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Performance evaluation and validation of ecological indices toward site-specific application for varying benthic conditions in Korean coasts

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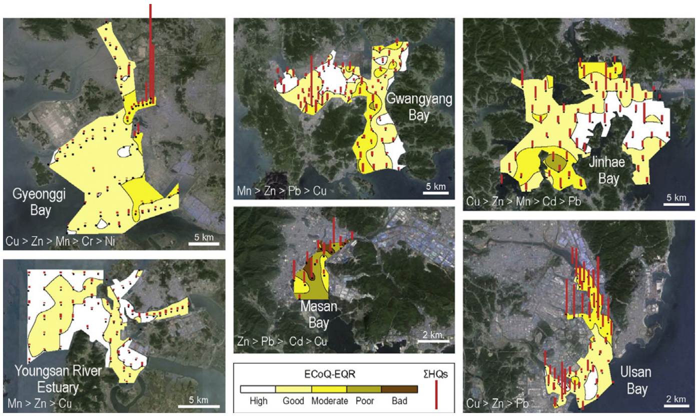
HIGHLIGHTS

- Performance of several univariate and multivariate benthic indices was evaluated.
- Macrozoobenthic biodiversity was generally well reflected by land use and activities.
- EQR was the most appropriate index for assessing the benthic quality of Korean coasts.
- Application of multi-indices was useful for evaluating ecological status vs. pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

Although several ecological indices have been developed worldwide to assess the ecological quality (EcoQ) status of coastal environments, their applicability remains in question. The present study evaluated the performance of 14 univariate and multivariate indices selected to provide a good description of benthic EcoQ status. We specifically investigated on i) spatial and regional variability, ii) (dis)similarity between ecological indices, and iii) the association of selected indices against heavy metal pollution. Benthic community data were collected from six coastal regions of Korea ($n = 365$) that have varying land-use activity in adjacent inland areas (municipal, industrial, and rural). Abiotic sedimentary parameters were also considered as possible pressures associated with benthic community responses, including grain size, organic carbon content, and heavy metal pollution. The macrozoobenthic biodiversity and EcoQ results generally well reflected the geographical settings and the pollution gradient of heavy metals between regions. Among the six selected indices (H', AMBI, BPI, BQI, EQR, and M-AMBI), BPI appeared to be the most tolerant index, with >90% of locations being classified as "High" to "Good" while EQR showed the clear classification across the EcoQ status range. Significant disagreement between BQI vs. AMBI, BPI vs. M-AMBI, and AMBI vs. M-AMBI were found. Overall, single or limited indices seemed to over- or underestimate the given benthic conditions, warranting the use of site-specific indices at specific areas and/or locations. In conclusion, our study demonstrates the utility of applying different ecological or

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multivariate indices to infer the general ecological status of specific sites to gauge the extent of sedimentary pollution.

1. Introduction

The legal regulation of coastal pollution has been increasing to counteract concerns about various anthropogenic stresses and to determine the ecological integrity of estuaries and coastal waters worldwide (Borja and Dauer, 2008; Fitch and Crowe, 2010). The first step in coastal ecosystem assessment is to quantify ecological responses. Thus, the assessment of ecological quality (EcoQ) status represents a key component of management tools, such as Marine Spatial Planning, aiming for the protection and sustainable use of marine and coastal waters (Hennessey and Nichols, 2011). An integral part of assessing ecological quality status involves various measurements of biological endpoints and/or environmental parameters.

A range of taxa have been targeted being utilized as indicators of the ecological status of coastal and marine systems. Such analyses involve assessing the typical assemblages of macroalgae, phytoplankton, sea grasses (Ballesteros et al., 2007), fish (Coates et al., 2007), and benthic macroinvertebrates (Borja et al., 2000; Cusack et al., 2005; Dauvin and Ruellet, 2007; Labrune et al., 2006; Muxika et al., 2007; Rosenberg et al., 2004; Simboura and Zenetos, 2002; Weisberg et al., 1997). However, few studies seemed to consider the dynamic interaction between biotic and abiotic conditions, when addressing the index performances. Consequently, events, such as episodic pollution, may mask biological associations with environmental changes when monitoring typical marine ecosystems (Maurer et al., 1999).

