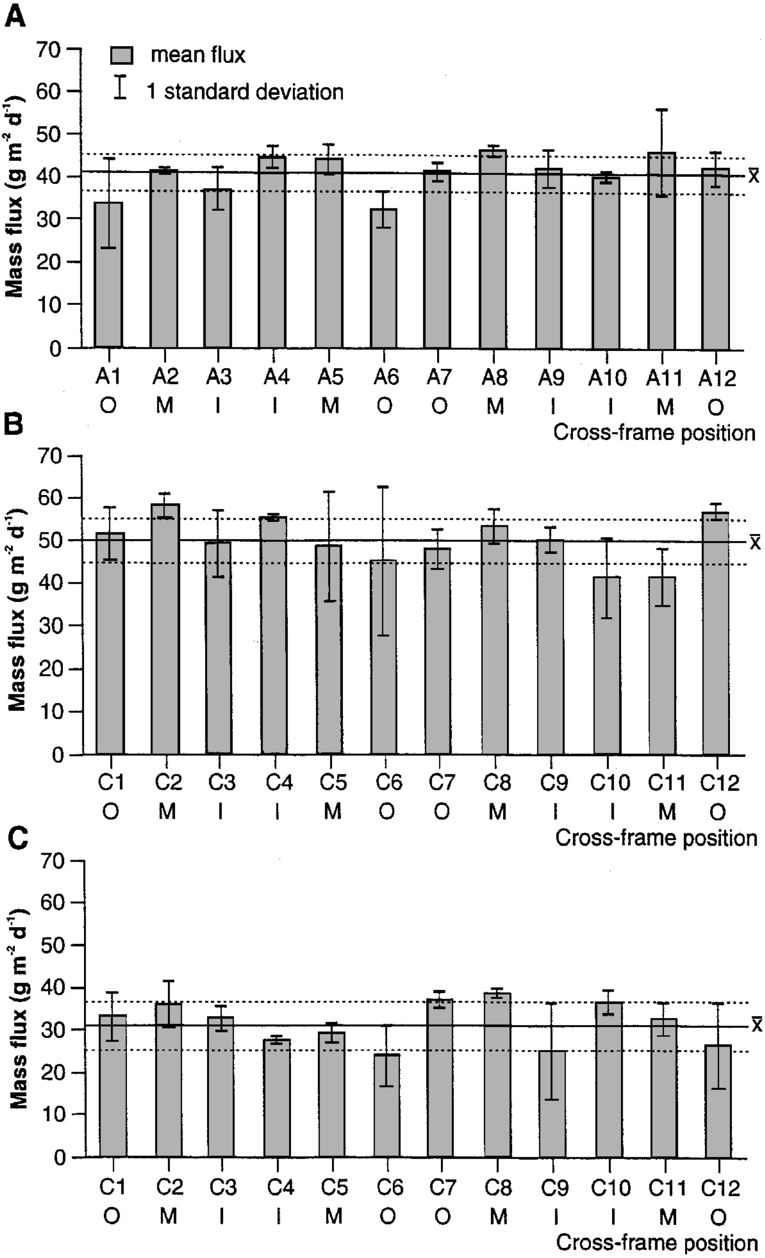

Figure 2. Effect of trap cross-frame position on average mass fluxes (±1 standard deviation) in Evans Bay, Wellington Harbour, in August 1994 (Experiment I). Along x-axis, A, B and C refer to the randomly chosen sites (refer Fig. 1C), 1–12 to cross-frame position and O, M and I to whether the traps were in "outer," "middle" or "inner" positions.

flux of 33 g m^{-2} d^{-1} was measured at site A, 34 at site B and 25 at site C with standard deviations ranging from 11–16% of the mean (Fig. 2).

These inter-site differences can be explained by a combination of: (a) analytical errors arising from several ripped filters during the filtration of subsamples from site C; and (b) the deployment of traps at site C in slightly shallower water than sites A and B. Traps at site C were deployed at a depth of 13.7 m in 16.8 m, compared with traps at approximately 15 m in 18 m water depth at the other sites (Fig. 1C). Particle focusing (e.g., Timothy and Pond, 1997) away from the steeply dipping western side of Evans Bay could have resulted in relative increases in mass flux at the slightly deeper A and B sites.

In Experiment V near Chatham Rise, there were no significant differences between particulate fluxes measured at inner, middle and outer positions on the MULTI-trap cross-frame (mass: *d.f.* $= 2$; $F = 1.35$; $P = 0.28$; power $= 0.23$; particulate carbon: *d.f.* $= 2$; $F = 1.90$; $P = 0.17$; power $= 0.31$; particulate nitrogen: *d.f.* $= 2$; $F = 0.46$; $P = 0.64$; power $= 0.11$) (Fig. 3). In addition, there were no significant differences between depths for both total mass and particulate carbon fluxes (*d.f.* $= 2$; $F = 1.59$; $P = 0.22$; power $= 0.26$ and *d.f.* $= 2$; $F = 0.62$; $P = 0.54$; power $= 0.13$, respectively). In contrast, significantly high particulate nitrogen fluxes were measured at 300 m at all cross-frame positions (*d.f.* $= 2$; $F = 8.64$; $P = 0.001$, power $= 0.90$).

b. *Experiment II: baffles*

Mass fluxes measured at each site during Experiment II ranged from 27 to 47 g m^{-2} d^{-1} and suggested that the trapping efficiency of NZOI-NIWA traps was not significantly affected by baffles (*d.f.* $= 1$; $F = 4.08$; $P = 0.181$; power $= 0.071$; Fig. 4). Statistical tests between site and interaction terms had one less degree of freedom because one trap at site C (cylinder 6) inadvertently remained capped during the course of the experiment (Fig. 4). Thus, a mean value from all the traps at site C was used for this sample. Currents at the height of the traps were generally between 2–7 cm s^{-1} with a period of variably southward-directed flows on 28 March and stronger northward-flowing currents on 29 March. The water temperature was 17°C. Trap Reynolds numbers were therefore between 2090–6050 (assuming seawater viscosity of 1.1×10^{-2} cm^2 s^{-1}; Sverdrup *et al.,* 1942).

