CHAPTER 3

GENERAL REGIONAL DESCRIPTION OF ESTUARINE BENTHIC COMMUNITIES AND LONGITUDINAL VARIATION WITH-IN ESTUARIES

3.1 Introduction

The coastline of NSW comprises some 1740 km (Zann 1996) and incorporates in excess of 950 estuaries (Williams et al. 1998), though most of these are very small systems and only 130 have been documented as having a water body greater than 0.05 km^2 (Bell & Edwards 1980; West et al. 1985). Most of the research on estuarine benthos in NSW has primarily focused on large estuaries that are close to cities or major urban centers, including the Hawkesbury River (Jones et al 1986; Jones 1987; MacFarlane & Booth 2001), Botany Bay (Jones & Candy 1981; Morrisey et al. 1992a, b) and the Great Lakes of the Central Coast (Hutchings et al. 1978; Atjinson et al. 1981). These estuaries are unusual in that they represent estuary types (i.e. drowned river valleys, large interconnected lake systems, embayments) that are not particularly common along this coastline (Hirst 2004).

Benthic studies in smaller intermittent systems have also mainly been conducted on those that are wholly within these major urban centers, such as the Dee Why, Curl Curl, Illawarra and Narrabeen lagoons (Dye 2005), all of which are highly modified. Additionally, a number of benthic studies have taken place in estuaries on the south-coast of NSW (Dalton et al. 2002; Dye 2005; Hirst 2004; Winberg 2004). In contrast, the estuarine infauna of the northern half of NSW has been poorly examined. As a result, the distribution of NSW estuarine benthic fauna is not well known. In terms of the Solitary Islands Marine Park, the largest marine park in NSW, it has only previously been considered in a few studies (Smith et al. 1994; Johnstone 1997; Smith 1997; Sawtell 2002) that have had small spatial and temporal scales, and have most often been conducted to address a specific issue in a specific estuary. Of the fifteen main estuaries in the marine park, the only ones included in these studies were Arrawarra, Darkum, Station, Willis and Moonee creeks, as well as Hearns Lake.

As a transistion zone between freshwater and marine environments, most estuaries usually have a gradient in physico-chemical properties between their upper to lower reaches, especially for salinity and sedimentary characteristics (McLusky 1974; Boesch 1976; Day et al. 1989; Deeley & Paling 1999). Consequently, it is generally assumed that biological gradients similarly exist, to the extent that estuarine organisms are often classified according to their tolerance of various salinity ranges (i.e. euryhaline, stenohaline) and each of these classifications have been assigned to specific areas along the length of an estuary (McLusky 1979). Whilst Sawtell (2002) has established significant community differences along the lengths of permanently open estuaries in the region, most of the intermittent estuaries are often without marine input for extended periods. It is thus plausible that such gradients, both physico-chemical and biological, may weaken periodically. In following chapters I intend to incorporate communities from a number of sites along the length of each estuary. Therefore, it was deemed necessary to determine the relationship between the communities of the upper, middle and lower sites in each estuary at times when all estuary entrances were open, as well as at times when all intermittent estuaries were closed.

This chapter gives a brief introduction to the benthic fauna in the estuaries of the SIMP, on the northern coast of NSW, and aims to: (1) present a descriptive overview of the fauna that inhabit each estuary; and (2) quantitatively assess assemblage differences between the upper, middle and lower sites of each estuary. The data examined here are part of a larger research programme comparatively assessing the spatio-temporal variation of both intermittently closed and permanently open estuary types. As such, the results presented on within-estuary spatial variation (i.e. between the upper, middle and lower sites) will provide an insight into community variation at this scale, before community variation is assessed at greater spatial scales.

3.2 Methods

3.2.1 Description of benthic macrofauna in the Solitary Islands Marine Park estuaries

This chapter presents preliminary analyses of the data that were collected for the major temporal component of this thesis (refer to 'Chapter 5' for a detailed description of the study design and sampling methods). In brief, 15 macrofaunal samples were collected from nine estuaries in the SIMP (Fig. 3.2.1), on nine occasions from January 2003 to October 2004. The estuaries surveyed represented two estuary types, including six intermittently closed and three permanently open estuaries. The intermittent estuaries were Station, Darkum, Arrawarra and Willis creeks, and Woolgoolga and Hearns lakes. The permanently open estuaries were Corindi River and Moonee and Coffs creeks. Macrofaunal samples were collected from subtidal, unvegetated sediments using a 0.068 m^2 van Veen grab and sieved through a 1 mm mesh.

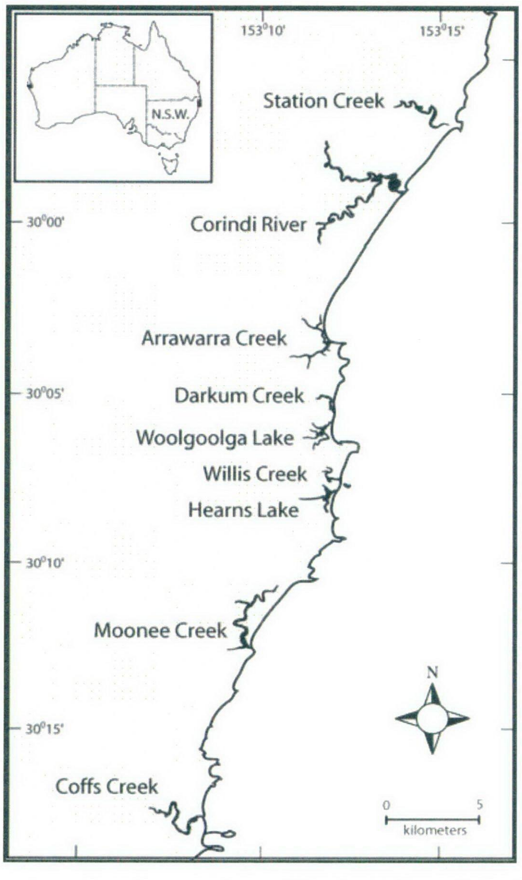


Fig. 3.2.1. Location of study estuaries within the Solitary Islands Marine Park.

Data were pooled within estuaries for each sampling time (*n* = 15) and both the total number of species and individuals are given as a descriptive summary for each estuary. Within these summaries the relative proportions contributed by various faunal groups (i.e. molluscs, polychaetes, crustaceans and all other species) are also identified as an indication of the fauna present during this time. In addition, the most common species in each estuary are listed, along with their rank abundances collected over the two-year period. The species listed as common are those that had a total abundance over the entire study duration that was greater than 20 in at least one estuary. This particular threshold gave a broad listing of species, yet maintained that macrofaunal species with abundances less than this could not accurately be considered common.

3.2.2 Assemblage comparisons along the length of each estuary

The fifteen samples collected from each estuary were equally divided among three sites, an upper, middle and lower, that had been established along the length of each estuary. Previous studies (Sawtell 2002) indicated that infaunal communities are distinct in each of these parts of local estuaries. Sites measured approximately 10 x 10 m and were situated in the middle of the main estuary channel. Surrounding vegetation and relative distance along the estuary were taken into consideration when establishing sites in order to facilitate valid comparisons between equivalent estuary regions.

Of the nine sampling times mentioned above (see 3.2.1) only four were concentrated on to examine assemblage relationships between the upper, middle and lower sites in each estuary. These included two times, March 2003 and October 2004, when all estuary entrances were open, as well as the two times, January 2003 and July 2004, when the greatest number of intermittent estuaries were closed. For the latter times there were six and five closed estuaries, respectively.

For each time, multivariate analyses of community structure were conducted using the PRIMER software package (Clarke & Gorley 2001). Data were analysed to test the null hypothesis that there were no differences in community structure between the sites in each estuary. For the intermittently closed estuaries, it was predicted that longitudinal site differences would be greater whilst entrances were open, as entrance closure could reduce the degree of some longitudinal gradients such as salinity. Data were square-root transformed prior to construction of a Bray-Curtis similarity matrix and two-dimensional ordinations of assemblages were subsequently created using non-metric multidimensional scaling (nMDS). The significance of differences in community structure between sites was assessed using one-way analyses of similarities (ANOSIM). The contribution of individual species to the differences observed was calculated using the similarity percentages (SIMPER) routine and indices of multivariate dispersion (IMD), both within and between sites, were calculated using the MVDISP routine.

3.2.3 Salinity comparisons along the length of each estuary

As biological gradients along the length of estuaries are most commonly suggested to be the result of changes in salinity from fresh to marine waters (McLusky 1974; Boesch 1976; Day 1989), salinity was also examined in these estuaries. For each of the five macrofaunal samples collected at the upper, middle and lower sites of each estuary, readings were also taken of total dissolved salts. These measurements were taken from the lower water column and repeated on all four sampling times, January and March 2003, July and October 2004. For each estuary, one-way analyses of variance (ANOVA) were used to test the null hypothesis that there was no significant difference between sites. This was again repeated for all four sampling times.

3.3 Results

3.3.1 Description of benthic macrofauna in the Solitary Islands Marine Park estuaries

A total of 130 species, representing 118 genera, 93 families, 30 orders and 8 phyla were collected from 9 estuaries over the two-year period. In terms of species, the most diverse groups were the bivalves (15), gastropods (22), polychaetes (35), amphipods (13) and decapods (14) (Table 3.3.1.1) Only 48 species satisfied the criterion to be listed as common (i.e. total number collected over the entire study duration were greater than 20 in at least one estuary) (Table 3.3.1.2). Of these, only 4 species were collected from all nine estuaries. These were the bivalve *Arthritica helmsi* and the polychaetes *Orthoprionospio cirriformia, Scoloplos normalis* and *Notomastus estuarius*. Another 11 species occurred in all estuaries except Willis Creek and included bivalves (3), gastropods (2), polychaetes (3), amphipods (2) and an oligochaete. Similarly, the polychaete *Scyphoproctus towraensis* was collected in all estuaries except Moonee Creek and Nemertean sp. 5 was, at some time, present in all estuaries except Darkum Creek. Amongst the common fauna, 16 species were highly abundant in at least one estuary (i.e. > 500 collected). These included: the bivalves (3) *Mysella vitrea, Arthritica helmsi*, and *Fluviolanatus subtortus*; the gastropods (4) *Cerithium corallium, Batillaria australis, Ascorhis tasmanica* and an unknown gastropod; the polychaetes (6) *Orthoprionospio cirriformia, Scoloplos normalis, Simplisetia aequisetis, Armandia intermedia, Scyphoproctus towraensis*, and *Notomastus estuarius*; as well as the amphipod *Urohaustorius metungi*, the phoronid *Phoronis* sp.2 and the insect larvae Chironomidae sp. 1 (Table 3.3.1.2).

Table 3.3.1.1 Summary of the macrofaunal taxonomic groups represented in benthic communities of the Solitary Islands Marine Park estuaries.

Phylum		No. Species
Mollusca	Bivalves	15
	Gastropods	22
Annelida	Polychaetes	35
	Oligochaetes	3
Nemertea		4
Echiura		2
Phoronida		3
Nematoda		1
Cnidaria		1
Arthropoda	Amphipods	13
	Isopods	2
	Tanaids	2
	Other Peracarids	1
	Decapods	14
	Insects (Dipteran larvae)	5
Chordata	Teleosts	7
	Total	130

A number of representatives from each of the mollusc, polychaete and crustacean faunal groups were generally always present in each estuary (Fig. 3.3.1.1). Exceptions to this included three occasions in both Moonee and Darkum creeks, as well as one time in both Woolgoolga and Hearns lakes. For each of these occasions the estuarine communities were fully comprised of molluscs, polychaetes and crustaceans, with a complete absence of representatives of any other faunal groups. Willis Creek was also unique for two reasons. Firstly, it had a low total species richness overall in comparison to all other estuaries; the maximum total species richness in Willis Creek less or equal to the minimum in any other estuary. Secondly, whilst crustaceans were present in all other estuaries at all times, for more than half of the sampling times, crustaceans were absent from Willis Creek (Fig. 3.3.1.1).

In contrast, the total abundances across each faunal group were less consistent between estuaries, resulting in characteristic profiles for each estuary that were relatively stable through time and often unique (Fig. 3.3.1.2). For example, Corindi River always had very low total abundances (< 200), with assemblages generally dominated by crustaceans. Moonee Creek, on the other hand, presented very high total abundances (> 1000) on most sampling occasions, the majority of which were molluscs and crustaceans (Fig. 3.3.1.2). By cross-referencing this information with that for the common species for this estuary (Table 3.3.1.2), it can be determined that Moonee Creek was generally dominated by the molluscs *Mysella vitrea*, *Arthritica helmsi* and the crustacean *Urohaustorius metungi*. Arrawarra Creek also presented high total abundances throughout the two-year period though, in this instance, the high abundances were largely attributable to polychaetes (Fig. 3.3.1.2), mainly *Orthoprionospio cirriformia*, *Scoloplos normalis*, *Simplisetia aequitsetis* and *Armandia intermedia* (Table 3.3.1.2).

Total abundances in the remaining estuaries generally ranged from 400 – 800 and almost wholly comprised molluscs, polychaetes and, to a lesser extent, crustaceans. In comparison, Arrawarra Creek supported relatively high abundances of species that were not polychaetes, molluscs, or crustaceans (i.e. “other” fauna) (Fig. 3.3.1.2), especially Oligochaete sp. 1 and *Phoronis* sp. 2 (Table 3.3.1.2). The abundances in this “other fauna” category were similarly notable in Willis Creek (Fig. 3.3.1.2), primarily due to high abundances of Chironomidae sp. 1 (Table 3.3.1.2).

Table 3.3.1.2 Total number of individuals collected in each estuary over the two-year study for the most common species (* = 1-20, ** 20-100, *** 100-500, **** > 500). Estuary names are abbreviated to their first three letters.

	Permanently open			Intermittently closed					
	COR	MOO	COF	STA	ARR	DAR	WOO	WIL	HEA
Bivalvia									
Phaphia undulata	*	**	***	*	**	*	*		*
Mysella vitrea	*	****	****	*	***	***	****		*
Spisula trigonella	*	*	*	***	*		*		*
Tellina imbellis	**	**	***	**	**		**		*
Arthritica helmsi	*	****	**	*	****	****	**	**	****
Soletellina alba	**	***	***	***	*	***	***		**
Fluviolanatus subtortus		*		*	*	***	*	****	**
Laternula sp.	*		*	*	**	*	*	*	
Mytillidae sp.	*				*	**	*		
Gastropoda									
Tornatina apicina	*	*	*		***		*		
Cerithium corallium	*	*	*	**	***	*	****		
Batillaria australis				*	**	*	****		
Pyrgulina ceria			*	*	*		***		
Nassarius jonasii	*	**	***	*	**	*	*		**
Ascorhis tasmanica	*				*	**		****	**
Nozeba topaziaca	**	**	**	*	*	*	*		*
Unknown gastropod (G19)		*	*		***	*		****	*
Polychaetea									
Orthoprionospio cirriformia	*	**	**	**	****	***	***	****	***
Sigalion bandaeensis	**	*	*		*	*			
Nephtys gravieri	***	**	**	*	*				
Scoloplos normalis	**	***	***	***	****	****	****	**	****
Australonereis ehlersi	**	**	**	*	**	*	**		***
Simplisetia aequisetis	*	***	*	*	****	***	**		****
Armandia intermedia	*	***		****	****	***	****		*
Scyphoproctus towraensis	*		*	**	**	*	***	****	***
Notomastus estuarius	**	**	*	***	***	**	**	***	****
Capitellidae sp. 2	*		*	*	**	*		*	*
Marphysa sp. 2	*	*	*		**	*	*		*
Sphaerosyllis nathani	*	*	*	*	*	*	**		*
Laonome triangularis	*	*	***		**	*	*		
Sabellidae sp. 1	*	*	*		***	*	*		**
Crustacea									
Victoriopisa australiensis	**	***	***	**	**	*	***		**
Melita matilda	*	*	*	**	*	*	*		*
Urohaustorius metungi	****	****	***	*	*	*	***		
Photidae sp.	*	*	*	*		*	**		**
Anthuridae sp.	*	***							
Leptocheliidae sp.		*		***	*	*	*		
Gastrosaccinae sp.	**	*	*	*		*			
Trypaea australiensis	***	***	**	*	*	*	*		*
Other									
Chironomidae sp.1			*	*			*	****	*
Unknown insect larvae								**	
Oligochaete sp.1	*	*	*	*	***	*	*		**
Phoronis sp. 2			*		****		*		
Nemertean sp. 5	**	*	*	*	*		*	*	*

