Vol. 26(1):0-0 | Ocean and Polar Research | March 2004

Article

Benthic Pollution Assessment Based on Macrobenthic Community Structure in Gamak Bay, Southern Coast of Korea

Bon Joo Koo*, **Jong-Geel Je**, and **Sang-Ho Shin**

Marine Living Resources Research Division, KORDI
Ansan P.O. Box 29, Seoul 425-600, Korea

Abstract : Benthic pollution assessment based on macrobenthic community structure with environmental variables was carried out at twelve stations during two periods on a presumed pollution gradient in Gamak Bay. Univariate and multivariate methods were applied to investigate structural changes in the benthic communities. A clear gradient of pollution effects on the macrobenthic community was observed from the interior to the exterior of the bay. The community on the northwestern basin was severely disturbed due to a low level of hydrodynamics and a large amount of pollutant input from nearby cities. Exterior regions on the southern basin appeared to have the best benthic environmental characteristics among all stations according to most methods of analysis. Central ridge regions and two stations around the islets in the mouth of the bay exhibited intermediate levels of perturbation when compared to the more disturbed interior and undisturbed exterior regions. Pollution effects on the communities were attenuated at the southern area of the central ridge during spring compared to those of summer, where aquacultural farming was densely distributed. The environmental variables primarily correlated to the macrobenthic community structure were total organic carbon (C), organochlorine pesticides (OCPs), and tributyltins (TBTs), contents found on the surface sediment, as anthropogenic variables indicating organic materials.

Key words : Pollution assessment, Macrobenthos, Community structure, Gamak Bay, Korea

1. Introduction

Many efforts have been devoted to measuring the levels of contamination for sediments and organisms by means of chemical analysis to determine if the observed level of contamination causing pollution generally requires a study of its biological effects (Clark *et al.* 1997). These effects may be detected at the level of the individual, or by changes in the population or the community, and a variety of techniques are available to identify and measure the response. The most realistic approach among them is to examine the response of the whole community. This is the most popular approach in pollution impact studies (Clark *et al.* 1997).

Communities in nature are composed of a large number of species adapted to the unique environment around them. Changes in the community structure depend on a suite of different environmental variables to which each of the species in the community may respond differently (Warwick and Clarke 1991). Especially, benthic organisms lack the ability to cope with changes of environment because most of them are sedentary and are limited in mobility. The environmental disturbance caused by pollutants such as organic matter and toxic materials gives rise to change in the community structure, through which the disturbance and its magnitude, in turn, can be assessed.

Data on the abundance and biomass of species comprising marine benthic communities can be exploited in a number of different ways in order to assess the degree to which the communities can be regarded as "disturbed", e.g. by some putative pollution impacts (Warwick and Clarke 1994). The analysis of changes in benthic community structure has now become one of the mainstays for detecting and monitoring the biological effects of marine pollution (Clarke and Warwick 2001). A wide variety of different solutions related to analyses of changes in community structure

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*Corresponding author. E-mail : bjkoo@kordi.re.kr have been developed, but broadly the available statistical methods fall under the three general headings of univariate, graphical/distributional and multivariate (Warwick and Clarke 1991). These methods are widely used in pollution assessment studies (Olsgard and Gray 1995; Simboura *et al.* 1995; Estacio *et al.* 1997; Lardicci and Rossi 1998; Drake *et al.* 1999; Lardicci *et al.* 1999; Je *et al.* 2003).

Gamak Bay was designated as a conservation area for fishery resources in 1982 by the Ministry of Construction and Transportation of Korea, because it had high production and good environmental conditions as a fishery. Since the 1990s, however, it has been exposed to contamination. Although there is not any industrial complex directly affecting the environments of the bay, the increase in urban sewage discharged from the City of Yosu and in aquaculture wastewater has caused pollution problems (Lee 1993). It is believed that the northwestern basin of the bay is severely polluted due to urban effluents found near the city and a reduced level of hydrodynamics within the basin (Shin 1995). The fish farming using raft culture for oysters and mussels is densely distributed on the surface water of the bay. The intensive raft culture generates considerable amounts of organic waste in the form of surplus feed and feces (Holmer 1991; Jung *et al.* 2002). Particularly, the yield of oysters from this location accounts for about 30% of the total oyster yield of Korea. It is necessary to assess the pollution conditions of Gamak Bay in order to manage aquacultural fisheries effectively for the sake of public health.

In this study, we are to assess the degree of benthic pollution in Gamak Bay based on the macrobenthic community structure. Four distinct stages in the identification of pollution effects are employed: (1) Univariate methods used to describe the faunal attributes at each station, (2) Multivariate methods employed to discriminate between stations based on species abundance data: MDS ordination (*Multi-dimensional Scaling Ordination*: Kruscal and Wish 1978) and Cluster analysis, (3) ABC (*Abundance-Biomass Comparison*: Warwick 1986) and BPI (*Benthic Pollution Index*: KORDI 1995) analysed to detect community perturbation, and (4) Correlation of biota and environmental data used to elucidate the main factors affecting the distributions: BIO-ENV procedure (Clarke and Ainsworth 1993).

2. Materials and methods

Study area

Gamak Bay is located between 34°33' and 34°45'N latitude, and between 127°38' and 127°45'E longitude along the southern coast of Korea. The bay is surrounded by Dolsan Island and the mainland, and has a water volume of 10.2×10^8 m^3. It is connected to the outer off-sea at its northeastern corner by a narrow channel and also at its southern part where about ten islands are located. The average depth is about 9 m with a maximum depth of about 40m at the southern basin.

