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Intrusions of surface sewage plumes into continental shelf waters: interactions with larval and presettlement juvenile fishes

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ABSTRACT: Primary treated sewage (domestic and industrial) is discharged through several shoreline and deepwater outfalls into the coastal waters off Sydney, southeastern Australia. The effluent discharged from the shoreline outfalls formed highly visible surface plumes that intruded up to 5 km seaward and 8 km along the coast from their point of discharge. Each sewage plume was a lens (1 to 5 m deep) of low-salinity turbid water that overlay high-salinity clear shelf water, and distinct frontal regions usually developed between plume and shelf water. Large numbers of young fishes in surface waters were caught in and around the sewage plumes. In particular, many fish were concentrated at the fronts (e.g. Carangidae, Engraulididae, Sparidae), which was probably the result of advection at fronts as well as behavioural responses of fish. Surface sewage plumes therefore affected small-scale (<1 km) patterns of distribution and density of young fishes. The oceanography of sewage plumes may increase and prolong exposure of fishes to pollutants during early development. Sewage plumes could affect young fishes spawned near to and at great distances from outfalls because of alongshore currents, and effects on fish populations could be manifest over large spatial scales. The influences of sewage plumes on larger-scale patterns of distribution, transport and survival of young fishes are discussed.

KEY WORDS: Sewage · Plumes · Oceanography · Young fishes · Distribution patterns

INTRODUCTION

Oceanographic features influence the distributions, densities and movements of small fishes and plankton in coastal waters (reviews in Haury et al. 1978, Owen 1981, Denman & Powell 1984, Le Fèvre 1986, Kingsford 1990). Aggregations of fish larvae and plankton are often greatest at the convergence zones of different water bodies (Kingsford 1990, Govoni & Grimes 1992, Govoni 1993) and are often manifest in surface waters. Larval fish and plankton have been found to be concentrated in and/or along the frontal regions of many oceanographic features, including: tidal, coastal and topographically controlled fronts and eddies (Epifanio 1987, Murdoch 1989, Kingsford et al. 1991); riverine and estuarine plumes (Mackas & Louttit 1988, Govoni et al. 1989, Grimes & Finucane 1991, Kingsford & Suthers 1994); slicks associated with internal waves (Zeldis & Jillett 1982, Shanks 1983, 1985, Kingsford & Choat 1986). Material such as flotsam, drift algae and various pollutants can also be advected and concentrated around oceanographic features (Kingsford 1990, 1993, Brown et al. 1991, Tanabe et al. 1991, Kingsford & Gray 1996).

The ways in which oceanographic features influence small fishes and plankton can vary depending on the type and magnitude of the oceanographic feature and according to the type, size and behaviour of the organism. For example, topographically controlled fronts and fine-scale currents can concentrate and retain small fish and plankton in a specific area (Alldredge & Hamner 1980, Owen 1981, Wolanski & Hamner 1988), whereas those entrained in large-scale eddies and the slicks associated with internal waves can be transported tens to hundreds of kilometres

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(Shanks 1983, Lobel & Robinson 1988). Furthermore, small zooplankton may be passively advected into such oceanographic features, whereas small fishes may voluntarily aggregate in these features due to their invertebrate prey being concentrated there (Kingsford 1990). Consequently, oceanographic features can have substantial influence on the transport, survival and recruitment of fish and other meroplankton in coastal waters (Shanks 1983, Kingsford 1990, Grimes & Finucane 1991).

In addition to the many natural oceanographic features, young fishes and plankton in estuaries and nearshore coastal waters may also be subjected to a wide variety of man-made intrusions, including breakwalls, groynes, wharves and various types of outfalls, which can interact with mainstream water bodies to create physical disturbances that behave in similar ways to natural oceanographic features. For example, eddies can fòrm behind groynes and breakwalls like those behind headlands, islands and reefs (Emery 1972, Wolanski & Hamner 1988, Murdoch 1989). The effluent released from different types of outfalls (e.g. sewage) often forms conspicuous plumes that have similar oceanographic attributes to natural (e.g. estuarine) plumes (Gray et al. 1992, Kingsford & Gray 1996). Thus, man-made intrusions may potentially impinge on the dynamics of planktonic organisms. Moreover, effluent plumes from outfalls often contain large levels of toxic wastes (e.g. Duedall et al. 1983, Beder 1989), which can cause sub-lethal and lethal affects to young fishes and zooplankton (reviews in Rosenthal & Alderdice 1976, Westernhagen 1988, Weis & Weis 1989, Costello & Read 1994, Kingsford & Gray 1996). Effluent plumes are therefore a potential hazard to planktonic organisms.

Most field studies concerning the numerical influences of pollutants on planktonic fauna have either compared assemblages and/or densities of organisms near to and away from a polluted source (e.g. Hardy et al. 1987b, Karas et al. 1991, Nair et al. 1991, Gray et al. 1992), or have examined changes in fauna over a gradient of pollution from the point-source (e.g. Arfi et al. 1981). Few researchers have stratified sampling to account for biological effects of oceanography of pollution plumes on plankton. For example, Gray et al. (1992) compared densities of young fishes in 3 sewage plumes to non-plume (control) waters located some distance away (>8 km). They sampled in and below each plume, but found no consistent differences in densities of fishes in plume and non-plume waters. They hypothesised, however, that densities of fish may differ between water masses of the plume, front and adjacent ocean. Kingsford & Gray (1996) found that densities of young fishes were often highest in the frontal edge of one sewage plume. The frontal hypothesis needs to be tested at several outfalls and potentially differential influences on different types and sizes of young fish need to be further examined. This paper documents how surface sewage plumes intrude into mainstream coastal currents off Sydney (Australia), and influence the distributions and densities of larval and presettlement juvenile fishes.

MATERIALS AND METHODS

Sydney's sewage outfalls. Until 1991 sewage was discharged into the coastal waters off Sydney via 7 shoreline (cliff-face) outfalls. The distributions of young fishes in and around the effluent plumes associated with the point-source shoreline sewage outfalls at North Head, Bondi and Potter Point (New South Wales, Australia) (Fig 1) were examined here. Each outfall discharged primary treated sewage effluent through a point-source into shallow subtidal waters (2 to 5 m) at the base of the coastal cliffs. The effluent formed conspicuous discoloured and turbid surface plumes that intruded into the surrounding coastal waters (Gray et al. 1992, Kingsford & Gray 1996; and see Fig. 1). The discharged effluent consisted of a cocktail of domestic and industrial wastes, and although freshwater was the major constituent of the discharge, it contained contaminants in solution and suspension, as well as varying concentrations of pathogens, bacteria and toxic substances (e.g. Cd, Cr, Zn, Hg) (Beder 1989). The catchment area, volume, rate and content of discharge of effluent differed among outfalls (Beder 1989, Fagan et al. 1992). The volume, rate and content of the effluent discharged from the sewage treatment plants also fluctuated considerably within and among days. The average dry weather discharge (Ml d^{-1}) was 293 at North Head, 163 at Bondi and 37 at Potter Point. Wet weather flows were considerably greater than flows during dry weather. Note that the North Head and Bondi (and Malabar) cliff-face outfalls have now been decommissioned and replaced by extended deepwater outfalls (see Fagan et al. 1992, Otway et al. 1996).

Design and procedure of sampling. Each outfall was sampled twice, once in December 1990 and once in January 1991. In December, samples were collected in 3 water masses near each outfall: in the effluent plume, along the frontal edge of the plume, and just outside (approximately 500 m) the plume in clear shelf water. In January, sampling was done in each of the 3 water masses, but at 2 distinct locations at each outfall. The order in which each water mass was sampled at each outfall was selected randomly.