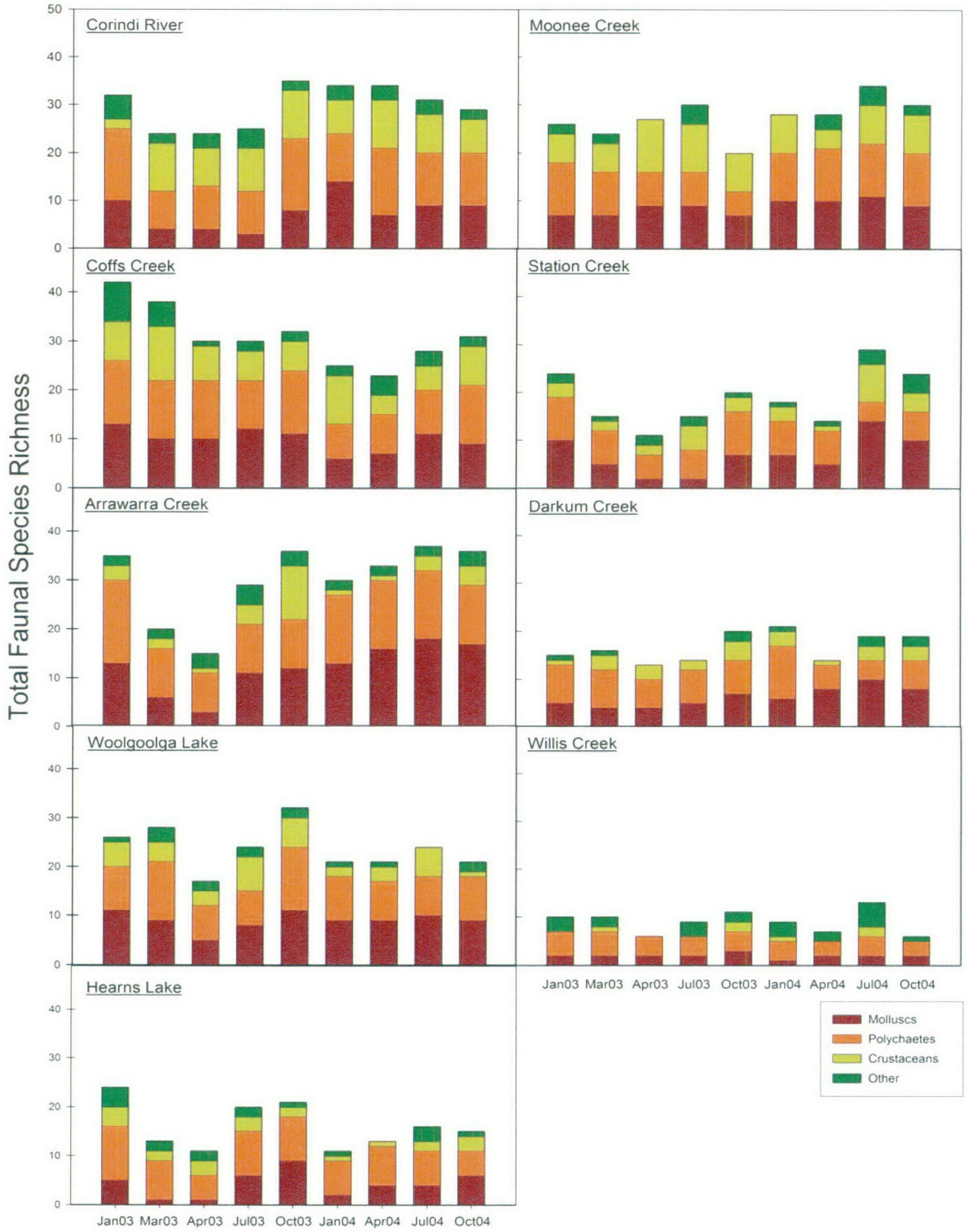


Fig. 3.3.1.1 Total number of species of molluscs, polychaetes, crustaceans, as well as all other fauna, collected in each estuary ($n = 15$) on nine sampling occasions over a two-year period.

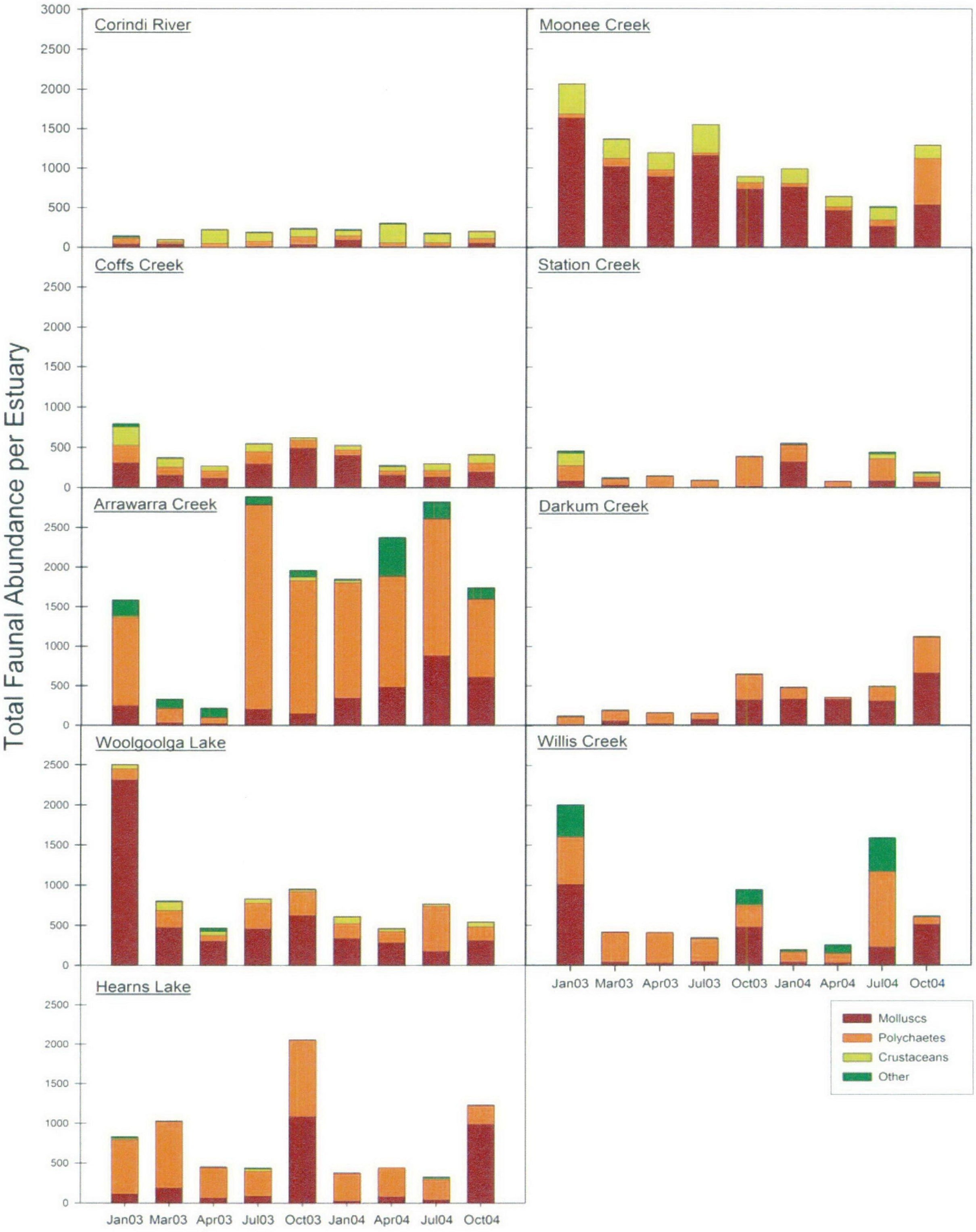


Fig. 3.3.1.2 Total abundance of molluscs, polychaetes, crustaceans, as well as all other fauna, collected in each estuary ($n = 15$) on nine sampling occasions over a two-year period.

3.3.2 Assemblage comparisons along the length of each estuary

In January 2004, when all intermittent estuaries were closed, nMDS ordinations revealed considerable separation between the assemblages of the upper, middle and lower sites for most estuaries (Fig. 3.3.2.1). ANOSIM indicated that the differences between sites were highly significant for all estuaries ($p \leq 0.002$) (Table 3.3.2.1) and community differences were therefore present along the length of each estuary. This was especially true when comparing the lower sites to both the upper and middle sites with significant differences for all pairwise comparisons ($p = 0.008$) (Table 3.3.2.1). However, community differences continued between the upper and middle sites in only five estuaries, with the remaining four presenting no significant differences between the upper and middle sites at this time. These four estuaries were Corindi River, Station Creek, Hearns Lake and Darkum Creek, the latter three being intermittent estuaries that were closed at the time of sampling. Whilst significantly different, sites in the remaining intermittent estuaries were either overlapping or grouped closely together, as supported by generally lower IMD values in the MVDISP analyses (Table 3.3.2.2). More defined gradients between the communities of the upper, middle and lower sites were evident in Moonee and Coffs creeks (Fig. 3.3.2.1, Table 3.3.2.2).

Communities were even more discrete in July 2004, when most intermittent estuaries were again closed, with no overlap between the upper, middle or lower sites at any estuary (Fig. 3.3.2.2). At this time the differences between sites were again highly significant for all estuaries ($p \leq 0.002$) and all pairwise comparisons were also significantly different ($p = 0.008$) (Table 3.3.2.3). Clear gradients in community structure along the length of the estuary were most apparent in Coffs, Darkum and Willis creeks, as well as in Woolgoolga and Hearns lakes. However, unlike the pattern in Coffs, Willis and Woolgoolga, where each site was tightly grouped and some distance from the other sites, the gradient pattern in Darkum Creek and Hearns Lake was more of a broad continuum in which each site was widely dispersed and generally more closely associated with neighbouring sites. Despite the occasional exception, these patterns were again generally supported by the multivariate dispersion indices (Table 3.3.2.2).

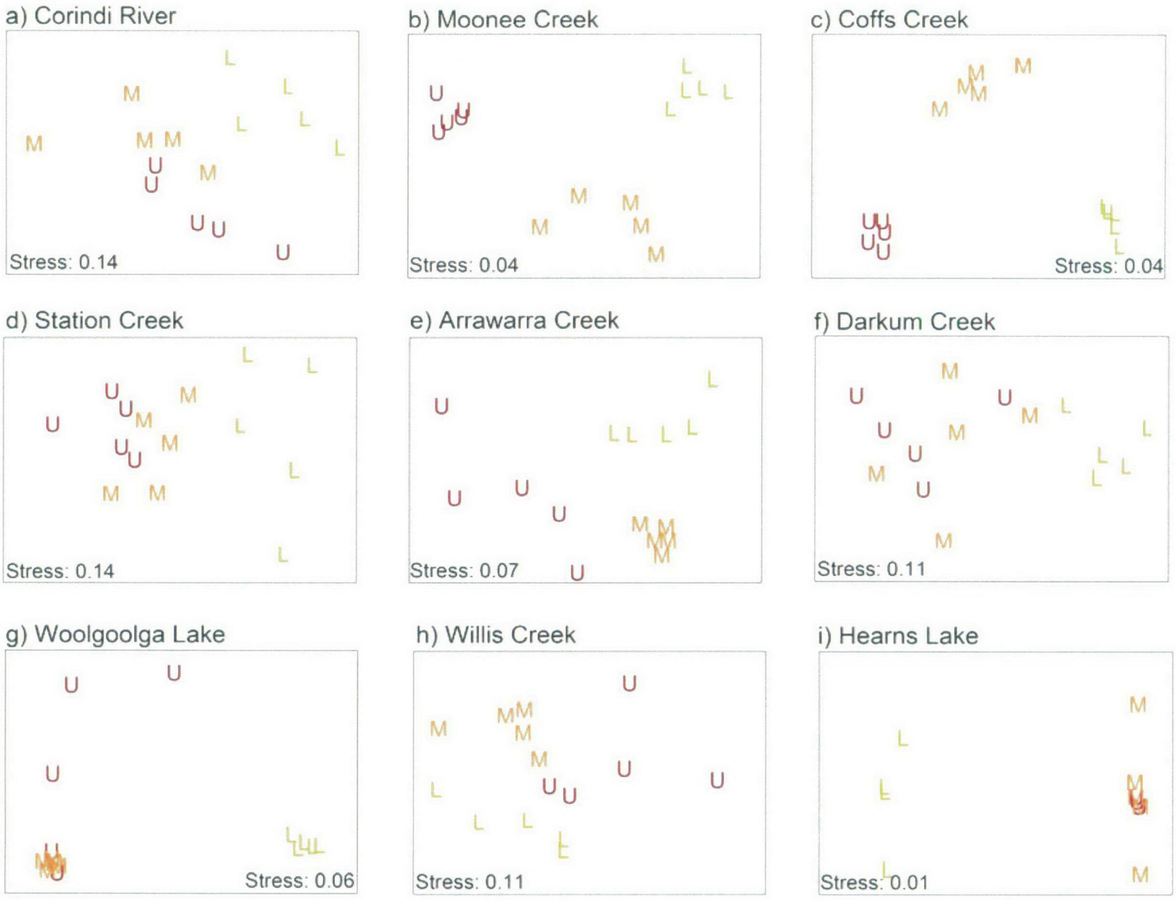


Fig. 3.3.2.1 Two-dimensional nMDS ordinations of benthic assemblages at each of the upper (U), middle (M) and lower (L) sites of each estuary in January 2003, a time when all intermittent estuaries (d – i) were closed.

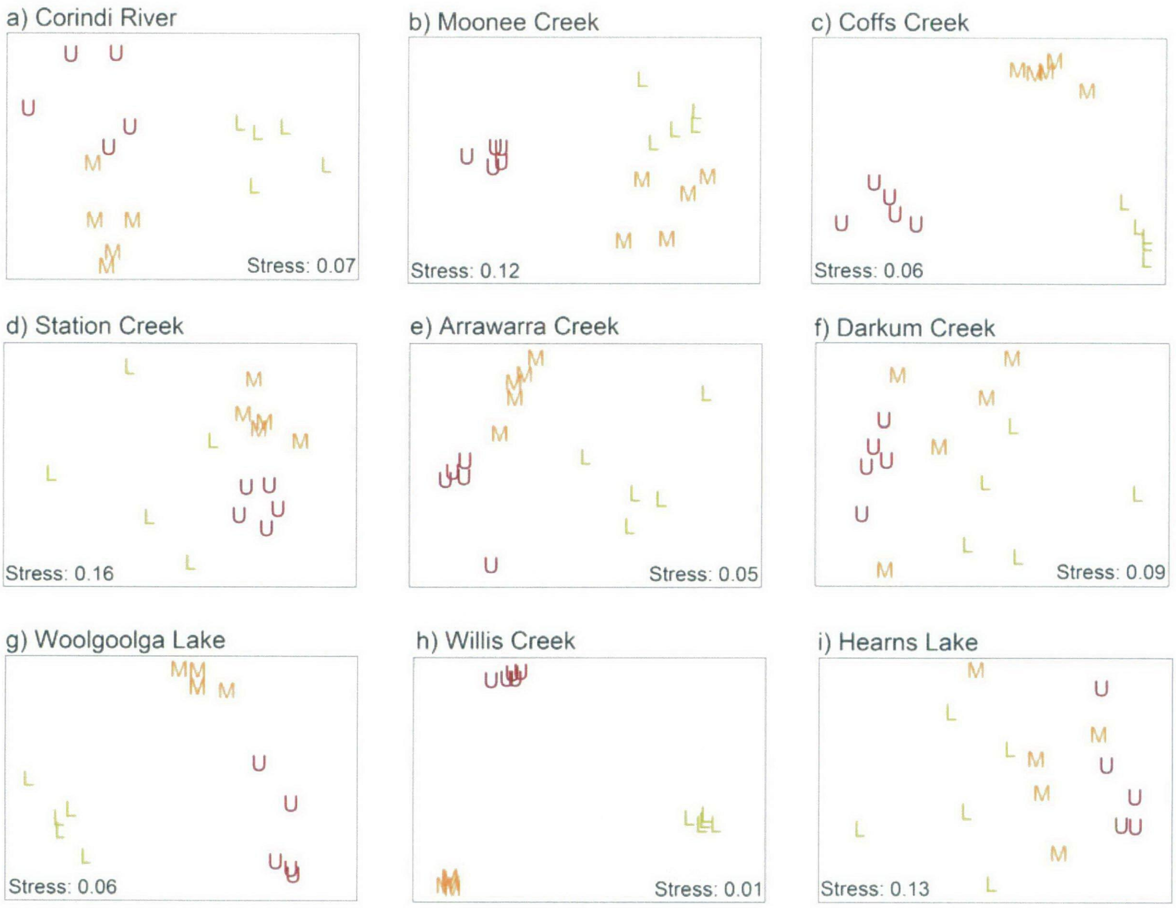
Table 3.3.2.1 Summary of one-way analysis-of-similarity (ANOSIM) results testing for differences between the communities of the upper, middle and lower sites of each estuary in January 2003. All pairwise comparisons between sites were significantly different ($p = 0.008$), except where stated otherwise.