The bay is divided into three areas according to its bathymetry. From the central through the northeastern part of the bay, an extended ridge has developed with an average depth of about 5 m. The fish farming for oysters is densely distributed on the surface water above the ridge. Two basins, the northwestern and southern basins, are separated by the ridge (Kang 1981; Shin 1995). The sheltered location of the northwestern area reduces the exposure to both wind and waves (Park *et al.* 1999) and the central ridge acts as a physical barrier for water movement between the interiors and the exteriors of the bay (Lee 1993). The basin water is strongly stratified in summer (Lee 1992, 1993), the pycnocline prevents mixing between surface and bottom water, and thus probably generates an anoxic condition in the bottom water. Dissolved oxygen present in bottom water was under 10 mg/*l* throughout the year, with hypoxic conditions (3 mg/*l*) present in northwestern basin, particularly in summer (Kim *et al.* 2000).

Water temperatures ranged from 5.7°C in winter to 24.2°C in summer and salinity showed a range of 30.0‰ to 33.6‰ (Kim *et al.* 2000). Granulometry of bottom sediments in the study area was predominantly fine and the mean particle size was found to be in the range of 7.07 to 9.22∅. The northern and central part were respectively dominated by silty clay and clayey silt, and slightly gravelly mud was distributed around the channels at the mouth of the bay (Kim *et al.* 2000).

Sample collection

Twelve sampling stations were selected on the basis of a presumed pollution gradient from the interior to the exterior of the bay: Stations 1, 2 and 3 located on northwestern basin, stations 4, 5, 6 and 7 on the central ridge, stations 8, 9 and 10 on the southern basin, and 11 and 12 close to the islets at the mouth of the bay (Fig. 1). Benthic sediment samples were collected in August 1998 (summer) and May 1999 (spring). During each collection, five replicate samples of at least 5 *l* volume were collected from each station to ensure the collection of a sufficient number of organisms for biological analyses and to ensure collection

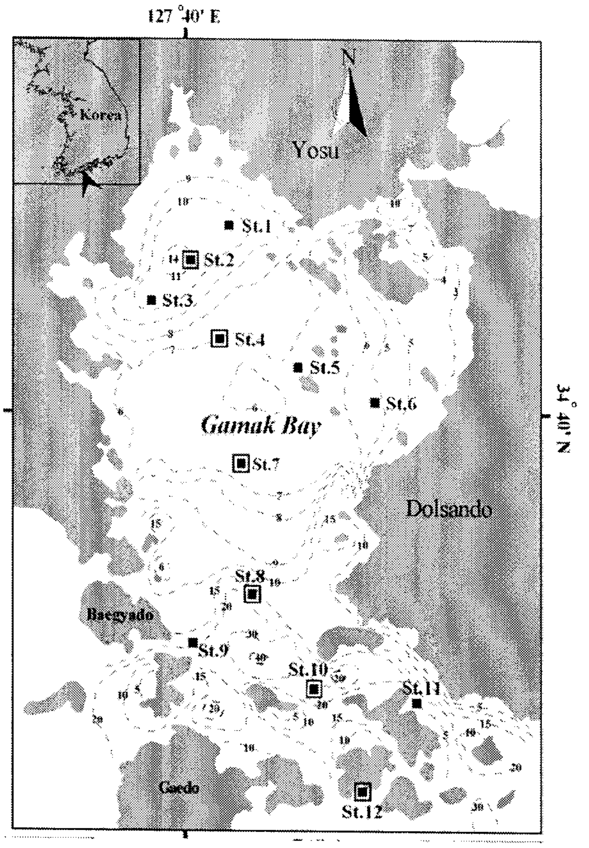


Fig. 1. Map of Gamak Bay showing location of sampling stations. Dotted lines represent bathymetric contours and double-rectangles indicate the stations employed in a BIO-ENV procedure.

of species which rarely occur. All samples were obtained using a van Veen grab sampler with a collection area of 0.1 m^2. Each grab sample was emptied into a clean plastic container and then sieved through a 1mm mesh screen. The remaining fauna on the sieve were fixed with 10% formalin solution neutralized by seawater. In the laboratory the samples were sorted into major taxonomic groups and the animals were identified according to species as clearly as possible. Counts and wet weight data were then obtained at each species level.

Data analysis

To examine the results obtained for the communities of the infaunal macrobenthos, a number of techniques were employed. Univariate analyses provided the total number of species, total abundance, and species diversity index (H') for each of the stations. These are calculated according to the datasets generated by aggregating all five samples. The differences between all of these parameters for all samples at each station were tested with one tailed ANOVA using the Tukey test for statistical significance following the Kolmogorov-Smirnov and Bartlett's tests for measuring the homogeneity of variances.

Using the Plymouth Routines in Multivariate Ecological Analysis (PRIMER) package (Clarke and Warwick 2001), the square-root transformed data were used for Bray-Curtis index similarity, and a dendrogram using group-average linked cluster analysis and non-metric Multidimensional Scaling (MDS) from Kruscal and Wish (1978) were created.