All sampling was done in daylight. Sampling was done over a short time interval to try to catch the same types of fish in each sampling period. Three replicate 3 min surface (0 to 1 m) tows were done in each water mass at all outfalls using a cylindrical/conical net with a 80 cm diameter mouth, and with 500 µm mesh in the body and 250 µm mesh in the collecting bag. Filtration efficiency of net was 1:5. The net was positioned at the front and to one side of the FRV 'Wobbegong' (a 7 m twin-hulled vessel) to avoid influences of the wake and bow waves on catches. The net was towed at 1 m s^{-1}, and a flow meter was positioned in the mouth of the net to measure the amount of water filtered per tow (average volume per tow was 100 m^3). Samples were preserved in 10% formalin/seawater immediately following capture, and after 2 wk transferred to 70% alcohol in the laboratory. All fishes were sorted from catches, identified to lowest taxonomic level possible, and counted using a binocular microscope Herein the term young fish refers to all fish caught in the sampling gear, excluding yolk-sac larvae.

Depth of water was 15 to 30 m around each outfall. The positions of plumes on each sampling date were mapped from the water and when available, from maps provided by the NSW (New South Wales) Beachwatch helicopter service. The temperature and salinity of water in and around each plume were determined by lowering a submersible data logger that measured depth, temperature and salinity from the surface to 2 m above the seabed. At Potter Point the data logger was also slowly towed at a depth of 1 m from the middle of the plume transversely across the front into clear shelf water to show the change in salinity at the front.

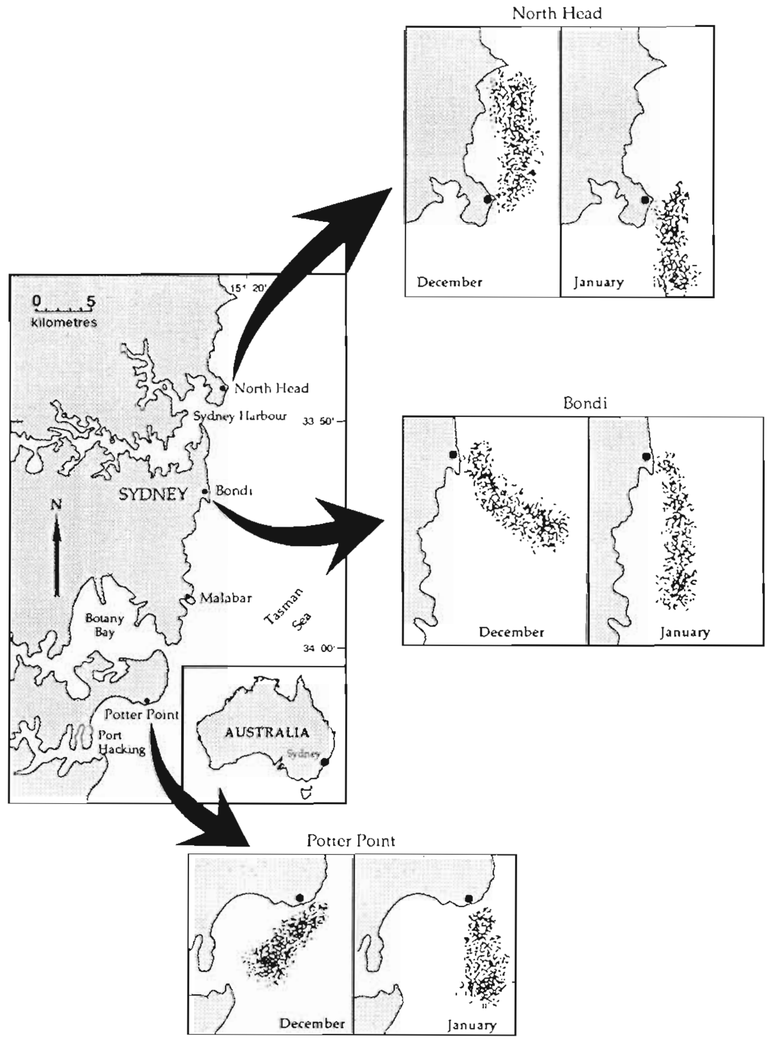

Fig 1 Locations of the North Head, Bondi and Potter Point (New South Wales, Australia) shoreline sewage outfalls and the orientation of each sewage plume during sampling in December 1990 and January 1991

Analysis of data. Catches of fishes were standardised to number caught (density) per 100 m^3 of water filtered. Data were transformed to $\ln(x+1)$ prior to statistical analysis.

Differences in the structure of the fish assemblages between plume, front and ocean waters were assessed using non-metric multidimensional scaling and similarity-based measures, following the procedures outlined in Field et al. (1982) and Clarke (1993). Two-dimensional ordination plots were generated by multidimensional scaling of similarity matrices based on the Bray-Curtis similarity measure. One-way analyses of similarities (ANOSIM) were used to determine which assemblages differed.

Density data and the derived variables (e.g. number of total taxa) were analysed by 2- and 3-factor analyses of variance (ANOVA) Each sampling period was analysed separately· December—Outfall (random) and Water mass (fixed); January—Outfall (random), Location (nested in Outfall-random) and Water mass (fixed). Data were checked for homogeneity of variances (Cochran's test) before analysis Heterogeneous data were still analysed because large and balanced data sets are robust to deviations from homogeneity, but alpha was set at p = 0.01 to reduce the risks of Type 1 errors (Underwood 1981)

RESULTS

Oceanography of surface sewage plumes

Each sewage plume was a lens of discoloured, turbid, low-salinity water 1 to 5 m deep overlaying clear high-salinity shelf water (Fig. 2). Salinity of water in each plume was generally 1 to 5 ppt less compared to the shelf waters surrounding and below each plume (Figs. 2 & 3). The plumes usually formed distinct fronts with the surrounding ocean (Fig. 3), which were observed as distinct changes in salinity, turbidity and colour (see also Kingsford & Gray 1996).

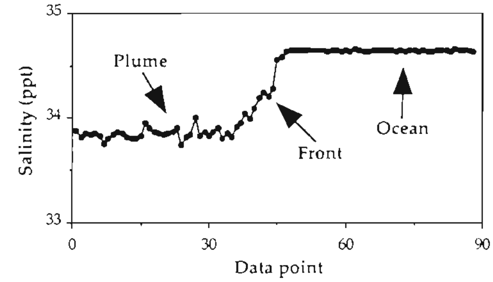

Fig. 3. Cross-section salinity structure of water column at 1 m depth across Potter Point sewage plume on 26 January 1991 Note the reduced salinity in the plume, and the abrupt change in salinity at the front between plume and ocean waters

