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Macrobenthic communities in Hong Kong waters: Comparison between 2001 and 2012 and potential link to pollution control



Zhi Wang^a, Kenneth M.Y. Leung^b, Xinzheng Li^{c,d,e}, Tong Zhang^f, Jian-Wen Qiu^{a,g,*}

^a Department of Biology, Hong Kong Baptist University, Kowloon, Hong Kong, China

^b The Swire Institute of Marine Science, School of Biological Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China

^c Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China

^d University of Chinese Academy of Sciences, Beijing 100029, China

^e Laboratory of Marine Biology and Biotechnology, Qingdao National Laboratory for Marine Science and Technology, 1 Wenhai Road, Qingdao 266071, China

^f Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, China

^g State Key Laboratory in Marine Pollution (SKLMP), City University of Hong Kong, Kowloon, Hong Kong, China

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ABSTRACT

Macrobenthic communities in 2001 and 2012 were compared across the marine environment of Hong Kong based on sediment grab samples collected from 28 stations. CLUSTER analysis showed in both surveys that the stations could be divided into four groups at 20% faunal similarity. However, there were notable changes in the macrobenthic community structure between 2001 and 2012 in three focal areas of pollution control (i.e., Victoria Harbour, Deep Bay and Tolo Harbour). The potential link between macrobenthos and pollution abatement measures, and the contributions of environmental conditions to the differential responsiveness of macrobenthos were explored. Notably, a reduction in nutrient input to the eastern part of Victoria Harbour might have led to recovery of benthic communities therein.

1. Introduction

Macrobenthos are widely used as bioindicators in marine pollution monitoring due to their limited motility and responsiveness to pollutant loading (Snelgrove and Butman, 1994; Magni et al., 2009). Different types of sediment are usually inhabited by macrobenthos of different life-history traits (Gray and Pearson, 1982; Gray et al., 1990), and their changes in abundance and species composition could correspond to the loading of pollutants (Warwick and Pearson, 1987; Clarke and Green, 1988; Wildsmith et al., 2011). For instance, along a gradient of organic pollution from highly polluted to pristine sites, macrobenthic community usually changes from a dominance of few opportunistic species to a diverse fauna (Pearson and Rosenberg, 1978); therefore, determining their community structure can reveal the status of organic pollution in the sediment. Nevertheless, there is limited knowledge on the recovery of degraded benthic communities from cessation of organic enrichment (Sanz-Lázaro and Marin, 2006; Shin et al., 2008). Although it is generally assumed that recovery in low latitude, tropical areas is rapid due to the dominance of short-living opportunistic species (Santos and Simon, 1980; Wu, 1982; Lu and Wu, 2000), other forms of disturbances in tropical marine systems such as storm and dredging may affect benthic community, making it difficult to detect the recovery from

organic enrichment (Shin, 1989; Qian et al., 2003; Cheung et al., 2008).

Assessment of benthic community changes caused by various human activities requires baseline data on the abundance, species composition, and community structure. However, such updated data are generally lacking in Hong Kong (Shin and Thompson, 1982; Shin et al., 2004). In this study, we therefore conducted a territory-wide survey of macrobenthic communities in 2012, and compared with data collected in 2001 (Shin et al., 2004) to provide an updated baseline, and identify areas that might have undergone substantial faunal changes. The period between 2001 and 2012 was interesting because several organic pollution control projects had either been completed or under construction (Nicholson et al., 2011). Around Victoria Harbour, Stage I of the Harbour Area Treatment Scheme (HATS) which aimed to collect and treat 75% of the sewage generated by an urban population of 4.5 million inhabiting the area, was commissioned in December 2001 (Shin et al., 2008; Xu et al., 2011). Under this scheme, sewage collected from Kowloon and northeastern Hong Kong Island was conveyed to the Stonecutters Island through deep tunnels, treated there and discharged to the western part of Victoria Harbour through a submarine outfall (Fig. 1). In the Tolo Harbour area, implementation of the Tolo Harbour Action Plan, especially the export of effluent from the Sha Tin and Tai Po Sewage Treatment Works to Victoria Harbour, had resulted in a reduction in total nitrogen load of 6000 kg d⁻¹ in 1987 to

* Corresponding author at: Department of Biology, Hong Kong Baptist University, 224 Waterloo Road, Hong Kong.
E-mail address: qiuwj@hkbu.edu.hk (J.-W. Qiu).

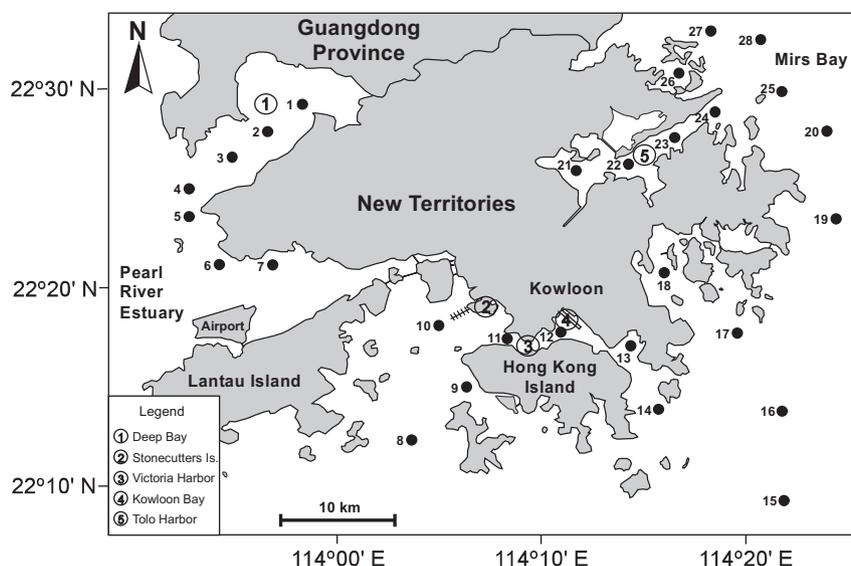


Fig. 1. A map of Hong Kong showing the 28 studied stations. Several places mentioned in the main text are marked with a circled number: Deep Bay (①); Stonecutters Island (②); Victoria Harbour (③); Kowloon Bay (④); Tolo Harbour (⑤).

600 kg d⁻¹ after 1998 (Shin, 2003). Deep Bay, which receives freshwater discharges from rivers in New Territories of Hong Kong to the south and Shenzhen to the north, has suffered from serious organic pollution since the 1980s (Qiu, 1999; Xu et al., 2010). The Hong Kong and Shenzhen governments have implemented various pollution control measures in recent decades, especially the Deep Bay (Shenzhen Bay) Water Pollution Control Joint Implementation Program (DSD, 2009; Zhao et al., 2014).

In the present study, we aimed to test the hypothesis that the macrobenthic communities would display considerable temporal changes in these three focal areas (i.e., Victoria Harbour, Tolo Harbour and Deep Bay) where pollution control intervention measures had been implemented. We expected more changes in macrobenthic community in both harbours than in Deep Bay due to the complicated issue of controlling trans-border pollution. In addition, we aimed to understand how the changes in sedimentary parameters might have restructured the benthic communities.