To investigate the effectiveness of baffles as zooplankton "swimmer" deterrents, as suggested by Martin *et al.* (*in* U. S. GOFS Report 10, 1989), identifiable zooplankton "swimmers," collected on a 200 μm mesh, were enumerated (Table 1). There were no significant differences between the plankton collected by unbaffled, compared to baffled, traps, except for copepods where a significant interaction between "site" and "baffle" was found (*d.f.* $= 2$; $F = 3.49$), reflected by slightly higher numbers of copepods collected at Site A (Table 1). Some inter-site variability is suggested for all "swimmers," except for polychaetes, with generally higher average numbers of zooplankton present in Site A traps (Table 1). A slightly lower number of diatoms were collected on average at Site B, compared with the other two sites (Table 1). All of the "swimmer" ANOVA calculations had low levels of power ($P = 0.05$–0.10).

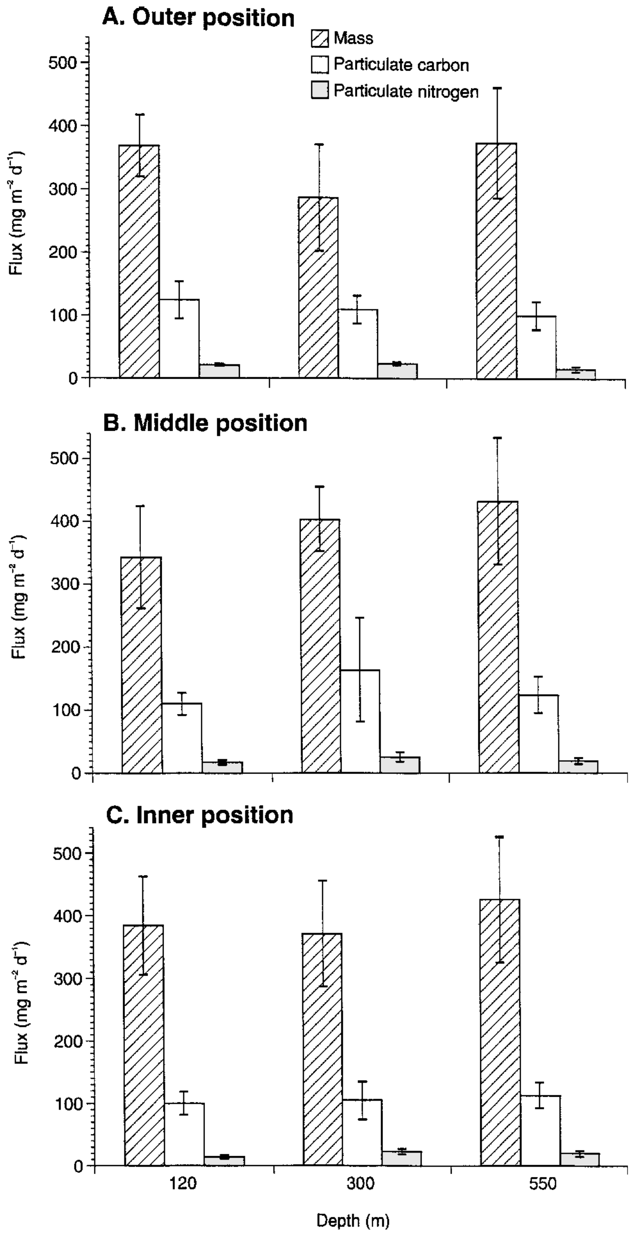

Figure 3. Effect of cross-frame position on average total particulate mass, carbon and nitrogen fluxes (±1 standard deviation) for cylindrical MULTI-traps deployed on a free-floating sediment trap array in austral autumn (April 1997) near Chatham Rise (refer Fig. 1A). The traps had a basal high density brine volume equivalent to 1-trap diameter. Trap cross-frames were deployed at 3 water depths: 120, 300 and 550 m. All fluxes were blank-corrected, except for mass fluxes.

