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The diversity and abundance of polychaetes (Annelida) are altered in sediments impacted by alumina refinery discharge in the Northern Territory, Australia

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ABSTRACT

We collected polychaete diversity and abundance data at a range of impacted and reference sites near an alumina refinery in Melville Bay, northern Australia. The aims were to measure the impact of sediment modified by the alumina refinery discharge on polychaete communities and secondly to gather baseline data from which to measure future changes. Polychaete communities in both soft-bottom habitats and subtidal areas adjacent to mangrove forests were studied. We also developed and deployed an artificial substratum device to sample polychaetes associated with hard-substrate habitats. For each habitat, polychaete community composition was different between impacted and reference sites and at multiple time points. The impact of future changes either from bioremediation or management practices can be measured against these baseline data. Indicator species analysis was used to identify polychaete species that were significantly different at the locations tested, and we discuss their potential as indicator species.

1. Introduction

Polychaete assemblages have been used as biological indicators of pollution for many years (Dean, 2008; Pocklington and Wells, 1992). They can be useful indicators because they are abundant, diverse, functionally significant and changes in polychaete diversity and abundance can be indicative of broader ecosystem change (Chariton et al., 2006; Olsgard et al., 2003). Many types of contaminants can also potentially influence polychaetes because they have a range of feeding guilds and life history characteristics that maximise the exposure of the group to different pollutants (Fauchald and Jumars, 1979; Pagliosa, 2005). For example, filter-feeding polychaetes are likely to accumulate dissolved or particulate contaminants, while non-tubiculous, benthic polychaetes come into close contact with sediment contaminants (Hill et al., 2009; Kalman et al., 2010; Rainbow et al., 2009). Polychaetes that are carnivorous or herbivorous may bioaccumulate contaminants from the food chain (Waring and Maher, 2005). The alteration of polychaete communities in response to contaminants can also occur quickly, as many polychaetes have short lifecycles and rapidly increase or decrease in abundance (Osman et al., 2010; Ramskov and Forbes, 2008). These characteristics make polychaetes ideal organisms for use as biological indicators of anthropogenic contaminants.

One source of anthropogenic contaminants in marine systems is discharges from industrial facilities. Bauxite is mined on the Gove peninsula, Northern Territory, Australia and refined at the adjacent alumina refinery using the Bayer process (Liu et al., 2007). During this process, a caustic sodium hydroxide liquid is used to extract metals (preferentially sodium aluminate) from the bauxite under high temperatures (Hind et al., 1999). At the Gove alumina refinery, seawater is used to cool the reactors before being released back into the marine environment (Alongi and McKinnon, 2011). Carryover events have sporadically occurred during the life of the refinery, though the number and duration of carryover events has decreased substantially in recent years. During these carryover events, caustic

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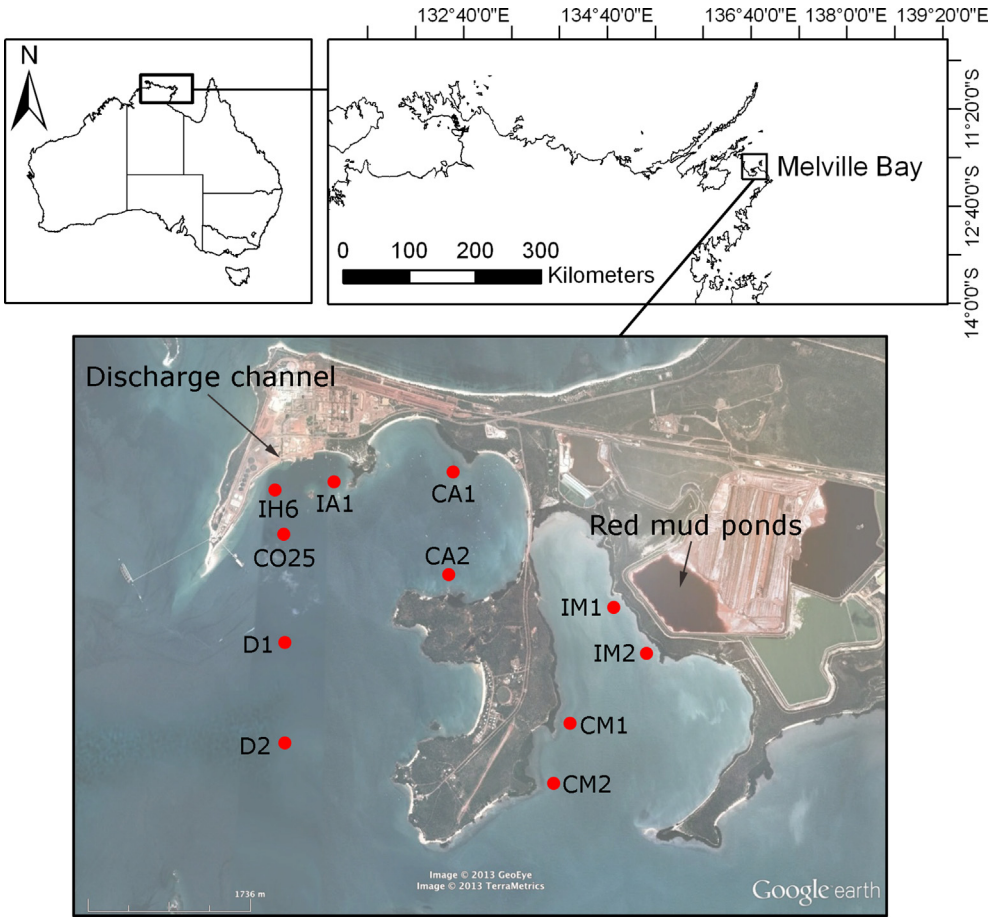

Fig. 1. Location of the impacted soft-bottom sampling sites (IH6, C025), the reference soft-bottom sites (D1, D2), the mangrove impacted sites (IM1, IM2), the mangrove reference sites (CM1, CM2), the impacted artificial substratum location (IA1) and the reference artificial substratum locations (CA1, CA2), in Melville Bay, Northern Territory, Australia.

sodium aluminate reacts with magnesium in the seawater to form a hydrotalcite precipitate (Smith et al., 2005). This precipitate is discharged along with other metals and organics, and settles into the near shore coastal sediments. The metals most likely to be associated with the precipitate are Al, Mo, Ga and V, and these can be considered as a chemical signature of the waste (Negri et al., 2011). During the Bayer process, a solid 'red mud' waste is also produced (Liu et al., 2007), which is collected in large containment ponds. This is another potential source of contaminants as the red mud ponds may leak into nearby coastal habitats.

Our primary aim was to measure the impact of sediment modified by the Gove alumina refinery discharges on different polychaete habitats and determine whether this caused changes in the polychaete assemblage. We predicted that the diversity, abundance and structure of polychaete communities near the alumina refinery would be different from polychaete communities at reference sites. We tested this by sampling polychaetes near the seawater discharge channel and near the red mud ponds of the alumina refinery, and compared the assemblage to those at reference sites. Two different benthic polychaete habitats were selected for this study because of their proximity to the alumina refinery discharges. A soft-bottom habitat was chosen because this was near the refinery discharge channel and a mangrove habitat was studied because it was adjacent to the red mud waste ponds and may be affected by potential seepages. We also deployed artificial substrata in Melville Bay to 'capture' hard-substrate polychaetes and examine hard-substrate community changes. From these data, we aimed to identify indicator species in each of the habitats and to use the data as a baseline against which to measure future changes that will occur over the continuing life of the refinery and after closure.

2. Methods

2.1. Sites

Inner Gove Harbour in Melville Bay is in the Northern Territory, Australia (Fig. 1). The inner harbour receives heated seawater effluent, which contains elevated levels of trace metals, from an adjacent alumina refinery. On rare occasions, small volumes of sodium aluminate are accidentally discharged which reacts with magnesium to form a hydrotalcite precipitate (Smith et al., 2005). In areas close to the discharge channel, the precipitate falls to the seafloor where it has created a sulfidic benthic zone (Alongi and McKinnon, 2011; Cornall et al., 2013).

The chemical composition and polychaete communities were analysed in Melville Bay during a wet season (Feb 2009) and during two dry seasons (Aug 2009 and Aug 2010). Two different habitats were sampled: soft-bottom sites and mangrove sites. The soft-bottom sites were two potentially impacted sites located in close proximity to the seawater discharge channel, IH6 and CO25, and two reference sites located further into the Harbour, D1 and D2 (Fig. 1). The mangrove sites were located in subtidal areas adjacent to mangrove forests (Fig. 1). Two potentially impacted sites IM1 and IM2 were in close proximity to red mud ponds, and two reference sites, CM1 and CM2, were near unpolluted mangroves. In addition, artificial substrata were deployed at a potentially impacted site, IA1, and at two

reference locations, CA1 and CA2 (Fig. 1). The reference locations were chosen after assessing sediment chemical data collected from the same sites in routine monitoring studies (unpublished data) and sediment data from other northern Australian estuaries and coastal environments (Munksgaard and Parry, 2002). These data showed that increases in metal concentrations are confined to inner Gove Harbour (Sites IH6, CO25, IA1). Sites further into Melville Bay (D1, D2) have not historically shown any increases in sediment metal concentrations, suggesting that they were appropriate reference sites.