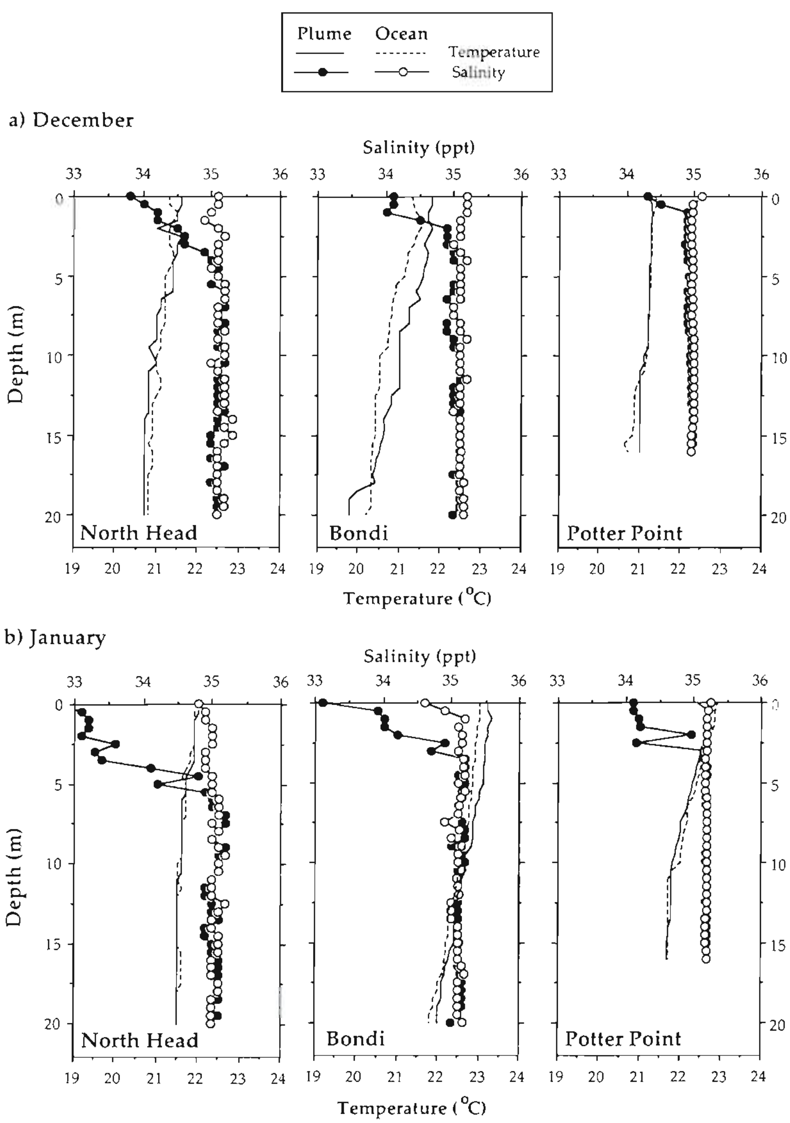

Fig. 2. Salinity and temperature profiles of the water column in and below the North Head, Bondi and Potter Point sewage plumes and in adjacent ocean waters. Note that the salinity of water was reduced by 1 to 3 ppt in the top 2 to 3 m in the plumes compared to adjacent ocean waters

The size, shape and orientation of each plume differed between outfalls and between sampling periods (Fig. 1). Essentially, each plume was generally orientated alongshore, trailing downstream in the prevailing (predominantly southerly) current from the point of discharge. All 3 plumes flowed in a southerly direction during both sampling periods, except North Head in December. The North Head plume was generally the largest, followed by Bondi and Potter Point. The North Head and Bondi plumes extended between 1 and 3 km offshore and between 3 and 5 km alongshore, whereas the plume at Potter Point was more confined to Bate Bay (particularly in December), but extended about 3 km alongshore in January (Fig. 1). In each period the front was easily distinguished at all 3 plumes, except at Potter Point in December The front of each plume usually degenerated with increasing distance from the actual outfall. In each period a southerly current predominated (except at North Head in December), the swell was generally <1 m and from either the northeast or southeast, whereas the wind was generally light (<10 m s^{-1}) and from the northeast or southeast.

Differences in assemblages of young fishes between water masses

A total of 11328 fish of 49 families was caught in water surrounding the 3 outfalls (Table 1). Overall, most fish were caught at fronts and least in ocean

Table 1. Taxonomic composition and total numbers of pre- and postflexion fishes caught in plume, front and ocean water pooled over the 3 sewage outfalls and both sampling periods (n = 27 for each water mass)

Family / Species	Preflexion			Postflexion		
	Plume	Front	Ocean	Plume	Front	Ocean
Clupeidae						
Sardinops neopilchardus	10	27	1	19	321	2
Engraulididae						
Engraulis australis	161	135	6	60	337	16
Aulopidae	7	2	0	0	0	0
Myctophidae	3	1	0	0	0	0
Gonorynchidae						
Gonorynchus greyi	13	308	9	1	0	0
Gobiesocidae	14	9	0	1	2	1
Antennariidae	0	0	0	0	1	0
Exocoetidae	0	0	0	0	2	0
Hemiramphidae	0	0	0	0	17	0
Atherinidae	9	190	0	7	57	0
Trachichthyidae	4	7	1	0	5	0
Berycidae						
Centroberyx affinis	0	1	0	0	0	0
Holocentridae	1	0	0	0	0	0
Macrorhamphosidae	0	1	0	0	1	0
Syngnathidae	0	0	0	1	5	0
Scorpaenidae						
Centropogon australis	6	0	0	3	1	0
Unidentified Scorpaenidae	1	1	1	0	0	0
Triglidae	11	7	0	0	0	0
Platycephalidae	30	32	1	1	6	0
Dactylopteridae	0	0	0	0	2	3
Ambassidae						
Ambassis jacksoniensis	39	6	1	11	5	2
Teraponidae						
Pelates quadrilineatus	4	7	0	18	85	4
Terapon jarba	0	0	0	0	1	0
Apogonidae	4	4	0	1	0	0
Sillaginidae	0					
Sillago ciliata	75	59	1	48	61	0
Sillago maculata	18	13	0	1	0	0
Carangidae	9					
Pseudocaranx dentex	43	8	0	0	1	0
Trachurus sp.	273	50	9	0	6	9
Seriola sp.	1	12	1	0	0	5
Lutjanidae	0	0	0	1	0	0
Gerreidae						
Gerres subfasciatus	116	389	18	126	219	17

Family / Species	Preflexion			Postflexion		
	Plume	Front	Ocean	Plume	Front	Ocean
Sparidae						
Acanthopagrus australis	574	1424	7	67	126	1
Pagrus auratus	26	23	2	1	2	0
Rhabdosargus sarba	3	0	0	0	0	0
Sciaenidae						
Argyrosomus hololepidotus	1	0	0	0	0	0
Mullidae	3	36	3	1	89	14
Monodactylidae						
Schuettea scalaripinnis	9	8	0	0	3	0
Pempherididae	10	17	1	1	0	0
Girellidae						
Girella tricuspidata	322	1974	48	4	32	28
Kyphosidae						
Kyphosus sp.	149	429	36	3	6	2
Scorpididae	4	54	7	0	5	3
Enoplosidae						
Enoplosus armatus	4	0	0	0	0	4
Pomacentridae	97	98	367	0	4	0
Mugilidae						
Liza argentea	6	0	1	4	30	6
Labridae	99	335	1	7	16	0
Pinguipedidae	1	0	0	0	0	0
Percophididae	1	1	0	0	0	0
Creediidae	1	0	0	0	0	0
Blenniidae						
Omobranchus anolius	22	22	3	12	11	2
Parablennius tasmanianus	0	0	0	1	0	0
Petroscirtes lupus	2	11	0	1	22	2
Clinidae/Tripterygiidae	95	339	0	32	19	0
Callionymidae	4	0	0	3	0	0
Gobiidae	64	87	4	79	32	3
Stromateidae	0	0	0	4	11	0
Bothidae	2	4	0	0	0	0
Paralichthyidae						
Pseudorhombus spp.	3	0	0	1	0	1
Monacanthidae	6	9	0	1	10	1
Unidentified/damaged	37	43	4	2	7	6
Total taxa	48	40	24	33	37	23
Total individuals	2388	6183	533	523	1560	141

water. Taxonomic composition of samples varied spatially and temporally. Assemblages in plumes and fronts were most similar and differed to those in adjacent shelf water (Fig. 4, Table 2). However, at Potter Point differences among assemblages in plume, frontal and ocean waters were not clear as few fish were caught.

Differences in densities of young fishes between water masses

In both sampling periods greatest densities of fish were found in the plume or front at North Head and Bondi, but there were no clear patterns at Potter Point (Fig. 5, Tables 3 & 4). This same pattern was also evident for most individual taxa, notably *Acanthopagrus australis*, *Gerres subfasciatus*, *Engraulis australis*, *Girella tricuspidata*, *Kyphosus* sp., *Sardinops neopilchardus*, *Pelates quadrilineatus*, *Liza argentea*, *Omobranchus anolius*, *Petroscirtes lupus*, Atherinidae, *Trachurus* sp., Labridae, Gobiidae, *Sillago ciliata*, Clinidae/Tripterygiidae, Mullidae, Pomacentridae, Platycephalidae (Tables 3–8). In December few fish were caught at Potter Point, but in January most Gobiidae, Atherinidae, Clinidae/Tripterygiidae, Platycephalidae, *Pagrus auratus* and *Ambassis jacksoniensis* occurred in the plume or front at Potter Point (Table 8).