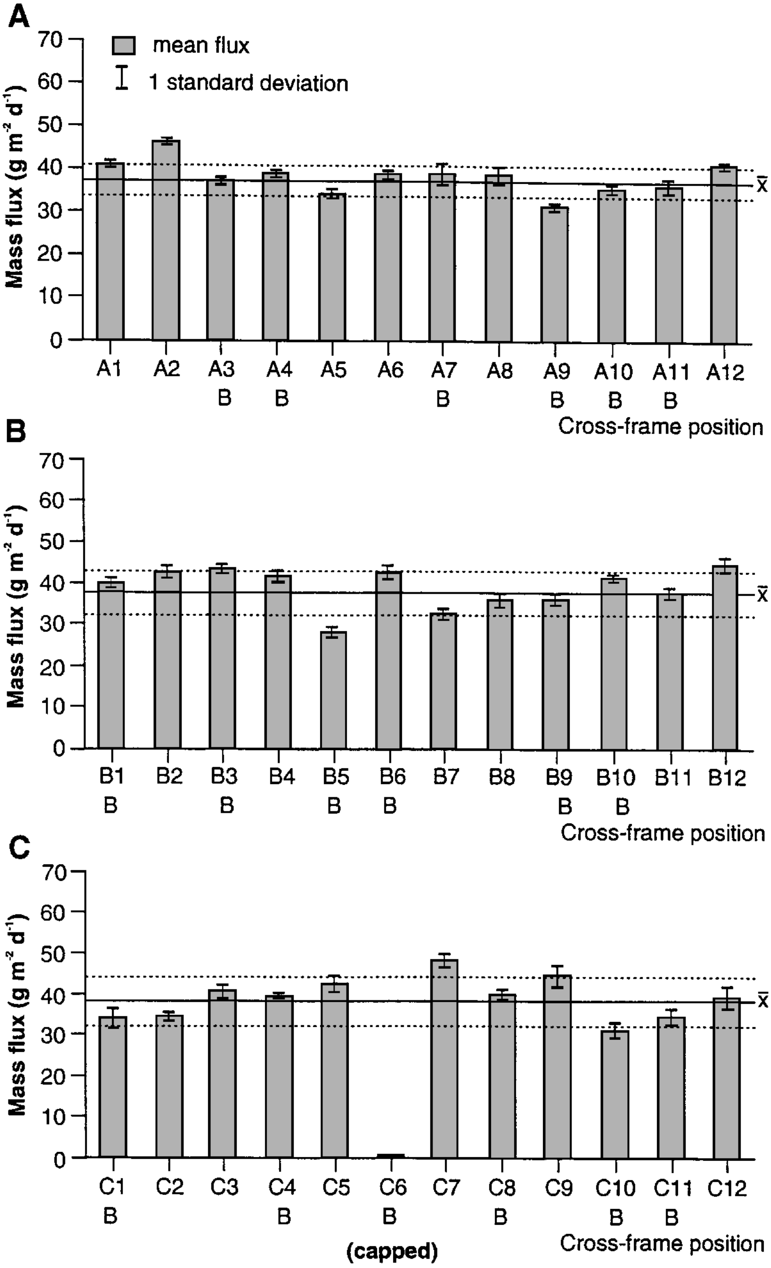

Figure 4. Effect of baffles on average mass fluxes (±1 standard deviation) in Evans Bay, Wellington Harbour, in March 1995 (Experiment II). Along x-axis, A, B and C refer to the randomly chosen sites (refer Fig. 1C), 1-12 to cross-frame position and B to whether traps were baffled or not (unlabeled).

Table 1. Effect of baffles on average zooplankton “swimmer” abundance in Evans Bay sediment trap Experiment II in March 1995.

	Mean zooplankton “swimmer” (>200 µm) abundance*				
	Copepods	Polychaetes	Medusae	Large worms	Diatoms
Site A					
Baffled	65.50 ± 24.98	28.83 ± 5.74	6.00 ± 5.51	2.50 ± 1.64	12.50 ± 6.92
Unbaffled	92.83 ± 34.98	38.17 ± 15.80	7.17 ± 3.87	3.67 ± 1.51	9.50 ± 3.08
Site B					
Baffled	50.40 ± 10.31	24.80 ± 9.23	6.00 ± 3.67	0.80 ± 0.84	5.60 ± 3.58
Unbaffled	67.25 ± 10.01	23.75 ± 7.41	4.00 ± 1.83	1.75 ± 1.83	6.50 ± 3.70
Site C					
Baffled	63.20 ± 18.30	24.20 ± 10.83	2.00 ± 0.71	2.00 ± 0.71	8.80 ± 3.42
Unbaffled	40.00 ± 5.34	21.00 ± 6.00	0.60 ± 0.55	1.40 ± 1.14	8.20 ± 4.09
All sites**					
$\bar{x} \pm s_{\text{baffled}}$	60.06 ± 19.28	26.13 ± 8.35	4.75 ± 4.19	1.81 ± 1.33	9.19 ± 5.59
$\bar{x} \pm s_{\text{unbaffled}}$	68.40 ± 31.79	28.60 ± 13.34	4.13 ± 3.82	2.40 ± 1.55	8.27 ± 3.56

*Average values ± 1 standard deviation are shown; typically, $n = 4$–6.
**For baffled traps, $n = 16$; for unbaffled traps, $n = 15$.

c. *Experiments III and IV: brine volume*

In the Evans Bay experiments, it was intended to use volumes equivalent to exactly 1*D*- and 2.5*D*-brine heights (corresponding to 0.576 *l* and 1.472 *l*, respectively). However, it was technically impossible to replicate these exact amounts for each trap due to bubbling during the back-filling process (e.g., Knauer, 1991). Accordingly, actual brine volumes for the 1D traps ranged from 0.960 to 2.0161 (average 1.536 ± 0.353 *l*, ±1 standard deviation), corresponding to brine heights of 15–31 cm (24.0 ± 5.5 cm or 2.7 ± 0.6 trap outside diameters, D_o). Brine volumes for 2.5D traps were between 1.600 and 3.136 *l* with an average brine volume in these traps of 2.437 ± 0.386 *l*, reflecting brine heights that ranged from 25–49 cm (38.0 ± 6.1 cm or 4.2 ± 0.7D_o). There was only minimal leakage from traps during pre-deployment and post-recovery phases, so that the loss of solution was related to upper trap flushing processes during the deployment period (e.g., Gardner, 1980a; Hawley, 1988; Gust *et al.,* 1996; Gardner and Zhang, 1997). Traps that were deployed filled completely with brine were recovered with variable amounts of brine. Trap volumes in the brine-filled traps at the end of the deployment ranged from as low as 2.432 *l* to a maximum of 5.856 *l* with an average brine volume in completely filled traps of 4.460 ± 1.183 *l*, out of a total trap volume of 6.044 *l*. These volumes correspond to brine heights of 45–92 cm (average 72.5 ± 18.5 cm), equivalent to 5.0–10.2 D_o (average 8.1 ± 2.1D_o).