2. Materials and methods

2.1. Study area and field sampling

Samples were collected on 5–8 June 2012 from 28 stations covering the entire Hong Kong waters that are different in hydrology and human impact (Fig. 1). The station localities and numbers corresponded to a subset of stations in the Environmental Protection Department (EPD)'s regular sediment monitoring program (EPD, 2012). The stations were located by differential Global Positioning System (GPS) and the water depths determined by echo sounding. At each station, five sediment samples were collected using a 0.1 m² van Veen grab for faunal analysis, and one sediment sample was collected for sediment analysis. The sediment samples for faunal analysis were gently rinsed through a 0.5 mm sieve. The residues retained on the sieve were carefully transferred into plastic containers and preserved in 5% formalin in seawater stained with 1% Rose Bengal. For sediment analysis, approximately 400 g of each sediment sample was kept in a Ziplock bag and placed on ice in a cooler on board the survey vessel, and stored at -20 °C in a refrigerator after the samples were transported to Hong Kong Baptist University.

2.2. Faunal analysis

For faunal analysis, sediment residues retained on the sieve were

sorted, and macrobenthos were transferred to 70% ethanol and later identified to the lowest possible taxonomic level. Specimens with an anterior fragment were counted to determine the abundance, and biomass was determined as ethanol-preserved wet weight using a SHIMADZU AUW220 electronic balance after the sample was blotted dry with a paper towel. To facilitate the determination of temporal changes in macrobenthic fauna, 28 of the 120 stations sampled in 2001 by Shin et al. (2004) that overlapped with our 28 stations were included in the analysis. Since Shin et al. (2004) showed that samples collected in summer (June–July) and winter (November–December) of the same year showed substantial differences in abundance and composition, we used their summer dataset only to avoid the confounding effect of season.

2.3. Sediment analysis

Several sedimentary parameters were analyzed to understand their influence on the faunal structure. The sediment samples were freeze-dried. For determination of total organic matter (TOM) content, approximately 20 g freeze-dried sediment from each sample was treated with 35% H₂O₂ overnight, dried at 100 °C to constant weight and combusted at 500 °C for 8 h in a muffle furnace. The content of TOM was calculated as the loss in weight after combustion, as compared with the weight after drying at 100 °C. Data for other sedimentary parameters, including chemical oxygen demand (COD), electrochemical potential (EP), silt and clay (S & C) content, total carbon (TC) content, total Kjeldahl nitrogen (TKN) content and total sulphide (TS) content were obtained from the Environmental Protection Department (Table 1).

2.4. Statistical analysis

Faunal data from the five grab samples of each station were pooled for calculation of univariate and multivariate community parameters. Univariate diversity parameters (i.e., Shannon-Wiener diversity index and Pielou's evenness index) were calculated for each station. Based on the species-abundance data, the stations were grouped using CLUSTER analysis, followed by non-metric multi-dimensional scaling (MDS) to spatially depict the relationships among the stations.

CLUSTER analysis was carried out based on the Bray-Curtis coefficient values between every pair of stations (Clarke and Warwick, 2001). The Bray-Curtis coefficient is a commonly used coefficient to describe the

Table 1

Major biological and environmental characteristics of the 4 station groups in the 2001 and 2012 surveys. Whenever there are replicates, data are presented as mean \pm standard deviation. Note that in the 2012 survey, group B had only one station.

No. stations		A	B	C	D
		2001	2001	2001	2001
		2012	2012	2012	2012
Biological parameters					
No. individuals	2001	104.9 \pm 75.8	3048.1 \pm 4184.5	463.2 \pm 642.7	26.6 \pm 17.6
	2012	218.2 \pm 378.6	2166.0	48.5 \pm 2.1	11.3 \pm 6.1
No. species	2001	33.8 \pm 16.9	43.0 \pm 8.5	20.0 \pm 10.1	7.6 \pm 4.2
	2012	29.9 \pm 14.3	77.0	12.5 \pm 2.1	4.0 \pm 1.73
Species diversity (<i>H'</i>)	2001	2.92 \pm 0.46	1.83 \pm 0.86	1.74 \pm 0.82	1.13 \pm 0.93
	2012	2.50 \pm 0.71	3.06	1.92 \pm 0.14	1.15 \pm 0.44
Species evenness (<i>J</i>)	2001	0.85 \pm 0.05	0.48 \pm 0.20	0.59 \pm 0.28	0.61 \pm 0.34
	2012	0.76 \pm 0.18	0.71	0.76 \pm 0.01	0.85 \pm 0.12
Percent polychaetes	2001	69.4 \pm 18.4	46.5 \pm 48.5	66.5 \pm 35.4	69.7 \pm 21.9
	2012	69.7 \pm 21.4	43.7	73.1 \pm 26.8	47.7 \pm 31.1
Percent molluscs	2001	4.9 \pm 6.1	21.9 \pm 24.2	26.4 \pm 37.6	28.0 \pm 22.0
	2012	7.8 \pm 8.0	32.7	19.7 \pm 22.2	48.6 \pm 29.1
Percent crustaceans	2001	8.4 \pm 7.5	7.1 \pm 9.9	2.7 \pm 1.9	0
	2012	7.2 \pm 8.6	23.3	2.1 \pm 2.9	0
Percent echinoderms	2001	6.6 \pm 8.6	0.1 \pm 0.1	3.0 \pm 5.6	0
	2012	4.4 \pm 7.9	0.2	0	3.7 \pm 6.4
Percent minor taxa	2001	10.7 \pm 9.7	24.4 \pm 34.3	1.4 \pm 2.0	2.3 \pm 2.8
	2012	10.8 \pm 14.7	0.1	5.1 \pm 1.6	0
Biomass (g)	2001	15.70 \pm 35.49	390.31 \pm 425.71	61.24 \pm 83.02	3.86 \pm 4.68
	2012	19.01 \pm 21.13	1407.12	4.59 \pm 4.24	1.25 \pm 1.08
Environmental parameters					
Chemical oxygen demand (mg/kg)	2001	14,250 \pm 3066	11,150 \pm 5445	15,600 \pm 1817	19,000 \pm 1414
	2012	11,205 \pm 2234	22,000	14,000 \pm 1414	17,000 \pm 4000
Electrochemical potential (mV)	2001	-173.7 \pm 75.4	-395.5 \pm 36.1	-167.8 \pm 46.3	-267.6 \pm 89.0
	2012	-180.0 \pm 96.7	-345.0	-72.0 \pm 28.3	-245.7 \pm 53.5
Silt & clay (% w/w)	2001	88.0 \pm 10.2	31.0 \pm 1.4	74.4 \pm 20.9	89.2 \pm 17.0
	2012	75.0 \pm 21.1	94.0	49.0 \pm 18.4	85.7 \pm 14.3
Total Carbon (% w/w)	2001	0.69 \pm 0.17	0.75 \pm 0.07	0.52 \pm 0.04	0.80 \pm 0.07
	2012	0.73 \pm 0.21	1.00	0.60 \pm 0.00	0.77 \pm 0.06
Total Kjeldahl nitrogen (mg/kg)	2001	426.3 \pm 132.2	350.0 \pm 14.1	324.0 \pm 80.2	614.0 \pm 81.4
	2012	515.9 \pm 133.6	750.0	480.0 \pm 70.7	660.0 \pm 43.6
Total sulphide (mg/kg)	2001	62.6 \pm 57.6	220.0 \pm 42.4	139.8 \pm 171.6	125.2 \pm 85.7
	2012	32.8 \pm 58.7	360.0	25.0 \pm 15.6	150.7 \pm 126.8
Total organic matter (% w/w)	2001	6.44 \pm 1.91	7.50 \pm 6.34	5.48 \pm 1.28	8.82 \pm 0.25
	2012	5.17 \pm 2.13	3.21	3.86 \pm 1.03	9.68 \pm 1.37
Depth (m)	2001	20.0 \pm 7.5	16.5 \pm 0.7	9.5 \pm 8.4	18.4 \pm 4.1
	2012	18.8 \pm 9.2	12.2	1.9 \pm 1.1	13.0 \pm 5.0