Coastal and marine sediments are considered to act as final sinks for land-based pollution (Borja et al., 2000), and represent sites where dynamic biological associations with environmental stresses tend to be expected. As benthic macrofauna primarily inhabit the top layers of the sediment, epifaunal community changes in structure might provide sufficient evidence for certain impacts by pollution. Benthic macroinvertebrates (i.e., clams, crabs, and polychaetes) are also present in the water column during a certain period of their life-histories (i.e., the larval stage); thus, benthic community may represent an integrative index of coastal and marine environmental health (Blanchet et al., 2008). Benthic organisms have also certain common characteristics, such as sedentary behavior and relatively long lifetime, which may provide better indication of bioaccumulation and biomagnification (Dauer, 1993; Reiss and Kröncke, 2005).

It is vital to quantify the spatio-temporal assemblages of benthic macroinvertebrate in given environments representing a key component of ecological impact assessments. Several benthic indices have been developed and validated as sensitive indicators of environmental quality in coastal sediments (Diaz et al., 2004; Marques et al., 2009). However, using benthic indices for sediment assessments across a range of geographic regions may be problematic, because many benthos are associated with specific habitats and/or limited ecoregions (Borja and Dauer, 2008). Given the large number of indices, metrics, and evaluation tools available when using benthic community data, emphasis should be placed on evaluating the suitability of existing indices, rather developing new ones (Borja and Dauer, 2008; Borja et al., 2008; Diaz et al., 2004). Several studies have compared the performance of different benthic indices (Benyi et al., 2009; Blanchet et al., 2008; Borja et al., 2007, 2008; Fitch and Crowe, 2010; Labrune et al., 2006; Quintino et al., 2006; Ranasinghe et al., 2002; Teixeira et al., 2012; Zettler et al., 2007). However, most of these studies only compared a few indices, with no widely accepted generalizations being suggested.

In the present study, we aimed to test the applicability of a set of univariate and multivariate indices for a better description of ecological quality status using a large data set ($n = 365$ sites). Our meta-data set of six coastal regions in Korea encompassed all of three coastal seas of the Korean peninsula with varying land-use activities in adjacent inland areas (three municipal, two industrial, and one rural). The abiotic sedimentary parameters that were considered as possible pressures associated with biological responses (viz., benthic community structure) included sediment particle size (Van Hoey et al., 2004), organic carbon content (Hyland et al., 2005), and heavy metal concentrations (Dauvin, 2008). Specifically, we examined the spatial variability of 14 ecological endpoints in six coastal regions, with respect to i) (dis)similarity between biotic indices, ii) regional comparability using selected multivariate indices, iii) performance evaluation of selected indices, and iv) the association of selected indices with metal pollution, as one example of environmental changes.

2. Materials and methods

2.1. Study area and site descriptions

A total of 365 locations were investigated in six coastal areas of Korea from 1995 to 1998. Sampling year, number of locations, target sedimentary parameters, surrounding activities, and current management regime are shown in Fig. 1. The six study areas were selected to be representative of west (Gyeonggi Bay and Yeongsan River Estuary), south (Gwangyang Bay, Masan Bay, and Jinhae Bay), and east (Ulsan Bay) Korean coastal waters. All semi-closed six areas were characterized by the dominance of soft bottoms and shallow water depth (ca. 20–30 m), with decreasing tidal regimes from the west (macro) to south (meso) and further to east (micro) coasts. Four areas (Gyeonggi Bay, Gwangyang Bay, Masan Bay, and Ulsan Bay) were expected to be influenced by land-based pollution because they are surrounded by highly industrialized cities, and are currently designated as Special Management Areas (SMA). The management plans of these areas were established in 2001–2008 by the Korean Marine Environment Act. Among six study areas, Masan Bay and Ulsan Bay are the most polluted areas by heavy metals and organic pollutants where feasibility studies are currently performed to establish Total Maximum Daily Loads (TMDL) for heavy metals. Because of microtidal regime, semi-closed bay and heavy land-based pollution, the two areas showed a slow rate of water exchange followed by a trapping effect of pollutants discharged from surrounding industrial complexes and municipalities (Khim and Hong, 2014).