In general, the mean fluxes recorded on the very calm day in winter during Experiment III were substantially less than the fluxes observed at other times in Evans Bay (Fig. 5 cf. Fig. 2 and 4), ranging from 2 to 12 g m^{-2} d^{-1}. Current meter records collected at this time indicate that flows at the height of the moored traps were less than 5 cm s^{-1} and variable in

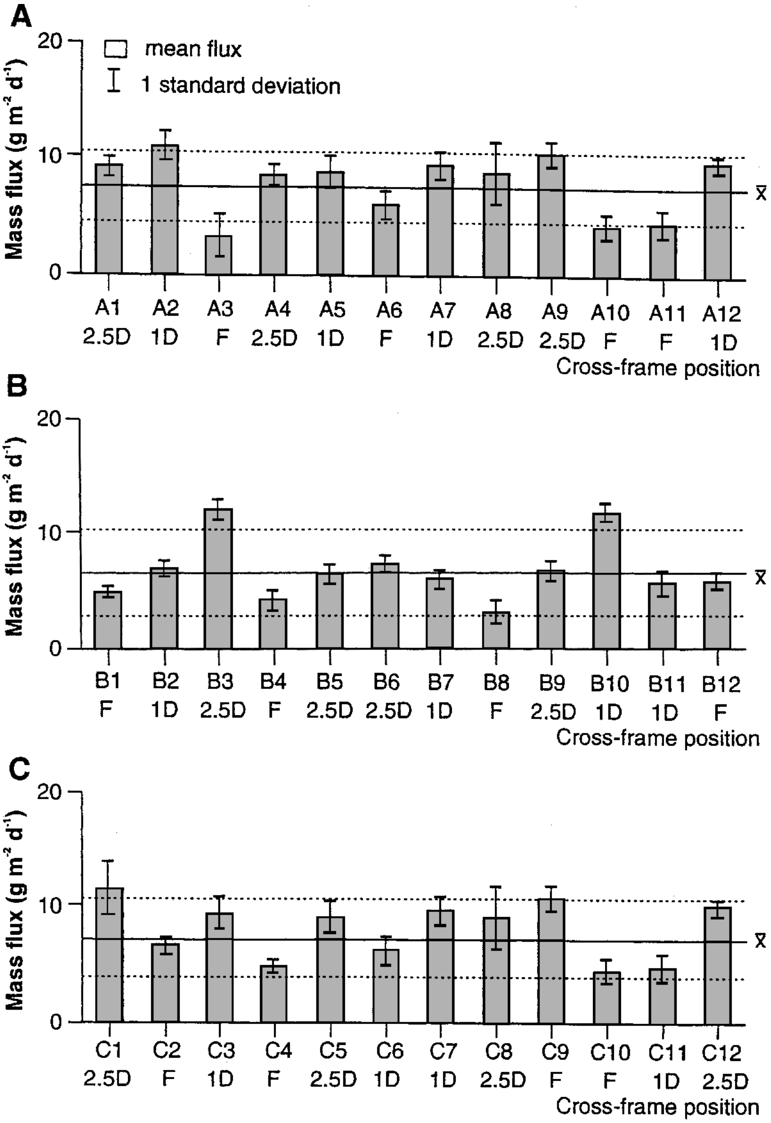

Figure 5. Effect of brine volume on average mass fluxes (±1 standard deviation) in Evans Bay, Wellington Harbour, in June 1995 (Experiment III). Along x-axis, A, B and C refer to the randomly chosen sites (refer Fig. 1C), 1-12 to cross-frame position and 1D, 2.5D and F to volume of 50‰ excess NaCl brine originally added to the traps. 1D and 2.5D correspond to basal brines with heights above trap bottom of 1- and 2.5-trap diameters, respectively, while F refers to traps that were filled completely with brine. Note the change in scale on the y-axis, compared to Figures 2 and 4.

direction (slightly to the north); the water temperature was 11°C. The maximum trap Reynolds number was about 3390 (assuming a seawater viscosity of 1.4 ± 10^{-2} cm^2 s^{-1}; Sverdrup *et al.,* 1942).

More importantly, mass fluxes calculated for traps that were filled completely with brine were significantly different from fluxes derived from other traps (*d.f.* = 2; $F = 42.73$; $P = 0.002$; power = 0.68). Brine-filled fluxes were typically 2–3 times less than those fluxes from traps containing less brine (Fig. 5). There was no clear pattern between those traps filled with 1*D*-brine volume, compared with those filled with 2.5*D*, although there was a tendency for the latter to trap slightly more material on average (Fig. 5).

In Experiment IV near Chatham Rise, significant interaction terms between "site" and "brine volume" were found for total mass and particulate carbon fluxes (*d.f.* = 2; $F = 3.74$ and *d.f.* = 2; $F = 4.27$, respectively). Thus, any statistically significant relationship between the two brine volume treatments (Full and 1*D*) was confounded by inter-site differences. For total mass, there was also a significant interaction term between "site" and "depth" (*d.f.* = 4; $F = 18.37$) as there was for particulate nitrogen fluxes across the three sites (*d.f.* = 4; $F = 3.37$). The high levels of variability associated with mass fluxes measured at 120 m for both brine volume treatments meant that a statistically significant result was not realized, although on average brine-filled traps collected more material than 1*D* traps (Fig. 6). In all cases, the power levels of the ANOVA tests were less than 0.1 (range: 0.05–0.08).