similarity between biological communities, which measures the similarities contributed by both species and abundance between two samples (Bray and Curtis, 1957). Since similarities may be over-dominated by a few high abundant species in both samples, the original abundance data were fourth-root transformed to down-weight the abundant species before applying the CLUSTER procedure. In the present study, we used the group-average mode to successively group samples. The significance within each group was tested by the SIMPROF procedure with 5% significant level and 999 simulations.

MDS is an ordination technique used to visually assess the similarities of samples. This technique aims to capture the dissimilarities of the original data matrix with distances in a low dimensional ordination (Clarke and Warwick, 2001). The PRIMER software provided a non-parametric regression of distances on dissimilarities among the samples, with *Stress* value calculated to show the matching degree of the regression (Kruskal, 1964).

The similarity percentage (SIMPER) routine was further applied to quantify the contributions of different species to the similarities within each faunal group. Multi-collinearity was conducted for the various sediment parameters, with parameters having a variance inflation factor ($VIF = 1 / (1 - R^2)$) > 10 being considered to have clear evidence of collinearity (Neter et al., 1990). The BEST procedure using the BIOENV method was applied to calculate the Spearman rank correlation between benthic community and sediment quality parameters with no collinearity using the fourth-root transformed abundance data and square-root transformed environmental data. The

univariate and multivariate analyses were conducted using the software package PRIMER 6 (Clarke and Gorley, 2006). To compare the biological and environmental parameters, a paired *t*-test was performed with the software SPSS 17.0.

3. Results

A total of 7095 specimens were collected in the 2012 survey, including 266 taxa from 116 families in 9 phyla. Among the 266 taxa, 252 were identified to species or genus level and 14 to family or higher level. The most diverse taxon was Annelida (127 polychaetes), followed in descending order by Crustacea (60 species), Mollusca (41 bivalves, 13 gastropods, 1 polyplacophoran, 1 scaphopod), Echinodermata (14 species) and five minor phyla (9 species). Polychaetes, crustaceans and bivalves were numerically dominant, comprising 69.7%, 12.8% and 6.8% of the specimens, respectively.

A total of 11,822 specimens were collected in the 2001 survey from the 28 stations, including 255 taxa from 101 families in 10 phyla. Among the 255 taxa, 247 were identified to species or genus level and 8 to family or higher levels. The most diverse taxon was Annelida (144 polychaetes and 1 oligochaete), followed in descending order by Mollusca (29 bivalves, 8 gastropods and 1 polyplacophoran), Crustacea (37 species), Echinodermata (13 species) and six minor phyla (22 species). Polychaetes, bivalves, oligochaetes, and crustaceans were numerically dominant, comprising 34.6%, 33.6%, 24.7% and 4.0% of the specimens, respectively.

From 2001 to 2012, the mean abundance per station declined from

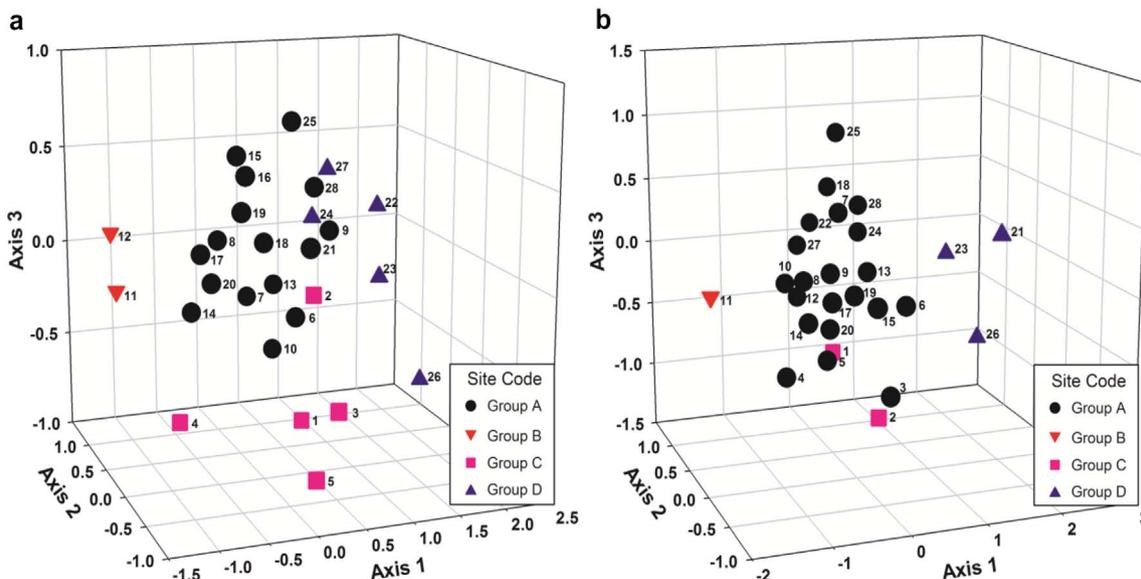


Fig. 2. Non-metric MDS configuration (*Stress* = 0.13) cover 28 stations in the 2001 (a) and 2012 (b) survey, four site groups independently overlaying CLUSTER in 2001 and 2012 survey at similarity level of 20%.

365 to 253 individuals, which was mainly due to the decline in the abundance in two stations (Supplementary data Fig. S1). Specifically, in station 1, the reduction in total number of specimens in 2012 survey was mainly due to the decline in the abundance of the bivalve *Potamocorbula laevis* from 1430 individuals to 0. Similarly, in station 12, there was a remarkable decline in the abundance of the oligochaete *Thalassodrilides gurwitschi* from 2920 individuals to 0 individual, and of the bivalve *Ruditapes philippinarum* from 2338 individuals to 0 individual. No substantial decline in abundance was apparent in other stations. In association with the decline in the respective dominant species from 2001 to 2012, station 1 showed a remarkable increase in *H'* from 0.45 to 1.82, and *J* from 0.20 to 0.80, respectively. Station 12 also showed a remarkable increase in *H'* from 1.23 to 2.92, and *J* from 0.34 to 0.75, respectively.

Results of CLUSTER analysis based on species abundance data showed that, at 20% similarity, the 28 stations could be clustered into four station groups in both the 2001 and 2012 surveys (Supplementary material Fig. S2). These groups were broadly consistent between the two surveys, but there were notable differences within each group, which are shown more nicely in MDS plots, calculated based on the same abundance-species matrix.