Differences in densities of fishes between water masses in January were not always the same at both locations at each outfall [significant L(O) × W in Table 4]. For example, densities of *Engraulis australis* and *Sillago ciliata* at North Head were greatest in the plume at Location 1, but at the front at Location 2 (Table 6). Similarly, at Potter Point, greatest numbers of taxa were in the plume at Location 1, but in ocean water at Location 2 (Table 8). Several taxa displayed consistent trends in densities between water masses at some outfalls, including Atherinidae and Mullidae which were most abundant at the front at both locations at North Head and Bondi (Tables 6 & 7).

Rank differences in densities of many fish among water masses at each outfall varied between periods. For example, there were no significant differences in the densities of *Kyphosus* sp. among water masses at North Head in December, but more were caught at the front in January (Tables 5 & 6).

Table 2. Summary of 1-way analysis of similarities and pairwise comparisons of fish assemblages in plume, front and ocean waters. Replicate data pooled for each site, and both periods combined. 5000 permutations were used for each test. Data transformed to $\log(x+1)$. **, ***: significant at $p < 0.01$, $p < 0.001$, respectively; ns: not significant at $p > 0.05$

Effect	R	Sample size	Significance
Treatment	0.211	5000	***
Plume vs Front	-0.028	5000	ns
Plume vs Ocean	0.381	5000	***
Front vs Ocean	0.322	5000	**

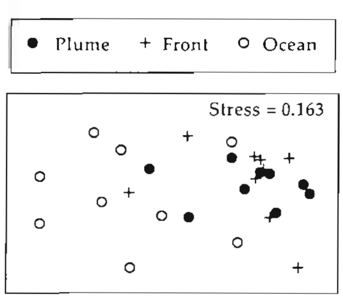

Fig. 4. Non-metric multidimensional scaling ordination plot displaying the relationships among the assemblages of larval fishes in plume, front and ocean waters. Replicate data pooled for each water mass in December and January. Data transformed to $\log(x+1)$

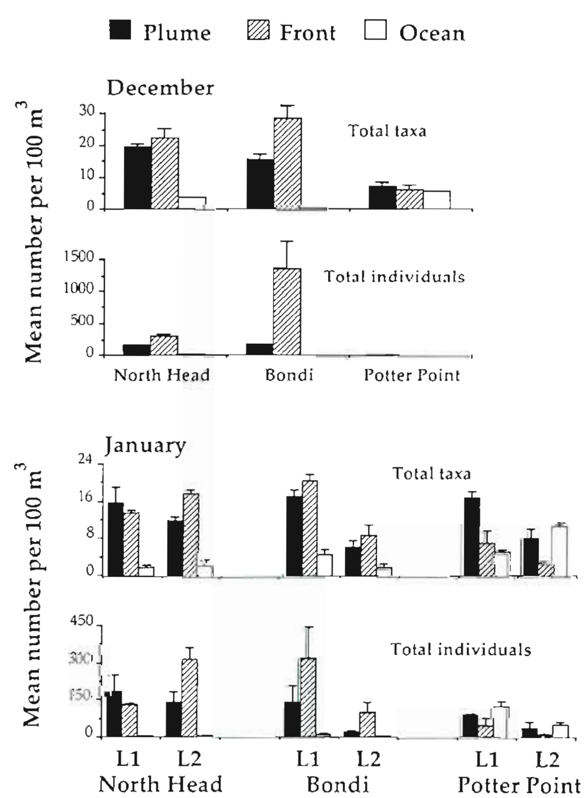

Fig. 5. Mean (+1 SE) numbers of total taxa and total individuals caught in plume, front and ocean waters at the North Head, Bondi and Potter Point sewage outfalls in December 1990 and January 1991. January: L1 = Location 1; L2 = Location 2

Table 3. Summary of ANOVAs of the numbers of total taxa, total individuals and individual taxa caught in plume, front and ocean water at North Head, Bondi and Potter Point sewage outfalls in December 1990. Mean square values are shown. Data transformed to ln(x+1). Significance: *p < 0.05, **p < 0.01, ***p < 0.001; ns: not significant at p > 0.05; CT: Cochran's test

Taxon	Source of variation Outfall	Water mass	O × W	Residual	CT
	Degrees of freedom in *F*-test (2, 18)	(2, 4)	(4, 18)	(18)	
Total taxa	0.819***	5.774ns	1.537***	0.076	ns
Total individuals	12.250***	22.763ns	7.550***	0.234	ns
Acanthopagrus australis	21.560***	23.107ns	5.836***	0.146	*
Ambassis jacksoniensis	1.436**	1.138*	0.080ns	0.173	*
Atherinidae	1.105ns	8.213ns	2.157*	0.620	*
Clinidae/Tripterygiidae	4.090***	13.328*	1.234***	0.159	*
Engraulis australis	8.209***	9.752ns	4.877***	0.394	ns
Gerres subfasciatus	4.218***	6.931ns	3.911***	0.353	ns
Girella tricuspidata	28.633***	24.204ns	7.708***	0.150	*
Gobiidae	3.656***	5.537ns	2.184***	0.213	ns
Kyphosus sp.	15.047***	4.211ns	2.228***	0.281	ns
Labridae	9.804***	10.680ns	2.989***	0.222	*
Mullidae	0.852**	9.518*	0.593**	0.085	ns
Omobranchus anolius	0.880ns	1.379ns	0.747ns	0.347	ns
Pagrus auratus	0.701*	0.385ns	0.826**	0.157	ns
Pelates quadrilineatus	0.423ns	0.880ns	0.574ns	0.452	*
Platycephalidae	0.829*	1.006ns	1.485***	0.139	*
Pomacentridae	1.311**	1.239ns	0.606*	0.179	*
Sardinops neopilchardus	7.835***	6.142ns	4.045***	0.565	*
Scorpididae	2.023**	1.412ns	1.412**	0.302	*
Sillago ciliata	4.785***	5.808ns	1.823***	0.232	*

Table 4. Summary of ANOVAs of numbers of total taxa, total individuals and individual taxa caught at 2 locations in plume, front and ocean water at North Head, Bondi and Potter Point sewage outfalls in January 1991. Mean square values are shown. Data transformed to ln(x+1). Other details as in Table 3

Taxon	Source of variation Outfall	Location(O)	Water mass	O × W	L(O) × W	Residual	CT
	Degrees of freedom in *F*-test (2, 3)	(3, 36)	(2, 4)	(4, 6)	(6, 36)	(36)	
Total taxa	0.037ns	1.212***	5.784ns	2.345*	0.367*	0.131	ns
Total individuals	0.666ns	4.742***	19.689ns	14.155***	0.224ns	0.507	ns
Acanthopagrus australis	28.693ns	7.298***	18.222ns	6.571ns	2.262***	0.370	*
Ambassis jacksoniensis	0.281ns	0.708*	2.692**	0.139ns	0.925***	0.170	*
Atherinidae	0.691ns	1.702ns	5.231*	0.485ns	0.739ns	0.688	ns
Engraulis australis	1.868ns	3.772***	5.187ns	2.732ns	2.085**	0.538	ns
Gerres subfasciatus	15.278ns	5.032***	7.187ns	4.965ns	1.714**	0.389	ns
Girella tricuspidata	0.811ns	4.178***	1.727ns	2.540ns	2.431***	0.388	ns
Gobiidae	3.810ns	0.812*	8.061*	0.653ns	0.938**	0.260	*
Gonorynchus greyi	19.790**	0.289ns	4.849ns	4.849***	0.139ns	0.210	*
Kyphosus sp.	7.883ns	5.233***	8.161ns	5.778ns	1.585**	0.367	*
Labridae	8.755*	0.564*	3.407ns	3.459ns	1.669***	0.186	*
Liza argentea	1.354*	0.097ns	0.173ns	0.998ns	0.293ns	0.228	*
Mullidae	3.452ns	1.002**	1.901ns	2.066*	0.343ns	0.160	*
Omobranchus anolius	0.569ns	0.844**	0.330ns	0.748ns	0.438*	0.149	*
Pagrus auratus	1.686*	0.133ns	0.986ns	0.397ns	0.762***	0.158	ns
Pelates quadrilineatus	3.452ns	3.273***	0.844ns	1.310ns	1.072***	0.092	*
Petroscirtes lupus	1.297ns	0.278ns	1.202ns	0.680*	0.093ns	0.226	*
Platycephalidae	1.514ns	0.776*	1.175ns	0.645ns	0.330ns	0.246	ns
Pomacentridae	43.428ns	19.765***	1.386ns	4.153ns	9.689***	0.821	*
Sardinops neopilchardus	1.187ns	0.391**	1.139ns	1.590*	0.343***	0.063	*
Sillago ciliata	9.705**	0.089ns	3.445ns	2.918ns	1.547***	0.210	*
Trachurus sp.	13.226**	0.314ns	11.368ns	5.545ns	2.191***	0.309	ns
Clinidae/Tripterygiidae	2.632ns	3.457***	11.552ns	6.632ns	1.677***	0.287	ns