2.2. Polychaete sampling and chemical analysis

At the soft-bottom sites, four replicate samples were collected from each of the four sites during each of the three sampling times. At the mangrove sites, four replicate samples were collected during the first sampling time (Feb 2009) and three replicate samples were collected during the final two sampling times (Aug 2009 and Aug 2010). The number of replicates was reduced at the mangrove sites because they contained high polychaete densities and three replicates provided adequate sample numbers for statistical analyses. A *post-hoc* power analysis was conducted using G*Power (Erdfelder et al., 1996) which confirmed that adequate sample numbers were collected in order to achieve power of 0.8 (data not shown). All of the samples were collected from a boat using a Van Veen sediment grab. The sediment was mixed with plastic trowels, taking care to avoid fractionation of different grain sizes. A representative portion of the sediment was placed into acid-washed falcon tubes for porewater chemical analysis, and into zip-lock bags for sediment chemical analysis. The remaining sediment was measured to 4 L and passed through a 500 μm sieve. The >500 μm fraction was expected to contain a sample of the polychaete assemblage and was preserved in 90% ethanol. The samples for chemical and polychaete analysis were placed on ice and transported back to the laboratory. The polychaetes collected from each of the >500 μm samples were then removed and identified.

The concentrations of Al, P, V, Cr, Fe, Mn, Co, Ni, Cu, Zn, Ga, As, Mo, Cd, Pb and U were analysed from both the porewater and sediment samples. The porewater samples were centrifuged in falcon tubes for 15 min at 3000 × g. The supernatant was removed and passed through a 0.45 μm syringe filter, before being analysed for the element concentrations by inductively coupled plasma-mass spectrometry (ICP-MS, Agilent 7500ce). The sediment samples were separated into two-grain size fractions using a 63 μm sieve, which were then dried and weighed. The element concentrations were analysed from the ≤63 μm fraction after a nitric: perchloric acid digestion at 100 °C for 30 min, 130 °C for 30 min and 200 °C for 30 min, by ICP-MS (Agilent 7500ce). The concentration of total organic carbon (TOC) was also analysed from the ≤63 μm sediment fractions by first reacting the sediment with concentrated hydrochloric acid to remove inorganic carbonates. Samples were then combusted in a LECO furnace at 1400 °C in the presence of strongly oxidizing iron/tungsten chips. The evolved carbon was then measured using infrared detection. For each 50 samples analysed, the quality control was 4 blanks, 2 spikes and 5 duplicates. In addition, certified reference materials were added to ensure reliable results. For the sediment digestions, PACS-1 and MESS-3 were included, the porewater analysis included CASS-4 and the total organic carbon analysis included Quasimeme reference materials.

2.3. Artificial substrata

The artificial substrata were 'exfoliating mesh sponges' (Priceline), which contained many complex microstructures suitable for polychaete settlement. Previous investigators have generally used 'pot scourers' as artificial substrata (Smith and Rule, 2002; Underwood and Chapman, 2006). These two devices are likely to have similarities although may also have important differences. Each substratum was tied to the middle of a 1 m length of rope. One end of the rope was then tethered to a Besser block and the other end to a small buoy. The Besser block stayed in place on the seafloor, with the buoy floating above, and the substratum approximately 70 cm from the bottom.

The artificial substrata were left in Melville Bay over two sampling periods, from 21 August 2009–20 October 2009 and from 12 August 2010–6 October 2010. The duration of deployment was selected based on preliminary studies, which showed that a period of approximately 2 months resulted in a high ratio of polychaetes to other invertebrates settling on the devices (data not shown). During each sampling time, three substrata were deployed within the zone impacted by the seawater discharge channel (IA1), two substrata were left at a reference site to the east (CA1) and two substrata were left at a reference site to the south (CA2; Fig. 1). At each of the locations, rocky-reef areas were no more than 5 m from each individual substratum. All of the substrata were deployed during spring low tides, with the buoy just below the water surface. This ensured that the substrata would remain completely submerged during the deployment period and that the substrata would be at approximately the same depth across the different sites. Following the deployment period, the artificial substrata were placed on ice, taken to the laboratory and processed within 48 h. The artificial substrata consisted of a 1.5 × 0.2 m piece of nylon mesh held into the shape of a sphere using a single string clip. They were processed by first severing the clip and drawing out the flat mesh. The mesh was then passed under a dissecting microscope and the polychaetes were removed and preserved in 90% ethanol for identification.

2.4. Statistical analysis

Analysis of variance (ANOVA), residual plots to test for homogeneity of variance and *post-hoc* pairwise comparisons using Tukey's test were processed in Minitab® Statistical Software. PERMANOVA was done using 1000 permutations in the PRIMER 6 and PERMANOVA+ package (Plymouth Routines in Multivariate Ecological Research, version 6). In situations with limited permutations in PERMANOVA, the Monte Carlo method was used to estimate *p* values. All ANOVA and PERMANOVA tests were calculated using the same 3-factored design: Time (3 levels; fixed); CvI (control versus impact; fixed); and Site (2 levels; random and nested within CvsI). Time was not considered a repeated factor because although the samples were taken in the same general area, they were not taken from exactly the same sediment.

An 'indicator species value' was calculated (Dufrêne and Legendre, 1997) to determine which polychaete species might indicate the presence or absence of pollution. The value was calculated using the *indval* command within the R package *labdsv* (Roberts, 2006). A permutation test for significance using 1000 randomisations was completed based on script from Borcard et al. (2011). The advantage of the indicator species value is that it takes into account both the abundance and frequency of species and is calculated individually for each species within the community (Bakker, 2008; Dufrêne and Legendre, 1997).

Multivariate analyses were completed in accordance with Anderson et al. (2008) using the PRIMER 6 and PERMANOVA+ package. The polychaete assemblage data from the soft-bottom and mangrove sites were analysed using canonical analysis of principal coordinates (CAP) based on a Bray–Curtis similarity matrix of square-root transformed polychaete abundance data. CAP was used because in the PERMANOVA analyses significant interactions between the factors were observed and CAP allows the use of the significant interaction as a primary axis for discriminating the

Table 1
Polychaete abundance and species richness and element concentrations and grain size at the soft-bottom sites, averaged for the three sampling times. The values are ± standard error.