Later, the total pollution load management system (TPLMS), which is similar to TMDL in the USA, was applied to Masan Bay in 2007 to control land-based organic pollutants, such as chemical oxygen demands (COD) (Chang et al., 2012). More recently, the second TPLMS was applied to Gyeonggi Bay (Lake Sihwa) in 2013, targeting good water quality in terms of COD and total phosphorus (Lee et al., 2014). A third TPLMS is planned for Ulsan Bay in 2017, mainly targeting the control of heavy metal pollution in this region, including neighboring Onsan Bay, which is highly industrialized for non-ferrous metal processing. Gwangyang and Jinhae bays are surrounded by narrow industrialized areas and broad rural areas. The inner half of Gwangyang Bay was designated as an SMA, with the management plan being established in 2005. The Yeongsan River Estuary is characterized as a rural area, mostly surrounded by agricultural land and numerous islands to the west.

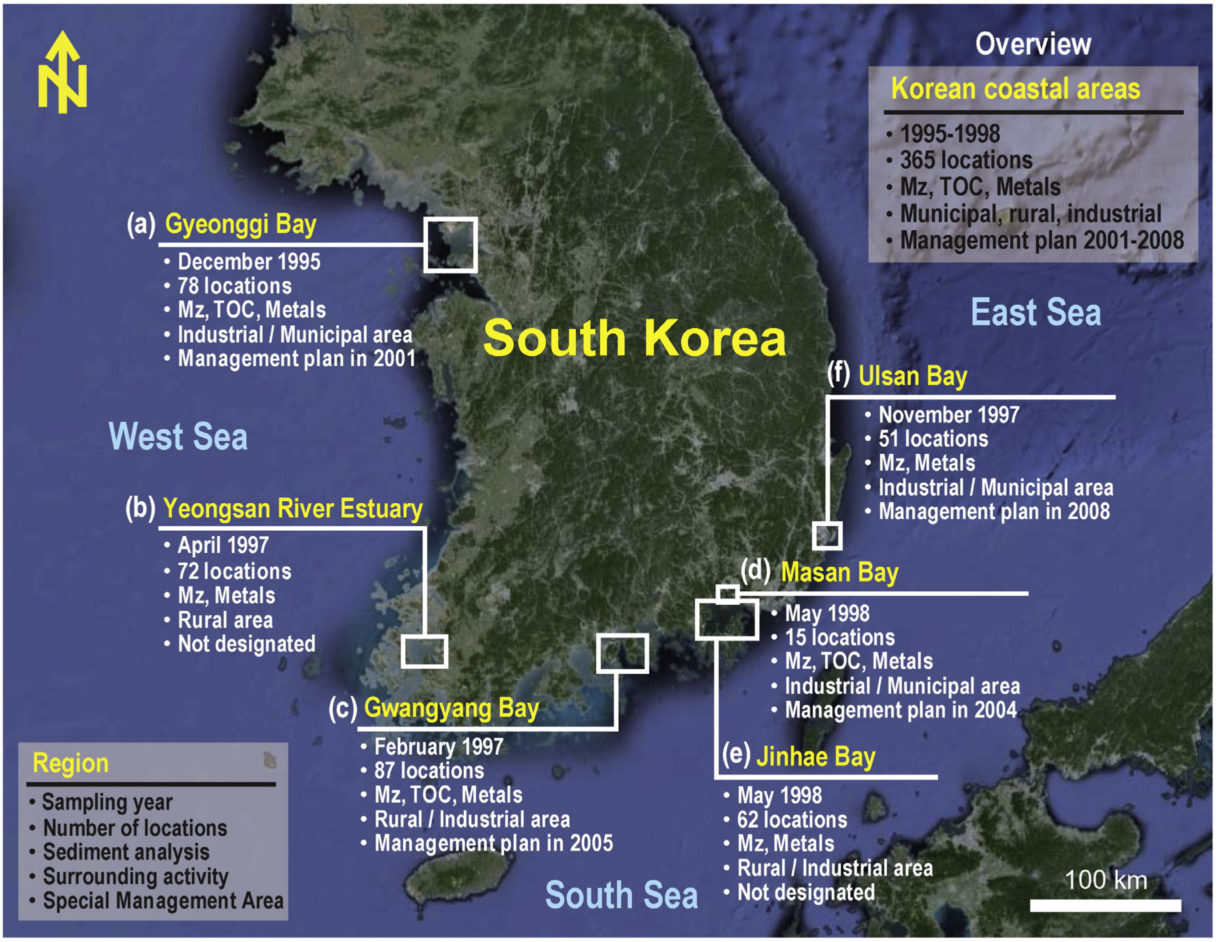


Fig. 1. Map showing the location of six coastal areas in Korea. The map also presents information on the sampling year, number of locations, target sedimentary parameters, surrounding activities, and current management regime.

Table 1
Summary of benthic indices with information about the input parameters, associated parameters, algorithms, and remarks.

Biotic indices	Input parameters	Associated parameters	Algorithms	Remarks	References