Three-dimensional MDS plots showing the similarities among the stations had low *Stress* values (0.12 for the 2001 survey and 0.13 for the

2012 survey), indicating their good representation of the data (Fig. 2). There were distinct spatial patterns in station grouping (Fig. 3): group A included most of the stations distributed throughout the study area; group B included 2 stations (11 and 12) in Victoria Harbour in 2001 and only one station (station 11) in 2012; group C had 5 stations (1, 2, 3, 4 and 5) in the Deep Bay area in 2001 and 2 stations in 2012; group D had 5 stations (22, 23, 24, 26 and 27) in the Tolo Harbour and western Mirs Bay area in 2001 and 3 stations (21, 23, and 26) in 2012. The station grouping was very similar between the two surveys, with the majority of stations being clustered in group A. However, there were notable changes in the other smaller groups from 2001 to 2012, with the number of stations in the smaller groups reduced and most of those with changed station grouping were merged into group A.

The station groups were also distinct in environmental characteristics and univariate biological parameters (Table 1). Group A, which including the majority of stations, had the highest mean depth, and relatively low total organic matter (TOM), total sulphide (TS), total carbon (TC), and chemical oxygen demand (COD). The bottom sediment was fine, and it supported the highest species diversity and evenness. The macrobenthic fauna was dominated numerically by polychaetes (69.7% in the 2012 survey, and 69.4% in the 2001 survey), followed by crustaceans and molluscs. Group B, located in Victoria Harbour, had a sandy bottom that supported the highest number of

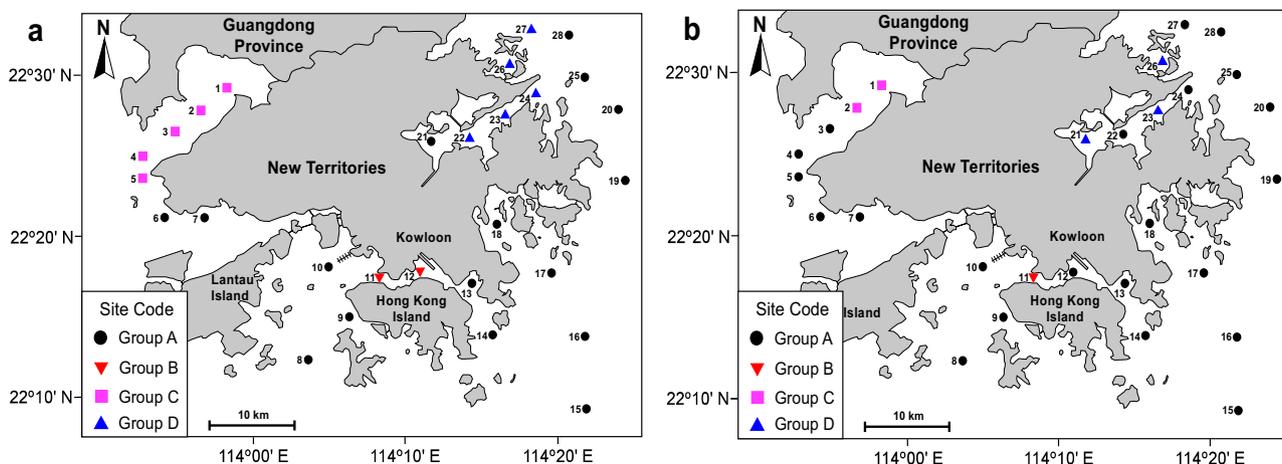


Fig. 3. Geographic distribution of the station groups in Hong Kong waters from 2001 (a) and 2012 (b) data, overlaying CLUSTER at similarity level of 20%.

Table 2

Results of BIOENV procedures, showing the best matches of biotic and environmental similarity matrices, as measured by spearman rank correlation (Corr.). Variables includes: 1, Chemical oxygen demand; 2, Electrochemical potential; 3, Silt & clay; 4, Total carbon; 5, Total Kjeldahl nitrogen; 6, Total sulphide; 7, Total organic matter.

2001			2012			
No.	No. vars	Corr.	Selections	No. vars	Corr.	Selections
1	5	0.597	1–3, 5, 6	3	0.534	1, 2, 7
2	6	0.587	1–3, 5–7	2	0.533	1, 7
3	4	0.586	2, 3, 5, 6	4	0.525	1, 2, 6, 7
4	5	0.578	2, 3, 5–7	3	0.514	1, 6, 7
5	4	0.578	1–3, 6	5	0.510	1, 2, 5–7
6	5	0.576	1–3, 6, 7	3	0.505	2, 6, 7
7	6	0.575	1–6	4	0.498	1, 2, 5, 7

species, number of individuals and biomass, but the lowest evenness in both surveys. This group was co-dominated by polychaetes and molluscs. The highest TS in both 2001 and 2012, highest TC, total Kjeldahl nitrogen (TKN) and COD in 2012 were noted in this group. Group C, located in the relatively shallow Deep Bay area with a bottom of fine sediment, had intermediate values of species number but low diversity. This group was co-dominated by polychaetes and molluscs in 2001 but polychaetes only in 2012. Relatively low TOM, TS, TKN, TC, and high electrochemical potential (EP) were noted in this group. Group D, situated in Tolo Harbour and western Mirs Bay with a bottom of fine sediment, had an impoverished fauna with the lowest number of species, number of individuals, and biomass. This group had the highest TOM, and high TKN, TC, and COD in both the 2001 and 2012 surveys among the four station groups.

There was no apparent multi-collinearity ($VIF < 5$) among the eight environmental parameters used, therefore all these parameters were used to analyze the correlation with macrobenthic community structure. The results of BIOENV (Table 2) showed that the four station groups described from the CLUSTER analysis were correlated with five environmental variables in 2001, including COD, EP, silt and clay (S & C), TKN, and TS (Spearman rank coefficient = 0.597, no. permutations = 999, $P < 0.001$), with EP being the single variable that best explained the grouping (Spearman rank coefficient = 0.405, no. permutations = 999, $P < 0.001$). In 2012, the CLUSTER result had high correlation with COD, EP, and TOM (Spearman rank coefficient = 0.534, no. permutations = 999, $P < 0.001$), and TOM was the single variable which best explained the faunal grouping (Spearman rank coefficient = 0.382, no. permutations = 999, $P < 0.001$).

Table 3 summarizes the results of SIMPER analysis showing species with > 50% cumulative contribution to station group similarities. In all station groups of the two surveys, polychaetes had the highest contribution to the similarities. In particular, the polychaete *Sigambra hanaokai* was a significant contributor to the similarity of stations within groups A, C and D. Group A was primarily represented by several species of small polychaetes, especially *Micronephthys oligobranchia*, *Sigambra hanaokai*, *Mediomastus* sp. and *Paraprionospio pinnata*. Group B with two stations in the 2001 survey was mainly represented by seven species of polychaetes with *Cirratulus* sp. and *Schistomeringos rudolphi* being the most dominant, and the bivalve *Ruditapes philippinarum*. With station 12 being merged to group A in 2012, group B had station 11 as the only station, which was still characterized by high abundance of *R. philippinarum* and high polychaete diversity. Group C was mainly represented by two species of polychaetes (*Heteromastus filiformis*, *S. hanaokai*) and the bivalve *Potamocorbula laevis*. Group D was primarily represented by the polychaete *Sigambra hanaokai* in both surveys. Although polychaetes were dominant in most station groups in both years, the bivalve *Ruditapes philippinarum* was also dominant in group B in both years, and so was the bivalve *Potamocorbula laevis* in group C in 2001. Moreover, due to their relatively heavy weight, these two species of bivalves were the most important contributors to the overall biomass of the two station groups, respectively.