Site		D2	D1	CO25	IH6
Depth (m)		11	12	13	6
	Richness[a]	10.5 ± 1.46	5.83 ± 0.638	3.58 ± 0.543	0.667 ± 0.188
	Abundance[a]	15.8 ± 2.36	9.67 ± 1.28	4.17 ± 0.626	0.667 ± 0.188
	Al	**73,200 ± 2170**	**72,500 ± 1020**	65,500 ± 1790	68,400 ± 4370
	As[a]	6.49 ± 0.209	6.69 ± 0.116	6.61 ± 0.283	9.48 ± 0.786
	Cd[a]	0.0647 ± 0.0038	0.0808 ± 0.0034	0.171 ± 0.00951	0.314 ± 0.015
	Co	8.40 ± 0.238	8.32 ± 0.147	7.5 ± 0.240	6.00 ± 0.378
	Cr	19.9 ± 1.22	18.2 ± 1.41	22.3 ± 1.81	22.8 ± 2.71
	Cu	9.8 ± 0.287	10.4 ± 0.297	11.2 ± 0.42	14.5 ± 0.753
	Fe	33300 ± 1050	32500 ± 599	29400 ± 1260	24500 ± 2130
Sediment(mg/kg)	Ga[a]	19.2 ± 0.571	19.1 ± 0.286	20.8 ± 0.558	35.5 ± 2.81
	Mn	239 ± 5.41	241 ± 3.43	235 ± 7.18	185 ± 12.0
	Mo[a]	0.811 ± 0.0487	1.32 ± 0.0917	2.72 ± 0.382	4.46 ± 0.674
	Ni	20.4 ± 0.593	20.6 ± 0.341	19.5 ± 0.67	20.0 ± 1.21
	P	572 ± 16.6	574 ± 10.5	584 ± 26.1	691 ± 52.9
	Pb	16.7 ± 0.486	17.1 ± 0.646	15.9 ± 0.592	13.7 ± 0.819
	U[a]	2.18 ± 0.0594	2.28 ± 0.045	2.41 ± 0.155	2.80 ± 0.215
	V	52.5 ± 1.24	51.8 ± 0.756	50.2 ± 1.88	57.0 ± 3.84
	Zn	41.5 ± 1.20	42.6 ± 0.648	45.1 ± 1.29	72.5 ± 5.17
	TOC (%)	0.93 ± 0.010	0.97 ± 0.017	0.98 ± 0.024	1.37 ± 0.052
	<63 μm (%)	85.6 ± 2.52	93.2 ± 1.19	96.5 ± 0.612	95.3 ± 0.852
	Al[a]	2.51 ± 0.256	2.29 ± 0.279	7.87 ± 2	25.1 ± 3.02
	As[a]	16.7 ± 1.77	20.7 ± 3.77	16.5 ± 3.34	41.2 ± 14.4
	Cd	0.0654 ± 0.016	0.158 ± 0.0335	0.234 ± 0.0595	0.297 ± 0.0759
	Co[a]	0.0951 ± 0.0126	0.0854 ± 0.0123	0.0608 ± 0.00994	0.0916 ± 0.0172
	Cr	0.0552 ± 0.0053	0.0704 ± 0.0056	0.0619 ± 0.0068	0.0361 ± 0.0048
	Cu	0.542 ± 0.135	0.597 ± 0.231	0.203 ± 0.0567	0.0621 ± 0.0123
Porewater(μg/L)	Fe[a]	93.9 ± 39.3	55 ± 33.8	10.5 ± 3.55	13 ± 3.54
	Ga[a]	0.019 ± 0.0017	0.0153 ± 0.0023	0.243 ± 0.0927	1.44 ± 0.241
	Mn	223 ± 37.9	159 ± 43.5	116 ± 14.1	91.5 ± 9.65
	Mo[a]	60.5 ± 18	151 ± 31.9	252 ± 69	323 ± 89
	Ni	2.72 ± 0.536	2.48 ± 0.504	1.72 ± 0.275	2.94 ± 0.42
	P[a]	481 ± 19.2	646 ± 40.5	586 ± 105	170 ± 13.3
	Pb	0.279 ± 0.0975	0.358 ± 0.132	0.257 ± 0.0924	0.238 ± 0.0929
	U	8.71 ± 1.63	9.87 ± 2.16	12.1 ± 2.45	4.16 ± 0.733
	V[a]	4.35 ± 1.02	6.3 ± 1.4	3.1 ± 0.68	2.09 ± 0.316
	Zn[a]	2.66 ± 0.717	2.87 ± 0.642	3.4 ± 0.857	4.14 ± 1.45

*Bold type indicates a significant difference ($p < 0.05$).
[a] Significant interactions observed between the factors, see Figs S1 & S2 for further analysis.

multivariate points (Anderson et al., 2008). The ordination gives the relative importance of the interaction compared to other significant differences in the ordination.

The chemical composition of the sites was analysed using principle component analysis (PCA) based on a Euclidean distance matrix of normalised, log-transformed chemical data. The chemical and polychaete matrices were compared using RELATE and then BioEnv with 1000 permutations.

3. Results

Of 3238 worms collected over the three sampling times (2009–2010), 2919 were identified as polychaetes to species level (species list provided in Appendix). The remaining worms were either not polychaetes, or were unidentifiable (usually because they were poorly preserved), and were removed from the analysis. The soft-bottom, mangrove and artificial substratum habitats all contained different polychaete assemblages and were analysed separately.

3.1. Soft-bottom sites

3.1.1. Chemical analysis of sediments and pore waters

The concentration of aluminium was significantly lower in the impacted sediments but tended to be higher in the impacted pore waters when compared to the reference sites (Table 1). No other metals tested showed significant differences between the reference and impacted treatments, although some trends were observed. The concentrations of molybdenum, cadmium and gallium in the sediments tended to be higher in the sites closer to the discharge channel. The site closest to the discharges (IH6) showed a trend of increasing copper and phosphorous in the sediments, and higher levels of arsenic and zinc. In contrast, the concentrations of iron, manganese and cobalt tended to be lower in the impacted sediments compared to the reference sediments.

In the sediment ANOVAs, significant interactions between the factors were observed for arsenic, cadmium, gallium, molybdenum and uranium concentration in the sediments. This interaction was due to varying concentrations at some sites during the different sampling times (Fig. S1, Table S1). Despite this, the concentrations of arsenic, cadmium, gallium and molybdenum appeared to be higher at the impacted sites relative to the reference sites.

In the porewater ANOVAs, interactions between the factors were observed for aluminium, arsenic, cobalt, iron, gallium, molybdenum, phosphorous, vanadium and zinc. These interactions were again due to variability in the concentrations at some sites during the three sampling times (Fig. S2, Table S1). Nevertheless, the concentrations of aluminium and gallium, and to a lesser extent molybdenum, consistently increased at the impacted sites. On the other hand, the concentrations of arsenic, cobalt, iron, vanadium and zinc did not obviously increase at any of the sites and the differences were probably natural variation based on comparisons to other near-pristine sites in northern Australia (Munksgaard and

Parry, 2002). The concentration of phosphorous in the pore waters was consistently lower at the impacted site, IH6.

In general, the replicate samples taken from the impacted sites showed differences in their metal compositions, especially at site IH6 (Fig. 2). The replicate samples from the control sites had relatively similar metal concentrations in the sediments (Fig. 2A), but there was some variability in their pore waters (Fig. 2B). Generally metal concentrations were higher at the impacted sites and lower at the reference sites.

3.1.2. Soft-bottom chemical temporal variation

The chemical composition of soft-bottom sites varied across the three sampling times (Fig. 3). Specifically, sediments and pore waters collected during the first sampling event (wet 2009) generally contained the highest metal concentrations, and concentrations tended to decrease through the study. In the final sampling event (dry 2010), the sediments and pore waters generally contained the lowest metal concentrations.

3.1.3. Soft-bottom polychaete communities

Polychaete species richness and abundance tended to be lower at sites closer to the seawater discharge channel, although there was no significant difference between the treatments (Table 1).

Differences in the abundances of all species in each sample were analysed using multivariate ordinations and significant differences in the ordinations were detected using PERMANOVA. When permutations were used to test for significance, there was a significant interaction between the sites and the sampling time ($p < 0.05$). When Monte Carlo p values were applied to the data, the control and impact sites were also significantly different ($p < 0.05$). Because there was a significant interaction between the sites and sampling time in the PERMANOVA, canonical analysis of principal coordinates (CAP) was used to explore this interaction further (Fig. 4). Samples taken at the same time from the same sites grouped together, explaining the interaction detected using PERMANOVA. Nevertheless, a clear gradient was seen as the polychaete communities changed toward the seawater discharge channel (Fig. 4).

All of the soft-bottom polychaete species decreased in abundance closer to the discharge channel. The abundance of two species, *Prionospio ehlersi* Fauvel, 1928 (Spionidae) and *Sigambra hanaokai* (Kitamori, 1960; Pilargidae), declined significantly at the impacted sites and had a high indicator species value (Table 2).

3.1.4. Correlation between soft-bottom polychaetes and chemistry

The patterns in the composition of the polychaete communities were compared to the patterns of the sediment and porewater metal concentrations using RELATE. The patterns in the polychaete communities were moderately correlated with patterns in the sediment metal concentrations (Spearman's rho = 0.31; $p < 0.05$) and in the porewater metal concentrations (Spearman's rho = 0.25; $p < 0.05$). BEST was then used to determine the most correlated individual metals with changes in the polychaete assemblage. The sediment metals that were best correlated with patterns in the polychaete assemblages were copper and cadmium (Spearman's rho = 0.42; $p < 0.01$); in the porewater it was gallium (Spearman's rho = 0.36; $p < 0.01$).

3.2. Mangrove sites

3.2.1. Chemical analysis of sediments and pore waters

The concentrations of cadmium, cobalt, iron and zinc were significantly higher in the impacted sediments but unchanged in the impacted pore waters when compared to the reference samples (Table 3). Aluminium concentration in the sediments was significantly higher at the impacted sites relative to the reference sites, however, an interaction in the ANOVA was observed and further examination suggested that the changes were due to natural variation (Fig. S3, Table S2).

The chemical composition of the sediment samples collected at the impacted sites showed some differences when compared to the control sites (Fig. 5A). Specifically, several of the impacted samples separated from the control samples and had higher metal concentrations. Metal concentrations in pore waters from the reference sites were variable, while samples from the impacted sites generally had higher metal concentrations, especially at IM1 (Fig. 5B).

3.2.2. Mangrove chemical temporal variation

The chemical composition of the mangrove sites followed a similar pattern to the soft-bottom sites. The pore waters and sediments collected during the wet season 2009 generally contained the highest metal concentrations, and the dry season 2010 tended to have the lowest metal concentrations (Fig. 6). The porewater metal concentrations during the dry season 2010 were markedly different from the other sampling times, showing an overall reduction in metal levels.