In order to detect disturbances in the benthic community structure, the following methods were employed. Benthic Pollution Index (BPI) modified by KORDI (1995) after Word's Infaunal Trophic Index (Word 1978) and Abundance-Biomass Comparison (ABC) curves proposed by Warwick (1986) were calculated and created. Adequate sampling seemed to be a prerequisite of the ABC method, since the dominant biomass is often represented by a few individuals, which will be liable to a higher sampling error than the numerical dominants (Clarke and Warwick 2001). Therefore, the total abundance and biomass data of five combined samples from each site were used in the ABC analysis and subsequent comparisons. Also, the pooled data was applied in BPI analysis. BPI is given in the range of 0 to 100, where '0' indicates the most polluted condition. ABC plots were constructed for each site and also reduced to a summary statistic, W statistic (Clarke 1990), which describes the configuration and relative distance between the abundance and biomass curves in ABC plots. In this statistical analysis, W assumes values in the range of $(-1, 1)$, with W at $+1$ for even abundance across species, but for a biomass dominated by a single species, representing an undisturbed community, and W at -1 in the converse case.

An alternative method that attempts to elucidate the main environmental factors affecting distributions of macrobenthic assemblages, the BIOENV procedure from Clarke & Ainsworth (1993) was used. The subset of environmental factors that best explains the observed patterns is then obtained by choosing the combination that gives the highest correlations using Spearman's test for non-parametric ranges. The following environmental variables surveyed on May 1999 from KORDI (1999) in addition to our macrobenthic data were used in this procedure: water depth, sediment temperature (Tem), particle size of sediment (Mz), dissolved oxygen content (DO) and salinity of bottom water (Sal) and some chemical data such as carbon (C), nitrogen (N), tributyltin (TBT), polychrolinated biphenyl (PCB), polycyclic aromatic hydrocarbon (PAH) and organochlorine pesticide (OCP) contents of surface sediment (see the KORDI (1999) for analytical methods). The abundance data of macrobenthos and above environments at six stations in May (2, 4, 7, 8, 10 and 12) were selected for this analysis based upon a presumed pollution gradient from the interior to the exterior of the bay (Fig. 1).

3. Results

Macrobenthos

A total of 182 species comprising 9,194 specimens during two periods were identified and the mean density of macrobenthos was 766 inds./m^2. Polychaetes were the most abundant faunal group. 78 species (42.9%) were polychaetes and were the main contributors to abundance (62.0%). Mollusks were the second important taxon in terms of numerical abundance (26.9%) and species richness (25.9%). The most dominant species was a polychaete, *Tharyx* sp., with a mean density of 135 inds./m^2 (Table 1). This species occurred at most of the stations except at the northwestern stations (1, 2 and 3) during two periods and showed the highest density of 1,518 inds./m^2 at station 11 in spring (Fig. 2). The second most dominant species was a bivalve, *Theora fragilis*, with a mean density of 114 inds./m^2, whose main habitat was on the central ridge and the exterior region during spring, but shifted onto the northwestern basin and the central ridge during summer. The third was

Table 1. Dominant species accounting for over 2% of the total macrofauna abundance in all stations during two sampling seasons. They are ranked according to total abundance (P : Polychaeta, M : Mollusca, C : Crustacea)

Dominant species	Faunal group	Total abundance	Percent occurrence (%)	Mean density (inds./m^2)	Occurring frequence
Tharx sp.	P	1,623	17.7	135	20
Theora fragilis	M	1,367	14.9	114	20
Capitella capitata	P	587	6.4	49	4
Lumbrineris longifolia	P	553	6.0	46	20
Praxillella affinis	P	480	5.2	40	10
Heteromastus filiformis	P	384	4.2	32	19
Moerella jedoensis	M	369	4.0	31	18
Eriopisella sechellensis	C	217	2.4	18	13
Glycinde sp.	P	201	2.2	17	17

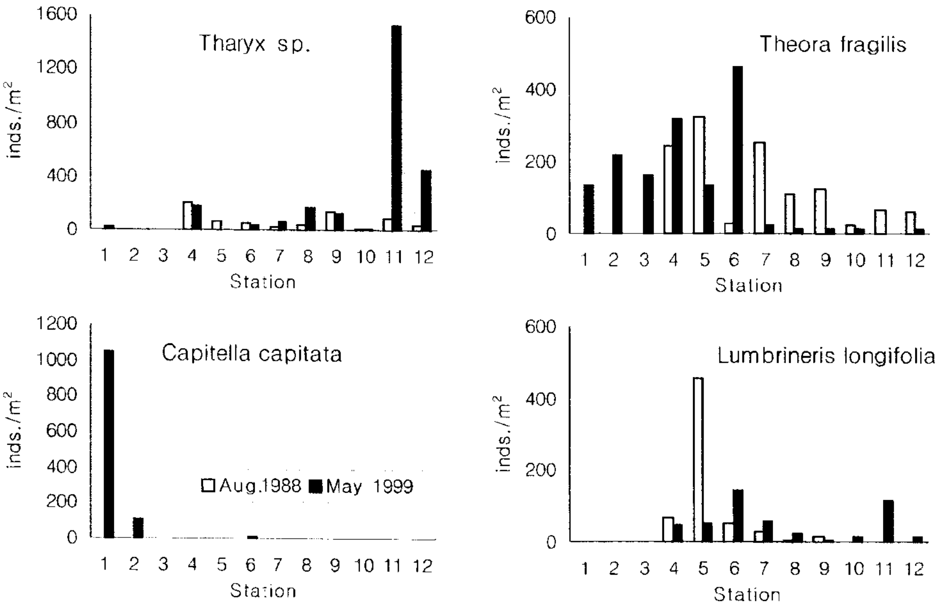


Fig. 2. Abundance of dominant species in the study area during two seasons.