To understand the changes in faunal composition between the two surveys, we compared the faunal and sedimentary data for the eight stations (3, 4, 5, 12, 21, 22, 24 and 27) that had changed their group assignment between 2001 and 2012. Station 3 and station 4 showed low abundance for all species in both surveys, and there was an increase in the abundance of the clam *Potamocorbula laevis* from 0 individual in 2001 to 25 individuals in 2012, and the crab *Xenophthalmus pinnotheroides* from 0 individual to 140 individuals. At station 5, there was a remarkable increase in the small opportunistic polychaete *Paraprionospio pinnata* from 0 individual to 1712 individuals. At these three stations located outside Deep Bay, sedimentary TOM ranged from 3.5% to 6.4% in 2001, and 3.5% to 4.5% in 2012. However, there was no significant difference in TOM between the two surveys ($P > 0.05$). At station 12 inside Victoria Harbour, there was dramatically decline in the abundance of the clam *Ruditapes philippinarum* and the oligochaete *Thalassodrilides gurwitschi* from 2338 and 2920, respectively, in 2001 to complete absence in 2012. During this period, the sedimentary TOM of station 12 decreased dramatically from 11.98% to 3.74%, and total sulphide from 250 mg/kg to 12 mg/kg. At station 21, there was a decline in the number of species from 22 in 2001 to 6 in 2012. During this period, the sedimentary TOM, TS and EP increased from 5.8% to 8.1%, 200 mg/kg to 290 mg/kg, and -362 mV to -185 mV, respectively. At station 22, there was an increase in the number of species from 5 in 2001 to 16 in 2012, and the presence of large bodied echiurid *Listriolobus brevisrostris* led to a great elevation of biomass in 2012. The sedimentary TOM, TS and EP increased from 8.4% to 9.6%, 200 mg/kg to 270 mg/kg, and -320 mV to -190 mV, respectively. At station 24, there was an increase in the abundance of the polychaete *Nereis longior* from 0 to 15 and the large bodied echiurid *Listriolobus brevisrostris* from 0 to 14, leading to a great elevation of biomass in 2012. Between the two surveys, the sedimentary TS increased from 64 mg/kg to 88 mg/kg, and the EP increased from -220 mV to -135 mV. At station 27, the number of species increased from 11 to 25, and the disappearance of the large bodied clam *Paratapes undulatus* led to a decline in biomass from 2001 to 2012. During this period, the sedimentary TOM, TS and COD decreased from 8.9% to 5.4%, 34 mg/kg to 6.1 mg/kg, and 20,000 mg/kg to 12,000 mg/kg, respectively; but the EP increased from -135 mV to -95 mV.

4. Discussion

Results from the present study clearly showed that there were four distinct macrobenthic communities in the marine environment of Hong Kong, which were characterized by different levels openness, water depth and sediment characteristics. Group A, the prevalent community encompassing most of the study area and dominated by small polychaetes, inhabited the deeper waters with a bottom of poorly sorted fine mud, reflecting the weak wave and low current movements in the near-shore waters of Hong Kong (Shin et al., 2004). This community was stable between 2001 and 2012, with only few changes in the MDS station group assignment. Other communities were smaller with more notable changes in the MDS station assignment between the two surveys.

Victoria Harbour had a community (group B) of the highest diversity, biomass, and number of specimens. This group inhabited a coarse sandy bottom, reflecting the higher tidal currents that flow in the southwest-northwest direction in the narrow harbour area (Morton and Wu, 1975). This community, co-dominated by the bivalve *Ruditapes philippinarum* and the polychaetes *Cirratulus* sp. and *Schistomeringos rudolphi*, comprised of only two stations (stations 11 and 12) in 2001. Due to the complete disappearance of high abundance species *R. philippinarum* and *Thalassodrilides gurwitschi* in 2012, station 12 was merged with group A in 2012. The two species were reported to flourish in eutrophic habitats (Svensson et al., 2001; Humphreys et al., 2007), and their abundance at station 12 was much higher than at all other stations in 2001, which was consistent with the high TOM in sediment

Table 3

Results of SIMPER analysis showing species with > 50% cumulative contribution to station group similarities in the 2001 and 2012 surveys. Abundance data are mean \pm standard deviation of stations. C = Crustacea, E = Echinodermata, M = Mollusca, N = Nemertea, P = Polychaeta, S = Sipuncula.

Faunal group	Species	Mean abundance (individuals 0.5 m ⁻²)	% contribution to faunal similarity within group	Cumulative % contribution to faunal similarity within group
Group A				
2001				
P	<i>Mediomastus</i> sp.	7.6 \pm 6.8	11.3	11.3
P	<i>Micronephthys oligobranchia</i>	5.7 \pm 5.7	8.6	19.9
P	<i>Sigambra hanaokai</i>	3.4 \pm 3.3	7.2	27.2
P	<i>Paraprionospio pinnata</i>	1.1 \pm 1.1	5.2	32.4
E	<i>Amphiodia (Amphispina) obtecta</i>	2.3 \pm 2.6	5.2	37.6
P	<i>Cossura dimorpha</i>	1.3 \pm 1.7	4.6	42.2
C	<i>Callianassa japonica</i>	2.0 \pm 2.1	4.2	46.4
S	<i>Apionsoma (Apionsoma) trichocephalus</i>	8.9 \pm 112.6	4.2	50.5
2012				
P	<i>Micronephthys oligobranchia</i>	5.8 \pm 3.1	16.6	16.6
P	<i>Sigambra hanaokai</i>	13.3 \pm 20.7	12.7	29.2
P	<i>Mediomastus</i> sp.	7.5 \pm 11.9	8.8	38.0
P	<i>Paraprionospio pinnata</i>	87.5 \pm 363.2	6.3	44.3
N	Nemertea	1.1 \pm 1.3	4.7	48.9
P	<i>Nereis longior</i>	6.5 \pm 16.8	4.7	53.6
Group B				
2001				
P	<i>Cirratulus</i> sp.	230.5 \pm 198.7	9.6	9.6
P	<i>Schistomeringos rudolphi</i>	206.5 \pm 219.9	8.4	18.0
M	<i>Ruditapes philippinarum</i>	1193.5 \pm 1618.6	8.3	26.3
P	<i>Dodecaceria</i> sp.	82.5 \pm 95.5	6.2	32.5
P	<i>Naineris</i> sp.	127.0 \pm 161.2	5.9	38.4
P	<i>Spiophanes</i> sp.	149.0 \pm 199.4	5.3	43.7
P	<i>Sthenelais</i> sp.	9.0 \pm 2.8	5.1	48.8
P	<i>Oxydromus obscurus</i>	41.0 \pm 50.9	4.7	53.4
2012				
	< 2 samples in group			
Group C				
2001				
P	<i>Heteromastus filiformis</i>	13.0 \pm 14.4	23.7	23.7
P	<i>Sigambra hanaokai</i>	5.6 \pm 5.9	14.4	38.1
M	<i>Potamocorbula laevis</i>	292.8 \pm 635.8	10.6	48.7
P	<i>Mediomastus</i> sp.	4.0 \pm 4.5	8.3	57.0
2012				
P	<i>Sigambra hanaokai</i>	15.0 \pm 4.2	42.6	42.6
P	<i>Magelona cincta</i>	5.0 \pm 2.8	30.1	72.8
Group D				
2001				
P	<i>Sigambra hanaokai</i>	11.4 \pm 12.2	57.7	57.7
2012				
P	<i>Sigambra hanaokai</i>	3.7 \pm 1.2	76.6	76.6