3.2.3. Mangrove polychaete communities

Polychaete abundance and species richness were not significantly different at any sampling sites using ANOVA (Table 3). However, when the data were analysed using multivariate analyses in PERMANOVA, the sampling times were significantly different and there was a significant interaction between the sampling times

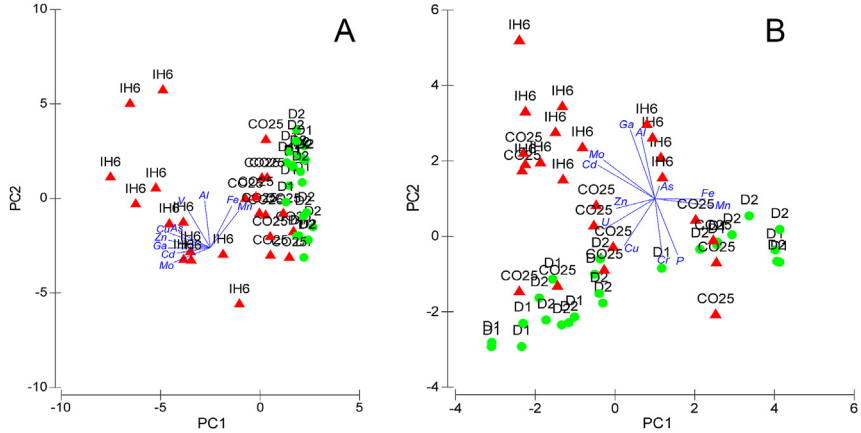

Fig. 2. Principal component analysis (PCA) of element concentrations in the sediments (A) and in the pore waters (B), red triangles indicate impacted sites and green circles indicate reference sites. See Fig. 1 for site locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

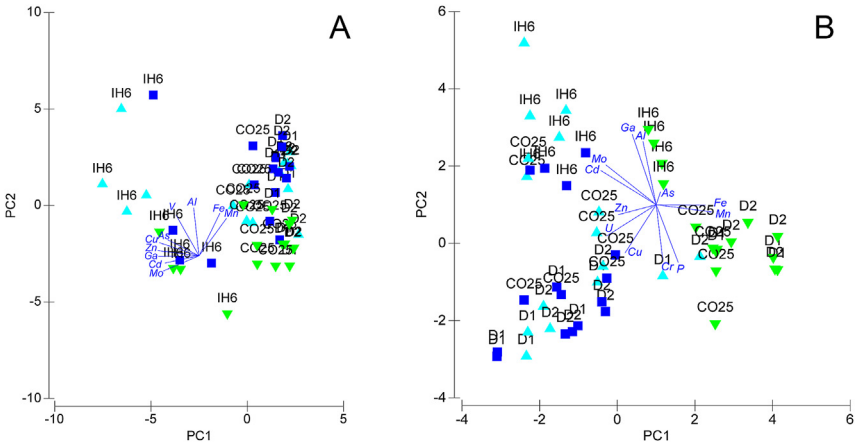

Fig. 3. Principal component analysis (PCA) of element concentrations in the sediments (A) and in the pore waters (B) at the three sampling times, dark blue squares indicate the wet season 2009, light blue triangles indicate the dry season 2009 and the green triangles indicate the dry season 2010. See Fig. 1 for site locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

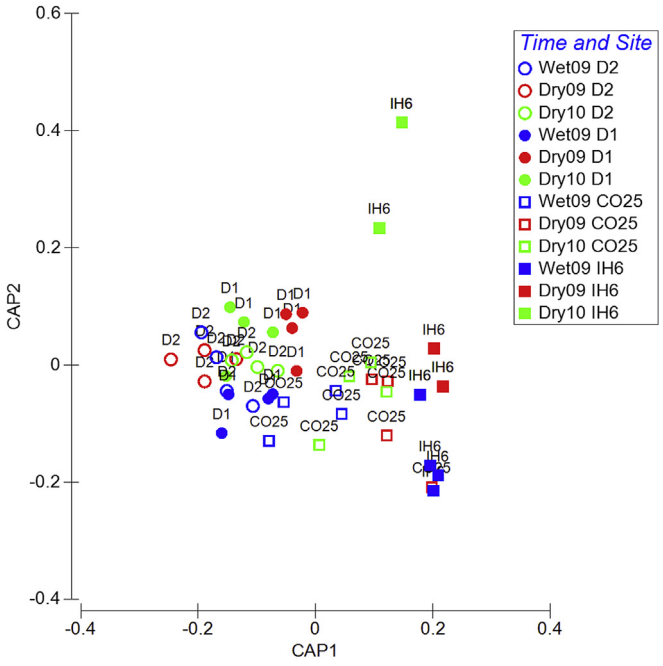

Fig. 4. The relationship between soft-bottom polychaete samples at the four sites and three sampling times, as shown using canonical analysis of principal coordinates (CAP). See Fig. 1 for site locations.

Table 2
Polychaetes that were significantly indicative of pollution based on the indicator species value of Dufrêne and Legendre (1997).

Species	Indicator of	Habitat	Indicator species value	*p* value
Polyophthalmus sp.1 (Opheliidae)	Unpolluted sites	Artificial substrate	88	0.004
Glycinde bonhourei (Goniadidae)	Impacted sites	Mangroves	84	0.001
Eupolymnia koorangia (Terebellidae)	Impacted sites	Artificial substrate	82	0.031
Lumbrinereis sp.1 (Lumbrineridae)	Impacted sites	Mangroves	74	0.001
Prionospio ehlersi (Spionidae)	Unpolluted sites	Soft-bottom	71	0.001
Sigambra hanaokai (Pilargidae)	Unpolluted sites	Soft-bottom	66	0.001

and the sites ($p < 0.05$). Using Monte Carlo p values, the control and impact sites were also significantly different (Monte Carlo $p < 0.05$).

In the PERMANOVA, a significant interaction between the sampling time and the sites was recorded; therefore, canonical analysis of principal coordinates (CAP) was used to explore this interaction further (Fig. 7). The samples that were collected during the same sampling time and from the same sites grouped together, which accounted for the significant PERMANOVA interaction. However, the control and impact sites clearly separated into two groups, verifying that they were significantly different (Fig. 7).

The abundance of two species, *Glycinde bonhourei* Gravier, 1904 (Goniadidae) and *Lumbrinereis* sp.1 (Lumbrineridae), increased significantly at the impacted sites and had a high indicator species value (Table 2).

3.2.4. Correlation between mangrove polychaetes and chemistry

The pattern of polychaete distribution at the mangrove sites was compared to the distribution of metals in the mangrove sediments and pore waters using RELATE. Patterns in the metal concentrations in the sediments were significantly correlated with patterns in the polychaete communities ($p < 0.05$), although the relationship was weak (Spearman's rho = 0.243). The patterns of metals in the pore waters were not correlated with polychaete distributions. In the sediments, changes in the copper and the total organic carbon concentrations were the most correlated with polychaete assemblage changes when analysed using BEST (Spearman's rho = 0.448; $p < 0.01$).

3.3. Artificial substrata

Artificial substrata that were placed at a site where sediment had been impacted by the seawater discharge channel had significantly fewer polychaete individuals than substrata at the reference locations (Table 4). Species richness was also lower, although not significantly (Table 4). Individual substrata tended to contain relatively unique polychaete communities when compared to each other, although substrata placed at control sites separated from those at impacted sites (Fig. 8). The differences in the polychaete communities at the impacted and control sites were compared using PERMANOVA and were found to be significantly different ($p < 0.05$).

The polychaete, *Polyophthalmus* sp.1 (Opheliidae), was an indicator of unpolluted sites, while *Eupolymnia koorangia* Hutchings and Glasby, 1988 (Terebellidae) was more abundant at the polluted sites (Table 2). Few of the polychaete species found on the artificial

Table 3
Polychaete abundance and species richness and element concentrations and grain size at the mangrove sites, averaged for the three sampling times. The values are ± standard error.