Capitella capitata, a polychaete species taking up 6.4% of the total abundance. This species was restricted to only stations 1 and 2 in spring, where the mean density showed 580 inds./m^2. In addition to the above three species, other polychaetes, such as *Lumbrineris longifolia, Praxillella affinis* and *Heteromastus filiformis*, were also important species. *L. longifolia* and *H. filiformis* showed the highest density in the central ridge, and *P. affinis* was restricted at station 7.

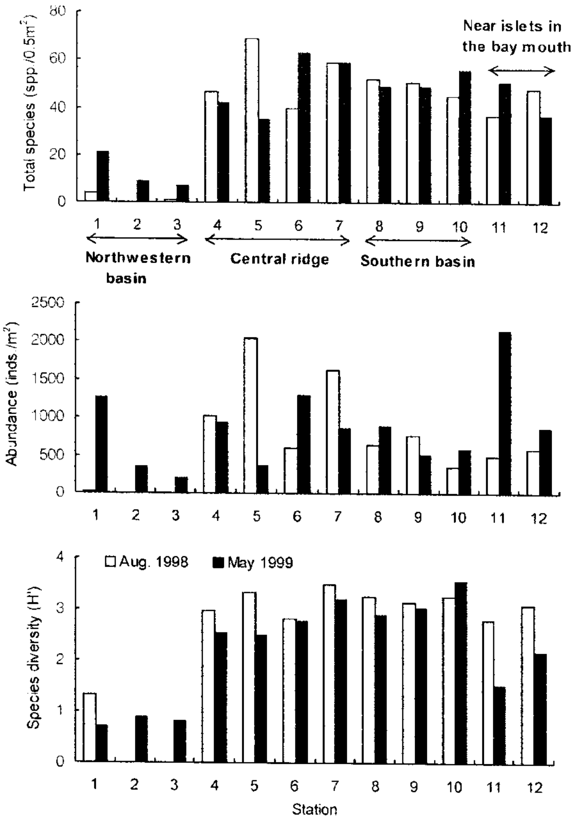


Fig. 3. Graphical representation of the total species, abundan and diversity at each station during two seasons (calculated in the datasets generated by aggregating all five samples).

Univariate analysis

Species richness, total number of individuals, and species diversity at each station during two sampling periods are shown in Fig. 3. The value of these parameters was extremely low or even reached 0 at the northwestern stations in summer. With the exception of these stations, total species was relatively constant with a range of 35 to 69 during two sampling seasons. The number of individuals at each station showed variations according to season and also fluctuated from station to station. The species diversity index (H') discriminated between the northwestern basin and the other areas during the two seasons.

The results of a one-way test of variance between samples in each station using the Tukey test is also shown in Table 2. Data from the northwestern stations were not significantly different (P>0.05) from each other for all parameters during the two seasons, but were significantly different (P<0.001) with respect to the central stations (4, 5, 6 and 7) which were themselves very different from each other with the exception of station 7 in spring. In turn, these showed clear differences from the southern stations (8, 9 and 10) which again showed high levels of similarity among themselves in summer. However, in spring,

Table 2. One-way ANOVA (*F*-ratio values) of values obtained for inter-station univariate analysis along the internal-external gradient (1 and 8 degrees of freedom, *: 0.05 < P, **: 0.01 < P, *: 0.001 < P and n.s.: not significant)**

(a) August 1988 b) May 1999

Sites	H'	Total Ind.	Total spp.	Sites	H'	Total ind.	Total spp.
1-2	n.s.	n.s.	n.s.	1-2	n.s.	n.s.	n.s.
2-3	n.s.	n.s.	n.s.	2-3	n.s.	n.s.	n.s.
3-4	428.14^{***}	307.15^{***}	161.86^{***}	3-4	79.14^{***}	234.96^{***}	165.62^{***}
4-5	n.s.	17.39^{**}	14.84^{**}	4-5	n.s.	108.85^{***}	33.98^{***}
5-6	n.s.	29.29^{***}	20.08^{***}	5-6	n.s.	8.25^{*}	9.11^{*}
6-7	n.s.	8.50^{*}	16.95^{**}	6-7	n.s.	n.s.	n.s.
7-8	7.36^{*}	7.63^{*}	13.30^{**}	7-8	n.s.	n.s.	n.s.
8-9	n.s.	n.s.	n.s.	8-9	n.s.	n.s.	n.s.
9-10	n.s.	n.s.	6.14^{*}	9-10	n.s.	n.s.	n.s.
10-11	7.63^{*}	n.s.	n.s.	10-11	84.36^{***}	13.89^{**}	n.s.
11-12	n.s.	n.s.	n.s.	10-11	84.36^{***}	13.89^{**}	n.s.
1-7	134.04^{***}	23.9^{***}	396.5^{***}	1-11	13.92**	n.s.	34.67^{***}
1-11	191.11^{***}	34.45^{***}	67.32^{***}	1-12	17.29**	n.s.	65.32^{***}

Table 3. One-way ANOVA (F-ratio values) of values obtained for inter-season univariate analysis (1 and 8 degrees of freedom, *: 0.05<P, **: 0.01 <P, ***: 0.001<P and n.s.: not significant)

Sites	H'	Total Ind.	Total spp.
1	7.51*	14.07**	18.84*
2	11.89**	14.73**	10.91*
3	19.70**	78.88**	38.53***
4	n.s.	n.s.	n.s.
5	11.36*	48.10***	71.12***
6	n.s.	n.s.	n.s.
7	n.s.	n.s.	n.s.
8	n.s.	n.s.	n.s.
9	n.s.	n.s.	n.s.
10	n.s.	n.s.	n.s.
10	n.s.	n.s.	n.s.
11	57.08***	18.41**	8.06*
12	n.s.	n.s.	n.s.

the central and southern stations were not significantly different. Stations 11 and 12 were similar not only to each other, but also to the central stations in summer, but were different from all of them in spring. When we compared the values obtained with these parameters at the most inner station, number 1, in each season to those obtained for stations 7 and 11 in summer and stations 11 and 12 in spring, respectively, significant differences between them were found, except for total individuals in spring (Table 2). When all parameters were compared between the two seasons, stations 1 to 3, 5 and 11 were significantly different, while such was not the case with the other stations (Table 3).