It is worthwhile noting that the apparent 1:1 ratio between mean mass and carbon fluxes at 300 and 550 m in brine-filled traps (Fig. 6) is probably an artifact of the subsampling method. About two times more trap solution was filtered to obtain carbon values than was used for determining mass fluxes, and samples of 500–1000 ml were mixed in a large volume 10 liter container before aliquots were dispensed. Furthermore, it is possible that the lengthy time that it takes to filter natural solutions through 0.2 μm membrane filters could have resulted in significant carbonate dissolution, thereby reducing the total dried mass collected on the filter. The anomalous 1:1 carbon-to-mass relationship, however, does not affect the conclusions of Experiment IV as the experiment was designed to test the hypothesis that differences in brine volume do not affect particulate fluxes, and not to establish accurate carbon-to-mass flux relationships. Other samples had average carbon-to-mass ratios that ranged from 30–70%, which is higher than normally expected from open ocean environments (approximately 10–30%). However, not only are the carbon fluxes presented here *total* particulate carbon measurements (i.e., organic + inorganic carbon), but the MULTI-traps were deployed in the vicinity of the biologically productive Subtropical Front, and carbon-to-mass flux ratios of up to 40 have been reported previously from this region (Nodder, 1997). C:N ratios from the Chatham Rise deployments were higher than the classic Redfield ratio of 6 in April 1996 (C:N 10–13), but were closer to this "average" in April 1997 (C:N 5–7). These observations suggest that at times the Chatham Rise region may act as a moderate sink for oceanic carbon (e.g., Nodder, 1997), albeit with an unknown degree of interannual variability.

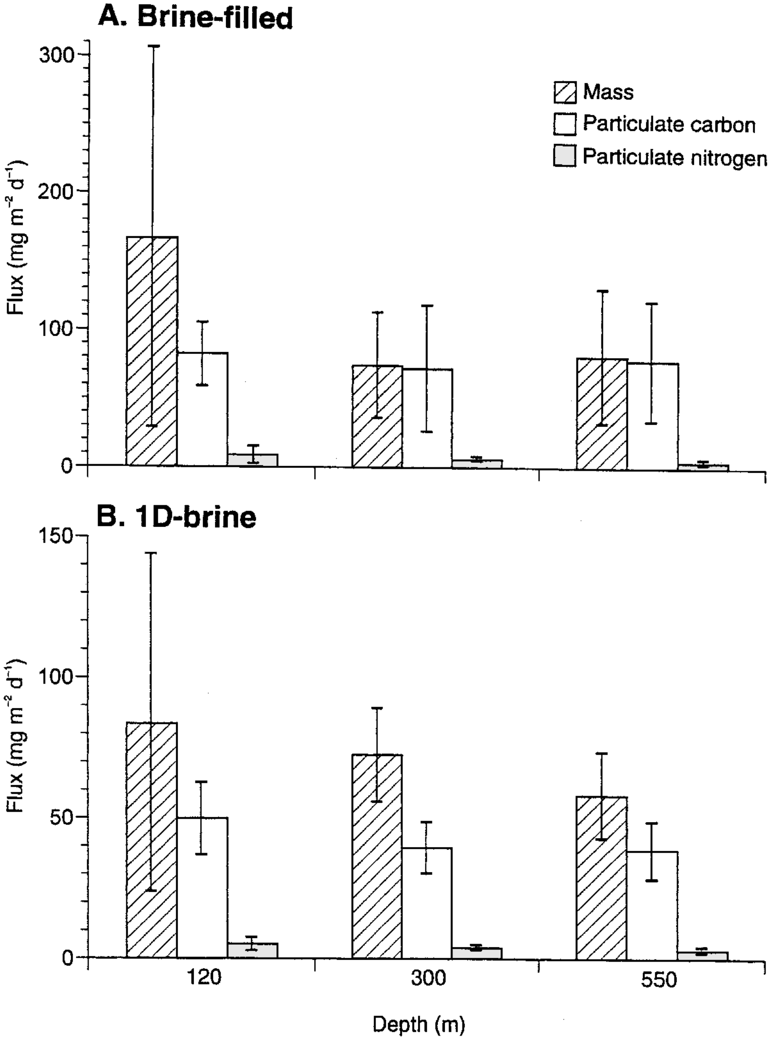

Figure 6. Effect of brine volume on average total particulate mass, carbon and nitrogen fluxes (±1 standard deviation) for cylindrical MULTI-traps filled completely with brine and traps with a basal brine volume equivalent to 1-trap diameter (1D). The fluxes represent mean values from three free-floating MULTI-trap deployments near Chatham Rise in austral autumn (April 1996) (refer Fig. 1A). Trap cross-frames were deployed at 3 water depths: 120, 300 and 550 m. All fluxes were blank-corrected.

d. Trap Reynolds number and brine-wash-out

Trap Reynolds numbers during the course of the Evans Bay experiments II and III ranged from 2090–6050 and up to 3390, respectively. These values encompass the ranges investigated by Gardner and Zhang (1997) in their flume study of the effect of brine on trapping efficiency (0–6500). In comparison, Hawley (1988) showed that for traps with an aspect ratio of 8, the bottom tranquil layer remained intact even at $R_t = 20{,}000$. Thus, for the traps used in the Evans Bay experiments, one would expect particles to be retained within the traps over the range of calculated R_t (e.g., Lau, 1979), with estimated basal tranquil layers of 3–4 cm (using the equation in Hawley (1988)).