Ecological variable					
Species abundance (A)			A		
Number of species (S)			S		
A/S	A, S		A/S		
Ecological index					
Simpson's diversity index (1-λ)	N	S	$1\text{-}\lambda = 1 - N(N-1) / \sum n(n-1)$		
Margalef's richness index (d)	N, S		$d = (S-1) / \ln(n)$		
Estimated species in 50 indiv. (ES50)	N	S	$ES50 = 1 - \sum\{((N - N_i)!(N-50)!) / (N - N_i - 50)!N!\}$		
Pielou's evenness index (*J*′)	S, *H*′		$J' = H'/H'_{max}$		
Shannon-Wiener diversity index (*H*′)	S		$H' = -\sum p_i \ln(p_i)$		
Taxonomic distinctness (delta+)		S	$\Delta^+ = \{\sum\sum_{i<j}\omega_{ij}\} / \{s(s-1)/2\}$		Clarke and Warwick (1998, 1999)
Multivariate index					
AMBI			$AMBI = \{(0 \times \%G_I) + (1.5 \times \%G_{II}) + (3 \times \%G_{III}) + (4.5 \times \%G_{IV}) + (6 \times \%G_V)\} / 100$	Organic matter enrichment considered	Borja et al. (2000)
BPI			$BPI = \{1 - (a \times N_1 + b \times N_2 + c \times N_3 + d \times N_4) / (N_1 + N_2 + N_3 + N_4) / d\} \times 100$	Feeding type considered	KORDI (1995)
BQI	A, S	ES50	$BQI = \{\sum(A_i / \text{Total } A) \times ES(50)_{0.05i}\} \times {}^{10}\log(S+1)$		Rosenberg et al. (2004)
EQR	A, S, 1-λ, AMBI		$EQR = \{(2 \times (1 - (AMBI/7)) + (1\text{-}\lambda')) / 3\} \times \{((1 - (1/A)) + (1 - (1/S))) / 2\}$		Borja et al. (2004)
M-AMBI	AMBI, *H*′, S		$M\text{-}AMBI = K + (a \times AMBI) + (b \times H') + (c \times S)$		Muxika et al. (2007)

N: total number of individuals.