Multivariate analysis

As a result of cluster analysis based on the total square-root transformed abundance data for all collections of the two seasons, except for the northwestern stations of summer, the twenty-one stations were largely separated into two groups (Fig. 4). The one was composed of the northwestern stations of spring, and the other, the remaining stations of both seasons, which may in turn be divided into three sub-groups. The sub-group integrated stations 4, 5 and 6 of both seasons, stations 7 to 12 in spring and the same stations in summer. This pattern of clustering was similar when the data were subjected to MDS analysis. MDS ordination confirmed a presumed disturbance gradient with the horizontal axis of the model representing the scale of disturbance from the interior to the exterior of the bay (Fig. 5).

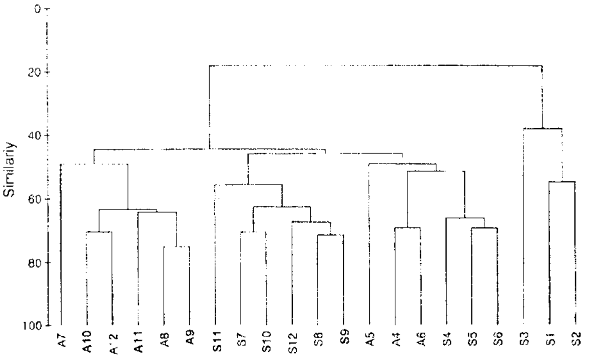


Fig. 4. Dendrogram for group-average clustering of Bray-Curtis similarity for square-root transformed abundance data from all sites excepts for stations 1, 2 and 3 in August 1988. 'A' represents stations for August 1998 and 'S' for May 1999.

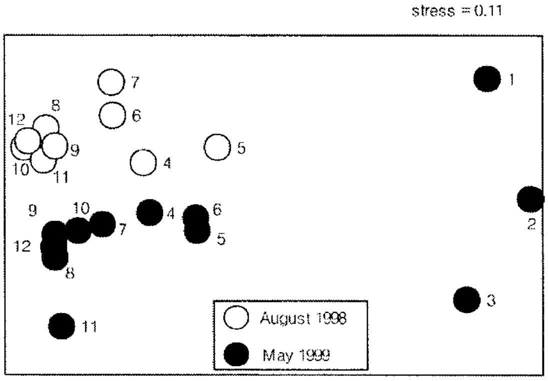


Fig. 5. Multi-dimensional scaling (MDS) ordination of Bray-Curtis similarity for square-root transformed abundance data from all sites except stations 1, 2 and 3 in August 1988.

Detection of pollution effects on the communities

The values of BPI could not be calculated at the northwestern stations in summer because macrobenthos were either absent or rare. While BPI values at these stations during spring were much lower with a range of 3.89 to 17.31, the values at the other stations were exhibited from 30.45 to 71.69 during the two seasons (Fig. 6). Spatial distribution of BPI values, however, was different between the two seasons. In spring, there was a distinct increasing trend in the BPI values towards the south of the bay. The value was between 49.77 and 62.37 in summer at all stations, except for the northwestern stations. Based on average values in the two seasons, Gamak Bay can be divided into four areas by means of the BPI criterion of Lee *et al.* (1997). Severely polluted areas (Grade IV) were composed of three stations on the northwestern basin (1 to