Table 5. Mean (+1 SE) numbers of fish caught in plume, front and ocean water at North Head, Bondi and Potter Point sewage outfalls in December 1990

Taxon	North Head			Bondi			Potter Point		
	Plume	Front	Ocean	Plume	Front	Ocean	Plume	Front	Ocean
Acanthopagrus australis	38.2 (9.5)	35.7 (1.0)	0.0 (0.0)	43.9 (6.4)	249.9 (141.6)	0.0 (0.0)	0.0 (0.0)	0.3 (0.3)	0.0 (0.0)
Atherinidae	0.0 (0.0)	25.8 (15.8)	0.0 (0.0)	0.0 (0.0)	13.4 (4.1)	0.0 (0.0)	1.0 (1.0)	0.3 (0.3)	0.0 (0.0)
Engraulis australis	6.3 (2.1)	8.8 (2.4)	0.0 (0.0)	16.3 (8.3)	116.8 (48.9)	0.0 (0.0)	0.3 (0.3)	0.6 (0.6)	1.6 (0.9)
Gerres subfasciatus	6.6 (1.8)	75.0 (8.9)	4.2 (1.2)	7.6 (1.1)	32.0 (10.5)	0 9 (0.9)	9.2 (3.8)	0.9 (0.0)	2.5 (1.3)
Girella tricuspidata	48.7 (2.8)	49.2 (12.3)	0.9 (0.5)	49.3 (7.4)	591.5 (325.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Ambassis jacksoniensis	1.1 (1.1)	0.0 (0.0)	0.0 (0.0)	0.9 (0.9)	0.0 (0.0)	0.0 (0.0)	3.4 (0.8)	0.6 (0.3)	0.9 (0.1)
Gobiidae	5.1 (2.3)	3.0 (1.0)	0.0 (0.0)	11.9 (2.0)	18.7 (9.3)	0.0 (0.0)	1.6 (0.3)	0.0 (0.0)	0.9 (0.5)
Kyphosus sp.	14.2 (5.5)	19.9 (6.8)	8.1 (2.9)	7.9 (1.2)	31.4 (12.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Labridae	4.3 (0.5)	13.4 (3.9)	0.0 (0.0)	9.0 (3.2)	72.1 (36.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Mullidae	0.0 (0.0)	11.5 (1.5)	0.9 (0.6)	0.0 (0.0)	8.0 (1.8)	0.0 (0.0)	0.0 (0.0)	1.9 (0.6)	0.3 (0.3)
Omobranchus anolius	3.9 (2.1)	1.5 (1.0)	0.0 (0.0)	1.3 (0.7)	5.2 (2.6)	0.4 (0.4)	0.7 (0.7)	0.3 (0.3)	0.3 (0.3)
Pagrus auratus	0.7 (0.7)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	4.1 (1.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.4 (0.4)
Pelates sexlineatus	0.8 (0.4)	2.2 (0.6)	0.0 (0.0)	0.4 (0.4)	7.7 (7.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.6 (0.3)
Platycephalidae	2.0 (0.4)	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	6.5 (3.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Pomacentridae	0.0 (0.0)	0.4 (0.4)	0.0 (0.0)	0.9 (0.5)	6.5 (3.5)	0.0 (0.0)	0.3 (0.3)	0.3 (0.3)	0.0 (0.0)
Sardinops neopilchardus	5.8 (3.0)	3.6 (2.2)	0.6 (0.6)	3.6 (1.0)	102.8 (47.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Scorpididae	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.4 (0.4)	17.8 (14.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sillago ciliata	7.3 (0.4)	3.4 (1.2)	0.0 (0.0)	5.7 (2.3)	19.9 (8.9)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)
Clinidae/Tripterygiidae	8.0 (0.9)	24.7 (4.8)	0.0 (0.0)	9.3 (1.6)	18.8 (6.2)	0.0 (0.0)	2.2 (1.5)	1.4 (0.2)	0.0 (0.0)

Developmental stages of young fishes

Most fish caught were preflexion (Table 1, Figs. 6 & 7). In both periods greatest numbers of pre- and postflexion fish were caught in plumes and fronts at North Head and Bondi, but there were no clear patterns at Potter Point (Figs. 6 & 7, Table 9) In January the water mass with the greatest numbers of pre- and postflexion fish differed between locations at each outfall (Fig. 7, Table 9). For example, at North Head most preflexion fish were caught in the plume at Location 1, but at the front at Location 2, whereas

Table 6. Mean (+1 SE) numbers of fish caught in plume, front and ocean water at the 2 locations at North Head sewage outfall in January 1991

Taxon	Location 1			Location 2		
	Plume	Front	Ocean	Plume	Front	Ocean
Acanthopagrus australis	19.7 (4.1)	46.7 (7.3)	1.7 (1.7)	76.7 (31.7)	110.7 (17.6)	0.3 (0.3)
Ambassis jacksoniensis	2.7 (0.3)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Atherinidae	1.0 (1.0)	14.7 (12.7)	0.0 (0.0)	0.3 (0.3)	2.7 (2.2)	0.0 (0.0)
Engraulis australis	41.7 (12.3)	9.0 (2.5)	0.0 (0.0)	0.7 (0.3)	6.7 (4.8)	0.0 (0.0)
Gerres subfasciatus	0.0 (0.0)	2.3 (1.3)	0.3 (0.3)	1.3 (0.9)	39.3 (1.3)	0.3 (0.3)
Girella tricuspidata	0.4 (0.4)	3.1 (1.7)	0.0 (0.0)	5.0 (2.5)	9.9 (4.6)	1.7 (1.2)
Gobiidae	9.2 (1.5)	3.9 (1.4)	0.0 (0.0)	1.7 (0.8)	3.3 (0.4)	0.0 (0.0)
Gonorynchus greyi	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Kyphosus sp.	0.0 (0.0)	2.6 (1.3)	0.0 (0.0)	2.9 (1.0)	37.6 (4.2)	0.9 (0.9)
Labridae	18.2 (11.2)	8.7 (5.1)	0.0 (0.0)	0.8 (0.8)	22.6 (5.0)	0.0 (0.0)
Liza argentea	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.9 (0.4)	0.0 (0.0)	0.0 (0.0)
Mullidae	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.8 (0.8)	0.0 (0.0)
Omobranchus anolius	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.9 (0.4)	0.0 (0.0)
Pagrus auratus	0.4 (0.4)	1.7 (0.4)	0.4 (0.4)	6.3 (1.3)	0.8 (0.8)	0.0 (0.0)
Pelates sexlineatus	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Petroscirtes lupus	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.2 (0.7)	0.0 (0.0)
Platycephalidae	1.3 (0.7)	0.0 (0.0)	0.5 (0.5)	0.4 (0.4)	0.4 (0.4)	0.0 (0.0)
Pomacentridae	3.4 (1.5)	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	1.0 (0.6)	0.0 (0.0)
Sardinops neopilchardus	0.0 (0.0)	8.1 (1.8)	0.0 (0.0)	0.0 (0.0)	1.4 (0.7)	0.0 (0.0)
Sillago ciliata	30.2 (17.6)	3.0 (1.8)	0.0 (0.0)	3.3 (0.7)	15.9 (5.4)	0.0 (0.0)
Trachurus sp.	39.7 (17.9)	5.3 (3.4)	0.0 (0.0)	38.0 (5.2)	11.5 (6.9)	0.4 (0.4)
Clinidae/Tripterygiidae	2.9 (1.5)	20 (5.9)	0.0 (0.0)	0.0 (0.0)	41.8 (14.4)	0.0 (0.0)