and high nutrient concentration reported in eastern Victoria Harbour before implementation of the Harbour Treatment Scheme (HATS) (Cheung et al., 2008; Shin et al., 2008; Xu et al., 2011), and reduction in TOM after the implementation of the sewage control measure that involved the transportation of sewage to Stonecutters Island that was originally channeled from Shatin and Taipo sewage treatment works and discharged to Kowloon Bay. However, station 11 showed an increase of *R. philippinarum* in 2012, consistent with the increase in COD, TC, TKN, TS, TOM and S & C contents after the implementation of HTAS due to the discharge of treated effluent from Stonecutters Island Sewage Treatment Works.

Deep Bay, characterized by low water depth and proximity to the Pearl River Estuary, supported a distinct community (group C) co-dominated by two polychaetes (*Heteromastus filiformis* and *S. hanaokai*) and the bivalve *Potamocorbula laevis* (Table 2) in 2001. Three outer stations (3, 4, 5) of this community was merged with group A in 2012. Previous studies of macrobenthos showed that the abundance of some estuarine species could experience dramatic fluctuation (Huang et al.,

2002), and such change could potentially affect the community structure and thus the assignment of stations to faunal groups. In these outer stations, there have been dramatic changes in even the dominant species, from the polychaete *Heteromastus filiformis*, and the bivalve *Potamocorbula laevis* in 2001 to the polychaete *Magelona cincta* in 2012 (Table 2). For faunal diversity, stations 3 and 4 were noted with increased H' and station 4 showed increased J . However, due to the dramatically increased opportunistic polychaete *Paraprionospio pinnata*, station 5 was noted with declined H' and J . For sediment parameters, only slightly declined mean values of TOM, COD, EP, TS and increased mean values of TC, TKN and S & C were noted in the three outer stations, but the changes were not significant ($P > 0.05$). Therefore, the changes in MDS station assignment between the two surveys in the Deep Bay area could not be attributed to the implementation of pollution control measures and thus the recovery of benthic community may need an even longer duration.

The area of Tolo Harbour and western Mirs Bay (group D) was land-locked with high water retention and poor tidal flushing (Lee et al.,

2006), and poor water quality had been reported especially from 1980s to 1990s (Lee and Arega, 1999; Xu et al., 2004). Despite implementation of organic pollution control measures since 1980s (EPD, 1997), there had been only minor change in TOM, and the changes of other organic nutrients (TC, TKN, TS) were not significant ($P > 0.05$) over our study period in this area. Consistent with previous reports (Shin, 2000, 2003; Shin et al., 2004), in both 2001 and 2012, group D was characterized by the presence of few species in low abundance, with the small polychaete *Sigambra hanaokai* being a dominant species, with high contribution to the similarities of group D in both the 2001 (57.7%) and 2012 (76.6%) surveys. No significant change in faunal diversity ($P > 0.05$) was noted between the two surveys. Due to the presence of only few species in low abundance in this area, small changes in abundance and number of species between the two surveys could lead to changes in MDS group assignment (Fig. 3). Thus, the limited water exchange with the open water appeared to have limited the improvement of the sedimentary environment, and changes in group assignment between the two surveys should not be viewed as a sign of faunal recovery.

In conclusion, our study has established a new baseline of macrobenthic community structure in Hong Kong waters. Our results have illustrated the importance of hydrological environment in shaping the differential responses of macrobenthos to pollution control measures. Together with data from other forms of marine life including bacteria (Guo et al., 2016), our data can be used for future assessment of the impact of human activities on environmental quality in subtropical Hong Kong.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.marpolbul.2017.04.026>.