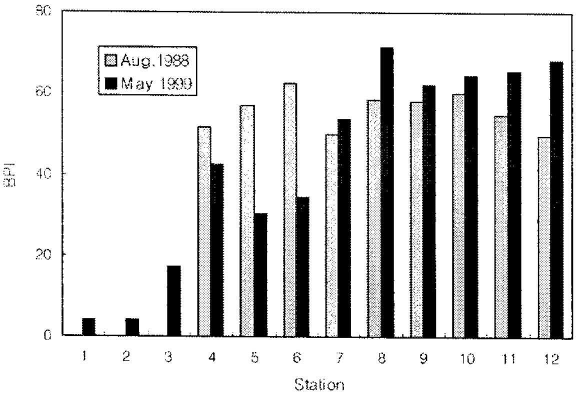
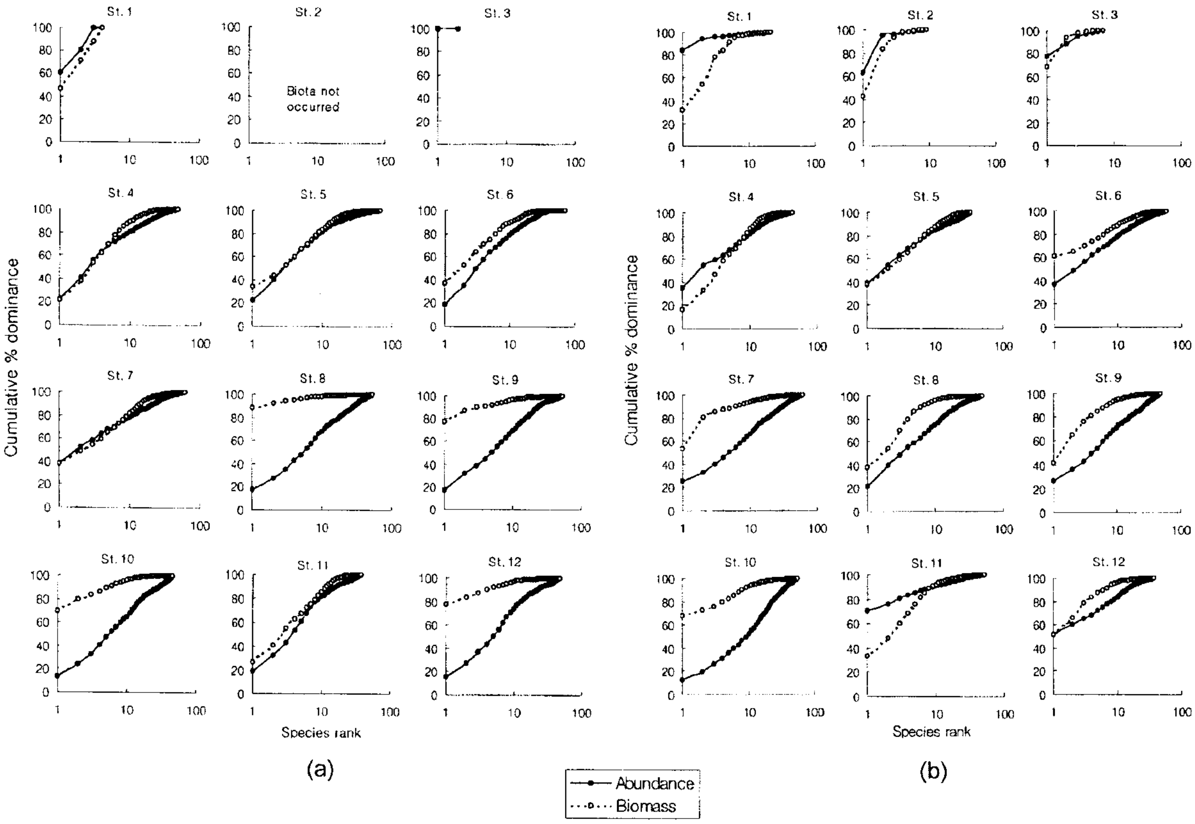


Fig. 6. Graphical representation of the BPI values for each station during two seasons.

3) and a moderately polluted area (Grade III) was also composed of three stations (4 to 6) on the central ridge. The other stations, a relatively unpolluted area, were in grades I and II.

ABC graphs of abundance/biomass data for individual collections at each station showed a gradient from the interior to the exterior (Fig. 7a, b). In summer, the northwestern stations with a poor biota showed a "severely disturbed" pattern and the central stations a "moderately disturbed" pattern, while the southern stations were shown to be "undisturbed". Stations 11 and 12 showed moderately disturbed and undisturbed patterns, respectively. The community structure at station 7, however, was changed to a more undisturbed pattern in spring and stations 8, 11 and 12 had a more disturbed status compared with those of summer. The results of condensing the abundance/ biomass data to the summary statistics are presented in Fig. 8.

Values obtained for the W statistics showed a similar pattern between summer and spring. An interpretation of the curves during the two seasons suggested a gradient of pollution effects from the interior to the exterior of the bay with a few outliers. At the northwestern stations during two periods, W statistic values were below 0, which may indicate that the communities were significantly disturbed.



(a)

(b)

Fig. 7. (a) ABC (Abundance and Biomass Comparison) plots based on combined data from five samples at each of the twelve stations in August 1998. (b) ABC (Abundance and Biomass Comparison) plots based on combined data from five samples taken at each of the twelve stations in May 1999.

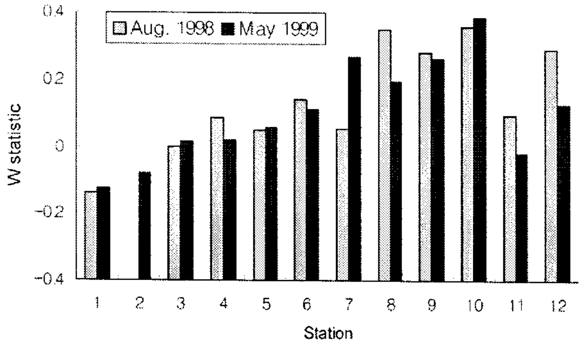


Fig. 8. Graphical representation of the W statistic values for each station during two seasons.

The southern stations were the only three stations that appeared to be undisturbed during two seasons. Stations 4, 5, and 6 had a W statistic value of 0 to 0.2, which indicated that the benthic communities were moderately disturbed in both seasons. Stations 7 and 12 were moderately disturbed for at least one season during the investigation. Although station 11 is located in the mouth of the bay, the values were low in both seasons, which reflected a disturbed condition.

Relationships between biotic and abiotic variables

In order to investigate the relationship between biotic and abiotic variables, the BIO-ENV procedure was used. This allowed us to extract those variables that show greatest correlations (Spearman's rank correlation, ρ_s). An analysis was undertaken which incorporated the organic pollutants, sediment variables, water depth and dissolved oxygen of bottom water. Six stations (2, 4, 7, 8, 10 and 12 in May 1999) were selected on a presumed pollution gradient from the interior to the exterior of the bay. The results are given in Table 4. The single abiotic factor which best grouped the stations, in a manner consistent with the faunal patterns, was total organic carbon (C) content of sediment (ρ_s = 0.613). The variables that gave the highest correlation were the combination of total organic carbon and compounds of organochlorine pesticides (OCP) (ρ_s = 0.796).