2.2. Sampling and laboratory analyses

Sediments and benthic organisms were collected from 365 locations in 1995–1998 and analyzed: Gyeonggi Bay (78 locations) in December 1995, Gwangyang Bay (87 locations) in February 1997, Yeongsan River Estuary (72 locations) in April 1997, Ulsan Bay (51 locations) in November 1997, Masan Bay (15 locations) and Jinhae Bay (62 locations) in May 1998 (Fig. 1). The sampling technique was designed according to the geography and coastal systems under analysis. For instance, sampling was focused in narrow or semi-closed areas and randomly distributed in the open seas (Fig. S1 of the Supplementary Materials (S)). At each location, replicates of sediment samples were taken using a 0.1 m^2 van Veen grab, covering a surface sampling area of 0.2 m^2. Surface sediment was retained for chemical analyses. Macrofauna were sampled with a 1 mm mesh sieve. The sorted fauna were then fixed in 4% buffered formalin solution and preserved in 70% ethanol for species identification and counting. Taxa were identified to the species level, using a dissecting microscope and an optical microscope where necessary.

For sediment parameters, sediment grain size was analyzed using a standard dry sieve (Ingram, 1971) and pipette method (McBride, 1971). Total organic carbon (TOC) of the sediments was estimated by the Walkley–Black titration method (McBride, 1971). Ten heavy metals in the sediments were measured using a Perkin Elmer 3100 flame Atomic Absorption Spectrometer (Norwalk, CT) after digestion with a mixed solution of acids (Kitano and Fujiyoshi, 1980), comprising concentrated nitric acid (HNO_3, 4 mL), hydrofluoric acid (HF, 4 mL) and perchloric acid ($HClO_4$, 2 mL). Precision and accuracy were validated using a certified standard reference material (SRM) NIST-1646a (estuarine sediment). Concentrations obtained for the SRM ($n = 3$) were within the 95% confidence interval of certified values, except for Mn and Pb. The relative standard deviations of the measured values for all analytes were within 10%, except for Pb (~40%). There was no sign of contamination in the analysis with <0.5% metal concentrations in the blanks ($n = 5$) relative to those in the SRM..

Heavy metal pollution was expressed as concentrations and/or target hazard quotients (HQ_{metal}), depending on the purpose (Eq. (1)).

$$HQ_{metal} = \Sigma\ SHC/SQG \qquad (1)$$

where, SHC is the heavy metal concentration of the sediments and SQG is the sediment quality guideline (Cd: 0.75 mg kg^{-1}; Cr: 116 mg kg^{-1}; Cu: 20.6 mg kg^{-1}; Ni: 47.2 mg kg^{-1}; Pb: 44.0 mg kg^{-1}; Zn: 68.4 mg kg^{-1} for Korean Threshold Effects Level (TEL); Mn: 460 mg kg^{-1} for Wisconsin TEL) (MOF, 2013; WDNR, 2003). The HQ_{metal} value was calculated as the sum of all risk factors (SHC/SQG > 1) for heavy metals in the sediment.

2.3. Data analysis

To compare environmental conditions and gradients over the six study areas, principal component analysis (PCA) was used. All sampling locations were placed in the 2-dimensional ordination plane with the first two principal component axes with respect to nine environmental variables (mud content and 8 heavy metals). Data on environmental variables were transformed with arcsine ($\sqrt{x}$) for mud content and with $\ln(x + 1)$ for heavy metals for the normality (Zar, 1984). PCA was examined using SPSS 12.0.