Site		CM1	CM2	IM1	IM2
Depth (m)		3	4	3	3
	Richness[a]	19.5 ± 1.41	15 ± 1.02	18.2 ± 1.81	20.3 ± 1.31
	Abundance	48.2 ± 9.59	29.6 ± 4.04	51.7 ± 4.63	65.5 ± 5.6
	Al[a]	61100 ± 2090	61500 ± 4170	**72900 ± 1950**	**70100 ± 2810**
	As	9.05 ± 0.409	7.57 ± 0.711	12.8 ± 1.26	11.9 ± 1.09
	Cd	0.0716 ± 0.00359	0.0807 ± 0.0229	**0.12 ± 0.0306**	**0.101 ± 0.0219**
	Co	6.78 ± 0.236	7.2 ± 0.609	**7.5 ± 0.173**	**7.73 ± 0.281**
	Cr	22.1 ± 2.95	17.1 ± 1.01	19.3 ± 1.38	20.4 ± 2.53
	Cu	8.57 ± 0.409	9.50 ± 1.43	8.78 ± 0.263	8.73 ± 0.449
	Fe	30,500 ± 1360	30,200 ± 1900	**33,300 ± 1620**	**33,900 ± 2130**
Sediment(mg/kg)	Ga[a]	18.5 ± 0.637	18.6 ± 1.24	24.1 ± 0.747	21.5 ± 0.942
	Mn[a]	185 ± 6.09	201 ± 16.1	203 ± 5.12	227 ± 7.84
	Mo	1.30 ± 0.205	0.865 ± 0.0404	1.82 ± 0.184	1.17 ± 0.126
	Ni	22.1 ± 2.19	20.1 ± 1.90	23.9 ± 1.28	22.9 ± 1.40
	P	618 ± 25.5	558 ± 35.6	579 ± 27.4	610 ± 29.6
	Pb	17.8 ± 1.06	17.8 ± 0.889	25.4 ± 4.48	20.8 ± 1.13
	U[a]	2.28 ± 0.108	1.92 ± 0.109	2.57 ± 0.133	2.11 ± 0.0732
	V	54.2 ± 2.10	49.6 ± 2.99	60.4 ± 3.75	58.0 ± 3.82
	Zn	35.9 ± 1.39	36.0 ± 2.55	**40.0 ± 1.50**	**38.9 ± 1.43**
	TOC (%)[a]	1.59 ± 0.174	1.14 ± 0.056	1.44 ± 0.041	1.26 ± 0.034
	<63 μm (%)[a]	1.93 ± 0.539	4.72 ± 0.814	5.78 ± 1.36	4.84 ± 0.966
	Al	3.38 ± 0.958	2.09 ± 0.155	2.99 ± 0.367	2.64 ± 0.401
	As[a]	44.2 ± 9.48	25.5 ± 4.02	36.4 ± 3.04	38 ± 3.57
	Cd	0.0386 ± 0.00716	0.0428 ± 0.00724	0.0684 ± 0.0153	0.0521 ± 0.0139
	Co	0.406 ± 0.12	0.27 ± 0.0552	0.34 ± 0.0877	0.549 ± 0.0612
	Cr	0.295 ± 0.111	0.109 ± 0.0222	0.132 ± 0.0153	0.128 ± 0.0167
	Cu	0.586 ± 0.117	0.571 ± 0.148	0.202 ± 0.0321	0.353 ± 0.0369
	Fe[a]	332 ± 172	34.2 ± 6.66	399 ± 150	526 ± 182
Porewater(μg/L)	Ga	0.0275 ± 0.00455	0.0251 ± 0.00353	0.0598 ± 0.00667	0.0321 ± 0.00598
	Mn	333 ± 45.9	374 ± 50.2	536 ± 156	1050 ± 313
	Mo[a]	20.9 ± 2.48	24.7 ± 3.47	58.7 ± 13.5	26.8 ± 4.23
	Ni	8.23 ± 2.64	4.26 ± 0.81	4.08 ± 0.553	6.34 ± 1.16
	P[a]	1050 ± 285	561 ± 112	572 ± 90.4	669 ± 143
	Pb	0.111 ± 0.0346	0.0927 ± 0.0198	0.0619 ± 0.0197	0.186 ± 0.106
	U[a]	12 ± 1.66	9.14 ± 1.14	14.4 ± 1.81	10.9 ± 0.734
	V[a]	6.63 ± 1.68	4.26 ± 0.761	5.02 ± 0.944	5.37 ± 1.43
	Zn	5.46 ± 2.12	3.18 ± 0.772	2.78 ± 0.502	4.54 ± 1.48

*Bold type indicates a significant difference ($p < 0.05$).
[a] Significant interactions observed between the factors, see Figs S3 & S4 for further analysis.

substrata were also recorded in the soft-bottom and mangrove habitats (see Appendix).

4. Discussion

The largest change in polychaete assemblages was seen for the soft-bottom sites of the inner Gove Harbour of Melville Bay. Here, polychaete abundance at reference sites was approximately 16 individuals per grab but decreased to less than 1 at impacted sites. Species richness was also lower at impacted sites and ordinations showed that the community structure at impacted sites was clearly different from reference sites. The changes in polychaete community structure were moderately correlated with sediment and porewater metal levels, specifically copper and cadmium in the sediment and gallium in the porewater. At the mangrove impacted sites the abundance and species richness of polychaetes were not significantly different between the impacted and control sites, however, ordinations revealed changes in community structure. This may reflect sensitive polychaete species being replaced by more tolerant species at the impacted sites, as has been seen elsewhere (Chen et al., 2010; Ward and Hutchings, 1996).

We measured the concentration of metals in sediments and pore waters at each soft-bottom site but apart from significantly lower aluminium concentration in sediments, there were no significant differences. Molybdenum, cadmium and gallium tended to be higher in impacted soft-bottom sediments. Copper, arsenic, zinc and phosphorus tended to be higher in sediment at the site closest to the discharges. Porewater aluminium, arsenic, gallium and molybdenum concentrations were highest at the site closest to the discharge channel. Iron and phosphorus concentrations were lowest at the same site. The impacted mangrove sites had significantly higher concentrations of aluminium, zinc and cadmium, while gallium also tended to increase. Of these metals, only aluminium, gallium and molybdenum are considered as fingerprint elements of the alumina refinery discharge (Negri et al., 2011).

Although metal concentrations were below ISQG-low trigger values, where available (ANZECC, 2000), the bioavailable concentrations of metals in the sediment and porewater may have been sufficiently high to cause changes in polychaete community structure, as reported for bacteria at these sites (Cornall et al., 2013). The sediment in the inner Gove Harbour of Melville Bay has received inputs of hydrotalcite derived from the alumina refinery effluent which has subsequently lead to increases in total organic carbon, high rates of bacterial sulphate reduction and high sulfide levels (Alongi and McKinnon, 2011; King et al., 2004; Magni et al., 2008). So an alternative explanation is that the sediment at the impacted sites has been altered by the alumina refinery effluent and this has lead to changes in the polychaete community.

Polychaete 'indicator species' that either decrease or increase in abundance at impacted sites can be useful for rapid impact assessments (Dean, 2008). However, suitable indicator species generally need to be found for new regions. We detected several species from

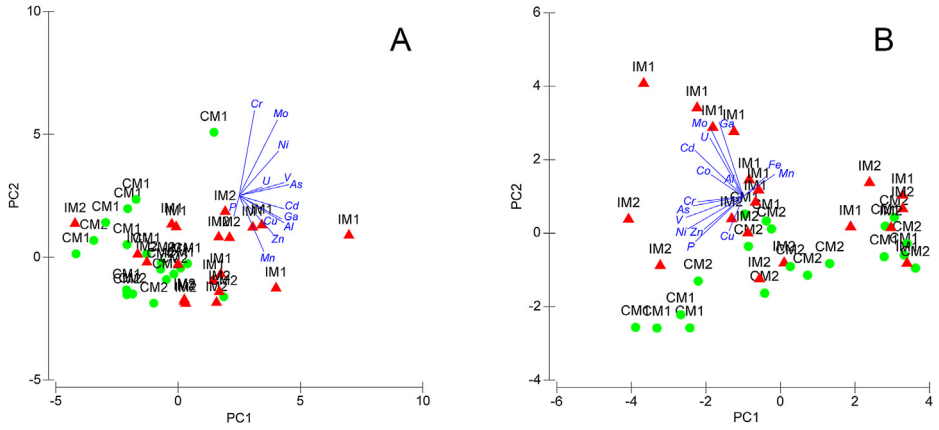

Fig. 5. Principal component analysis (PCA) of mangrove element concentrations in the sediments (A) and in the pore waters (B), red triangles indicate impacted sites and green circles indicate reference sites. See Fig. 1 for site locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