4. Discussion

Results of environmental assessment from the BPI and W statistics were summarized in Table 5, where the values of each analysis were converted to a disturbance grade. Assignment of the grade was followed after the criteria from Lee *et al.* (1997) for BPI (0 < IV (severely polluted) ≤ 40, 40 < III ≤ 50, 50 ≤ II < 60, 60 < I (unpolluted) < 100), and from Warwick (1986) for W statistics (U: unpolluted, M: moderately polluted, G: grossly polluted). Although there was a little difference between the results of BPI and W statistics, we can generalize that the pollution effects on benthic communities decreased from the interior towards the exterior stations with some outliers located near the islets in the mouth of the bay.

Stations 1, 2 and 3 were regarded as being severely polluted by all methods of analysis. And these northwestern

Table 4. Combinations of the 11 environmental variables, taken k at a time, yielding the best matches of biotic and abiotic similarity matrices for each k, as measured by Spearman rank correlation (ρ_s); Acronyms are represented in the text

k	Best variable combination (ρ_s)										
1	C 0.613	Mz 0.563	OCP 0.562	Sal 0.492	TBT 0.442	DO 0.369	N 0.316	PCB 0.308	Depth -0.105	PAH -0.224	Tem -0.301
2	**C, OCP** **0.796**	C, Mz 0.655	C, TBT 0.637	Depth, OCP 0.614	OCP, PCB 0.61	...					
3	C, OCP, TBT 0.753	Sal, C, OCP 0.747	DO, C, OCP 0.716	...							
4	Sal, C, OCP, TBT 0.735	DO, C, OCP, TBT 0.719	Depth, Sal, C, OCP 0.71	...							
5	Depth, Sal, C, N, OCP 0.704	Sal, C, N, OCP, TBT 0.703	...								
6	Sal, C, N, Mz, PCB, OCP 0.694	...									
11	Depth, Tem, Sal, DO, C, N, Mz, OCP, PCB, TBT, PAH 0.479	...									

Table 5. Summary of the results of environmental assessment from BPI and W statistics

Station	BPI		W Statistic	
	Aug. 1988	May 1999	Aug. 1988	May 1999
1	IV	IV	G	G
2	IV	IV	G	G
3	IV	IV	G	G
4	II	III	M	M
5	II	IV	M	M
6	I	IV	M	M
7	III	III	M	U
8	II	I	U	U
9	II	I	U	U
10	I	I	U	U
11	II	I	M	G
12	III	I	U	M

stations were similar to each other in univariate parameters and multivariate analyses, but were significantly different from station 4 on the central ridge in both seasons.

Although total species number and total individuals in central stations (4 to 6) were themselves different from each other for two seasons, these stations were well grouped together in multivariate analyses, which are much more sensitive than univariate and graphical/distributional methods in discriminating between sites (Warwick and Clarke 1991). These stations exhibited intermediate levels of environmental perturbation (Table 5). Whereas BPI values of the stations showed differences between the two seasons with more disturbed conditions in spring than in summer, the results from the statistical analysis for W clearly indicated moderately disturbed conditions in both seasons.

In spring, station 7 on the southern edge of the ridge was grouped with the exterior stations in mutivariate analyses and was similar to the exterior in terms of univariate parameters. In summer, however, the station was different from the exterior in terms of univariate parameters. The results of BPI and W statistical analysis indicated this station was more disturbed in summer than in spring.

Stations 8, 9 and 10 located on the southern basin were shown by most methods of analysis to have the best environmental characteristics among the stations in this study, although a less optimistic result was obtained from the BPI analysis showing the presence of environmental perturbations at stations 8 and 9 in summer.

In spite of the location of stations 11 and 12, our study revealed the perturbation of environments in these stations. In the multivariate analysis, stations 11 and 12 were well grouped together with other exterior stations (8, 9 and 10) in summer but station 11 strayed away from the others in spring. It appeared initially that station 11 should be similar to its apparent homologues at station 1 from ABC curves in spring, but this turned out not to be the case for univariate parameters ($P > 0.01$) and in species composition.

This pollution gradient was confirmed in the meiobenthos results of Kim *et al.* (2000). They reported that the value of the nematodes/benthic harpacticods ratio significantly increased from the exterior towards the interiors of the bay, which is indicative of greater pollution in the interior. It was also reflected in the water quality grade established on Gamak Bay by the Ministry of Environment of Korea.

The community structures were primarily correlated to the total organic carbon (C), organochlorine pesticides (OCPs) and tributyltins (TBTs) contents found in the surface sediment. These anthropogenic parameters are indicative of organic materials originating from human activities such as aquacultural and agricultural farming and urban waste discharge from various sources around the bay. Especially, the concentrations of organic pollutants on the northwestern basin were two to four times higher than those on the exteriors showing normal conditions (KORDI 1999). The main environmental variables affecting the faunal patterns were organic pollutants, but it is well known that DO content in bottom water is a main factor causing changes in benthic communities, especially in the inner bay during the summer season (Friligos and Zenetos 1988; Holland 1985; Lim 1993; Lim and Park 1998). And some studies reported anoxic conditions on the northwestern basin of Gamak Bay during the summer season (Lee 1992; 1993; Shin 1995; Kim *et al.* 2000). Our results revealed an azoic zone in the basin during summer (Fig. 3).