In Experiment III, completely brine-filled traps had initial aspect ratios of <1. Upon recovery, depending on the degree of brine wash-out, aspect ratios generally remained <2 and always <4. Gardner and Zhang (1997) showed that even at low R_t brine-filled traps (aspect ratio 4.3) experienced significant wash-out with a 75% reduction in brine volume at $R_t = 3500$ and a 90% decrease at $R_t = 6500$. In comparison, wash-out from brine-filled NZOI-NIWA traps was $<25\%$ ($s = 20\%$, $n = 12$) in Evans Bay, despite similar R_t values as used by Gardner and Zhang (1997). Presumably, this is related to differences in aspect ratio between the two types of traps since brine wash-out was only 37% ($s = 3\%$, $n = 10$) for NZOI-NIWA traps deployed during storm conditions in Cook Strait in March–April 1993 (S. D. Nodder, unpublished results).

In comparison, brine-filled MULTI-traps deployed in Experiment V experienced about 51% brine wash-out on average (standard deviation, $s = 5.5\%$, $n = 43$). R_t values can not be determined for this data-set since flow velocities, relative to the traps (e.g., Gust *et al.,* 1994), were not measured contemporaneously. Based on data from Chatham Rise current meter moorings (Chiswell, 1994), R_t values are anticipated to reach maximums of 15,000–30,000 (corresponding to peak flows of 20–40 cm s^{-1}) with mean R_t numbers equivalent to 4500–9000 (average currents of 6–12 cm s^{-1}). These estimated values are higher than the maximum R_t measured during Experiment III in Evans Bay which explains the higher degree of brine wash-out experienced by the MULTI-traps deployed near Chatham Rise (e.g., Gust *et al.,* 1996; Gardner and Zhang, 1997). As mentioned above, under highly turbulent storm conditions and in free-floating mode, the higher aspect ratio NZOI-NIWA traps do experience greater levels of brine wash-out than those observed in Experiment III in Evans Bay. Wash-out from brine-filled traps is probably accentuated on such free-floating sediment trap arrays, regardless of aspect ratio, due to surface wave heaving motions that are transferred down mooring lines to suspended trap cross-frames (e.g., Gust *et al.,* 1994).

4. Discussion

a. Hydrodynamic implications of using multiple trap arrays

Disturbance of the mean flow field by individual traps deployed on the same array may affect relative trapping efficiency depending on the horizontal spacing between each trap. Gardner (1980a) and Butman (1984 *in* U. S. GOFS Report 10, 1989) proposed that a minimum of three trap diameters cross-stream and ten diameters downstream should be employed to eliminate inter-trap hydrodynamic interactions. The cross-frame array designed for use at NZOI-NIWA had a trap spacing interval of at least 30-cm, which is in accordance with these previous recommendations. In comparison, the 7.5 cm outside

Table 2. Mean coefficients of variation (C.V.% = standard deviation/mean%) for parameters measured during Evans Bay experiments (I–III).

Experiment	Parameter	Site A	Site B	Site C	Overall	*n*
I—trap position	Inner	7.95	11.32	15.74	11.67	12
	Middle	8.55	13.79	9.52	10.62	12
	Outer	16.62	20.09 ($n = 3$)	22.44	19.68	11
II—baffles	Baffled	3.15	2.74	4.71 ($n = 5$)	3.49	17
	Unbaffled	2.04	3.42	4.46	3.31	18
III—brine	1-D	7.75	3.32	13.85	8.31	12
	2.5-D	12.83	3.73	16.42	10.99	12
	Unfilled	10.29	3.53	15.14	9.65	24
	Filled	17.80	8.73	7.19	11.24	12

diameter MULTI-traps, used on free-floating trap deployments at JGOFS time-series stations and in the Chatham Rise component of this study, have an inter-trap spacing of 14–16 cm which is less than the 3-D_o spacing recommended in U.S. GOFS Report 10 (1989).

Results from Experiment I conducted in Evans Bay show that the inter-trap spacing interval recommended by previous workers and used for the NZOI-NIWA traps is sufficient to minimize the hydrodynamic effects of multiple trap interactions on trapping efficiency. Similarly, results from Experiment V near Chatham Rise suggest that, despite the $<$3-D_o spacing of traps on MULTI-trap cross-frames, there were no significant differences in particulate fluxes measured at inner, middle and outer trap positions on MULTI-trap cross-frames (Fig. 3). The low power levels of the tests conducted near Chatham Rise, however, indicate that additional replication at more sites and more depths is required to enable firm conclusions to be drawn on the effects of inter-trap spacing on trapping efficiency.

Although there were no significant differences between fluxes measured in traps at different positions on the NZOI-NIWA cross-frame, the highest amount of variation was found for traps in the outermost position at all sites (Table 2). Overall, fluxes from outer traps were almost twice as variable as fluxes calculated from inner and middle positions. It is difficult to determine the reasons for this variability, although it is surmised that hydrodynamic interactions between traps, adjacent cross-frame arms and possibly even the mooring line or buoys could be mitigating factors. Nevertheless, traps at *all* positions on the cross-frame collected "representative" flux samples despite the observation of high variability in outermost traps. These conclusions were not so apparent from the MULTI-trap deployment in Experiment V where there was no obvious bias in terms of sampling variability that could be ascribed to trap position on the cross-frames. Coefficients of variation for total mass, particulate carbon and nitrogen fluxes estimated during this experiment ranged from 5–51% (Table 3).

Table 3. Coefficients of variation (C.V.% = standard deviation/mean%) for total mass, particulate carbon (PC) and nitrogen (PN) fluxes measured from free-floating sediment trap deployments near Chatham Rise in austral autumn 1996 and 1997. O, M and I refer to outer middle and inner positions on MULTI-trap cross-frames deployed at three water depths on a single free-floating array in April 1997 (see Fig. 1A). F and 1D refer to brine-filled traps and traps back-filled with a volume of high-density brine equivalent to 1-trap diameter. In this experiment, three individual MULTI-trap arrays were deployed 9 km apart in April 1996 (see Fig. 1A). In each experiment, traps were deployed at 3 water depths: 120, 300 and 550 m.