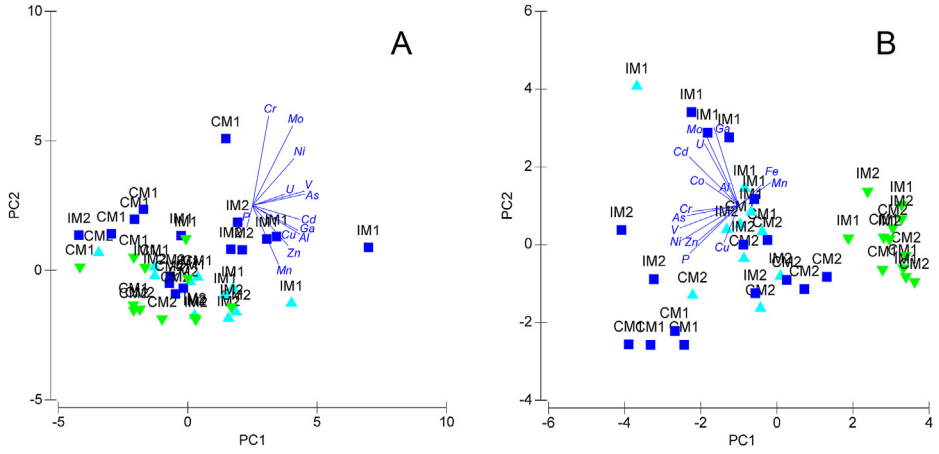

Fig. 6. Principal component analysis (PCA) of element concentrations in the mangrove sediments (A) and in the mangrove pore waters (B) at the three sampling times, dark blue squares indicate the wet season 2009, light blue triangles indicate the dry season 2009 and the green triangles indicate the dry season 2010. See Fig. 1 for site locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

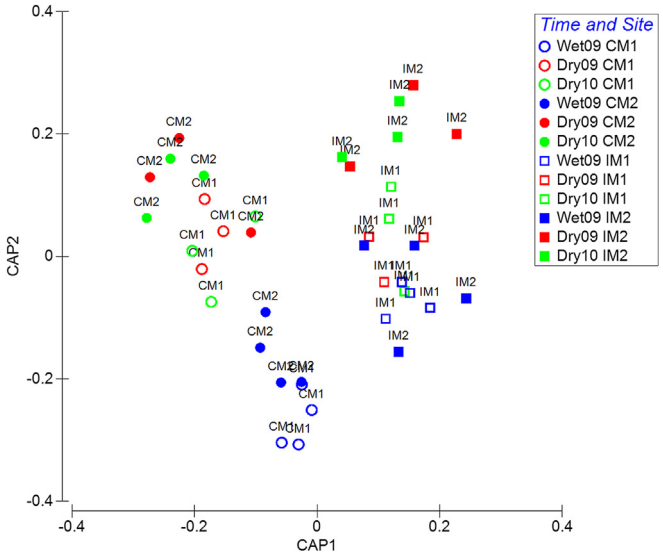

Fig. 7. Canonical analysis of principal coordinates (CAP) showing the relationship between mangrove polychaete samples at the four sites and three sampling times. See Fig. 1 for site locations.

each habitat that may be useful indicator species for Melville Bay. From the soft-bottom assemblages, two polychaete species, *P. ehlersi* (Spionidae) and *S. hanaokai* (Pilargidae), recorded high indicator species values (Dufrêne and Legendre, 1997) and increased in abundance at control sites, however, these results should be treated cautiously. Sediments near the discharge are highly impacted and contain few species, which means that any species abundant at reference sites would record a high indicator value simply because of a large drop in abundance. Interestingly, one polychaete species, *Spiochaetopterus* sp.1 (Chaetopteridae), was found consistently at these highly impacted sites. This species did not record a high indicator species value because its abundance was low overall, nevertheless, an abundance increase for this species may indicate impact. Moreover, this tolerant species may be useful for studying sub-lethal biomarkers at contaminated sites.

At the impacted mangrove sites, polychaete indicator species included families that are opportunistic at organically enriched sites, such as Spionidae, Cirratulidae and Capitellidae (Giangrande et al., 2005; Sukumaran and Devi, 2009). These polychaetes are generally small bodied and probably have a short life span (Souza and Borzone, 2000; Sukumaran and Devi, 2009), which is consistent with many opportunistic species (Grassle and Grassle, 1974; Sukumaran and Devi, 2009). One polychaete species, *G. bonhourei* (Goniadidae), was significantly more abundant in the impacted mangrove sediments and recorded a very high indicator species value of 84. Although the Goniadidae are not thought of as indicator species (Giangrande et al., 2005), this species may be useful in northern Australia marine sediments.

Table 4
Polychaete abundance and species richness on the artificial substrata, averaged for the two sampling times. See Fig. 1 for site locations.

	CA1	CA2	IA1
Richness	7.75 ± 0.854	7.00 ± 0.707	5.6 ± 0.812
Abundance	69.8 ± 18.8	51.8 ± 11.2	**24 ± 7.02**

*Bold type indicates a significant difference ($p < 0.05$).

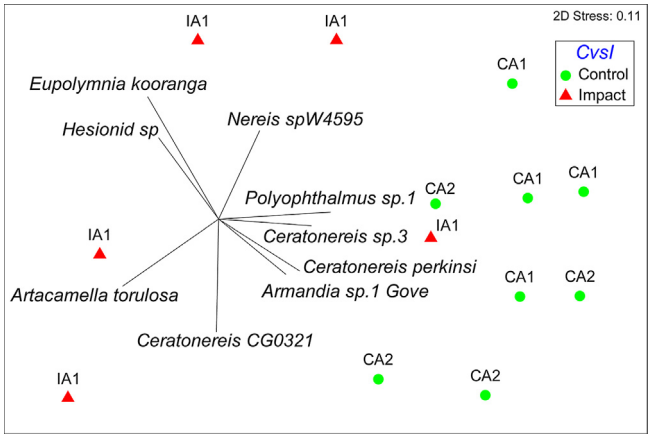

Fig. 8. Multi-dimensional scaling (MDS) plot of the polychaete samples from artificial substrata placed in impact and control sites. The polychaete species that contributed the most to differences between the impact and control sites have been overlayed onto the plot. See Fig. 1 for site locations.

The artificial substrata were composed of 'exfoliating mesh sponges', which were easy to deploy and retrieve, and assessment of the polychaete assemblage was more economical than assessment of the benthic polychaete samples. Polychaetes were easily removed from the artificial substrata and they were less diverse, resulting in rapid identification. In addition, this technique gave very consistent results between sampling periods, which further adds to their utility for routine monitoring. Despite the lower diversity, a clear difference was still seen between impacted and reference sites, i.e. the artificial substrata deployed adjacent to a rocky islet within the zone impacted by the seawater discharge channel, had significantly fewer polychaetes compared to reference sites. Ordinations also showed that community structure changed. The cohort of polychaetes that settled on the artificial substrata was different to the cohort of polychaetes recovered by benthic sampling. The artificial substrata species mostly belonged to the family Nereididae, and many of the species inhabit only hard-substrata (Gómez et al., 1997; Naim, 1988), suggesting that the artificial devices provided a sample of the hard-substratum polychaete assemblage. It is possible that fewer polychaetes were detected at the site nearest the discharge channel because it is in the middle of the contaminated sediment zone, which contained fewer polychaetes (see soft-bottom results), decreasing the number of breeding individuals and thus larvae available for settlement. On the other hand, the majority of artificial substrate settlers are likely to originate from the hard-substrate polychaete community. The artificial substrata placed at reference sites contained, on average, more than 40 specimens of *Polyopthalmus* sp.1 (Opheliidae), whilst at impacted locations their abundance dropped to less than 6. This species also recorded the highest indicator species value in this study (88) making it a potential indicator of changes to communities associated with hard substrates.

5. Conclusion

In each of the soft-bottom sites, mangrove sites and artificial substrata, changes in polychaete communities were detected, which probably resulted from the impacts of refinery discharges on the sediments. We cannot be certain of this as pre-impact data for the inner harbour does not exist and there may be natural differences between the inner and outer harbour due to restricted water circulation and greater productivity in the inner harbour (Alongi and McKinnon, 2011). Several polychaete species were especially sensitive or tolerant, which is an important characteristic of a good indicator group. Sensitive species are required for the early detection of impacts and tolerant species can be used at impacted sites to study sub-lethal biomarkers, such as changes in protein or gene expression. Although changes in the polychaete communities were correlated with changes in the concentration of copper and cadmium in sediments, other factors were probably more important drivers of change, such as degree of anoxia, sulfide concentration and the physical consistency of the sediment. To take account of these factors, we recommend that future studies measure salinity, oxygen and sulfide concentrations, and take more detailed grain size fractionation measurements.

Disclosure and contributions

All authors declare that they have no conflict of interest. MJN conducted the sampling, processed the samples and wrote the manuscript. CJG assisted with sampling and identified the polychaetes. KAM conceived of the sampling strategy and provided the statistical analyses. DLP assisted with site selection and chemical methods and analyses. CS-J aided with site selection and data analyses. KSG assisted with planning, data analyses and project management. All authors edited and approved this manuscript.
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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marenvres.2013.10.005.

Appendix. Polychaete species detected in Melville Bay, Northern Territory, Australia. See Fig. 1 for site locations.