Table 7. Mean (+1 SE) numbers of fish caught in plume, front and ocean water at the 2 locations at Bondi sewage outfall in January 1991

Taxon	Location 1			Location 2		
	Plume	Front	Ocean	Plume	Front	Ocean
Acanthopagrus australis	33.3 (19.0)	72.7 (61.2)	0.0 (0.0)	0.3 (0.3)	0.0 (0.0)	0.0 (0.0)
Ambassis jacksoniensis	3.0 (2.5)	1.7 (1.2)	0.0 (0.0)	0.3 (0.3)	0.0 (0.0)	0.0 (0.0)
Atherinidae	2.3 (2.3)	20.3 (15.5)	0.0 (0.0)	0.0 (0.0)	0.7 (0.7)	0.0 (0.0)
Engraulis australis	3.3 (0.9)	11.3 (8.4)	0.0 (0.0)	0.3 (0.3)	1.0 (1.0)	0.0 (0.0)
Gerres subfasciatus	44.0 (28.0)	49.0 (17.6)	2.0 (1.2)	11.7 (5.2)	3.3 (3.3)	1.0 (1.0)
Girella tricuspidata	2.1 (0.4)	9.4 (3.5)	0.0 (0.0)	0.0 (0.0)	1.1 (1.1)	0.0 (0.0)
Gobiidae	2.1 (0.4)	1.3 (0.8)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)
Gonorynchus greyi	3.2 (1.3)	39.4 (16.5)	2.4 (0.3)	1.4 (0.8)	63.3 (29.2)	0.7 (0.7)
Kyphosus sp.	22.4 (5.6)	38.9 (15.7)	0.0 (0.0)	2.4 (0.5)	14.4 (11.0)	0.3 (0.3)
Labridae	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Liza argentea	0.9 (0.4)	4.5 (2.7)	0.0 (0.0)	0.0 (0.0)	3.2 (2.4)	1.2 (0.7)
Mullidae	0.4 (0.4)	15.1 (8.6)	2.0 (0.9)	0.5 (0.5)	3.7 (0.7)	0.0 (0.0)
Omobranchus anolius	4.8 (3.0)	2.2 (1.6)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)
Pagrus auratus	0.0 (0.0)	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Pelates sexlineatus	5.5 (1.2)	20.5 (8.9)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)
Petroscirtes lupus	0.8 (0.8)	4.9 (2.5)	0.6 (0.6)	0.0 (0.0)	3.1 (1.9)	0.0 (0.0)
Platycephalidae	0.0 (0.0)	0.9 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Pomacentridae	0.0 (0.0)	1.4 (1.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sardinops neopilchardus	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sillago ciliata	0.0 (0.0)	2.2 (1.2)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)
Trachurus sp.	0.4 (0.4)	0.4 (0.4)	0.6 (0.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Clinidae/Tripterygiidae	6.6 (2.8)	11.2 (5.4)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)

at Potter Point most preflexion fish occurred in the ocean at Location 1, but there was no significant difference between plume and ocean water at Location 2 (Fig. 7).

A greater percentage of preflexion fish were caught in all water masses at North Head and Bondi in December, but this was not the case at Potter Point (Fig. 6). In January a greater percentage of preflexion

Table 8. Mean (+1 SE) numbers of fish caught in plume, front and ocean water at the 2 locations at Potter Point sewage outfall in January 1991

Taxon	Location 1			Location 2		
	Plume	Front	Ocean	Plume	Front	Ocean
Acanthopagrus australis	1.3 (0.9)	0.7 (0.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.7 (0.3)
Ambassis jacksoniensis	4.3 (0.9)	0.0 (0.0)	0.0 (0.0)	0.7 (0.7)	1.3 (0.9)	0.0 (0.0)
Atherinidae	1.0 (1.0)	4.3 (4.3)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Engraulis australis	2.3 (1.2)	3.0 (1.7)	1.0 (0.6)	1.7 (0.9)	0.0 (0.0)	4.7 (2.4)
Gerres subfasciatus	0.0 (0.0)	0.7 (0.7)	0.3 (0.3)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Girella tricuspidata	0.0 (0.0)	4.5 (2.6)	0.5 (0.5)	3.2 (0.9)	0.0 (0.0)	22.3 (10.9)
Gobiidae	9.8 (1.7)	4.0 (4.0)	1.5 (0.9)	4.2 (0.5)	5.7 (1.5)	0.0 (0.0)
Gonorynchus greyi	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Kyphosus sp.	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	3.4 (1.0)
Labridae	2.4 (0.5)	0.0 (0.0)	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Liza argentea	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.2 (0.7)
Mullidae	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	2.3 (0.6)
Omobranchus anolius	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)
Pagrus auratus	0.5 (0.5)	1.0 (1.0)	0.0 (0.0)	0.6 (0.6)	0.5 (0.5)	0.0 (0.0)
Pelates sexlineatus	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.9 (0.4)
Petroscirtes lupus	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Platycephalidae	5.9 (2.2)	3.5 (1.8)	0.0 (0.0)	1.1 (1.1)	1.0 (1.0)	0.0 (0.0)
Pomacentridae	5.9 (0.0)	23.9 (13.3)	121.8 (16.7)	21.9 (17.2)	0.0 (0.0)	0.5 (0.5)
Sardinops neopilchardus	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.5 (0.5)
Sillago ciliata	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.4 (0.4)
Trachurus sp.	24.6 (5.9)	0.0 (0.0)	0.0 (0.0)	1.6 (0.9)	1.6 (1.6)	4.6 (1.9)
Clinidae/Tripterygiidae	12.8 (2.8)	1.0 (1.0)	0.0 (0.0)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)

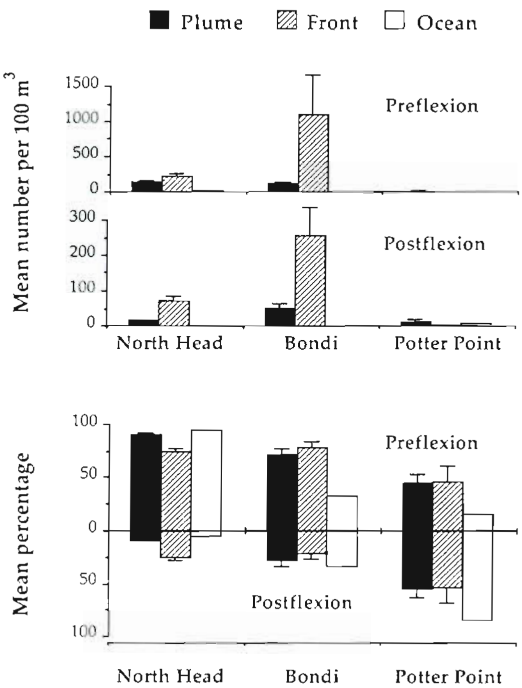

Fig. 6. Mean (+1 SE) numbers and proportions of pre- and postflexion fishes caught in plume, front and ocean waters at the North Head, Bondi and Potter Point sewage outfalls in December 1990