Water depth (m)	Mass flux C.V.%					PC flux C.V.%					PN flux C.V.%				
	O	M	I	F	1D	O	M	I	F	1D	O	M	I	F	1D
120 m	14	24	26	85	73	23	15	19	29	21	5	17	20	79	46
300 m	29	13	22	51	24	20	51	27	65	23	8	27	25	35	27
550 m	23	24	24	60	27	22	24	17	55	26	27	23	19	26	32

b. The effect of baffles on trapping efficiency

Baffles are used widely in many sediment trap applications to minimize trap turbulence, although the actual effect of baffles has not been tested rigorously (U.S. GOFS Report 10, 1989). Field tests in Evans Bay to investigate the effect of baffles on trapping efficiency (Experiment II) showed that there were no significant differences between total mass fluxes measured in baffled and unbaffled cylindrical traps. Thus, for high aspect ratio, cylindrical traps (AR without brine = 10.6, average AR with brine = 3.8 ± 0.6, $n = 36$), as used in Experiment II, the effect of baffles on trapping efficiency was minimal, in contrast to the suggested use of baffles for improving the collection efficiency in cones (Gardner, 1980b). The observation from Experiment II is not surprising since recent flume tests by Gust *et al.* (1996) show that the depth and velocities of circulation cells in cylindrical traps are not affected by baffles, although flow unsteadiness in circulation cells increases when baffles are not present.

The effect of baffles on trapping efficiency in free-floating deployments was not investigated since the baffles used in NZOI-NIWA traps and JGOFS MULTI-traps have similar proportions, relative to their parent cylindrical traps (e.g., height of baffles = outside diameter of trap, $AR = 4.75$ for NZOI-NIWA traps cf. ~6.0 for MULTI-traps). Furthermore, an *ad hoc* result from a set of previous drifting deployments near Chatham Rise using the NZOI-NIWA traps indicated that baffles had an equivocal effect on relative trapping efficiency (S.D Nodder, unpublished data; Nodder and Alexander, 1998). However, differences between the free-floating mode commonly used for MULTI-trap arrays and the results from bottom anchored traps in the present study needs to be properly tested before the conclusions can be extrapolated to other trap systems.

The observation of Martin *et al.* (U. S. GOFS Report 10, 1989) that zooplankton "swimmer" effects were generally reduced by using baffles of any design in MULTI-traps is not supported by the present study since there were no significant differences in zooplankton "swimmer" numerical abundance in baffled or unbaffled traps. The very low levels of power associated with these ANOVA tests (<0.1), however, indicates that to statistically determine the effect of baffles on "swimmer" abundance would require a substantial increase in the level of replication to improve the power of the statistical analysis. This increased effort is unlikely to match the apparent unimportance of baffles as "swimmer" deterrents in cylindrical traps, as suggested by the results from Experiment II. Hence, efforts would be better expended in designing and implementing other means of reducing zooplankton "swimmer" contamination in field sediment trap deployments (e.g., "Labyrinth of Doom," Coale, 1990; Indented Rotating Sphere, Peterson *et al.,* 1993), than in trying to determine whether baffles affect the "swimmer" contribution to trap samples. This approach is also especially important in cases where larger "swimmers," such as fish, may enter traps that are unbaffled (unpublished reports—P. Biscaye and B. Butman).

Butman (1986) showed that while there were no differences between the fluxes in baffled and unbaffled traps, traps with baffles tended to result in more variable measurements. This observation was not obvious from Evans Bay Experiment II where low overall levels of variability were found at all sites (2–5%) and the variation between fluxes from baffled and unbaffled traps was similar (overall mean C.V. 3.5 and 3.3%, respectively) (Table 2).

c. *The effect of brine volume on trapping efficiency*

High-density salt brine solutions are used in traps to minimize sample and additive wash-out from the tranquil layer present at the bottom of cylindrical traps (e.g., Gardner, 1980a,b). Presently, however, a dichotomy exists within the international sediment trap community, regarding the manner in which high-density brines are used in field studies using free-floating trap arrays. Cylindrical traps are filled up completely with brine, as in the VERTEX program (Knauer *et al.,* 1979; Martin *et al.,* 1987) and at the two JGOFS time-series stations near Hawaii (Karl *et al.,* 1990, 1996) and Bermuda (Lohrenz *et al.,* 1992; Michaels and Knap, 1996). Alternatively, traps are back-filled with a specific volume of brine that is markedly less than the total volume of the trap (e.g., Lee *et al.,* 1992). There are valid hydrodynamic reasons for arguing against the former practice since the addition of a high-density brine acts as a "false" bottom within the trap, thereby, altering the trap's aspect ratio (Gardner, 1979; U.S. GOFS Report 10, 1989; Gardner and Zhang, 1997). Since aspect ratio is a critical factor affecting sediment trapping efficiency (e.g., Hargrave and Burns, 1979; Gardner, 1980a; Butman, 1986; Butman *et al.,* 1986; and others), U.S. GOFS Report 10 (1989) recommended that a brine volume equivalent to a brine height of 1-trap diameter should be sufficient to ensure that trapping efficiency was not compromised. Gardner and Zhang (1997) showed that particle collection rates declined in brine-filled traps as a function of flow velocity with trap efficiencies of 54% calculated at 5 cm s^{-1} and 75% at three times this speed. Variable results have been noted at the Bermuda time-series station where 0, 25 and 60% higher carbon fluxes were found in free-floating MULTI-traps deployed without brine (A. Michaels, unpublished data, *in* Gardner, 1997).