Estuary	Global *R*	*p*	Pairwise comparisons – summary of non-significant results
Corindi	0.521	0.001	upper *vs* middle: $p = 0.079$
Moonee	0.980	0.001	-
Coffs	0.998	0.001	-
Station	0.496	0.001	upper *vs* middle: $p = 0.183$
Arrawarra	0.765	0.001	-
Darkum	0.521	0.002	upper *vs* middle: $p = 0.413$
Woolgoolga	0.756	0.001	-
Willis	0.444	0.001	-
Hearns	0.668	0.001	upper *vs* middle: $p = 0.087$

Table 3.3.2.2 Multivariate dispersion indices (IMD) from the MVDISP analyses of the dispersion within the (1) upper, (2) middle and (3) lower sites of each estuary, as well as for all pairwise comparisons of the relative dispersion between sites. All estuary entrances were open in March 2003 and October 2004, whilst six were closed in January 2003 and five were closed in July 2004.

	COR	MOO	COF	STA	ARR	DAR	WOO	WIL	HEA
January 2003									
Upper (1)	0.958	0.535	0.677	0.729	0.381	0.548	0.665	0.768	0.574
Middle (2)	0.987	0.974	0.710	0.819	1.071	1.135	0.806	1.000	1.161
Lower (3)	1.055	1.490	1.613	1.452	1.548	1.316	1.529	1.232	1.265
1, 2	-0.04	-0.90	-1.00	-0.12	1.00	-0.26	0.80	0.46	-0.92
1, 3	-0.09	-0.54	0.00	-0.72	0.70	0.68	0.84	0.26	-0.40
2, 3	-0.08	0.62	0.90	-0.68	-0.92	0.72	-0.24	-0.26	-0.10
March 2003									
Upper (1)	0.813	0.523	0.497	0.626	0.748	0.477	0.426	0.839	0.845
Middle (2)	0.816	1.194	1.090	1.168	0.981	0.968	1.277	0.968	1.032
Lower (3)	1.371	1.284	1.413	1.206	1.271	1.555	1.297	1.194	1.123
1, 2	-0.62	-0.68	-0.72	-0.62	0.54	-1.00	0.02	-0.18	0.28
1, 3	0.04	-0.08	-0.84	-0.54	0.30	-0.62	0.84	-0.32	0.10
2, 3	0.53	0.20	-0.44	0.02	-0.24	0.72	0.94	-0.28	-0.20
July 2004									
Upper (1)	0.761	0.406	0.477	0.665	0.703	0.426	0.626	0.665	0.600
Middle (2)	0.839	1.284	1.168	0.806	0.884	1.181	1.161	1.142	0.981
Lower (3)	1.400	1.310	1.355	1.529	1.413	1.394	1.213	1.194	1.419
1, 2	0.58	-0.96	0.20	0.20	-0.28	-0.94	0.52	0.52	-0.44
1, 3	0.66	-0.88	0.90	-0.8	-0.64	-0.84	-0.02	0.08	-0.80
2, 3	0.08	0.00	0.72	-0.84	-0.64	0.28	-0.64	-0.52	-0.50
October 2004									
Upper (1)	0.490	0.768	0.455	0.948	0.458	0.916	0.800	0.981	0.587
Middle (2)	0.865	1.097	0.955	0.974	0.974	0.987	0.897	1.000	1.045
Lower (3)	1.645	1.135	1.600	1.077	1.568	1.097	1.303	1.019	1.368
1, 2	1.00	-0.42	-0.86	0.10	-0.68	0.06	0.46	0.06	-0.84
1, 3	1.00	-0.30	0.72	0.14	-1.00	-0.10	0.48	-0.06	-0.44
2, 3	0.58	0.00	1.00	-0.06	-0.76	-0.20	0.14	0.00	0.30

All estuary entrances were open in both March 2003 and October 2004 and, on both occasions few estuaries displayed any overlap between sites in the nMDS ordinations (Figs. 3.3.2.3, 3.3.2.4). Highly significant differences between sites were again present in all estuaries at these times ($p = \leq 0.002$) (Tables 3.3.2.4, 3.3.2.5), though there were differences in the pairwise comparisons between specific sites. In October 2004 all pairwise comparisons were significantly different for all estuaries ($p = 0.008$), similar to the previous results for July 2004. In March 2003, however, there was no significant difference between the middle and lower sites of both Corindi River and Station Creek ($p = 0.063$; 0.175, respectively) (Table 3.3.2.4).



a) Corindi River

b) Moonee Creek

c) Coffs Creek

d) Station Creek

e) Arrawarra Creek

f) Darkum Creek

g) Woolgoolga Lake

h) Willis Creek

i) Hearns Lake

Fig. 3.3.2.2 Two-dimensional nMDS ordinations of benthic assemblages at each of the upper (U), middle (M) and lower (L) sites of each estuary in July 2004, a time when most intermittent estuaries (e – i) were closed.

Table 3.3.2.3 Summary of one-way analysis-of-similarity (ANOSIM) results testing for differences between the communities of the upper, middle and lower sites of each estuary in July 2004. All pairwise comparisons between sites were significantly different ($p = 0.008$), except where stated otherwise.

Estuary	Global *R*	*p*	Pairwise comparisons – summary of non-significant results
Corindi	0.896	0.001	-
Moonee	0.907	0.001	-
Coffs	0.996	0.001	-
Station	0.499	0.001	-
Arrawarra	0.879	0.001	-
Darkum	0.462	0.001	-
Woolgoolga	0.976	0.001	-
Willis	1.000	0.001	-
Hearns	0.475	0.002	-

Also in March 2003, the upper and middle sites of Willis Creek were not significantly different ($p = 0.103$). Returning to the nMDS ordinations, an excellent example of a community gradient between the upper, middle and lower sites was at Moonee Creek in October 2004 (Fig. 3.3.2.4) and clear gradients were also present at Coffs Creek and Woolgoolga Lake in March 2003 (Fig. 3.3.2.3), as well as at Station and Arrawarra creeks in October 2004 (Fig. 3.3.2.4).

On each sampling occasion, the species contributing the most to differences between sites tended to be consistent through time and are summarised accordingly (Table 3.3.2.6). These species and the sites at which they were most abundant did, however, vary between estuaries. For example, *Mysella vitrea* was considered to be one of the species primarily responsible for the community differences between sites in four estuaries, though the site at which it was most abundant was different in each of these, with the greatest average abundances at the lower site in both Arrawarra and Darkum creeks, the middle site in Coffs Creek and at the upper site of Moonee Creek. Likewise, *Scoloplos normalis* was important in differentiating between sites in four estuaries, Coffs, Darkum, Moonee and Arrawarra creeks, and the sites where it was most abundant were also variable between estuaries, being most abundant in the upper site of the former two and in the middle site of the latter two (Table 3.3.2.6).

Other species were more consistent, contributing to site differences by always being more abundant in one particular site. *Urohaustorius metungi*, for example, was one of the species primarily responsible for the differences between sites in each of the permanently open estuaries and this was always due to greater average abundances at their lower sites. Similarly, *A. helmsi* contributed greatly to site differences in Moonee, Arrawarra and Darkum creeks, as well as in Hearns Lake, due to higher average abundances in the upper sites (Table 3.3.2.6). In addition, the contribution of many other key species to community differences between sites was estuary specific, with a further 11 species highlighted as being primarily responsible for site differences in only one or two estuaries in the SIMPER analyses.

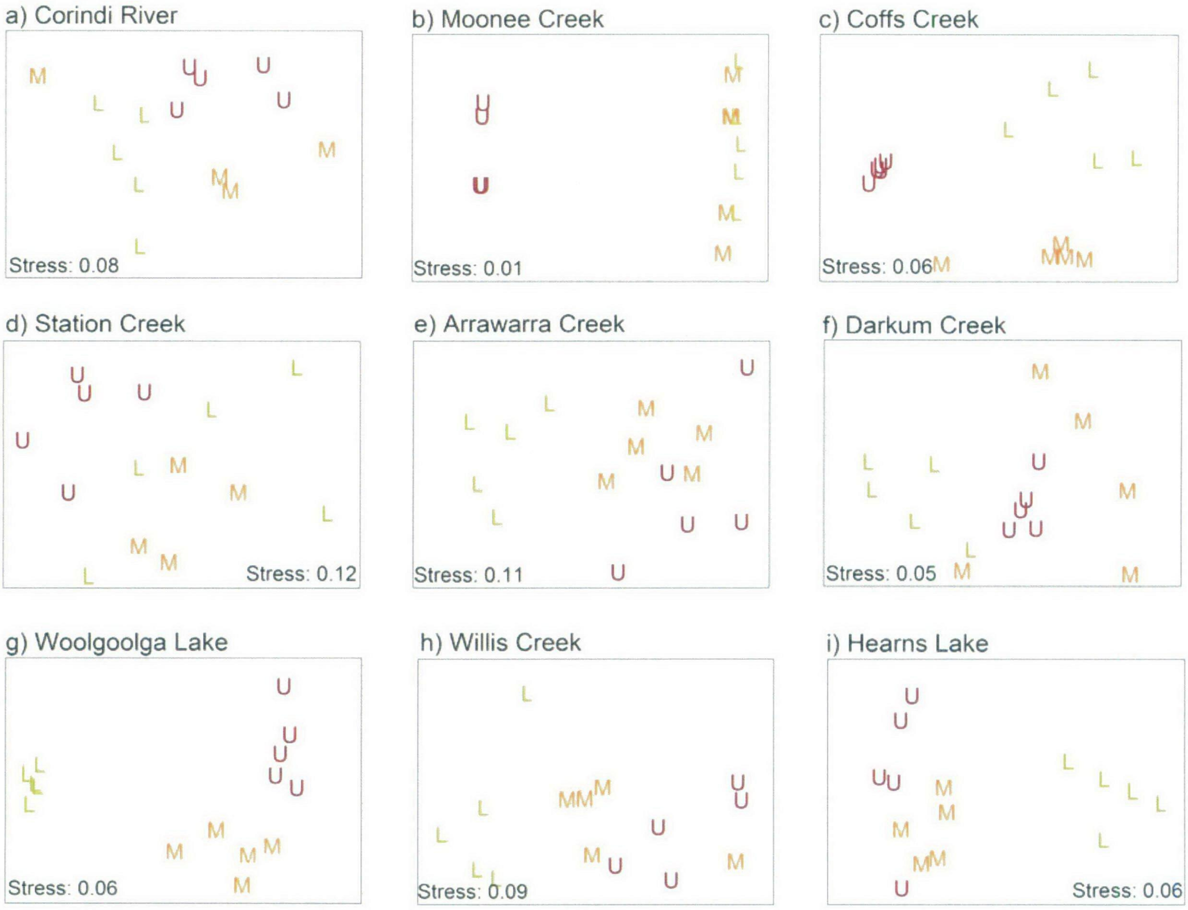


Fig. 3.3.2.3 Two-dimensional nMDS ordinations of benthic assemblages at each of the upper (U), middle (M) and lower (L) sites of each estuary in March 2003, a time when all intermittent estuaries (d – i) were open.

Table 3.3.2.4 Summary of one-way analysis-of-similarity (ANOSIM) results testing for differences between the communities of the upper, middle and lower sites of each estuary in March 2003. All pairwise comparisons between sites were significantly different ($p = 0.008$), except where stated otherwise.

Estuary	Global *R*	*p*	Pairwise comparisons – summary of non-significant results
Corindi	0.450	0.002	middle *vs* lower: $p = 0.063$
Moonee	0.837	0.001	-
Coffs	0.932	0.001	-
Station	0.456	0.002	middle *vs* lower: $p = 0.175$
Arrawarra	0.745	0.001	-
Darkum	0.488	0.001	-
Woolgoolga	0.971	0.001	-
Willis	0.451	0.001	Upper *vs* middle: $p = 0.103$
Hearns	0.884	0.001	-

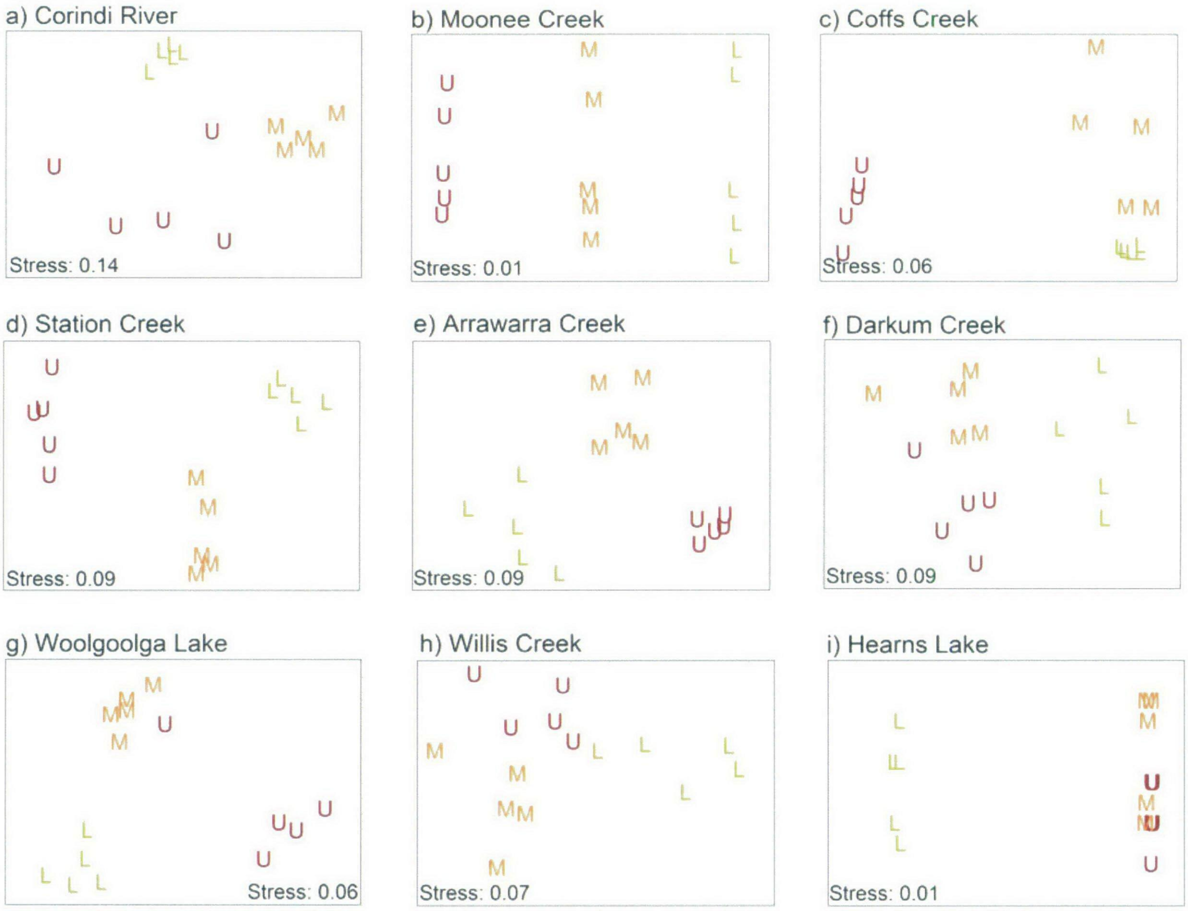


Fig. 3.3.2.4 Two-dimensional nMDS ordinations of benthic assemblages at each of the upper (U), middle (M) and lower (L) sites of each estuary in October 2004, a time when all intermittent estuaries (d – i) were open.