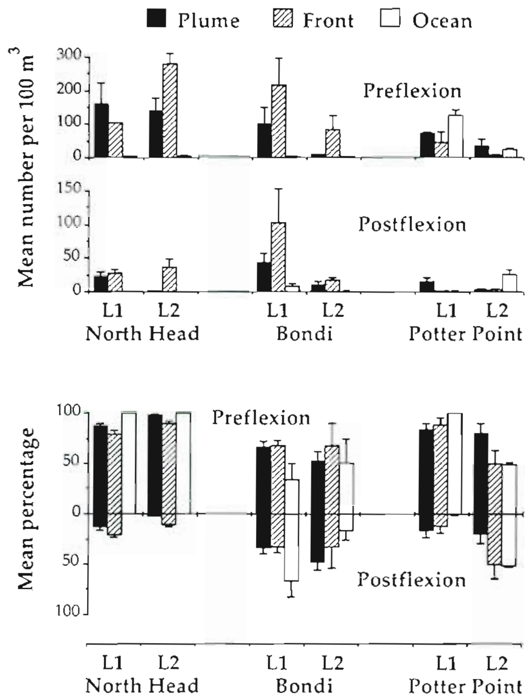

Fig. 7 Mean (+1 SE) numbers and proportions of pre- and postflexion fishes caught in plume, front and ocean waters at the North Head, Bondi and Potter Point sewage outfalls in January 1991 L1 = Location 1; L2 = Location 2

fish was caught in all water masses at both locations at North Head, but there were no consistent trends at Bondi and Potter Point (Fig. 7, Table 9).

Postflexion fishes, including some well developed juveniles of several taxa, notably *Sardinops neopilchardus*, *Engraulis australis*, Atherinidae, Hemiramphidae, Stromateidae, Mullidae, Teraponidae and Blenniidae, were caught at fronts (Table 1).

Flotsam and drift algae

Small amounts of flotsam, including drift algae and seagrass shoots, and garbage, such as plastic bags and containers, were collected at fronts of all 3 plumes. Greatest amounts of drift algae/seagrass were collected at fronts at North Head (Table 10). There were no significant relationships between the quantity of drift algae collected and total numbers of fish caught at fronts (Fig. 8). Mulched toilet paper was collected in all plume samples.

Table 9. Summary of ANOVAs of numbers and percentages of pre- and postflexion fishes caught in plume, front and ocean water at North Head, Bondi and Potter Point sewage outfalls in December 1990 and January 1991 Abundance data transformed to $\ln(x+1)$, percentage data transformed to arcsin. df: degrees of freedom; MS: mean square. Other symbols as in Tables 3 & 4

	df	Abundance		Percentage	
		Preflexion MS	Postflexion MS	Preflexion MS	Postflexion MS
December 1990					
Outfall	2	23.783***	3.605***	1.164**	0.929**
Water mass	2	28.016 ns	15.533 ns	0.047 ns	0.159 ns
O × W	4	5.930***	6.513***	0.169 ns	0.118 ns
Residual	18	0 268	0.320	0.122	0.132
Total	26				
Cochran's test		ns	ns	ns	ns
January 1991					
Outfall	2	3.103 ns	4.076 ns	1.836 ns	0.501 ns
Location (O)	3	5.503***	4.917***	0.493***	0.199***
Water mass	2	20.221 ns	15.993 ns	0.088 ns	0.011 ns
O × W	4	13.952***	5.923 ns	0.300 ns	0.040 ns
L(O) × W	6	0.609 ns	2.650***	0.148*	0.116**
Residual	36	0.624	0.263	0.053	0.029
Total	53				
Cochran's test		ns	ns	ns	ns

Table 10. Mean weight (g) (+1 SE) of drift algae/seagrass collected in plume, front and ocean waters at North Head, Bondi and Potter Point sewage outfalls in December 1990 and January 1991

	North Head	Bondi	Potter Point
December 1990			
Plume	0 (0)	0 (0)	0 (0)
Front	17.5 (5.6)	8.4 (4.4)	0 (0)
Ocean	1.4 (1.4)	0 (0)	0 (0)
January 1991			
Location 1			
Plume	0 (0)	0 (0)	0 (0)
Front	20.8 (5.4)	0 (0)	0.9 (0.9)
Ocean	1.3 (0.8)	0 (0)	0 (0)
Location 2			
Plume	0 (0)	0 (0)	0 (0)
Front	10.5 (3.9)	0 (0)	0 (0)
Ocean	0 (0)	0 (0)	0 (0)

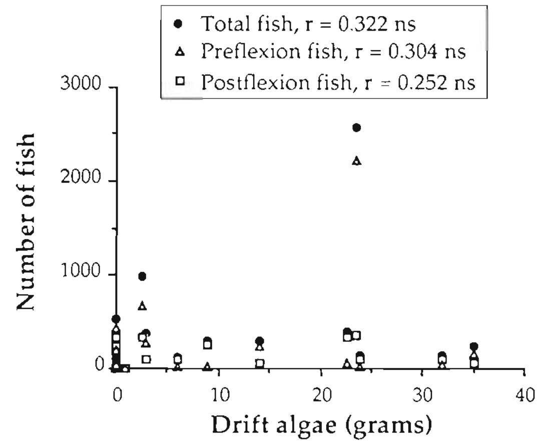

Fig. 8. Relationships between numbers of young fish and weight of drift algae/seagrass collected at the fronts of sewage plumes. Data for all 3 outfalls and both sampling periods combined (n = 27). The correlation coefficient (r) and its significance are given for each correlation. ns: not significant

DISCUSSION

Oceanography of surface sewage plumes

Sewage plumes formed significant physical intrusions into mainstream continental shelf waters off Sydney. These plumes can extend many kilometres seaward and alongshore (observed up to 5 km seaward and 8 km alongshore; see also Gray 1995, Kingsford & Gray 1996). This is of similar extent to that of estuarine plumes from Botany Bay (observed up to 11 km offshore; Kingsford & Suthers 1994). However, both sewage and estuarine plumes were mostly confined to within 2 km of the coast, and aligned in alongshore currents. Variations in orientation and spatial extent of sewage plumes over the continental shelf would probably be caused by variations in the amount and rates of discharge among outfalls and throughout time, differing oceanographic conditions, and the degree of mixing of plume and shelf waters. In contrast to estuarine plumes, the oceanographic structure of sewage plumes did not alter significantly with tidal phase. Thus sewage plumes formed persistent intrusions into the shelf waters off Sydney, potentially posing a constant structure that may influence fishes during early development.

The oceanography of each sewage plume was similar and resembled that of estuarine/riverine plumes, i.e. a shallow wedge of turbid lower-salinity water overlaying clear high-salinity shelf water (Govoni et al. 1989, Grimes & Finucane 1991, Kingsford & Suthers 1994). The observed depth of the sewage plumes ranged between 1 and 5 m and a distinct frontal region (1 to 3 m wide) was usually associated with each plume. This front was observed as a distinct change in turbidity, colour and usually salinity (see also Kingsford & Gray 1996). The accumulation of drift algae and flotsam along fronts of sewage plumes suggested these fronts were areas of convergence, similar to that described for estuarine plumes (Govoni & Grimes 1992) and other oceanographic features (Kingsford 1990). The depth of the sewage plumes, the width and intensity of the front and the disparity in salinity change at the front (see Kingsford & Gray 1996), and thus the intensity of convergence of surface waters around these plumes, would probably be influenced by the rate and quantity of the discharge, distance from the point-source and interactions of plumes with surrounding shelf waters and bottom topography (e.g. Wolanski & Hamner 1988, Govoni & Grimes 1992). Thus, oceanographic influences of plumes on young fish and other plankton may vary according to interactions between plume and shelf waters.