References

- Bray, J.R., Curtis, J.T., 1957. An ordination of the upland forest communities of southern Wisconsin. *Ecol. Monogr.* 27, 325–349.
- Cheung, S.G., Lam, N.W.Y., Wu, R.S.S., Shin, P.K., 2008. Spatio-temporal changes of marine macrobenthic community in sub-tropical waters upon recovery from eutrophication. II. Life-history traits and feeding guilds of polychaete community. *Mar. Pollut. Bull.* 56, 297–307.
- Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth, UK.
- Clarke, K.R., Green, R.H., 1988. Statistical design and analysis for a 'biological effects' study. *Mar. Ecol. Prog. Ser.* 46, 213–226.
- Clarke, K.R., Warwick, R.M., 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation, second ed. Primer-E Ltd, Plymouth, pp. 25–50.
- DSD, 2009. Yuen Long Sewage Treatment Works. Drainage Services Department, HKSAR Government.
- EPD, 1997. Tolo Harbour Action Plan (an Updated Report with Progress Up to December 1996). Water Policy and Planning Group. Environmental Protection Department, Hongkong Government.
- EPD, 2012. Marine Water Quality in Hong Kong in 2012. Environmental Protection Department, HKSAR Government.
- Gray, J.S., Pearson, T.H., 1982. Objective selection of sensitive species indicative of pollution-induced change in benthic communities. I. Comparative methodology. *Mar. Ecol. Prog. Ser.* 9, 111–119.
- Gray, J.S., Clark, K.R., Warwick, R.M., Hobbs, G., 1990. Detection of initial effects of pollution on marine benthos: an example from the Ekofisk and Eldfisk oilfields, North Sea. *Mar. Ecol. Prog. Ser.* 66, 285–299.
- Guo, F., Li, B., Yang, Y., Deng, Y., Qiu, J.W., Li, X., Leung, K.M.Y., Zhang, T., 2016. Impacts of human activities on distribution of sulfate-reducing prokaryotes and antibiotic resistance genes in marine coastal sediments of Hong Kong. *FEMS Microbiol. Ecol.* 92 (fiw128).
- Huang, H.H., Lin, Y.T., Li, C.H., Lin, Q., Cai, W.G., 2002. Ecological study on the benthic animals of Pearl River estuary. *Acta Ecol. Sin.* 22, 603–607 (in Chinese with English abstract).
- Humphreys, J., Caldow, R.W.G., McGrorty, S., West, A.D., Jensen, A.C., 2007. Population dynamics of naturalised manila clams *Ruditapes philippinarum* in British coastal waters. *Mar. Biol.* 151, 2255–2270.
- Kruskal, J.B., 1964. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* 29, 1–27.
- Lee, J.H.W., Arega, F., 1999. Eutrophication dynamics of Tolo Harbour, Hong Kong. *Mar. Pollut. Bull.* 39, 187–192.
- Lee, J.H.W., Harrison, P.J., Kuang, C., Yin, K., 2006. Eutrophication dynamics in Hong Kong coastal waters: physical and biological interactions. In: Wolanski, E. (Ed.), *The Environment in Asia Pacific Harbours*. Springer, Netherlands, pp. 187–206.
- Lu, L., Wu, R.S.S., 2000. An experimental study on recolonization and succession of marine macrobenthos in defaunated sediment. *Mar. Biol.* 136, 291–302.
- Magni, P., Tagliapietra, D., Lardicci, C., Balthis, L., Castelli, A., Como, S., Frangipane, G., Giordani, G., Hyland, J., Maltagliati, F., Pessa, G., 2009. Animal-sediment relationships: evaluating the 'Pearson-Rosenberg paradigm' in Mediterranean coastal lagoons. *Mar. Pollut. Bull.* 58, 478–486.
- Morton, B., Wu, S.S., 1975. The hydrology of the coastal waters of Hong Kong. *Environ. Res.* 10, 319–347.
- Neter, J., Wasserman, W., Kutner, M.H., 1990. *Applied Linear Statistical Models*, third ed. Irwin, Chicago.
- Nicholson, S., Hui, Y.H., Lam, P.K.S., 2011. Pollution in the coastal waters of Hong Kong: case studies of the urban Victoria and Tolo Harbours. *Water Environ. J.* 25, 387–399.
- Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Annu. Rev.* 16, 229–311.
- Qian, P.Y., Qiu, J.W., Kennish, R., Reid, C.A., 2003. Recolonization of benthic infauna subsequent to capping of contaminated dredged material in East Sha Chau, Hong Kong. *Estuar. Coast. Shelf Sci.* 56, 819–831.
- Qiu, J.W., 1999. Composition, structure and distribution of polychaete assemblages in Deep Bay, Hong Kong. In: Lee, S.Y. (Ed.), *The Mangrove Ecosystem of Deep Bay and the Mai Po Marshes*, Hong Kong, pp. 13–21.
- Santos, S.L., Simon, J.L., 1980. Response of soft-bottom benthos to annual catastrophic disturbance in a South Florida estuary. *Mar. Ecol. Prog. Ser.* 3, 347–355.
- Sanz-Lázaro, C., Marin, A., 2006. Benthic recovery during open sea fish farming abatement in Western Mediterranean, Spain. *Mar. Environ. Res.* 62, 374–387.
- Shin, P.K.S., 1989. Natural disturbance of benthic infauna in the offshore waters of Hong Kong. *Asian Mar. Biol.* 6, 193–207.
- Shin, P.K.S., 2000. The detection of ecological stress in a sub-tropical macrobenthic community in Hong Kong. *Asian Mar. Biol.* 17, 149–160.
- Shin, P.K.S., 2003. Changes in benthic infaunal communities in Tolo Harbour: will the trend continue. In: Morton, B. (Ed.), *Perspectives on Marine Environment Change in Hong Kong and Southern China, 1977–2001: Proceedings of an International Workshop Reunion Conference*, Hong Kong, 21–26 October 2001. Hong Kong University Press, Hong Kong, pp. 579–592.
- Shin, P.K., Thompson, G.B., 1982. Spatial distribution of the infaunal benthos of Hong Kong. *Mar. Ecol. Prog. Ser.* 10, 37–47.
- Shin, P.K.S., Huang, Z.G., Wu, R.S.S., 2004. An updated baseline of subtropical macrobenthic communities in Hong Kong. *Mar. Pollut. Bull.* 49, 128–135.
- Shin, P.K.S., Lam, N.W.Y., Wu, R.S.S., Qian, P.Y., Cheung, S.G., 2008. Spatio-temporal changes of marine macrobenthic community in sub-tropical waters upon recovery from eutrophication. I. Sediment quality and community structure. *Mar. Pollut. Bull.* 56, 282–296.
- Snelgrove, P.V.R., Butman, C.A., 1994. Animal-sediment relationships revisited: cause versus effects. *Oceanogr. Mar. Biol. Annu. Rev.* 32, 111–177.
- Svensson, J.M., Enrich-Prast, A., Leonardson, L., 2001. Nitrification and denitrification in a eutrophic lake sediment bioturbated by oligochaetes. *Aquat. Microb. Ecol.* 23, 177–186.
- Warwick, R.M., Pearson, T.H., 1987. Detection of pollution effects on marine macrobenthos: further evaluation of the species abundance/biomass method. *Mar. Biol.* 95, 193–200.
- Wildsmith, M.D., Rose, T.H., Potter, I.C., Warwick, R.M., Clarke, K.R., 2011. Benthic macroinvertebrates as indicators of environmental deterioration in a large microtidal estuary. *Mar. Pollut. Bull.* 62, 525–538.
- Wu, R.S.S., 1982. Periodic defaunation and recovery of a subtropical epibenthic community, in relation to organic pollution. *J. Exp. Mar. Biol. Ecol.* 64, 253–269.
- Xu, F.L., Lam, K.C., Dawson, R.W., Tao, S., Chen, Y.D., 2004. Long-term temporal-spatial dynamics of marine coastal water quality in the Tolo Harbour, Hong Kong, China. *J. Environ. Sci. (China)* 16, 161–166.
- Xu, J., Yin, K., Lee, J.H.W., Liu, H., Ho, A.Y., Yuan, X., Harrison, P.J., 2010. Long-term and seasonal changes in nutrients, phytoplankton biomass, and dissolved oxygen in Deep Bay, Hong Kong. *Estuar. Coasts* 33, 399–416.
- Xu, J., Lee, J.H.W., Yin, K., Liu, H., Harrison, P.J., 2011. Environmental response to sewage treatment strategies: Hong Kong's experience in long term water quality monitoring. *Mar. Pollut. Bull.* 62, 2275–2287.
- Zhao, C., Zhang, S., Mao, X., 2014. Variations of annual load of TN and TP in the Deep Bay watershed, Shenzhen. *Environ. Sci.* 35, 4111–4117 (in Chinese with English abstract).