Table 3.3.2.5 Summary of one-way analysis-of-similarity (ANOSIM) results testing for differences between the communities of the upper, middle and lower sites of each estuary in October 2004. All pairwise comparisons between sites were significantly different (p = 0.008), except where stated otherwise.

Estuary	Global *R*	*p*	Pairwise comparisons – summary of non-significant results
Corindi	0.771	0.001	-
Moonee	1.000	0.001	-
Coffs	0.875	0.001	-
Station	0.998	0.001	-
Arrawarra	0.973	0.001	-
Darkum	0.782	0.001	-
Woolgoolga	0.871	0.001	-
Willis	0.745	0.001	-
Hearns	0.910	0.001	-

Table 3.3.2.6 Summary of SIMPER results for comparisons between sites in each estuary. The primary species contributing to the dissimilarity between sites are listed for each pairwise comparison and the site (U = upper, M = middle, L = lower) at which they were most abundant is also given.

Site comparisons	Dissimilarity (%)				Species contributing the most to dissimilarities between sites
	Jan ‘03	Jul ‘04	Mar ‘03	Oct ‘04	
Corindi					
Upper *vs* Middle	73.49	75.08	93.55	83.84	*T. australiensis* (M)
Middle *vs* Lower	81.28	**94.91**	**93.02**	**82.32**	*T. australiensis* (M); *U. metungi* (L)
Upper *vs* Lower	**86.40**	91.37	88.58	79.42	*U. metungi* (L)
Moonee					
Upper *vs* Middle	75.95	86.94	74.17	65.48	*A. helmsi*, *M. vitrea* (U)
Middle *vs* Lower	66.52	68.32	40.38	60.31	*M. vitrea*, *S. normalis* (M); *U. metungi* (L)
Upper *vs* Lower	**91.06**	**87.11**	**85.80**	**100.00**	*A. helmsi*, *M. vitrea* (U); *U. metungi* (L)
Coffs					
Upper *vs* Middle	75.67	85.59	92.57	87.25	*S. normalis*, *V. australiensis* (U); *M. vitrea* (M)
Middle *vs* Lower	80.45	82.56	86.13	58.59	*U. metungi* (L)
Upper *vs* Lower	**99.07**	**94.53**	**93.06**	**87.32**	*L. triangularis*, *T. imbellis* (U); *U. metungi* (L)
Station					
Upper *vs* Middle	49.01	55.26	75.10	63.71	*C. coralium* (U)
Middle *vs* Lower	68.73	**65.59**	74.48	55.24	*S. trigonella*, *A. intermedia* (M)
Upper *vs* Lower	**77.45**	63.75	**77.97**	**79.25**	*A. intermedia*, *C. coralium* (U)
Arrawarra					
Upper *vs* Middle	68.39	50.19	64.07	57.62	*Phoronis* sp.2, *S. normalis* (M); *A. helmsi* (U)
Middle *vs* Lower	61.79	65.78	81.14	61.10	*Phoronis* sp.2, *A. intermedia*, *O. cirriformia* (M)
Upper *vs* Lower	**75.15**	**76.00**	**88.13**	**68.12**	*A. helmsi*, *A. intermedia* (U); *M. vitrea*, *S. normalis* (L)
Darkum					
Upper *vs* Middle	65.98	44.74	79.68	32.41	*S. normalis* (U)
Middle *vs* Lower	80.72	51.16	**93.60**	**47.65**	*M. vitrea*, *S. alba*, *S. normalis* (L); *A. helmsi* (M)
Upper *vs* Lower	**88.91**	**59.00**	84.44	46.04	*S. normalis*, *A. helmsi* (U); *S. alba* (L)
Woolgoolga					
Upper *vs* Middle	65.67	70.66	60.18	72.87	*O. cirriformia* (U); *C. coralium*, *B. australis* (M)
Middle *vs* Lower	89.41	73.42	79.06	63.52	*C. coralium*, *B. australis*, *A. intermedia* (M)
Upper *vs* Lower	**91.94**	**89.83**	**92.52**	**84.03**	*O. cirriformia*, *C. coralium* (U)
Willis					
Upper *vs* Middle	27.93	36.06	44.41	34.10	*N. estuarius* (M)
Middle *vs* Lower	**77.40**	**67.15**	58.78	**49.89**	*N. estuarius*, *O. cirriformia* (M)
Upper *vs* Lower	76.58	53.45	**74.71**	41.79	*N. estuarius*, *O. cirriformia* (U)
Hearns					
Upper *vs* Middle	27.93	54.98	43.79	39.36	*A. helmsi*, *S. aequisetis* (U)
Middle *vs* Lower	**77.40**	61.15	73.58	70.13	*O. cirriformia*, *N. estuarius*. *A. helmsi* (M)
Upper *vs* Lower	76.58	**76.98**	**80.78**	**77.91**	*S. aequisetis*, *A. helmsi*, *N. estuarius* (U)

Another interesting result of the SIMPER analyses is evident in the dissimilarity values for pairwise comparisons between the sites in each estuary (Table 3.3.2.6). If the community relationship between sites showed a single monotone gradient along the length an estuary, then it would be expected that the greatest dissimilarity values would be for comparisons between the upper and lower sites. However, this was only the case for all sampling occasions in four estuaries, Moonee, Arrawarra, Darkum and Coffs creeks (Table 3.3.2.6). Hence, there were exceptions to this expectation in the remaining five estuaries. For all but one of these exceptions, the greatest dissimilarity resulted when comparing the middle and lower sites. This occurred once in Station Creek and Hearns Lake, twice in both Darkum Creek and Corindi River and, for three of the four sampling occasions, in Willis Creek. There was also one occasion, March 2003, in Corindi River when the greatest dissimilarity was between the upper and middle sites (Table 3.3.2.6). The timing of these ten examples, when a continual gradient along the full length of an estuary was lacking, was not related to entrance closure, as half occurred at times when all estuary entrances were open and three occurred in the permanently open Corindi River. This left only three that occurred in estuaries that were closed, these being Willis Creek in both January 2003 and July 2004, as well as Hearns Lake in January 2003.

3.3.3 Salinity comparisons along the length of each estuary

Salinity was typically highly variable along the length of each estuary and, in the intermittent estuaries, did not display any consistent trends between open and closed entrance states (Fig. 3.3.3.1). There were only three non-significant differences ($p < 0.05$) between sites in all estuaries on all occasions, including Coffs and Station creeks in January 2003 and Arrawarra Creek in July 2004 ($p = 0.326$; 0.124; 0.337, respectively). In these instances there were no significant pairwise differences between any sites (Table 3.3.3.1).

However, salinity differences along the length of each estuary were not necessarily always a continuous gradient between the upper and lower sites (Fig 3.3.3.1). In most estuaries, particularly during January and March 2003, there were no significant differences between at least two sites. These were usually between either the upper and middle or middle and lower sites, and even occurred in the permanently open Corindi River and Coffs and Moonee creeks (Table 3.3.3.1). Other atypical patterns included the reverse salinity gradients that were evident at Station and Arrawarra creeks in January 2003, Willis Creek in March 2003 and at Darkum Creek in October 2004. In these instances the mean salinity was greatest at the upper site and lowest at the lower site of each estuary.

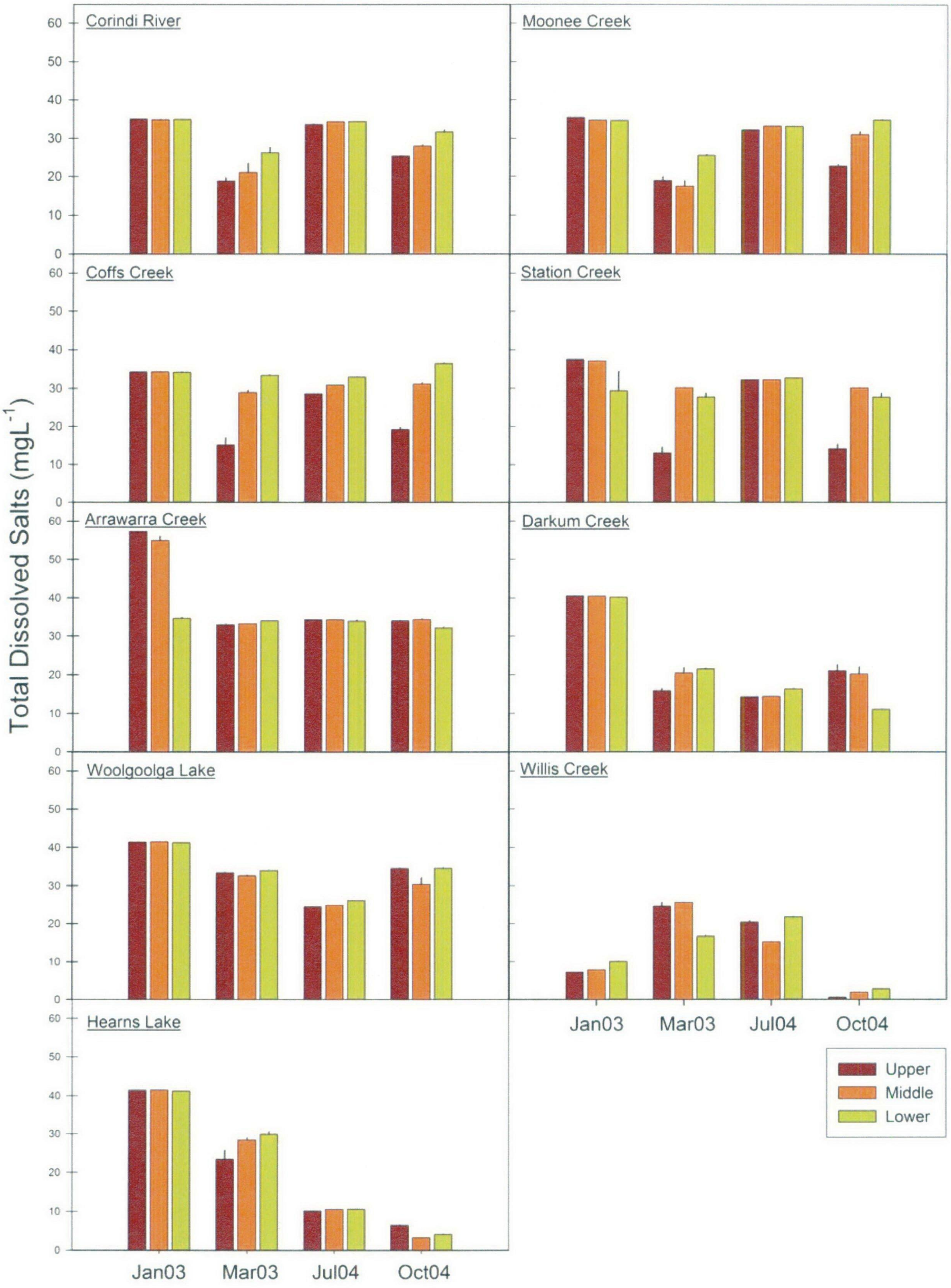


Fig. 3.3.3.1 Total dissolved salts (mean ± SE) at the upper, middle and lower sites of each estuary during the January 2003, March 2003, July 2004 and October 2004 sampling times.

Table 3.3.3.1 One-way analyses-of-variance results testing for differences in salinity (total dissolved salts) between the upper, middle and lower sites of each estuary. Bold font indicates significant p-values. Also provided are the results for non-significant pairwise comparisons between sites (U = upper, M = middle, L = lower). All other pairwise comparisons were significant ($p < 0.05$).

	January 2003		March 2003		July 2004		October 2004	
	p		p		p		p	
Corindi	**0.039**	L = U, M	**0.025**	M = U, L	**0.000**	M = L	**0.000**	-
Moonee	**0.000**	M = L	**0.000**	U = M	**0.000**	M = L	**0.000**	-
Coffs	0.326	U = M = L	**0.000**	-	**0.000**	-	**0.000**	-
Station	0.124	U = M = L	**0.000**	M = L	**0.000**	U = M	**0.000**	M = L
Arrawarra	**0.000**	U = M	**0.000**	U = M	0.337	U = M = L	**0.000**	U = M
Darkum	**0.000**	U = M	**0.002**	M = L	**0.000**	U = M	**0.001**	U = M
Woolgoolga	**0.001**	U = M	**0.001**	U = L	**0.000**	-	**0.023**	U = L
Willis	**0.000**	-	**0.000**	U = M	**0.000**	-	**0.000**	-
Hearns	**0.001**	U = M	**0.021**	M = U, L	**0.000**	-	**0.000**	-

3.4 Discussion

3.4.1 Benthic macrofauna of the Solitary Islands Marine Park estuaries

Species richness and the dominant faunal groups in the benthic communities of the SIMP estuaries were comparable to those of other estuaries in NSW. The number of species collected from a single estuary at any one time was generally in the range of 20 – 40, although Willis Creek, Darkum Creek and Hearns Lake often contained notably fewer. Although it is difficult to make comparisons with other studies due to the variation in sampling effort, similar numbers of species have been observed in both intermittently closed and permanently open estuaries in south-east Australia (Platell & Potter 1996; Edgar et al. 1999; Moverley & Hirst 1999; Hirst 2004). In contrast, Jones (1987) collected 177 species in benthic samples from the Hawkesbury River but, being the second largest estuary in NSW, its massive area would have increased the probability of a greater number of resident species. In the current study a total of 130 species were collected from the nine estuaries. Other studies of multiple estuaries in south-east Australia (Moverley 2000; Hirst 2004) have observed a greater total number of species, 260 and 275 respectively, however, both of these also surveyed more than three times as many estuaries. There was also some commonality in species composition between the SIMP estuaries and those of other NSW regions. At least 9 species from the Hawkesbury River (Jones 1987) and 10 from south coast estuaries (Hirst 2004) were present in the SIMP.

As in most soft-sediment environments worldwide, the dominant faunal groups collected in this study were the molluscs, polychaetes, and crustaceans. The proportions each contributed to the total number of species was quite evenly spread among the three groups, representing 28, 27 and 25 % of the total number of species, respectively. However, their relative proportions to one another, and to the total species, did vary somewhat to that reported in the larger south-east Australian studies of estuarine benthos. As in the current study, both Jones (1987) and Moverley (2000) found molluscs, polychaetes, and crustaceans to be the dominant faunal groups. However, both reported that polychaetes were the most diverse, representing 44 and 33 % of the total species number, respectively. In comparison, the molluscs only ranked second in Jones (1987) and third, at 18 % of the total number of species, in Moverley (2000). In the latter, this was almost half the number of polychaetes and crustaceans.

Focusing on abundances, the polychaetes dominated in at least half, but not all, of the SIMP estuaries. In Moonee Creek, for example, the majority of total abundances was comprised of molluscs, with up to 1600 collected from 15 samples at any one time. Three of the four common species that were present in all estuaries were also polychaetes, as were another three that were present in all estuaries other than Willis Creek. In comparison, the molluscs contributed one of the common species present in all estuaries and five of those present in all but Willis Creek. Willis Creek was also unique in that no crustaceans were present on more than half of the sampling occasions. The presence of crustaceans in this estuary is most likely affected by a combination of factors, including: (1) reduced salinities along the full length of the estuary due to high levels of freshwater inputs through a sewage and stormwater outfall; (2) increased occurrences of anoxia and hypoxia, also a result of treated sewage inputs; and (3) a high frequency of entrance closures, which limit marine exchange and the opportunities for external recruitment.

Already, these descriptive comparisons have highlighted differences in community structure between different estuaries. This variation between individual estuaries will be explored further in later chapters.

3.4.2 Comparisons along the length of each estuary

There were significant differences in assemblages between sites in all estuaries on all occasions, including those when intermittent estuaries were closed. However, the relationship between specific sites in some estuaries appeared to be highly variable. For example, both the permanently open Corindi River and intermittently closed Station Creek repeatedly presented similarities between sites at some times, and significant differences at other times. Therefore, the within-estuary community trends can be inconsistent over time. Interestingly, the sites that were similar changed through time and these changes were paralleled in the two estuaries. These variable results appear to reflect the range reported in the literature. For example, Schlacher and Wooldridge (1996a) found significant differences between sites along a longitudinal estuary axis to be characterised by distinct macrofaunal assemblages. These communities were limited by salinity at the upper and lower reaches, whilst sedimentary characteristics were more important in determining faunal distributions at the middle sites. In contrast, in a study of 28 estuaries, Hirst (2004) generally found few significant community differences along the lengths of estuaries, with only weak clustering between sites. In this instance, spatial differences were at a larger scale and closely associated with broad geographical patterns.