A total of 14 ecological indices were selected to analyze the benthic community. The ecological indices were categorized into three groups based on their characteristics; specifically three variables, six simple indices, and five multivariate indices (Table 1). The fundamental variables included total species abundance (A, density), total number of species (S), and A/S (abundance/species ratio). The second group included the Simpson diversity index (1-λ), the Margalef richness index (d), the Hurlbert index (ES 50; expected number of species in a random sample of 50 individuals), the Pielou evenness index (J'), the Shannon–Wiener diversity index (H'; natural log), and taxonomic distinctness (delta+). The third group included the Azti Marine Biotic Index (AMBI), the Benthic Pollution Index (BPI), the Benthic Quality Index (BQI), the Ecological Quality Ratio (EQR; calculated according to the UK MBITT multimetric approach), and the M-AMBI. Table 1 provides a summary of each index, with information about the input parameters, associated parameters, algorithms, and additional remarks. More details about the multivariate indices are provided previous publications (Blanchet et al., 2008; KORDI, 1995; Labrune et al., 2006; Quintino et al., 2006).

After calculating the stated suite of indices for each region, the resulting matrix was submitted to an ordination analysis, such as non-metric multidimensional scaling (NMDS). NMDS was used to explore similarities and differences in indices behavior within each area. Similarity was calculated using Bray–Curtis similarity coefficients with indices data log transformed and standardized. Pair-wise comparisons for significant differences in indices composition between areas were

Table 2
Summary of the six data sets used in this study: benthos and sedimentary environment.

	Gyeonggi Bay	Yeongsan River estuary	Gwangyang Bay	Masan Bay	Jinhae Bay	Ulsan Bay
Sampling						
Date # of locations	Dec 1995 78	Apr 1997 72	Feb 1997 87	May 1998 15	May 1998 62	Nov 1997 51
Benthos data						
Number of species	78	205	295	28	225	117
Density (ind. m^{-2})	570	241	875	182	991	535
Sediment data						
Mud content	1.5–97 (49 ± 30)[a]	15–100 (88 ± 22)	21–100 (86 ± 20)	43–98 (84 ± 20)	46–99 (94 ± 8.4)	35–100 (87 ± 16)
TOC (%)	0.0–1.2 (0.3 ± 0.2)	na[b]	0.4–2.0 (1.2 ± 0.4)	0.8–4.1 (1.8 ± 0.8)	na	0.1–6.9 (1.8 ± 1.5)
Metals						
Al (%)	3.1–8.0 (6.2 ± 1.0)	3.8–8.5 (7.0 ± 1.0)	2.3–10 (8.2 ± 1.4)	7.4–12 (10 ± 1.2)	4.4–10 (8.9 ± 0.9)	4.8–9.5 (7.5 ± 1.1)
Fe (%)	1.0–4.2 (2.4 ± 0.6)	1.4–4.4 (3.2 ± 0.6)	1.4–5.0 (3.8 ± 0.7)	3.5–4.7 (4.2 ± 0.3)	2.7–4.7 (4.0 ± 0.3)	2.1–4.2 (3.4 ± 0.6)
Mn (mg kg^{-1})	200–2100 (510 ± 220)	410–970 (640 ± 140)	310–1500 (920 ± 230)	470–680 (590 ± 69)	430–2000 (770 ± 270)	310–730 (482 ± 74)
Cr (mg kg^{-1})	24–360 (69 ± 42)	18–83 (60 ± 13)	26–93 (68 ± 14)	31–110 (68 ± 18)	23–82 (58 ± 11)	23–77 (47 ± 13)
Co (mg kg^{-1})	6.4–22 (14 ± 3.2)	4.6–16 (12 ± 2.3)	8.0–17 (13 ± 1.8)	9.3–16 (14 ± 1.7)	11–16 (14 ± 1.1)	9.7–76 (17 ± 10)
Cu (mg kg^{-1})	1.4–510 (66 ± 25)	6.4–27 (19 ± 4.6)	8.0–44 (19 ± 5.0)	24–160 (97 ± 39)	18–91 (42 ± 12)	26–400 (89 ± 64)
Ni (mg kg^{-1})	9.7–110 (25 ± 13)	8.6–37 (25 ± 6.0)	11–42 (33 ± 5.9)	13–49 (32 ± 7.6)	22–39 (34 ± 3.5)	21–55 (35 ± 7.8)
Zn (mg kg^{-1})	31–540 (91 ± 83)	25–100 (73 ± 16)	35–180 (96 ± 22)	92–570 (360 ± 140)	67–350 (130 ± 43)	81–480 (170 ± 80)
Pb (mg kg^{-1})	na	18–27 (24 ± 2.0)	9.0–770 (36 ± 80)	24–120 (67 ± 24)	10–69 (28 ± 8.2)	21–110 (43 ± 16)
Cd (mg kg^{-1})	na	0.1–0.4 (0.2 ± 0.05)	na	0.2–3.5 (2.0 ± 0.9)	0.2–1.8 (0.6 ± 0.4)	0.3–2.0 (0.6 ± 0.3)