Results from Experiment III in Evans Bay indicate that cylindrical traps filled completely with brine could potentially lead to undertrapping of the order of 2–3 times less than traps only partially filled with brine (Fig. 5). These results confirm the recommendations contained in U.S. GOFS Report 10 (1989), and highlighted further in a recent laboratory flume study by Gardner and Zhang (1997). In contrast, the results from the free-floating MULTI-trap deployments in Experiment IV indicated that there were no significant differences in mass and particulate carbon and nitrogen flux due to brine volume over 3 sampled water depths (Fig. 6). However, strong interaction terms due to significant inter-site differences are the main reason why a "brine volume" signal could not be extricated from the Chatham Rise experiment. The inherent patchiness of sinking particulate populations in open ocean environments (e.g., Siegel *et al.,* 1990; Siegel and Deuser, 1997) and low levels of coherence between physical parameters in the Chatham Rise region (e.g., Chiswell, 1994) are believed to be the main reasons for such significant "site" interactions.

Flux results from Experiment III in Evans Bay indicated that at two sites (A and B) brine-filled traps exhibited the most variability (approximately two-times greater than that estimated for unfilled traps) (Table 2). At site C, this relationship was reversed, although at all sites traps with less brine were found on average to have lower levels of subsampling variability. In general, traps filled completely with brine resulted in slightly more variable flux measurements (mean C.V. 11.2% cf. 9.7% for unfilled (1D and 2.5D) traps; Table 2). This effect was accentuated in the MULTI-trap deployments near Chatham Rise in Experiment IV where fluxes calculated from brine-filled traps were generally 2–3 times more variable than those from 1D traps (Table 3). Thus, not only does it appear that brine-filled traps can collect 2–3 times less material than unfilled traps (e.g., Experiment III; Fig. 5), but the fluxes calculated from the former are likely to be more variable (Experiments III and IV; Tables 2 and 3). Coefficients of variation between individual cylinders deployed at the same depth at JGOFS time-series stations off Hawaii and Bermuda, where brine-filled cylindrical traps are employed, range from 1–79% (overall mean C.V. 21%, $n = 137$) and 1–90% (20%, $n = 255$), respectively. The wide levels of variation observed at these stations are possibly in part due to the continued practice of completely filling traps with high-density brine.

Finally, it is difficult to conclude from the free-floating Chatham Rise deployments whether brine volume affected trapping efficiency, as observed in the moored Evans Bay experiments and in the flume studies by Gardner and Zhang (1997). Certainly, there are additional difficulties in extrapolating trap observations derived from moored traps or static flume experiments to those conducted as free-floating deployments, especially as the latter are affected by hydrodynamic complications arising from wave-induced vertical motions (Gust *et al.,* 1994) and tilting effects (Gardner, 1985).

5. Conclusions

The hydrodynamic effects of trap cross-frame position, baffles and brine volume on trapping efficiency were evaluated under field conditions in five short-term sediment trap experiments in Evans Bay, Wellington Harbour, New Zealand and near Chatham Rise, east of New Zealand. Results from these experiments indicate that a spacing of about 3-trap diameters is sufficient to minimize inter-trap interactions (Experiments I and V). Furthermore, baffles had little effect on the collection efficiency of cylindrical traps (Experiment II). In addition, baffles do not seem to act as sufficiently powerful deterrents to zooplankton ''swimmer'' contaminants to warrant their use solely for this purpose, although there are benefits in retaining baffles in order to exclude larger ''swimmers,'' such as fish. Finally, it was found that in bottom moored deployments in the shallow marine environment of Evans Bay, traps filled completely with 50‰ excess NaCl brine collected 2–3 times less material than those traps that had a basal brine height equivalent to 1- and 2.5-trap diameters (Experiment III). In Experiment IV near Chatham Rise using free-floating MULTI-trap arrays, however, no significant effect on trapping efficiency due to brine volume could be detected due mainly to strong inter-site differences. The Evans Bay results confirm previous assertions that cylindrical traps filled completely with a high-density brine solution may not provide accurate estimates of sinking particulate fluxes (Gardner, 1980a,b; Gardner and Zhang, 1997). In addition, fluxes measured in brine-filled traps, including MULTI-traps used in many JGOFS studies, exhibited higher degrees of variability than traps only partially filled with high-density brine.

Therefore, important time-series sediment trap studies conducted at JGOFS sites in central equatorial Pacific and off Bermuda may be compromised by high levels of sampling variability introduced by filling traps up completely with high density brines. This observation may provide one possible explanation for the perceived failure of such traps to accurately measure open ocean export flux (e.g., Buesseler, 1991; Buesseler *et al.,* 1992, 1994; Michaels *et al.,* 1994; Murnane *et al.,* 1996). Thus, the three-fold carbon imbalance observed at the JGOFS Bermuda station (Michaels *et al.,* 1994) could potentially have arisen solely from the poor hydrodynamic performance of brine-filled sediment traps, as documented independently by Gardner and Zhang (1997).

Acknowledgments. We are grateful to Bill Main who helped with all sediment trap deployments and boat driving in Evans Bay. Thanks also to the NZOI-NIWA divers (Peter Hill, Greg Foster and Edward Abraham) who participated in the Evans Bay fieldwork. Thanks go to the officers and crew of the R. V. *Tangaroa,* and NZOI-NIWA scientific staff (in particular, John Hunt, John Mitchell, Megan Oliver and Matt Walkington) for their assistance during the Chatham Rise deployments. Thanks also to Janet Grieve, Rob Murdoch and Lionel Carter (all NIWA), and two anonymous reviewers, for commenting on and improving earlier drafts of the manuscript. This work was funded by the Foundation of Research Science and Technology (CO1214, CO1518 & CO1623).

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Received: *12 February,* 1998; revised: *1 March, 1999.*