Influences of surface sewage plumes on distributions of young fishes

Surface sewage plumes are capable of influencing small-scale (<1 km) patterns of distribution of larval and presettlement fishes in coastal waters. Densities of a wide taxonomic suite of fish were usually greater in plumes or fronts than in adjacent shelf water, which concurs with that reported for small fish and plankton in many types of natural oceanographic features (see 'Introduction'). Increased concentrations of small fishes along frontal regions of oceanographic features may be due to a combination of active and passive

processes, but have often been attributed to oceanographic convergence (e.g. Govoni et al. 1989, Kingsford 1990, Sabates 1990). The similarity in oceanography of sewage plumes to natural plumes suggests that convergence of surface waters may have facilitated the concentration of young fishes along the fronts of sewage plumes. Passive concentration would most likely be the case for preflexion fishes, but postflexion fishes may have been attracted to these plumes by other factors, such as the potential increase in prey concentrations. Increased catches of some small preflexion fish in plumes may have been the result of the fibrous material in plumes altering the functional mesh size and sampling efficacy of the net (see Kingsford & Gray 1996). However, this does not negate the fact that large numbers of young fish were found in plumes and were thus exposed to pollutants. Future work is required to assess the effects of fibrous materials in plumes on catchability of young fishes.

Aggregation of fishes at fronts was variable. Rank abundances of fishes among water masses varied among taxa, locations around an outfall (e.g. *Sillago ciliata* and Labridae at North Head in January) and throughout time. This variability concurred with that documented between these sewage plumes and distant shelf waters (Gray et al. 1992). Such variation among water masses was not unexpected given the inherent heterogeneity in distributions of planktonic organisms (Haury et al. 1978, Gray 1993, 1996, Thorrold et al. 1994), changes in behaviour, immigration and emigration of young fishes from plumes, and spatial and temporal variation in the physical attributes of each outfall and plume. In particular, changes in the behaviour and intensity of the front along different parts of the plume would probably be important in concentrating fish, and require greater investigation.

Small quantities of drift algae and flotsam were collected at fronts. Although there were no significant correlations between quantity of drift algae and abundances of fish, these structures may have accounted for higher abundances of some organisms at fronts. In particular, certain types of small fishes (e.g. postflexion Hemiramphidae, Exocoetidae, Carangidae, Stromateidae, Mullidae and Mugilidae) may have been attracted to, or were living among, clumps of drift algae collected in fronts. Small fishes have been documented as being associated with floating objects, such as drift algae, elsewhere (Hunter & Mitchell 1967, Mitchell & Hunter 1970, Safran & Omori 1990, Kingsford 1992, 1993).

Depth of the sewage plumes suggested that greatest influences on planktonic organisms would be in surface waters (1 to 3 m). However, plumes are 3-dimensional structures (e.g. Wolanski & Hamner 1988) and may affect vertical patterns of water circulation and vertical movements and transportation of small fish and plankton, particularly those that migrate vertically (e.g. Kendall & Naplin 1981, Brewer & Kleppel 1986, Haney 1988, Neilson & Perry 1990). Subduction at the front may displace young fish to a deeper layer of water (Franks 1992). Moreover, young fish and plankton may be concentrated at the subsurface halocline between plume and ocean, similar to that around subsurface thermoclines (Kendall & Naplin 1981, Frost 1988, Haney 1988).

Sewage plumes move across and along the continental shelf and may modify the distributions and densities of young fish and other plankton over large spatial scales (>1 km). The size and orientation of these sewage plumes off Sydney suggest that fish in surface waters within at least 5 km of the outfalls are likely to encounter these plumes. These plumes could thus alter cross-shelf distributions of young fishes. In particular, fish may be entrained in, or follow, plumes and fronts, potentially altering their patterns of transport and recruitment, similar to other oceanographic processes (Shanks 1983, Grimes & Finucane 1991). Exposure of young fish to sewage plumes may vary among different taxa, depending on where they were spawned and where they spend their early life, larval behaviour and oceanography. Surface dwelling taxa that predominately occur in nearshore waters during their early development (e.g Tripterygiidae, *Acanthopagrus australis*, *Sillago ciliata*) would probably be most vulnerable to sewage plumes. Furthermore, ontogenetic shifts in horizontal and vertical distributions displayed by some taxa (e.g. *Liza argentea*) may mean that either smaller or larger individuals of a species are affected by these plumes. For example, larger *L. argentea* occur in surface waters (Gray 1993). The oceanographic conditions off Sydney change throughout the year, influencing both the distributions of young fishes and the behaviour of sewage plumes. For example, in winter (July-August) offshore winds predominate, sweeping plumes greater distances offshore, potentially enhancing exposure to a wider suite of taxa. In winter many oceanic pelagic taxa (e.g. Myctophidae) are transported onto the inner shelf off Sydney (Gray 1993, 1995). In winter, therefore, a wider suite of nearshore and offshore taxa may be affected by these plumes.

The oceanography of sewage plumes may enhance and prolong exposure of young fishes to pollutants. Pollutants (e.g. organochlorines) are often concentrated at fronts (Hardy et al. 1985, Brown et al. 1991, Tanabe et al. 1991), similar to the sea-surface microlayer (Hardy 1982, Hardy et al. 1987a), and models that assume simple dilution of pollutants from point-sources are inappropriate (see also Cross et al. 1987, Hardy et al. 1987b). Entrainment of fish and pollutants in plumes and fronts may create a greater risk to sur-

vival during early development. Quantifying lethal effects of plumes on young fishes in the field would be extremely difficult given that fish may not necessarily die from contact with plumes immediately, but may die further downstream from the actual outfall. In the absence of toxic substances and lethal effects, the potential increased food resources in sewage plumes could be beneficial to young fish.

The situation of multiple sewage plumes off Sydney (7 shoreline outfalls within 50 km of coastline) may significantly enhance exposure to pollutants and effects of plumes on young fishes. Plumes from the 3 largest shoreline outfalls (North Head, Bondi and Malabar) sometimes merged (author's pers. obs.), potentially creating 1 large polluted field covering virtually all the nearshore waters off Sydney. Reversing currents, eddies and other oceanographic events may also lead to prolonged exposure. At certain times it would be possible for fish to be swept by alongshore currents through all plumes within a couple of hours. These plumes often covered the entrances to the main estuaries in this region; Sydney Harbour, Botany Bay and Port Hacking These plumes, therefore, may not only have affected young fish in coastal waters, but fish entering or leaving these estuaries. Subsequently, these plumes could have considerable influence on the recruitment dynamics of small fishes and other meroplankton in both nearshore and estuarine waters around Sydney. It is plausible that sizes of adult stocks of these organisms around Sydney may be affected due to the loss of young.

Of greater concern is that, unlike benthic organisms and adult fishes, young fishes from a wide field may be affected by sewage plumes, and effects may be manifest over large spatial scales (see also Keough & Black 1996, Raimondi & Reed 1996). Young fishes entrained in mainstream coastal water bodies that were spawned tens to hundreds of kilometres upstream may be transported through these plumes, potentially affecting supply of recruits to downstream areas. Small changes in rates of mortality during early development can have dramatic effects on levels of recruitment (Underwood & Fairweather 1989, Fogarty et al. 1991). Therefore, sewage plumes could influence the dynamics and vitality of marine communities over a wide area of a coast, particularly if many such outfalls occur along a coastline, as in New South Wales (40 ocean sewage outfalls occur along 1000 km of coastline).

Ultimately, location of the plume point-source, the amount, type and concentration of effluent, the place and timing of spawning, length of the pelagic phase, distribution and behaviour patterns of young fish and their resilience to pollutants, and interactions with oceanography will determine taxa most vulnerable to anthropogenic plumes and potential influences to adult stock. Effects on health and condition of young fishes (review in Ferron & Leggett 1994) and genetic, immunological and teratological (e.g. Longwell et al. 1992, Bodammer 1993, MacLean 1993) influences of plumes on development of embryos and larvae need to be considered. Both field and laboratory studies may be needed to successfully quantify effects of sewage plumes on young fishes in the future (e.g. Hardy et al. 1987b). Future field studies need to place more emphasis on oceanography in modifying the effects of pollutants on young fishes.

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