Patterns of assemblage structure along the length of each estuary seldom showed a simple gradient. When similarities did occur between either the upper and middle or middle and lower sites, as mentioned above for Station Creek and Corindi River, it meant that community gradients were weakened along the estuary length. Similar patterns were also observed in Darkum Creek, Hearns Lake and Willis Creek. These episodes were not necessarily related to entrance closure as more than half occurred in open estuaries. However, when similarities between sites did occur, the salinities in each estuary were either uniform between sites or there was a reverse salinity gradient, which suggests a connection between weakened biological and physico-chemical gradients.

Whilst a continual community gradient was always present in the Moonee, Coffs, and Arrawarra creeks, there were exceptions in the remaining estuaries. At such times, even when there were significant differences between all sites, the greatest dissimilarity was not between the upper and lower sites, as would be expected if a continuous biological gradient existed along the estuary length. Instead, on these occasions, the greatest dissimilarity was usually between the middle and lower sites. This trend was, again, not necessarily an effect of entrance closure and limited marine input as, in addition to closed estuaries, it was also observed in the permanently open Corindi River and in Willis Creek when it was connected to the sea. The instances when the greatest dissimilarity was between the middle and lower sites suggest that factors other than salinity are responsible for this rapid transition in community structure. One likely explanation is provided by Teske and Wooldridge (2003) who suggest that, in many estuaries, salinity is of minimal importance in determining faunal distributions. They propose that community structure is often more closely associated with sediment grain size and organic content, which change abruptly between the sandy lower reaches and central mud basis. In addition, many estuarine fauna, especially those in intermittently closed estuaries are tolerant to fluctuating salinities and are, therefore, more sensitive to other factors, including sediment properties (Teske & Wooldridge 2004).

It is necessary to focus on the episodic occurrence of reverse salinity gradients observed in some estuaries. When estuaries are closed, it is likely that they do not have the marked longitudinal salinity gradient typically associated with estuaries, through the tidal mixing of marine and fresh waters (Moverley & Hirst 1999). In Australia, this phenomenon has been observed by Platell and Potter (1996), Moverley and Hirst (1999), Moverley (2000) and is related to estuarine morphology. For example, when closed, estuaries are systems that can function in a similar way to lakes (Webster & Harris 2004). Wind becomes the predominant means of mixing and narrow estuaries are more likely to be poorly mixed (Haines 2004). If a closed, narrow estuary develops a halocline, fresher surface waters will overlie a submerged brackish layer. Subsequently, a layer of low salinity water will extend to the entrance so that a shallow site in the lower reaches of an estuary will have a lower bottom salinity than that of a deeper site further upstream (Moverley & Hirst 1999). This salinity model is relevant to understanding the structure and function of estuaries in the region and is also significant in the recognition that, in terms of physico-chemical and hydrological parameters, not all estuaries behave as those typically described in the more traditional and widely utilised models.

In summary, this study achieved its aims of (1) presenting a descriptive overview of the fauna that inhabit each estuary; and (2) quantitatively assessing assemblage differences between the upper, middle and lower sites of each estuary. However, causative explanations for the patterns detected require further investigation. The initial hypothesis, that there would be differences in community structure between the sites in each estuary, was supported but the relationship between specific sites was inconsistent over time in some estuaries. This variation over time was not related to entrance closure. Hence, the prediction that longitudinal site differences would be reduced in closed estuaries due to the effects of entrance closure on physicochemical gradients, such as salinity, was partially rejected. This was because, although this trend was observed in closed estuaries, similar community patterns also occurred in a permanently open estuary, as well as in an open intermittent estuary. To explain the inconsistent with-in estuary patterns observed here, future studies need to incorporate a closer examination of the longitudinal variation in a wider number of environmental variables, especially sedimentary parameters, so that the biological and environmental variables can be comprehensively correlated.

CHAPTER 4

SPATIAL VARIATION IN THE BENTHIC COMMUNITIES OF INTERMITTENTLY CLOSED AND PERMANENTLY OPEN ESTUARIES

4.1 Introduction

Despite the fact that intermittently closed estuaries comprise over 90% of estuaries in New South Wales (Williams et al. 1998), very little is known about their ecology. As these systems generally have small catchments and highly variable physical and chemical conditions, it might be expected that their ecology would differ from that of permanently open estuaries. However, this has only recently been recognized in terms of different estuary-by-estuary management approaches (Edgar et al. 2000; HRCNSW 2002).

Intermittent estuaries can undergo dramatic changes in physico-chemical parameters, particularly water volume and salinity, over short time periods due to their dynamic and variable connection with the sea (Pollard 1994b). Most biological impacts of entrance closure are thought to be a result of changes in the physical and chemical environment, though the timing of entrance closure can also interrupt recruitment and reproductive processes (Griffiths 2001; Young & Potter 2002). Closure from the sea for extended periods limits the flushing of an estuary and its capacity to eliminate potential pollutants (Whitfield 1992), which may lead to a number of issues such as nutrient enrichment and eutrophication, of which algal blooms and fish kills can be indicators. The reduced opportunities for flushing potentially exacerbates the susceptibility of these estuaries to a range of anthropogenic impacts; for this reason, amongst others, intermittent estuaries are receiving increased attention. However, data on the infauna of their sedimentary habitats remain scant.

An opportunity to examine the intermittent estuaries of the Solitary Islands Marine Park (SIMP) and the composition of their infaunal communities during a particular climate extreme, presented itself with a drought that began in July 2002. This study was conducted at the height of the drought in January 2003, by which time up to 90% of New South Wales had been declared drought-affected, with many regions experiencing the lowest rainfalls on record. The entrances of the six intermittent estuaries examined herein, closed off from the ocean and remained closed for periods varying from five to eight months. Although the estuaries are prone to closure, anecdotal evidence suggests that most usually close for a maximum of one or two months.

The subtidal benthic macrofauna were the primary focus of this study as intertidal habitats are non-existent during times of closure in intermittent estuaries. Long-term studies have also demonstrated the value of benthic macroinvertebrates as indicators of water quality, particularly in intermittent estuaries where dramatic salinity shifts can occur following the processes of entrance closure and breakout (Barton 1989; Mackay & Cyrus 2001). Additionally, the macrobenthos integrates environmental influences at a particular place over a relatively long time span and constitutes a substantial component of estuarine ecosystems (Herman et al. 1999).

The primary objective of this study was to provide a quantitative description of the spatial variation in benthic infaunal communities at the scale of estuary type in order to determine whether or not intermittently closed estuaries, as a class, supported different infaunal assemblages to adjacent, permanently open estuaries. Being that the intermittent estuaries were experiencing extended closure, it was predicted that now would be the time that any community differences between the two estuary types would most likely be detected. As a number of estuaries of each type were sampled, the study also provided the opportunity to determine the variation among estuaries of the same type.

4.2 Methods

4.2.1 Study Location

The SIMP (30°08'S 153°08'E) is the largest marine protected area in New South Wales, and includes all estuarine systems to their upper tidal limits and to mean high water mark. Intermittent estuaries comprise 10 of the 15 main estuaries in the SIMP and range in catchment size from 3.3 to 25.0 km2. These catchments are subject to various levels of modification for agriculture, and residential and urban development. The degree of development within the catchments of the intermittent estuaries ranges from negligible at Station Creek, to extensive urbanisation surrounding Woolgoolga Lake (Table 4.1). Beyond these, the most notable long-term anthropogenic influence is a sewage treatment plant situated near Willis Creek, which has only recently been decommissioned and had previously discharged tertiary treated sewage effluent directly into the creek.

Table 4.1 Summary of the key characteristics of each of the estuaries surveyed during the study. Data on catchment size courtesy of Coffs Harbour City Council.

Estuary	Entrance type	Catchment size (km^2)	Main human influences
Station Creek	Intermittent	24.0	Most pristine, no urbanisation
Corindi River	Open	148.0	Minimal urbanisation
Arrawarra Creek	Intermittent	20.0	Minimal urbanisation
Darkum Creek	Intermittent	7.0	Minimal urbanisation, some agriculture
Woolgoolga Lake	Intermittent	25.0	Considerable urbanisation (pop. ~ 4000), agricultural land clearing and soil erosion
Willis Creek	Intermittent	3.3	High level impacts from sewage treatment plant
Hearns Lake	Intermittent	9.0	Minimal urbanisation some agriculture
Moonee Creek	Open	39.5	Minimal urbanisation, some land clearing for agriculture and urban growth
Coffs Creek	Open	25.0	Highly urbanised – pop. ~ 60 000, industrial and agricultural activities also present

4.2.2 Sampling Procedure

All sampling was conducted in the last two weeks of January 2003 and, as intermittently closed estuaries are more common than permanently open estuaries in the study area, more closed estuaries were surveyed than open estuaries. Thus, using a nested design, six intermittent and three permanently open estuaries were sampled (Table 4.1). The intermittent estuaries, all of which had been closed for at least 5 months at the commencement of the study, were Station, Darkum, Arrawarra and Willis creeks, and Woolgoolga and Hearns lakes (Fig. 2.1). The permanently open estuaries were Corindi River and Moonee and Coffs creeks (Fig. 2.1). Three sites were established along the length of each estuary, one in each of the lower, middle and upper reaches (refer Chapter 2). Previous studies (Sawtell 2002) have indicated that infaunal communities are distinct in each of these parts of local estuaries. Sites measured approximately 10 x 10 m and were situated in the middle of the main estuary channel. Surrounding vegetation and relative distance along the estuary were taken into consideration when establishing these sites in order to facilitate valid comparisons between equivalent estuary regions.

4.2.2.1 Macrofauna Methods

Five macrofaunal samples were collected from each of the upper, middle and lower sites in each estuary. A pilot study had determined that this number of replicate samples would be necessary for acceptable precision (i.e. ratio of the standard error : mean ≤ 0.2) for measures of species richness and total number of individuals at all sites. The positions of the samples within each site were haphazard rather than random due to the restrictions imposed by using a remote sampling device and manoeuvring a vessel in a relatively small area. Samples were collected, from only non-vegetated substrates, using a 0.068 m2 van Veen grab and immediately sieved using a pump-operated hose that was designed to enable the manageable removal of sediments whilst aboard a small vessel. The sieve had a mesh size of 1 mm and the fauna retained were washed into a mesh bag (approx. 0.4 mm mesh size) then relaxed in a magnesium chloride solution. In the laboratory, the specimens were preserved in 10 % formalin before identification and enumeration.

4.2.2.2 Physico-chemical Variables

At each site a calibrated TPS 90-FLT multi-probe was used to measure the total dissolved salts (TDS), dissolved oxygen (DO), temperature and pH of the lower water column. A 50 ml sediment sample was also collected for analyses of organic content and physical sediment characteristics (graphic mean grain size and graphic standard deviation as a measure of sediment homogeneity). Sediment samples were oven-dried at 100°C for 24 hr and weighed prior to combustion at 550°C for 6 hr to calculate the organic content (percentage difference after combustion). To measure sediment grain size, samples were initially wet-sieved through a 63 μm mesh to extract the mud fraction, which was dried and weighed. The remaining sand fraction (> 63 μm) was then sieved through a stack of nested sieves to enable calculations of grain size and sediment homogeneity (Buchanan 1984).

4.2.3 Statistical Methods

Multivariate analyses of community structure were conducted using the PRIMER software package (Clarke & Gorley 2001). Analyses were conducted separately for data from the upper, middle and lower sites as assemblage structure was already known to differ at this scale (Sawtell 2002). Data were analysed to test the null hypotheses that: (1) there were no differences in community structure among estuaries nested within each estuary type; (2) there were no differences in community structure between the intermittent and permanently open estuaries. Data were square-root transformed prior to construction of a Bray-Curtis similarity matrix and two-dimensional ordinations of assemblages were subsequently created using non-metric multidimensional scaling (nMDS). The significance of differences in community structure across the scales of investigation was assessed using a series of one-way analyses of similarities (ANOSIM). Following Rule and Smith (2005) one-way analyses were conducted separately for each estuary type as two-way nested ANOSIMs were not found to be particularly powerful (i.e. nested ANOSIMs did not indicate a significant difference between types when nMDS ordinations clearly displayed a complete separation of data). The contribution of individual species to the differences observed was calculated using the similarity percentages (SIMPER) routine and the relative dispersion among samples was also computed using the MVDISP routine. The BIOENV procedure was used to explore correlations between the macrofaunal data and environmental variables. These environmental variables included those measured from the water column and sediments, as well as the catchment size for each estuary. It was necessary to include the catchment size in these tests for a number of reasons. Firstly, the size of a catchment ultimately influences the amount of runoff that is available to maintain the status of the entrance of an intermittent estuary. Secondly, catchment size is an approximate indicator of other physical attributes such as estuary length and water volume, and also provides an indication of the potential compounding effects of some anthropogenic influences.

Two-way nested analysis-of-variance (ANOVA) was used to evaluate differences in species richness (S), the total number of individuals (N), and the abundances of the most common species between estuary types and between the estuaries nested within each type. Analyses were also performed to compare the physico-chemical variables over the same factors. Where necessary, data were transformed prior to analysis to improve homoscedasticity. Because measurements of sediment variables were not replicated within each site (i.e. they were determined from a single sample), they could only be used in the multivariate, BIOENV analysis.

4.3 Results

A total of 10 510 individuals from 94 taxa were collected from the 135 samples collected during the study. Almost half of the taxa (46) were uncommon or rare. For example, both the serpulid polychaete *Galeolaria caespitosa* and the Sydney Rock Oyster, *Saccostrea glomerata*, which are usually associated with hard substrata, were recorded as singletons. In contrast, the bivalves *Mysella vitrea* and *Arthritica helmsi* commonly contributed 100s of individuals per sample.

4.3.1 Community Variation Among Intermittently Closed Estuaries

The nMDS ordination of the macrofaunal assemblages in the upper sites of the intermittent estuaries showed considerable separation between most estuaries at each of the upper, middle and lower sites (Fig. 4.1a-c). At the upper sites ANOSIM indicated an overall significant difference (Global $R = 0.739$, $p = 0.001$) between estuaries and pairwise comparisons returned significant differences ($p < 0.05$) between all combinations of estuaries (Table 4.2). Dissimilarity between estuaries in these upper sites was primarily due to differences in the abundance of the gastropods *Cerithium coralium*, *Batillaria australis* and *Ascorhis tasmanica*, the polychaetes *Notomastus estuarius* and *Simplisetia aequisetis*, and the bivalves *Arthritica helmsi* and *Spisula trigonella* (Table 4.3).

Samples from the middle sites showed highly significant differences between estuaries (Global R = 0.907, p = 0.001), with significant differences (p < 0.01) between all estuaries in the pairwise comparisons (Table 4.2). Overall, these differences were driven mainly by the differences in abundances of the polychaetes *Scoloplos normalis*, *N. estuarius* and *Armandia intermedia*, the gastropods *C. corallium* and *B. australis*, and the bivalve *S. trigonella* (Table 4.3).

Table 4.2 Summary of all sequential, one-way ANOSIMs testing for differences between estuary types and for differences between the estuaries nested within each type at each of the upper, middle and lower sites. Results of individual pairwise comparisons among the estuaries within each type are also given. 'ns' indicates a non-significant value ($p > 0.05$); all other tests were significant and are shown in bold font.