Family	Species	Detected at sites
Ampharetidae	*Amphicteis* sp Darwin	CM1, CM2, IM1, IM2, D1, D2
Ampharetidae	*Auchenoplax* sp.1	CM1, CM2, IM1, IM2
Ampharetidae	*Isolda pulchella*	D2
Amphinomidae	*Pseudeurythoe oculifera*	CM1, CM2, IM1, IM2, D1, D2, CO25
Capitellidae	*Dasybranchus* sp.1 Gove	CM1, CM2, D2
Capitellidae	*Mastobranchus* sp.1 Gove	CM1, CM2, IM1, IM2, D1, D2
Capitellidae	*Mediomastus* sp.1 Gove	CM1, CM2, IM1, IM2, D1, D2
Capitellidae	*Notomastus* sp.2 Gove	CM2
Chaetopteridae	*Chaetopterid* sp.2	CM1
Chaetopteridae	*Spiochaetopterus* sp Gove	CM1, CM2, IM2, D1, D2, CO25, IH6
Chrysopetalidae	*Chrysopetalid* sp.1 Gove	D1, D2

(*continued on next page*)

(*continued*)

Family	Species	Detected at sites
Cirratulidae	*Aphelochaeta* sp.1 Gove	CM1, CM2, IM1, IM2, CO25
Cirratulidae	*Aphelochaeta* sp.2 Gove	IM1, IM2, D1, D2, CO25
Cirratulidae	*Aphelochaeta* sp.3 Gove	IM1
Cirratulidae	*Caulleriella* sp.1 Gove	CM1, CM2, IM1, IM2
Cirratulidae	*Caulleriella* sp.2 Gove	CM1, CM2, IM1, IM2, D2
Cirratulidae	*Caulleriella* sp.3 Gove	CM1, IM1, IM2
Cirratulidae	*Chaetozone* sp.1	CM2
Cirratulidae	*Cirriformia* sp.1	CM1, IM1, IM2
Cirratulidae	*Cirriformia* sp.2	CA2
Cirratulidae	*Monticellina* sp.1	CM1, CM2, IM1, IM2, D1, D2, CO25
Cirratulidae	*Monticellina* sp.2	IM2
Cirratulidae	*Protocirrineris* sp.1 Gove	IM2
Cossuridae	*Cossura* sp.1	D1, D2
Dorvilleidae	*Dorvilleid* sp.2	D2
Dorvilleidae	*Schistomeringos* sp.1 Gove	CM1, CM2, IM1, IM2, D2, CO25, CA2
Eunicidae	*Eunice* sp.1 Gove	CM1, CM2, IM1, IM2
Eunicidae	*Eunice* sp.2 Gove	D2
Eunicidae	*Nematonereis* sp.1 Gove	IM1, IM2
Flabelligeridae	*Piromis* sp	D2
Glyceridae	*Glycera cinnamomea*	CM1
Glyceridae	*Glycera* sp Gove	CM2, D2, CO25
Goniadidae	*Glycinde bonhourei*	CM1, CM2, IM1, IM2, D1
Goniadidae	*Goniada emerita*	CM2
Hesionidae	*Hesionid* sp.2	IM2, D2
Hesionidae	*Parasyllidea* sp.1	CM1, CM2, IM1, IM2, D2
Lumbrineridae	*Lumbrineris* sp.1 Gove	CM1, CM2, IM1, IM2
Magelonidae	*Octomagelona* sp.1	CM1, CM2, IM1, IM2, D1, D2
Magelonidae	*Octomagelona* sp.2	CM1, CM2, IM1, IM2, D1
Maldanidae	*Maldane* sp.1	D2
Maldanidae	*Maldanid* sp.1	CM2, IM2, D2
Maldanidae	*Maldanid* sp.3	CM1
Maldanidae	*Maldanid* sp.4	IM1
Maldanidae	*Maldanid* sp.5	CM1
Nephtyidae	*Micronephtys maryae*	CM1, CM2, D2
Nephtyidae	*Micronephtys sphaerocirrata*	CM1
Nephtyidae	*Nephtys mesobranchia*	CM1, CM2, D1, D2, CO25
Nereididae	*Ceratonereis* CG0321	IA1, CA1, CA2
Nereididae	*Ceratonereis perkinsi*	IA1, CA1, CA2
Nereididae	*Ceratonereis* sp.3	CA1, CA2
Nereididae	*Gymnonereis yurieli*	IM1
Nereididae	*Leonnates persicus*	CM2
Nereididae	*Neanthes cricognatha*	CM2, IM1, IM2, IH6
Nereididae	*Nereis* sp. Gove	D2
Nereididae	*Nereis* spW4595	IA1, CA1, CA2
Nereididae	*Platynereis* sp.1 Gove	IA1, CA1, CA2
Nereididae	*Solomononereis phuketensis*	CM1, IM1, IM2, CO25
Oenonidae	*Arabella* sp.	CM1, CM2, IM2, D2
Oenonidae	*Drilonereis* sp	CM1, D2
Onuphidae	*Diopatra* sp.1 Gove	D1, D2
Opheliidae	*Armandia* sp.1 Gove	CM1, CM2, IM1, IM2, IA1, CA1, CA2
Opheliidae	*Ophelina cyprophilia*	D2
Opheliidae	*Ophelina tessellata*	CM1, CM2, IM1, IM2, D2
Opheliidae	*Polyophthalmus* sp.1	IA1, CA1, CA2
Orbiniidae	*Leitoscoloplos* sp.1 Gove	CM1, IM1, IM2
Orbiniidae	*Leitoscoloplos* sp.2 Gove	IM1, IM2
Orbiniidae	*Leodamas* sp.1 Gove	CM1, CM2, IM1, IM2
Orbiniidae	*Scoloplos* sp.1	CM1, CM1, IM1
Oweniidae	*Oweniid* spp	CM1, CM2, IM1, IM2, D1, D2
Paralacydoniidae	*Paralacydonia* sp	CM1, CM2, D1, D2
Paraonidae	*Acmira* sp.1	CM1, CM2, IM1, D2
Paraonidae	*Paradoneis* sp 1	CM1, CM2, IM1, D2
Paraonidae	*Paraonid* sp.3	CM1, CM2, IM1, IM2
Paraonidae	*Paraonid* sp.4	CM1, CM2, IM1, IM2, D1
Paraonidae	*Paraonid* sp.5	D2
Paraonidae	*Paraonid* sp.6	D2
Paraonidae	*Paraonid* sp.7	D2
Phyllodocidae	*Phyllodocid* sp.1	IM1, IM2
Phyllodocidae	*Phyllodocid* sp.2	CM2, IM2
Phyllodocidae	*Phyllodocid* sp.3	CM1, CA1
Pilargidae	*Ancistrosyllis* cf. *hartmanae*	IM1, D1, D2, CO25
Pilargidae	*Sigambra hanaokai*	CM1, CM2, IM1, IM2, D1, D2, CO25

(*continued*)

Family	Species	Detected at sites
Poecilochaetidae	*Poecilochaetus* sp.1	D1, D2
Polynoidae	*Polynoid* sp.1	CM2, D1
Polynoidae	*Polynoid* sp.2	D1
Polynoidae	*Polynoid* sp.3	CO25
Polynoidae	*Polynoid* sp.4	D1
Sabellidae	*Branchiomma nigromaculata*	IA1, CA1, CA2
Sabellidae	*Sabellid* sp.1	CM1, CM2, IM1, IM2
Sabellidae	*Sabellid* sp.2	CM1
Sabellidae	*Sabellid* sp.3	IM1, IM2
Sabellidae	*Sabellid* sp.4	IM1
Scalibregmatidae	*Scalibregma* sp.1	CM1, IM1, IM2
Scalibregmatidae	*Scalibregmatid* sp.1	CM1, IM1, IM2
Serpulidae	*Vermiliopsis* sp.	CA2
Sigalionidae	*Sthenelais* sp.1 Gove	IM1, D1, D2, CO25, IH6
Spionidae	*Aonides* sp.1 Gove	IM1, IM2
Spionidae	*Paraprionospio* sp.	CM1, CM2, IM1, IM2, D1, D2
Spionidae	*Polydora* sp.1	CM1
Spionidae	*Prionospio cirrifera*	CM1, CM2, IM1, IM2, D1, D2
Spionidae	*Prionospio ehlersi*	IM2, D1, D2, CO25, IH6
Spionidae	*Prionospio* sp.1 Gove	CM1, CM2, IM1, IM2, D1, D2, CO25, IH6
Spionidae	*Prionospio* sp.3 Gove	IM1, IM2, D1, D2, CO25
Spionidae	*Prionospio* sp.4 Gove	CM1, IM1
Spionidae	*Spionid* sp.1	IM1, D2
Sternaspidae	*Sternaspis* sp.1	CM1, IM1, IM2, D1, D2
Syllidae	*Exogoninae* sp.1	CM1, CM2, IM1, IM2
Syllidae	*Exogoninae* sp.2	CM1, IM1, IM2
Syllidae	*Syllid* sp.1	CM1, CM2, IM1, IM2
Syllidae	*Syllid* sp.2	CM1, CM2, IM1, IM2, IA1, CA1, CA2
Syllidae	*Syllid* sp.3	CM1, CM2, IM1, IM2
Syllidae	*Syllid* sp.4	CM1, CM2, IM1, IM2
Syllidae	*Syllid* sp.5	IM1, IM2
Syllidae	*Syllid* sp.6	IM1
Syllidae	*Syllid* sp.7	CM1
Syllidae	*Syllid* sp.8	CM2, IM1, IM2
Syllidae	*Syllid* sp.9	CM1, IM1, IM2
Syllidae	*Syllid* sp.10	CA1
Terebellidae	*Eupolymnia koorangia*	IM2, IA1, CA1, CA2
Terebellidae	*Pista* sp.1	D2
Terebellidae	*Terebellid* sp.2	D2
Trichobranchidae	*Artacamella torulosa*	CM2, IM2, D2, IA1
Trichobranchidae	*Terebellides* sp Gove	CM1, CM2, IM2, D1, D2

References

Alongi, D.M., McKinnon, A.D., 2011. Impact of hydrotalcite deposition on biogeochemical processes in a shallow tropical bay. Mar. Environ. Res. 71, 111–121.