Supplementary material

Macrobenthic communities in Hong Kong waters: comparison between 2001 and 2012 and potential link to pollution control

Zhi Wang^a, Kenneth M.Y. Leung^b, Xinzheng Li^c, Tong Zhang^d, Jian-Wen Qiu^{a,e,*}

a. Department of Biology, Hong Kong Baptist University, Kowloon, Hong Kong, China

b. The Swire Institute of Marine Science and School of Biological Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China

c. Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China

d. Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, China

e. State Key Laboratory in Marine Pollution (SKLMP), City University of Hong Kong, Kowloon, Hong Kong, China

* Corresponding author:

Jian-Wen Qiu, Department of Biology, Hong Kong Baptist University, 224 Waterloo Road, Hong Kong; E-mail: qiuwjw@hkbu.edu.hk; Phone: +852-34117055

Supplementary figures

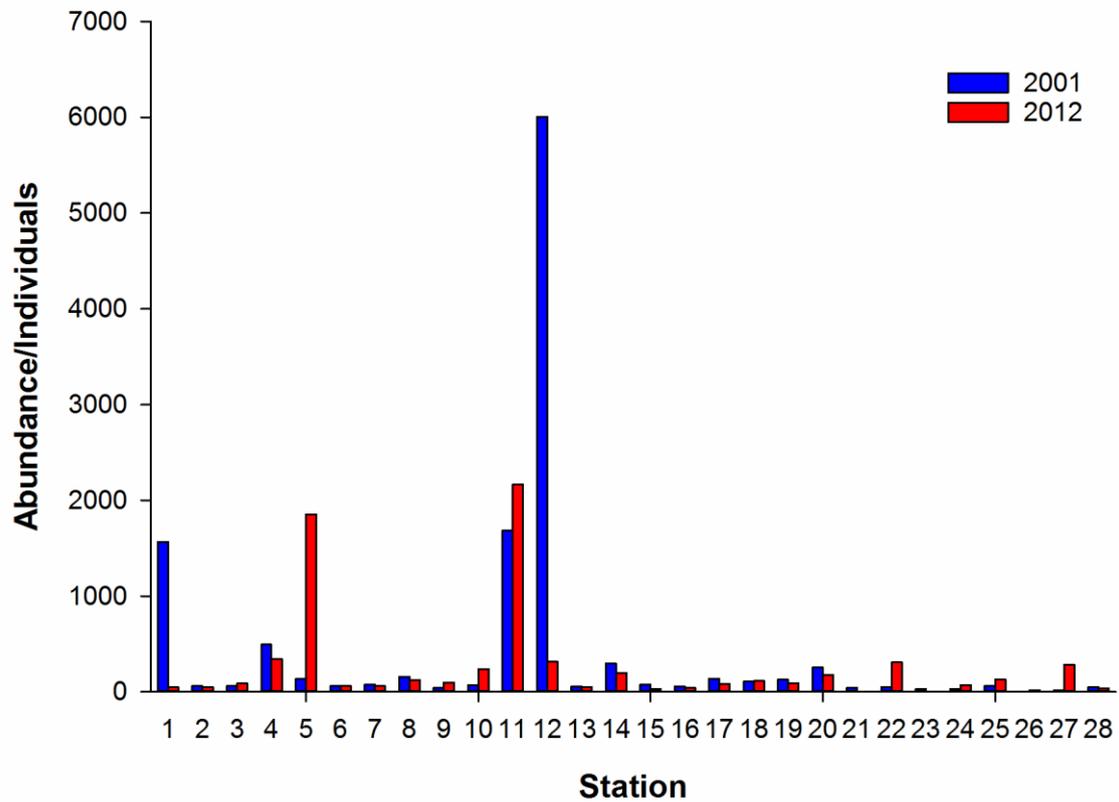


Fig. S1. Abundance pattern of benthos in the 28 stations across Hong Kong waters in the 2001 and 2012 surveys. Data for each station were pooled from five replicate grab samples. Note that in several stations there were substantial differences in abundance between the two surveys.

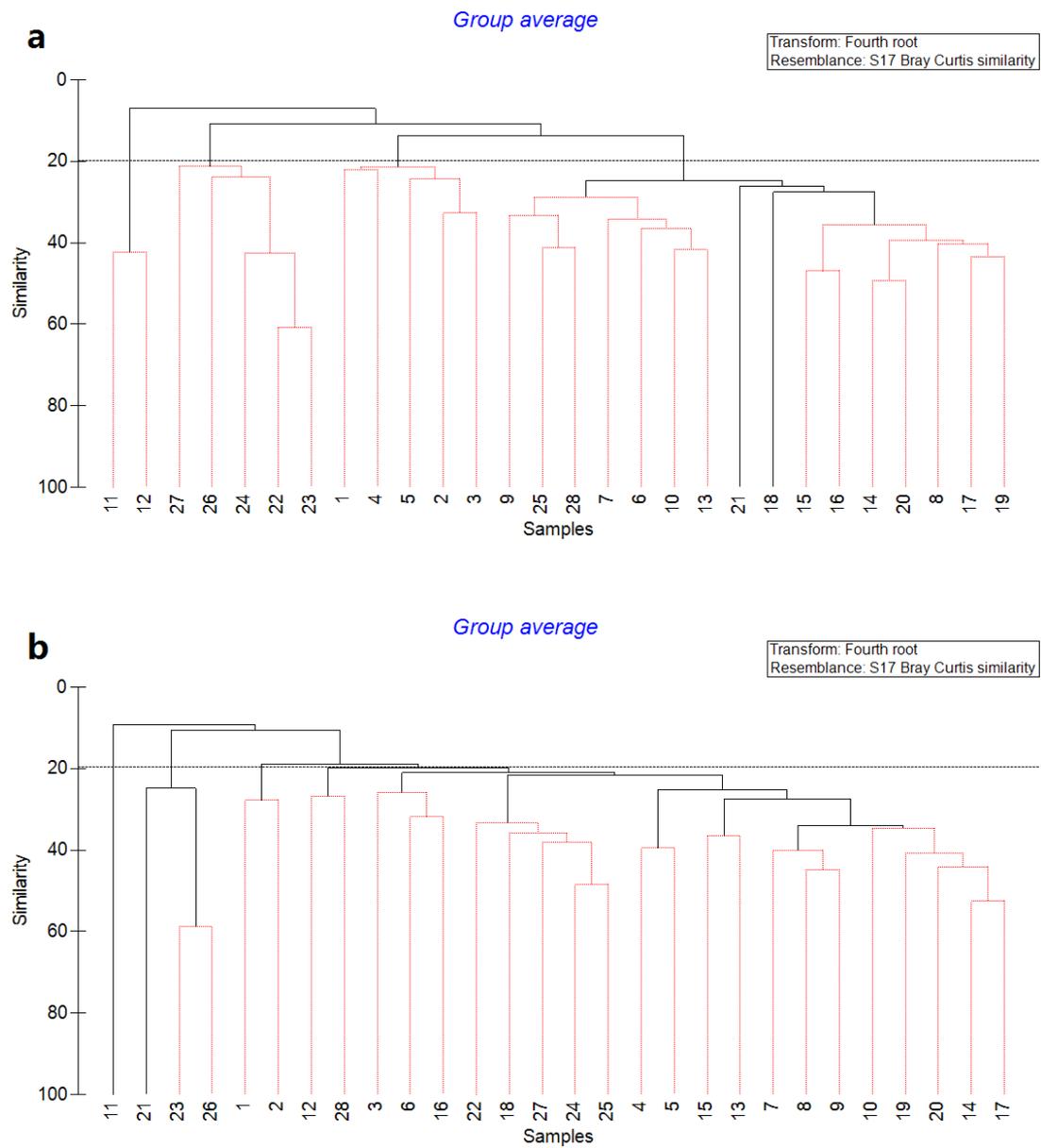


Fig. S2. CLUSTER analysis results based on species abundance data in the 2001 (a) and 2012 (b) surveys. There are four station groups at 20% similarity.