The ridge may have created conditions of reduced water renewal within the northwestern basin (Lee 1992), favouring sedimentation processes (Estacio *et al.* 1997). This would have encouraged the formation of substrata with a large portion of fine particles as well as organic matter discharged from adjacent cities in the basin. Concerning the substratum, dominance of opportunistic species such as *Capitella capitata* present only in the interior of the bay is indicative of environmental perturbations. An extensive literature has described this species as having high pollution-tolerance and as being a pollution indicative species. This species showed a high density of 580 inds/m^2 on the basin during spring, but became extinct during summer as well as other species, which may reflect an anoxic condition in the basin in this season. Lee (1993) reported that this area had a possibility of changing into an anoxic zone due to water stagnancy on the bottom, and polychaete worms did not occur on the northwestern basin during the two sampling periods of July and September in a study of Shin (1995) for the benthic polychaete community in Gamak Bay. The pycnocline was destroyed during the winter by strong off-shore winds, which transfer surface water and in turn cause anoxic bottom water to rise to the surface (Lee 1992). With the improvement of environments, this area was reoccupied by macrobenthos during spring, but most of them were opportunistic species. The extinction and the recruitment of opportunistic species was a feature similar to the macrofaunal succession in Lake Shihwa (Hong *et al.* 1997; KORDI 2002).

There was, however, only a slight difference in organic pollutant contents between the central stations and the southern stations (KORDI 1999). While the central ridge is an area influenced by a great amount of organic materials discharged from aquaculture farms, active water exchange with the outer off-sea also prevails in these areas (Lee 1992; 1993; Shin 1995). Jung *et al.* (2002) reported in their macrobenthic study at the intensive fish farming grounds in Gamak Bay that the farming area was highly enriched with organic materials within 30 m of the cage and that *C. capitata* was the dominant species within 5 m and *Theora fragilis* within 30 m. However, *C. capitata* was not present at the stations near the farming cage in our study. It might be due to the fact that our sites are more than 30 m away from the cage. The dominant species on the ridge was *Theora fragilis* with a mean density of 252 inds./m^2 in this region during two seasons. This species, an opportunistic species on organic-enriched bottom sediment of the interior bay (Imabayashi and Tsukuda 1984; Lim *et al.* 1995), predominated in most stations during summer, except for the northwestern stations. The distribution, however, shifted onto the northwestern basin and the central ridge during spring. And also, the benthic community of station 7 shifted from being moderately perturbed during summer to being undisturbed during spring from an ABC interpretation. It meant the pollution zone had shrunk to an area north of the ridge region during spring, compared to that of summer. The effects of organic materials discharged from farming cages on the macrobenthic assemblages in this area seemed to be attenuated by the water exchanges, especially through winter to spring. It offered an expectation whereby the boundary between an organic-enriched water body and a clean off-sea one moved into more northern regions on the ridge during this period as a result of active water exchange, resulting in the polluted area being shrinking into an area further north.

The central ridge was thought to be a transition area between severely perturbed interior areas and unperturbed exterior ones. Both the number of species and abundance of species are higher in the transitional zone than on either side (Pearson and Rosenberg 1978), and it also has characteristics of an unstable community due to the drastic environmental changes. These features were well reflected in our results, where there are more abundant species' numbers and individuals and more fluctuated univariate parameters, showing up in certain seasons in the central ridge regions.

Although being similar to the northwestern basin in bathymetry, the southern basin was the cleanest area of the bay, being apart from pollution sources and close to the outer off-sea. The faunal assemblage of this area did not have any predominant species and the community was stable with high species diversity. Stations 11 and 12 were also close to off-sea, but were moderately disturbed in both seasons. Especially, the environmental perturbation became worse during spring based on ABC curves. In this season, *Tharyx* sp. mainly inhabiting organically enriched areas (Lim and Choi 2001; Shin 1995), showed a high density of 982 inds./m^2 in these areas. But we did not identify any relationship between densities of this species and organic material contents in our study.

Overall, the results of all the analyses help to distinguish between the effects of the pollutants within an almost enclosed system, such as the northwestern basin, and their effects in open coastal waters. The community on the northwestern basin was severely disturbed due to a low level of hydrodynamics and a large amount of pollutant input from nearby cities. Exterior regions on the southern basin appeared to have the best benthic environmental characteristics among all stations by most methods of analysis. Central ridge regions and two stations around the islets in the bay mouth exhibited intermediate levels of perturbation when compared to the more disturbed interior and undisturbed exterior regions. The environmental variables primarily correlated to the macrobenthic community structure were total organic carbon (C), organochlorine pesticides (OCPs) and tributyltins (TBTs) contents on the surface sediment as anthropogenic variables, indicating organic materials. In addition, dissolved oxygen contents of bottom water were also considered a factor affecting the macrobenthic communities, especially on the northwestern basin where an azoic zone prevailed due to the anoxic condition of bottom water during summer. Pollution effects on the communities were attenuated at the southern area of the central ridge during spring compared to those of summer, where aquacultural farming was densely distributed. It was thought that the polluted area had retreated to an area north of the ridge as a result of active water exchanges between an organically enriched water body and a clean off-sea one through winter to spring.

Acknowledgements

We would like to thank all those who assisted with the field program, especially Y. H. Kim for identifying polychaetes and Y. S. Kim for sorting out the macrofauna. We would also like to thank Dr. J. W. Choi for his valuable comments on this study. This work was funded by the Korean Ministry of Maritime Affairs and Fisheries as part of the project "Development of monitoring methods for mariculture farms" (BSPG 98292-00-1196-3).

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Received , 2003
Accepted , 2003