Anderson, M.J., Gorley, R.N., Clark, K.R., 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK.

Bakker, J.D., 2008. Increasing the utility of indicator species analysis. J. Appl. Ecol. 45, 1829–1835.

Borcard, D., Gillet, F., Legendre, P., 2011. Numerical Ecology with R, first ed. Springer, New York, USA.

Chariton, C., Chryssanthi, A., Yiannis, K., 2006. Can polychaetes be used as a surrogate group in assessing ecological quality of soft substratum communities (NE Thermaikos Gulf). Fresenius Environ. Bull 15, 1199–1207.

Chen, K., Tian, S., Jiao, J.J., 2010. Macrobenthic community in Tolo harbour, Hong Kong and its relations with heavy metals. Estuar Coasts 33, 600–608.

Cornall, A.M., Beyer, S., Rose, A., Streten-Joyce, C., McGuinness, K., Parry, D.L., Gibb, K., 2013. HCL-extractable metal profiles correlate with bacterial population shifts in metal-impacted anoxic coastal sediment from the wet/dry tropics. Geomicrobiol J. 30, 48–60.

Dean, H.K., 2008. The use of polychaetes (Annelida) as indicator species of marine pollution: a review. Rev. Biol. Trop. 56, 11–38.

Dufrêne, M., Legendre, P., 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol. Monogr. 67.

Erdfelder, E., Faul, F., Buchner, A., 1996. GPOWER: a general power analysis program. Behav. Res. Meth Ins C 28, 1–11.

Fauchald, K., Jumars, P.A., 1979. The diet of worms: a study of polychaete feeding guilds. Oceanogr Mar. Biol. Annu. Rev. 17, 193–284.

Giangrande, A., Licciano, M., Musco, L., 2005. Polychaetes as environmental indicators revisited. Mar. Pollut. Bull 50, 1153–1162.

Gómez, P., Mercado, J.A., Mitchell, L.M., Salazar-Vallejo, S.I., 1997. Hard bottom Polychaeta in Huatulco and Puerto Angel bays, Oaxaca, Mexico. Rev. Biol. Trop. 45, 1067–1074.

Grassle, J.F., Grassle, J.P., 1974. Opportunistic life histories and genetic systems in marine benthic polychaetes. J. Mar. Res. 32, 253–284.
Hill, N.A., King, C.K., Perrett, L.A., Johnston, E.L., 2009. Contaminated suspended sediments toxic to an Antarctic filter feeder: aqueous- and particulate-phase effects. Environ. Toxicol. Chem. 28, 409–417.
Hind, A.R., Bhargava, S.K., Grocott, S.C., 1999. The surface chemistry of Bayer process solids: a review. Colloids Surf. Physicochem. Eng. Aspects 146, 359–374.
Kalman, J., Smith, B.D., Riba, I., Blasco, J., Rainbow, P.S., 2010. Biodynamic modelling of the accumulation of Ag, Cd, and Zn by the deposit-feeding polychaete *Nereis diversicolor*: inter-population variability and a generalised predictive model. Mar. Environ. Res. 69, 363–373.
King, C.K., Dowse, M.C., Simpson, S.L., Jolley, D.F., 2004. An assessment of five Australian polychaetes and bivalves for use in whole-sediment toxicity tests: toxicity and accumulation of copper and zinc from water and sediment. Arch. Environ. Contam. Toxicol. 47, 314–323.
Liu, Y., Lin, C., Wu, Y., 2007. Characterization of red mud derived from a combined Bayer process and bauxite calcination method. J. Hazard Mater. 146, 255–261.
Magni, P., Rajagopal, S., van der Velde, G., Fenzi, G., Kassenberg, J., Vizzini, S., Mazzola, A., Giordani, G., 2008. Sediment features, macrozoobenthic assemblages and trophic relationships ($\delta^{13}C$ and $\delta^{15}N$ analysis) following a dystrophic event with anoxia and sulphide development in the Santa Giusta lagoon (western Sardinia, Italy). Mar. Pollut. Bull 57, 125–136.
Munksgaard, N.C., Parry, D.L., 2002. Metals, arsenic and lead isotopes in near-pristine estuarine and marine coastal sediments from northern Australia. Mar. Fresh Res. 53, 719–729.
Naim, O., 1988. Distributional patterns of mobile fauna associated with *Halimeda* on the Tiahura coral-reef complex (Moorea, French Polynesia). Coral Reefs 6, 237–250.
Negri, A.P., Harford, A.J., Parry, D.L., van Dam, R.A., 2011. Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 2. The early life stages of the coral *Acropora tenuis*. Mar. Pollut. Bull 62, 474–482.
Olsgard, F., Brattegard, T., Holthe, T., 2003. Polychaetes as surrogates for marine biodiversity: lower taxonomic resolution and indicator groups. Biodivers Conserv 12, 1033–1049.
Osman, I.H., Gabr, H.R., Saito, H., El-Etreby, S.G., 2010. Reproductive biology of the highly commercial polychaetes in the Suez Canal. J. Mar. Biol. Assoc. U K 90, 281–290.
Pagliosa, P.R., 2005. Another diet of worms: the applicability of polychaete feeding guilds as a useful conceptual framework and biological variable. Mar. Ecol. 26, 246–254.
Pocklington, P., Wells, P.G., 1992. Polychaetes, key taxa for marine environmental quality monitoring. Mar. Pollut. Bull 24, 593–598.
Rainbow, P.S., Smith, B.D., Luoma, S.N., 2009. Biodynamic modelling and the prediction of Ag, Cd, and Zn accumulation from solution and sediment by the polychaete *Nereis diversicolor*. Mar. Ecol. Prog. Ser. 390, 145–155.
Ramskov, T., Forbes, V.E., 2008. Life history and population dynamics of the opportunistic polychaete *Capitella* sp.1 in relation to sediment organic matter. Mar. Ecol. Prog. Ser. 369, 181–192.
Roberts, D.W., 2006. Labdsv: Laboratory for Dynamic Synthetic Vegephenomenology. R Package, Version 1.4.
Smith, H.D., Parkinson, G.M., Hart, R.D., 2005. In situ absorption of molybdate and vanadate during precipitation of hydrotalcite from sodium aluminate solutions. J. Cryst. Growth 275, 1665–1671.
Smith, S.D.A., Rule, M.J., 2002. Artificial substrata in a shallow sublittoral habitat: do they adequately represent natural habitats or the local species pool? J. Exp. Mar. Biol. Ecol. 277, 25–41.
Souza, J.R.B., Borzone, C.A., 2000. Population dynamics and secondary production of *Scolelepis squamata* (Polychaeta: Spionidae) in an exposed sandy beach of southern Brazil. Bull Mar. Sci. 67, 221–233.
Sukumaran, S., Devi, K.S., 2009. Polychaete diversity and its relevance in the rapid environmental assessment of Mumbai Port. Curr. Sci. 97, 1439–1444.
Underwood, A.J., Chapman, M.G., 2006. Early development of subtidal macrofaunal assemblages: relationships to period and timing of colonization. J. Exp. Mar. Biol. Ecol. 330, 221–233.
Ward, T.J., Hutchings, P.A., 1996. Effects of trace metals on infaunal species composition in polluted intertidal and subtidal marine sediments near a lead smelter, Spencer Gulf, South Australia. Mar. Ecol. Prog. Ser. 135, 123–135.
Waring, J., Maher, W., 2005. Arsenic bioaccumulation and species in marine Polychaeta. Appl. Organomet. Chem. 19, 917–929.