Comparison groups	Upper		Middle		Lower	
	R	p	R	p	R	p
Type						
Intermittent *vs* Permanent	**0.444**	0.001	**0.595**	0.001	**0.509**	0.001
Estuaries (Type)						
Intermittently closed	**0.739**	0.001	**0.907**	0.001	**0.891**	0.001
Permanently open	**0.799**	0.001	**0.876**	0.001	**0.621**	0.001
Intermittently closed						
Station - Arrawarra	**0.872**	0.008	**1.000**	0.008	**0.912**	0.008
Station - Darkum	**0.700**	0.008	**0.704**	0.008	**0.972**	0.008
Station - Woologoolga	**0.576**	0.008	**1.000**	0.008	**0.984**	0.008
Station - Willis	**1.000**	0.008	**1.000**	0.008	**1.000**	0.008
Station - Hearns	**1.000**	0.008	**1.000**	0.008	**1.000**	0.008
Arrawarra - Darkum	**0.528**	0.008	**0.740**	0.008	**0.976**	0.008
Arrawarra - Woolgoolga	**0.396**	0.024	**1.000**	0.008	**0.796**	0.008
Arrawarra - Willis	**0.928**	0.008	**1.000**	0.008	**1.000**	0.008
Arrawarra - Hearns	**0.432**	0.008	**1.000**	0.008	**0.992**	0.008
Darkum - Woolgoolga	**0.520**	0.016	**0.764**	0.008	**1.000**	0.008
Darkum - Willis	**0.964**	0.008	**0.772**	0.008	**1.000**	0.008
Darkum - Hearns	**0.804**	0.008	**0.724**	0.008	0.136 ns	0.151
Woolgoolga - Willis	**0.800**	0.008	**1.000**	0.008	**1.000**	0.008
Woolgoolga - Hearns	**0.552**	0.008	**1.000**	0.008	**1.000**	0.008
Willis - Hearns	**1.000**	0.008	**1.000**	0.008	**1.000**	0.008
Permanently open						
Corindi - Moonee	**0.820**	0.008	**0.916**	0.008	**0.996**	0.008
Corindi - Coffs	**0.816**	0.008	**0.864**	0.008	**0.924**	0.008
Moonee - Coffs	**1.000**	0.008	**0.992**	0.008	**0.360**	0.016

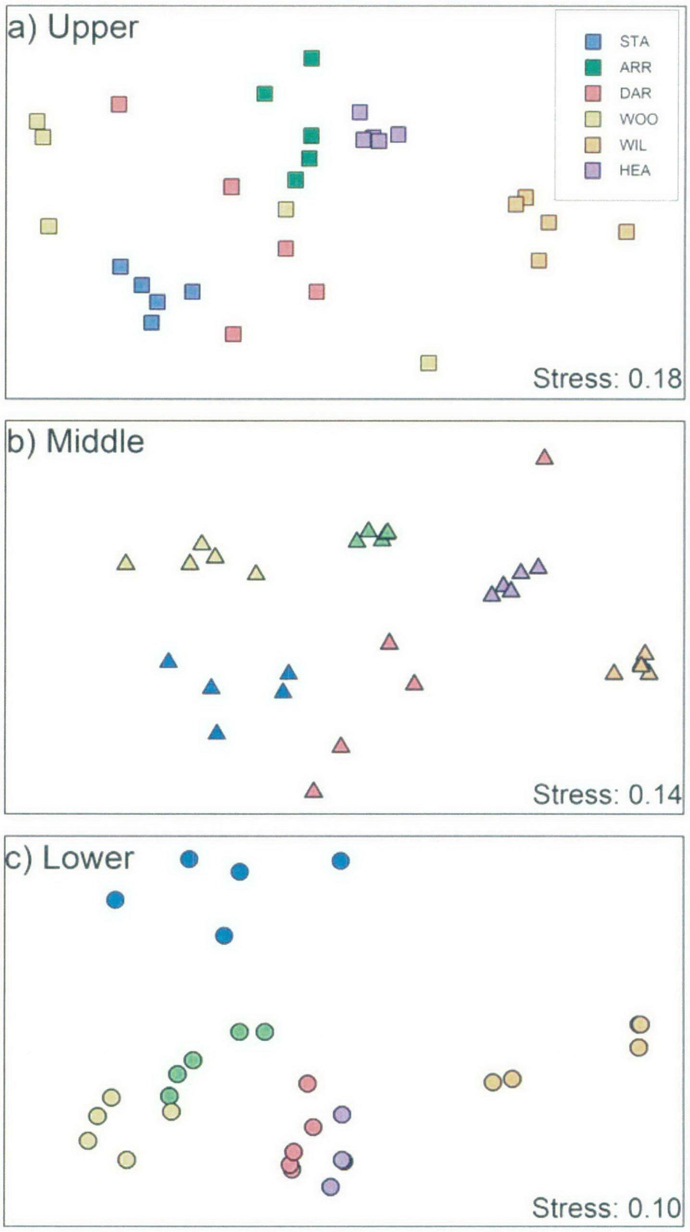


Fig. 4.1 Two-dimensional nMDS ordinations of patterns of community structure in the intermittent estuaries for: a) upper; b) middle; and c) lower sites. Whilst different shapes have been used to represent each site, a consistent colour scheme has been used to identify estuaries across all sites (i.e., blue squares, blue triangles and blue circles represent samples from the upper, middle and lower sites of Station Creek). Estuary names are abbreviated to their first three letters.

Table 4.3 Summary of SIMPER analyses for all sites in the intermittently closed estuaries. The three highest ranked species that contributed > 10 % to the average dissimilarity (given as a percentage) for each pairwise comparison are shown. Species shown in bold font were more abundant in the estuary with the bold font.

	Upper	Middle	Lower
Station, **Arrawarra**	80.22% ***Arthritica helmsi***	83.81% ***Scoloplos normalis*** **Sabellidae sp. 1** ***Phoronis* sp. 2**	81.01% ***Scoloplos normalis*** ***Mysella vitrea***
Station, **Darkum**	71.39% *Spisula trigonella* *Armandia intermedia* *Victoriopisa australiensis*	82.97% *Spisula trigonella* *Armandia intermedia*	92.95% Leptocheliidae sp. *Armandia intermedia* *Scoloplos normalis*
Arrawarra, **Darkum**	74.92% *Arthritica helmsi* *Notomastus estuarius*	84.76% *Scoloplos normalis* Sabellidae sp.1 *Phoronis* sp. 2	67.93% *Mysella vitrea* *Scoloplos normalis* *Armandia intermedia*
Station, **Woologoolga**	79.88% ***Cerithium coralium*** *Spisula trigonella* *Armandia intermedia*	83.00% ***Batillaria australis*** ***Cerithium coralium***	90.99% ***Mysella vitrea***
Arrawarra, **Woolgoolga**	77.46% ***Cerithium coralium***	82.46% ***Cerithium coralium,*** ***Batillaria australis*** Sabellidae sp. 1	69.94% ***Mysella vitrea*** *Scoloplos normalis*
Darkum, **Woolgoolga**	81.33% ***Cerithium coralium*** ***Victoriopisa australiensis***	86.07% ***Cerithium coralium*** ***Batillaria australis***	75.73% ***Mysella vitrea***
Station, **Willis**	92.64% ***Ascorhis tasmanica,*** **Chironomidae sp. 1** ***Fluviolanatus subtortus***	95.61% *Armandia intermedia,* ***Scyphoproctus towraiensis*** ***Notomastus estuarius***	98.19% ***Ascorhis tasmanica*** ***Orthoprionospio cirriformia*** ***Notomastus estuarius***
Arrawarra, **Willis**	88.60% **Chironomidae sp. 1** ***Ascorhis tasmanica*** ***Fluviolanatus subtortus***	95.15% *Scoloplos normalis* Sabellidae sp. 1 *Phoronis* sp. 2	95.42% ***Ascorhis tasmanica*** ***Orthoprionospio cirriformia*** *Mysella vitrea*
Darkum, **Willis**	88.63% ***Ascorhis tasmanica*** **Chironomidae sp. 1** ***Fluviolanatus subtortus***	89.27% ***Notomastus estuarius*** ***Scyphoproctus towraiensis*** ***Ascorhis tasmanica***	92.29% ***Ascorhis tasmanica*** ***Orthoprionospio cirriformia***
Woolgoolga, **Willis**	93.49% ***Ascorhis tasmanica*** **Chironomidae sp. 1** ***Fluviolanatus subtortus***	99.13% *Cerithium coralium* *Batillaria australis*	95.97% *Mysella vitrea* ***Ascorhis tasmanica***
Station, **Hearns**	88.02% ***Notomastus estuarius*** ***Simplisetia aequisetis*** ***Arthritica helmsi***	92.70% ***Scoloplos normalis*** ***Orthoprionospio cirriformia*** ***Simplisetia aequisetis***	97.15% *Scoloplos normalis* Leptocheliidae sp. *Armandia intermedia*

Table 4.3. Cont.

	Upper	Middle	Lower
Arrawarra, **Hearns**	56.19% *Simplisetia aequisetis* *Armandia intermedia* ***Notomastus estuarius***	65.55% Sabellidae sp. 1 *Phoronis* sp. 2 *Armandia intermedia*	69.99% *Mysella vitrea* *Armandia intermedia* *Scoloplos normalis*
Darkum, **Hearns**	77.26% ***Notomastus estuarius*** ***Simplisetia aequisetis*** ***Arthritica helmsi***	84.93% ***Scoloplos normalis*** ***Notomastus estuarius*** ***Orthoprionospio cirriformia***	43.30% ***Scoloplos normalis*** ***Mysella vitrea*** *Soletellina alba*
Woolgoolga, **Hearns**	78.09% *Cerithium coralium* ***Notomastus estuarius*** ***Simplisetia aequisetis***	87.48% *Cerithium coralium* *Batillaria australis*	81.84% *Mysella vitrea*
Willis, **Hearns**	71.06% Chironomidae sp. 1 *Ascorhis tasmanica* *Fluviolanatus subtortus*	66.03% ***Scoloplos normalis*** ***Simplisetia aequisetis*** *Ascorhis tasmanica*	90.64% *Ascorhis tasmanica* ***Orthoprionospio cirriformia***

In the lower sites (Fig. 4.1c) differences between estuaries were also shown to be significant (Global R = 0.891, p = 0.001). However, the pairwise comparisons revealed no significant difference (p = 0.151) between Darkum Creek and Hearns Lake; all other contrasts were significant ($p < 0.05$) (Table 4.2). SIMPER analysis revealed that the overall differences between estuaries in these lower sites were largely attributable to *S. normalis*, *A. tasmanica*, the bivalve *Mysella vitrea* and a tanaid from the Family Leptocheliidae (Table 4.3).

The results of the SIMPER analyses also showed some consistent differences at the scale of individual estuaries. Thus, *C. coralium* and *B. australis* were only present in high abundances in Woolgoolga Lake. Similarly, *A. tasmanica*, *Fluviolanatus subtortus* and Chironomidae sp. 1 were only present in Willis Creek. This contributed to Willis Creek consistently separating from the other closed estuaries at all sites (Fig. 4.1a-c).

4.3.2 Community Variation Among Permanently Open Estuaries

There was no overlap in community structure between the permanently open estuaries for the upper and middle sites (Fig. 4.2a-b). Corindi River displayed a higher level of variation in comparison to Moonee and Coffs creeks at all sites (Relative Dispersion = 1.458 – 1.645; Table

4.4), which is more than likely due to samples containing lower species and abundance counts. Results of ANOSIM (Table 4.2) for the upper and middle sites (Global R = 0.799, p = 0.001; Global R = 0.876, p = 0.001; respectively) confirmed that there were significant differences between the permanently open estuaries. Similarly, highly significant differences (p = 0.008) were recorded between estuaries for each pairwise comparison. The results of SIMPER indicated that dissimilarity between the upper areas of these estuaries was primarily due to differences in the abundance of *M. vitrea* and *S. normalis*, whilst the bivalves *M. vitrea* and *Tellina imbellis* were the primary contributors to the differences between the middle sites (Table 4.5).

Table 4.4 Summary of multivariate dispersion (MVDISP) analyses indicating the relative dispersion (Disp.) of replicate samples within each estuary type and within the individual estuaries nested within each type, for the upper, middle and lower sites. Rank order among each comparison group is also given, whereby the groups with the lowest rank (1) exhibit the least dispersion, or variability, among replicate samples.

Comparison groups	Upper		Middle		Lower	
	Disp.	Rank	Disp.	Rank	Disp.	Rank
Type						
Intermittently closed	1.001	2	1.051	2	1.051	2
Permanently open	0.954	1	0.787	1	0.791	1
Estuaries (Type)						
Intermittently closed						
Station	0.879	3	1.534	5	1.734	6
Arrawarra	1.259	4	0.561	2	0.970	4
Darkum	1.377	5	1.744	6	1.154	5
Woolgoolga	1.567	6	0.492	1	0.711	2
Willis	0.698	2	0.633	3	0.711	1
Hearns	0.220	1	1.036	4	0.718	3
Permanently open						
Corindi	1.645	3	1.458	3	1.645	3
Moonee	0.600	1	0.690	1	0.806	2
Coffs	0.755	2	0.852	2	0.548	1

In the lower sites, the nMDS ordination (Fig. 4.2c) showed that samples from Coffs and Moonee Creeks overlapped, whilst those from Corindi River remained separate. The ANOSIM showed a significant difference between estuaries (Global R = 0.621, p = 0.001; Table 4.2) and, despite the apparent overlap in the nMDS, for all pairwise contrasts (p = 0.016 for Moonee vs. Coffs; p = 0.008 for the other contrasts). The SIMPER analysis revealed that differences in the abundance of the amphipod *Urohaustorius metungi*, which was most abundant in Coffs and Moonee creeks, drove the overall dissimilarities between the lower sites of these estuaries (Table 4.5).

Fig. 4.2 Two-dimensional nMDS ordinations of patterns of community structure in the permanently open estuaries for: a) upper; b) middle; and c) lower sites. Corindi River, Moonee Creek and Coffs Creek are represented by blue, red and green symbols, respectively. Estuary names are abbreviated to their first three letters.

Table 4.5 Summary of SIMPER analyses for all sites in the permanently open estuaries. The three highest ranked species that contributed > 10% to the average dissimilarity (given as a percentage) for each pairwise comparison are shown. Species shown in bold font were more abundant in the estuary with bold font.

	Upper	Middle	Lower
Corindi, **Moonee**	91.53% ***Mysella vitrea*** ***Arthritica helmsi***	87.15% ***Mysella vitrea*** ***Urohaustorius metungi*** ***Nassarius jonasii***	94.57% ***Urohaustorius metungi***
Corindi, **Coffs**	91.34% ***Scoloplos normalis*** ***Arthritica helmsi*** ***Victoriopisa australiensis***	83.40% ***Tellina imbellis*** ***Soletellina alba***	85.36% ***Urohaustorius metungi***
Moonee, **Coffs**	62.05% *Mysella vitrea* *Arthritica helmsi*	72.86% ***Tellina imbellis***	34.55% *Urohaustorius metungi* ***Nassarius jonasii*** *Soletellina alba*

4.3.3 Differences In Community Structure Between Intermittent And Permanently Open Estuaries

Multivariate analyses of data pooled within estuary type showed a strong and significant separation by type for each of the sites (Fig. 4.3a-c; Table 4.2) (ANOSIM: Global R = 0.444, p = 0.001; Global R = 0.595, p = 0.001; Global R = 0.509, p = 0.001; upper, middle and lower respectively). For the upper region, there was a tendency for Moonee and Coffs creeks to group near the intermittent estuaries but there was no overlap.

The species primarily responsible for the differences between the upper sites (average dissimilarity = 87.98%) were the bivalves *Arthritica helmsi* and *M. vitrea*, both of which were more abundant in the permanently open estuaries. In the middle sites (average dissimilarity = 94 %), differences were primarily associated with the polychaetes *A. intermedia* and *S. normalis*, both of which were more abundant in the intermittent estuaries. In the lower sites (average dissimilarity = 93.39%), differences were mainly associated with of the comparatively very low abundances *U. metungi* and *M. vitrea*, and high abundances of *S. normalis*, in the intermittent estuaries.

Analysis of the total data set (i.e. pooled across sites within estuaries) also indicated no overlap in the community structure of estuary types (Global R = 0.403, p = 0.001) (Fig. 4.3d), suggesting fundamental differences between the two. The average dissimilarity between types (92.08%) was largely due to *M. vitrea* and *U. metungi*, which had higher abundances in permanently open estuaries, and *S. normalis*, which was more abundant in intermittent estuaries.

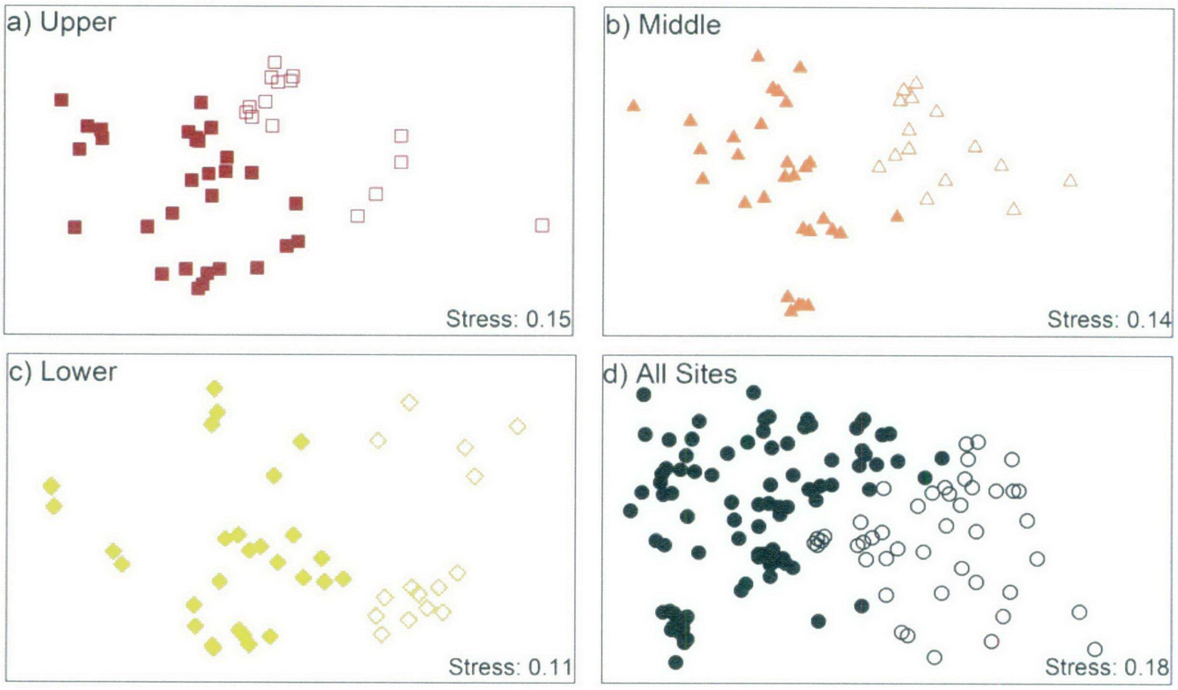


Fig. 4.3 Two-dimensional nMDS ordinations of community variation between intermittent and permanently open estuaries for: a) upper sites; b) middle sites; c) lower sites; and d) all sites combined. Closed estuaries (filled symbols); open estuaries (unfilled symbols).

4.3.4 Summary Community Variables

Very high levels of variation, both within and between estuary types, were evident across all summary community variables (Figs. 4.4 and 4.5). The average species richness per sample ranged from 2, in the lower Hearns Lake, to 17 in the middle of Coffs Creek (Fig. 4.4). Analyses of species richness showed a highly significant difference between estuaries nested within estuary type at each of the sites (p < 0.001; Table 4.6), with pairwise comparisons between individual estuaries (Table 4.7) showing numerous differences between estuaries at each site. There was, however, no significant difference in species richness between estuary types at any site ($p = 0.663$, 0.599 and 0.226; upper, middle and lower sites, respectively) (Table 4.6).

Similarly, the total number of individuals was highly variable between the estuaries nested within type ($p < 0.001$; Table 4.6), ranging from 3 individuals per sample in lower Darkum Creek to 323 in upper Moonee Creek (Fig. 4.5). No significant differences were evident between estuary types for any site ($p = 0.511$, 0.227 and 0.452; upper, middle and lower sites, respectively), with a variable range of significant pairwise comparisons between individual estuaries at each site (Table 4.7).

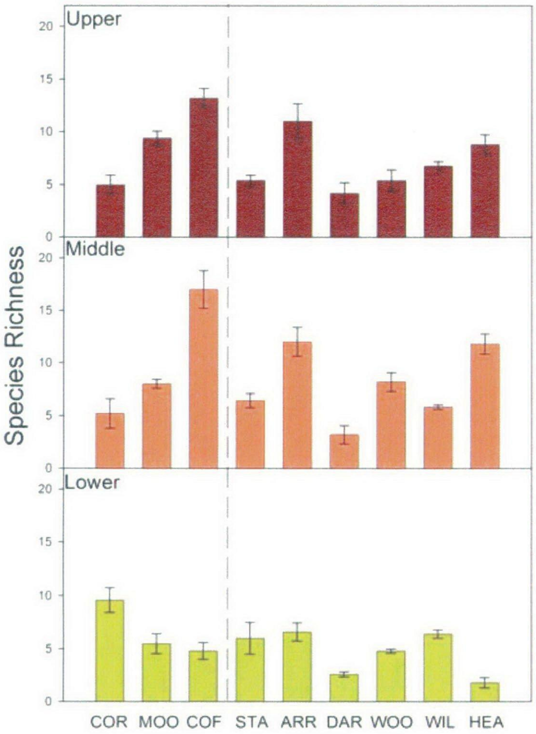


Fig. 4.4 Mean species richness (± SE) for each estuary in the upper, middle and lower sites. Each estuary name is abbreviated to its first three letters and the three permanently open estuaries are grouped to the left.

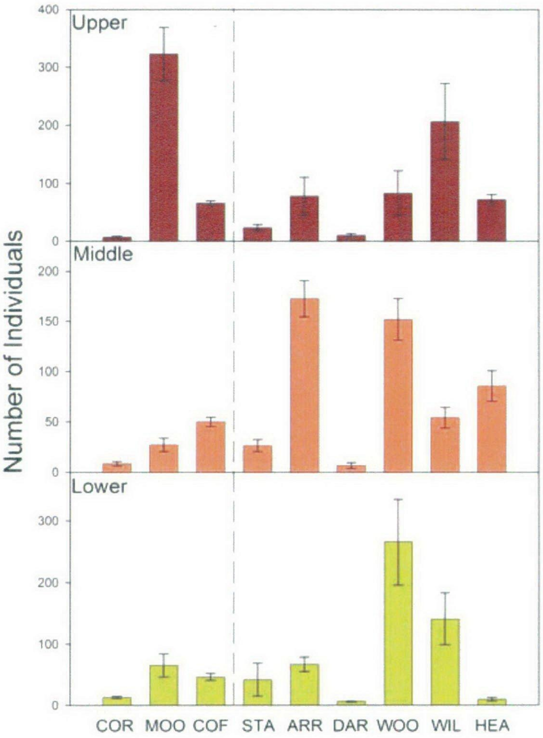


Fig. 4.5 Mean number of individuals (± SE) for each estuary in the upper, middle and lower sites. Each estuary name is abbreviated to its first three letters and the three permanently open estuaries are grouped to the left.

Table 4.6 Summary of the results of two-way nested ANOVA for species richness (S) and the total number of individuals (N). *df* = 1, 36 for comparisons between estuary types and *df* = 7,36 for comparisons between estuaries nested within type. *** $p < 0.001$, ns $p > 0.05$.

Variable	Source of variation	Upper		Middle		Lower	
		MS	F	MS	F	MS	F
S	Type	4.90	0.21 ns	24.54	0.30 ns	40.00	1.76 ns
	Estuary (Type)	23.76	**6.48** ***	80.82	**15.64** ***	22.74	**9.43** ***
N	Type	27353	0.48 ns	29276	1.76 ns	23168	0.64 ns
	Estuary (Type)	56963	**11.13** ***	16730	**25.16** ***	36451	**8.47** ***

Table 4.7 Results of Tukey's pairwise comparisons between the individual estuaries of each estuary type for species richness (S) and the total number of individuals (N). Estuaries are abbreviated to their first significant letters and '>' indicates the direction of significant differences (i.e. Cf>Cr shows Coffs was significantly greater than Corindi). '-' indicates a non-significant test (p > 0.05); * p < 0.05, ** p < 0.01, *** p < 0.001.

Comparison groups	Upper		Middle		Lower	
	S	N	S	N	S	N
Intermittently closed						
Station - Arrawarra	A>S **	-	-	A>S **	-	
Station - Darkum	-	-	-	-	-	
Station - Woologoolga	-	-	-	W>S ***	-	W>S ***
Station - Willis	-	W>S **	-	-	-	
Station - Hearns	-	-	-	H>S *	S>H *	
Arrawarra - Darkum	A>D ***	-	A>D ***	A>D ***	A>D *	
Arrawarra - Woolgoolga	A>W **	-	-	-	-	W>A ***
Arrawarra - Willis	A>W *	-	A>W *	A>W ***	-	
Arrawarra - Hearns	-	-	-	A>H ***	A>H **	
Darkum - Woolgoolga	-	-	-	-	-	W>D ***
Darkum - Willis	-	W>D **	-	W>D ***	-	
Darkum - Hearns	H>D *	-	H>D ***	H>D ***	-	
Woolgoolga - Willis	-	-	-	Wo>W ***	-	
Woolgoolga - Hearns	-	-	-	W>H **	-	W>H ***
Willis - Hearns	-	-	H>W *	-	W>H *	
Permanently open						
Corindi - Moonee	-	M>Cr ***	-	-	Cr>M **	-
Corindi - Coffs	Cf>Cr *	-	Cf>Cr ***	-	Cr>Cf ***	-
Moonee - Coffs	-	M>Cf ***	Cf>M ***	-	-	-

Eight species, which were consistently identified by SIMPER analyses as being primary discriminators between estuary types, were chosen for comparisons of abundance across particular sites (Fig. 4.6). However, with the exception of one species, the haustorid amphipod *Urohaustorius metungi* in the lower sites (p = 0.031), no significant differences were evident between estuary types, with most of the significant variation evident among estuaries nested within estuary type (Table 4.8).

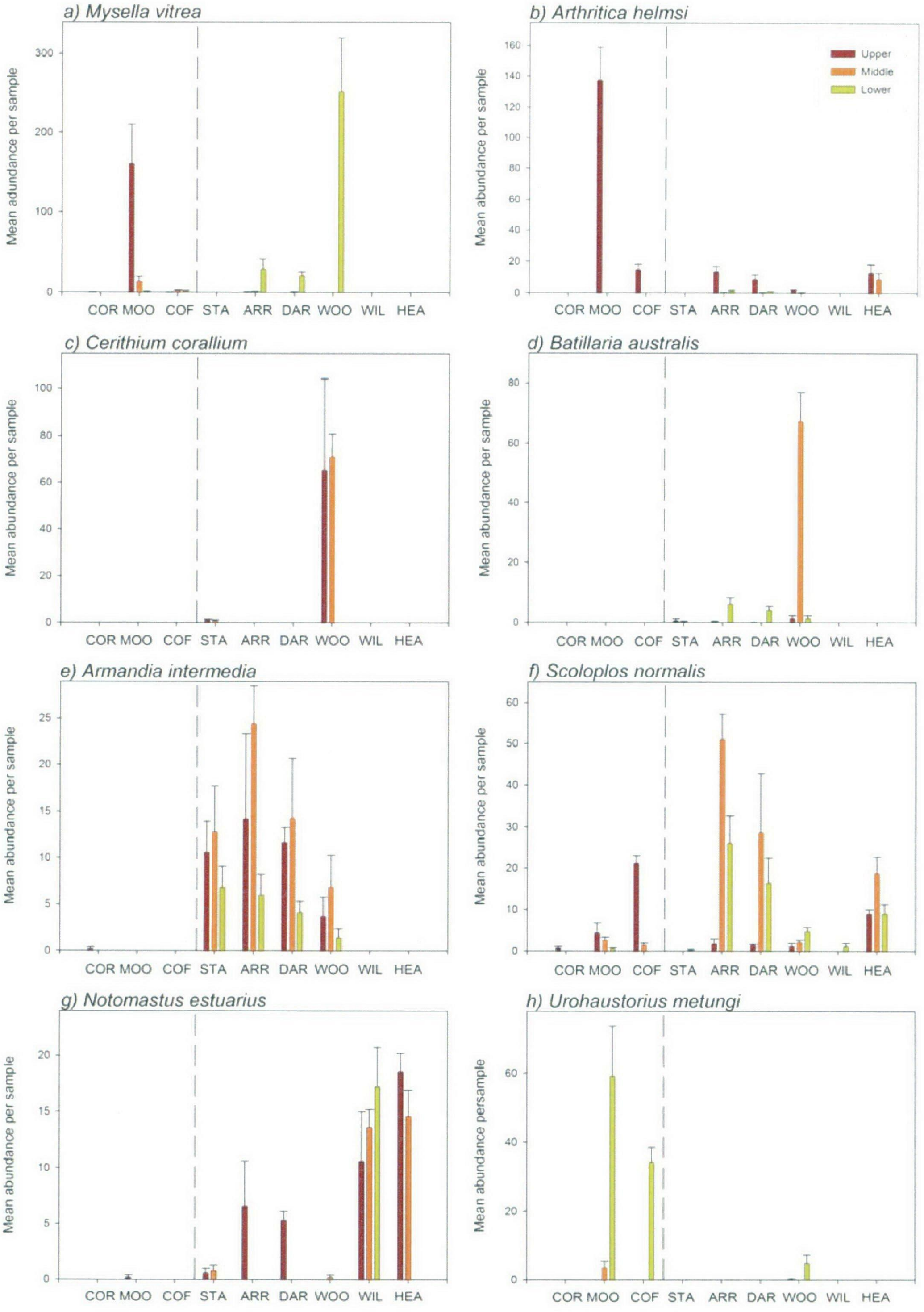


Fig. 4.6 Mean abundance per sample (±SE) of the eight most common species at each of the upper (red), middle (orange) and lower (yellow) sites. Each estuary name is abbreviated to its first three letters and the three permanently open estuaries are grouped to the left.

Table 4.8 Summary of the results of two-way nested ANOVA for the abundances of the most common species. d.f. = 1,36 for comparisons between estuary types and d.f. = 7,36 for comparisons between estuaries nested within type. Significant results are in bold font (* $p < 0.05$, ** $p < 0.005$, *** $p < 0.001$). 'ns' $p > 0.05$. '-' indicates that the species did not occur in sufficient abundances to test for differences at that site. Higher taxa denoted as bivalves (B), gastropods (G), polychaetes (P) and amphipods (A).

Variable	Source of variation	Upper		Middle		Lower	
		MS	F	MS	F	MS	F
Mysella vitrea (B)	Type	-	-	255.34	3.71 ns	21160	0.58 ns
	Estuary (Type)	-	-	68.20	**2.63** *	36532	**13.73** ***
Arthritica helmsi (B)	Type	21098.7	2.55 ns	22.50	0.55 ns	-	-
	Estuary (Type)	8286.7	**28.72** ***	40.90	**3.60** **	-	-
Cerithium coralium (G)	Type	1224.7	0.49 ns	1432	0.48 ns	-	-
	Estuary (Type)	2512.6	**2.99** *	2987.5	**54.19** ***	-	-
Batillaria australis (G)	Type	-	-	1261.9	0.47 ns	-	-
	Estuary (Type)	-	-	2684.8	**51.48** ***	-	-
Armandia intermedia (P)	Type	-	-	608.40	1.90 ns	-	-
	Estuary (Type)	-	-	320.17	**10.28** ***	-	-
Scoloplos normalis (P)	Type	-	-	1152	0.77 ns	542.68	1.67 ns
	Estuary (Type)	-	-	1487.1	**46.49** ***	325.62	**11.42** ***
Notomastus estuarius (P)	Type	376.18	1.93 ns	240.10	1.32 ns	-	-
	Estuary (Type)	194.48	**9.09** ***	181.99	**39.75** ***	-	-
Urohaustorius metungi (A)	Type	-	-	-	-	9180.9	**7.19** *
	Estuary (Type)	-	-	-	-	1276.6	**9.76** ***

4.3.5 Univariate Analysis of Physico-chemical Variables

Water column parameters were highly variable between individual estuaries nested within estuary type ($p < 0.001$ for all sites – Table 4.9, Fig. 4.7). The three permanently open estuaries had salinity levels that were similar to that of seawater (34–35 mg L-1), whilst there was considerable variation among the intermittent estuaries, which ranged from 57.4 mg L-1 in the upper and middle sites of Arrawarra Creek to 7.1 mg L-1 in the upper site of Willis Creek. With the exception of Willis Creek, which reached a maximum salinity of only 10 mg L-1, the closed estuaries were generally hypersaline in at least the upper and middle sites. Dissolved oxygen ranged from 0.9 ppm in the muddy, upper region of Moonee Creek to 7.9 ppm in mid-Corindi River. Temperature and pH ranges were 23.8 – 31.5 °C and 7.4 – 9.1, respectively.

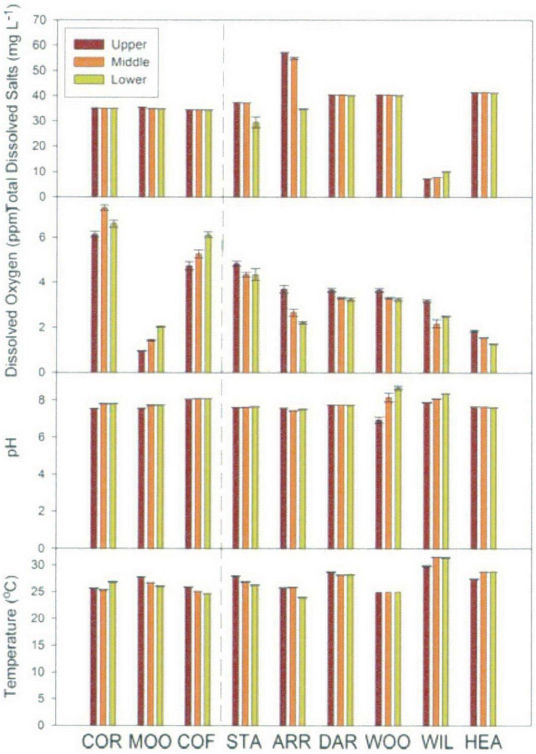


Fig. 4.7 Water column physico-chemical variables (mean ± SE) for each of the upper, middle and lower sites for all estuaries. Each estuary name is abbreviated to its first three letters and the three permanently open estuaries are grouped to the left.

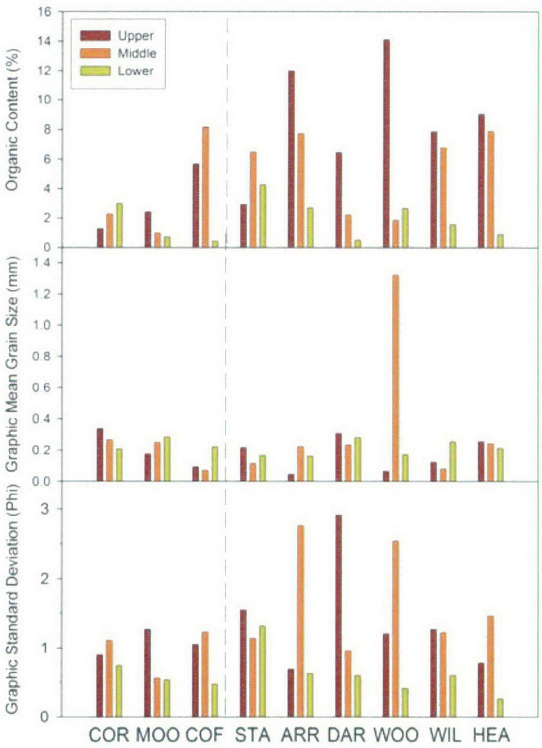


Fig. 4.8 Sediment parameters for each of the upper, middle and lower sites for all estuaries. Each estuary name is abbreviated to its first three letters and the three permanently open estuaries are grouped to the left.

There were no significant differences for all water column measurements between estuary types at any of the sites (Table 4.9). Pairwise comparisons revealed some consistent differences between individual estuaries (Table 4.10). For example, Willis Creek had a significantly greater temperature and significantly reduced salinity when compared to all other intermittent estuaries.

Sediment characteristics showed a high degree of variation between individual estuaries and also between sites within an estuary (Fig. 4.8). Organic content was generally greater in the intermittent estuaries, particularly in the upper sites. Sediment grain size ranged from a graphic mean of 0.05 mm in the upper site of Arrawarra to 1.32 mm in the middle region of Woolgoolga Lake. The graphic standard deviation of the latter, however, revealed a high level of heterogeneity as the sample contained a high proportion of gravel combined with muddy sediments. Similarly, the sediments of two other intermittent estuary sites, mid-Arrawarra Creek and upper Darkum Creek, were relatively heterogeneous due to high proportions of both the gravel and silt components.

Table 4.9 Summary of the results of two-way nested ANOVA for the physico-chemical water column variables. d.f. = 1,36 for comparisons between estuary types and d.f. = 7,36 for comparisons between estuaries nested within type. Significant results are in bold font (*** $p < 0.001$), 'ns' indicates $p > 0.05$.

Variable	Source of variation	Upper		Middle		Lower	
		MS	F	MS	F	MS	F
Temp.	Type	9.34	0.69 ns	39.37	1.91 ns	26.68	1.10 ns
	Estuary (Type)	13.47	**233.11** ***	20.56	**596.79** ***	24.20	**124.24** ***
DO	Type	2.20	0.16 ns	30.85	1.92 ns	0.41	1.80 ns
	Estuary (Type)	13.59	**50.86** ***	16.09	**45.51** ***	0.23	**89.89** ***
ph	Type	0.02	0.11 ns	0.21	0.97 ns	0.03	0.03 ns
	Estuary (Type)	0.15	**130.94** ***	0.22	**45.33** ***	0.85	**32.42** ***
TDS	Type	72.26	0.07 ns	57.40	0.07 ns	31.35	0.06 ns
	Estuary (Type)	964.69	**110000** ***	844.25	**48000** ***	519.37	**37.25** ***

Table 4.10 Summary of results of Tukey's pairwise comparisons between individual estuaries for all water quality variables at each site. Rank order given, whereby '>' indicates a significantly greater value when compared to all following estuaries; there are no significant differences (p > 0.05) among estuaries that are grouped within brackets. Willis (Wi), Darkum (D), Station (S), Hearns (H), Arrawarra (A), Woolgoolga (Wo), Moonee (M), Coffs (Cf), Corindi (Cr).

Variable	Site	Intermittently closed	Permanently open
		Rank order	Rank order
Temp.	Upper	Wi > D > S > H > A > Wo	M > (Cr, Cf)
	Middle	Wi > H > D > S > A > Wo	M > (Cr, Cf)
	Lower	Wi > (H,D) > S > (Wo, A)	(Cr, M) > Cf
DO	Upper	S > (A, D, Wo, Wi) > H	Cr > Cf > M
	Middle	(S, D, Wo) > (A, Wi , H)	Cr > Cf > M
	Lower	(S, D, Wo) > (A, Wi) > H	(Cr, Cf) > M
pH	Upper	Wi > (D, H) > S > (Wo, A)	Cf > (Cr, M)
	Middle	Wi > Wo > (H, D, S) > A	Cf > (Cr, M)
	Lower	(Wo, Wi) > (S, A, D, H)	Cf > M (Cr not sig. diff. to either)
TDS	Upper	A > (Wo, H) > D > S > Wi	M > Cr > Cf
	Middle	A > (Wo, H) > D > S > Wi	(Cr, M) > Cf
	Lower	(D, Wo, H) > (S, A) > Wi	(Cr, M, Cf)

4.3.6 Multivariate Correlations Between Biotic and Physico-chemical Patterns

The BIOENV procedure revealed relatively strong correlations of biotic patterns with most physico-chemical variables, with the exception of temperature, sediment grain size and sediment homogeneity (Table 4.11). The highest correlation coefficient for a single variable was returned by catchment size ($\rho = 0.453$) with the next highest ranked being for salinity ($\rho = 0.255$). Two combinations of five environmental variables provided the highest overall correlations ($\rho = 0.497$) although these relationships were only slightly greater than the strength of the relationship for catchment size alone.

Table 4.11 BIOENV results showing the Spearman rank correlation coefficient (ρ) for correlations between individual environmental variables, and the best combinations of environmental variables, with the full community data.

Variable no.	Variable	ρ
1	Salinity	0.255
2	Dissolved oxygen	0.210
3	pH	0.075
4	Temperature	0.196
5	Grain size	0.089
6	Sediment homogeneity	0.135
7	Organic content	0.226
8	Catchment size	0.453
	Best combinations	
	2, 5 - 8	0.497
	2, 4, 6 - 8	0.497

4.4 Discussion

All community and environmental variables revealed extremely high levels of variability among estuaries nested within estuary type. Despite this, differences were still consistently observed between the macrofaunal assemblages of the intermittent and permanently open estuaries. These findings support those of Hirst (2004) who, in a study of 28 estuaries in south-eastern Australia, found that entrance status of an estuary at the time of sampling was important in explaining the composition of benthic macrofauna. He considered this to be primarily due to open entrances being able to facilitate the intrusion and survival of marine species. In this study, the species that were primarily responsible for the differences between estuary types were *M. vitrea*, *U. metungi* and *S. normalis*.

The amphipod *U. metungi* warrants particular mention as it contributed more than 21% of the differences between estuary types in the lower sites, the largest percentage contribution made by a single species to the overall dissimilarity between estuary types at any site. This species was common amongst the samples from the permanently open Moonee and Coffs creeks but, in contrast, was only ever collected in one of the intermittent estuaries, and then only in low abundances. In addition, *U. metungi* was the only one of the common species to reveal a significant difference in abundance between the estuary types, and this was despite a high level of within-type variation. The dominance of *U. metungi* in permanently open estuaries and its near absence from intermittent estuaries, further suggest that it would be prudent to focus on this species as a biological indicator that could be considered in estuarine classification. Indeed, the identification and testing of suitable indicators to use in the biological classification of estuaries is an area of estuarine ecology that urgently requires development (Edgar et al. 2000).

While the patterns of community structure support the idea that the two types of estuaries have different ecology, at least during periods when intermittent estuaries are closed, the data generated here do not provide strong explanatory power. The biological impacts of entrance closure are generally thought to be a result of changes in the physico-chemical environment. The present study, however, did not detect any significant differences in physico-chemical variables between the estuary types, although the primary reason for this was that these data were so variable, especially among the intermittent estuaries. Moverley and Hirst (1999) also found physico-chemical conditions were highly variable from estuary to estuary and, consequently, had difficulties attributing faunal differences to these variables. This is perhaps due to the relationships between such variables and the fauna being quite complex. For example, Teske and Wooldridge (2003) found salinity to be most important in structuring benthic communities in the upper and lower extremes of permanently open estuaries, whereas sediment type was more important at the intermediate sites, as well as throughout closed estuaries where salinity tended to be more uniform.

Salinity, in particular, was variable across this study and many of the intermittent estuaries experienced hypersaline conditions, at least in their upper reaches. This would have been caused by both the reduced freshwater input due to the drought, and high rates of evaporation, as this part of the study was conducted in the middle of summer. Hypersaline conditions following entrance closure have also been reported in other intermittent estuaries in Australia and South Africa (Owen & Forbes 1997; Teske & Wooldridge 2001; Dalton et al. 2002; Young & Potter 2002; Mondon et al. 2003). These studies reported that faunal communities were affected by hypersalinity to varying degrees, presumably due to the relative extent of hypersalinity in each estuary. All, however, agreed that elevated salinities favoured an increase in marine associated fauna and a simultaneous decline in some non-marine species. The most obvious differences at sites that experienced the highest salinity in this study (upper and middle sites of Arrawarra Creek) were high abundances of Sabellidae sp. 1 and *Phoronis* sp. 2, which were not collected elsewhere. However, a causal relationship between the occurrence of these species and high salinities cannot yet be established.

In contrast, conditions in Willis Creek were hyposaline. This creek receives stormwater and sewage drainage from a moderately-sized urban area (approx. 4000 residents), which reduced salinities to a maximum of 10 mg L-1. It is, therefore, not surprising that Willis Creek consistently separated from the other intermittent estuaries in the community analyses. Assemblages at Willis Creek were characterised by the molluscs *Fluviolanatus subtortus*, *A. tasmanica* and the insect larvae Chironomidae sp.1, which were not collected in any of the other estuaries. These fauna are usually only associated with the brackish waters of upper estuarine areas (Ponder & Clark 2000; Wilson et al. 2003) and their presence in this estuary was clearly influenced by the high freshwater input. The capitellid polychaetes *N. estuarius* and *Scyphoproctus towraiensis* were also present in relatively high abundances in Willis Creek. Similarly, other species of the Family Capitellidae are often found in higher abundances in polluted areas, particularly in response to sewage-related nutrient enrichment (Bridges et al. 1994).

In the correlations of physico-chemical variables with biotic patterns, all but three showed relatively strong correlations with community data and thus, potentially, some causative link to assemblage structure. The fact that the contributions were not additive and, indeed, are likely to be autocorrelated to some extent, is evident in that the optimal list of variables (i.e. the combination that together returned the highest correlation coefficient), left the majority of the variation between the two data sets unexplained and resulted in a correlation only slightly greater than the highest ranked, single variable - catchment size. Such results suggest that there are other key variables that are important in driving the observed community patterns. Indeed, the relationships between benthic fauna and specific physico-chemical variables may be naturally weaker as a consequence of the dynamic nature of south-east Australian estuaries (Hirst 2004), when compared to those in the northern hemisphere and other parts of Australia.

The close association between size of the estuary and biotic patterns also introduces unavoidable confounding into the interpretation of differences between estuary types. Catchment size, and hence the amount of runoff generated relative to waterway area, will determine how an estuary responds physically to rainfall, and therefore has an effect on chemical and biological processes (Haines 2004). Thus, it might be expected that small estuaries are more likely than large estuaries to close during periods of reduced rainfall and patterns of difference between the two estuary types may simply reflect the effect of catchment size. In the present study, it can be seen from Table 1 that, for the most part, the intermittent estuaries are smaller than the permanently open ones. Similarly, in a study of 46 estuaries by Mondon et al. (2003) a relationship between catchment size and estuary type was evident, whereby 75% of the intermittently closed estuaries had catchment areas smaller than that of the smallest permanently open estuary. Therefore, a seemingly viable alternative hypothesis is that the size of the estuary is primarily driving community patterns.

There are a number of reasons to suspect that state of the entrance is also of importance, however. Firstly, extended closure is likely to have a major effect on a range of important parameters due to the lack of marine influence. The change in the hydrodynamic environment will affect both physico-chemical (e.g. water movement, salinity) and biological (e.g. recruitment, trophic supply) processes. The variability in a wide range of variables that were unmeasured in this study (e.g. nutrient loads, retention of pollutants) is also likely to play a key role in determining the distribution and abundance of macrofauna in the intermittent estuaries (Perissinotto et al. 2000). A working model for these systems suggests that only fauna that are able to withstand relatively extreme ranges of physico-chemical conditions, for extended periods, would survive during such lengthy closures. While this has been found to be true in estuarine fish communities (Pollard 1994; Griffiths 2001; Young & Potter 2002), few studies have examined long-term temporal changes of benthic communities in intermittent estuaries, particularly in relation to extended closure.

The possible explanations for the patterns evident in this study are necessarily speculative as this is the first time that these systems have been evaluated. Clearly, these hypotheses require rigorous testing. Given the importance of these systems and the unwieldy number of government agencies that have input into their management, the experimental manipulation of entrance status is unfortunately difficult to achieve. Instead, these hypotheses will be tested by conducting additional sampling during periods when at least some of the intermittent estuaries are open. The event-based sampling protocol that has been built in to this project will allow the effects of natural breakout of intermittent estuaries to be addressed when it occurs in the future (refer Chapter 5). This will provide the opportunity to determine if community structure converges between the two estuary types during periods of opening and thus the comparative importance of estuary size and entrance status.

Finally, the results of this study have some clear implications for the management of these systems. The remarkable individuality, both biologically and physico-chemically, displayed by the estuaries within each estuary type, reflects the fact that they represent a variety of intrinsic features. All of the estuaries, regardless of their current entrance status, varied in characteristics such as size, predominant catchment uses and degree of entrance modification. Hirst (2004), likewise, found that, over a regional scale, different estuaries are far from biologically and physico-chemically homogenous and highlighted the implications of this when considering effective estuarine classification and management. The long residence time of water and sediments of intermittent estuaries, in particular, can make their faunal communities vulnerable to environmental degradation suggesting that, as a class, they require very careful management (McComb 1995). This, in addition to the considerable range of differences found between the estuaries in this study, emphasizes the importance, where feasible, of managing each on an individual basis.