[a] Min.–max. (mean ± SD).

[b] na: not analyzed.

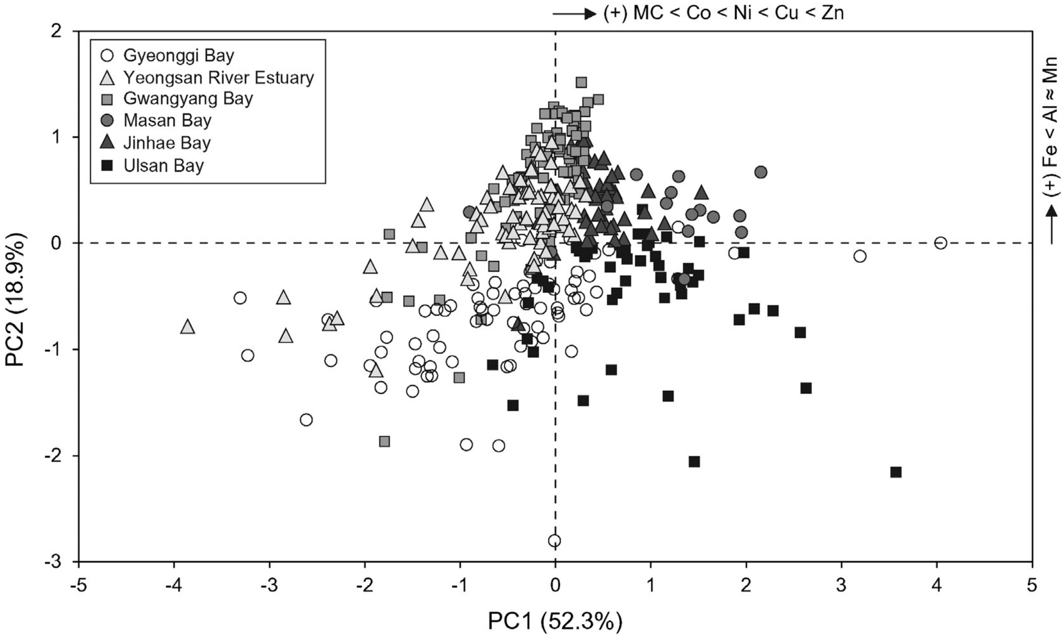


Fig. 2. PCA ordination of environmental conditions at sampling locations in six coastal areas of Korea. Locations are marked by area identifiers.

made using Analysis of Similarity (ANOSIM). Similarity percentage analysis (SIMPER procedure) was used to determine the percent of dissimilarity of locations and the particular indices responsible for differences between areas. Calculations of all univariate indices, NMDS, ANOSIM, and SIMPER were performed with the software PRIMER, v6 (Clarke and Gorley, 2006). AMBI and M-AMBI were computed using AMBI software (http://www.azti.es).

2.4. EcoQ assessment and index performance evaluation

To evaluate index performance to derive ecological quality (EcoQ), six indices were selected for comparison: one simple index of H' and well known five multivariate indices of AMBI, BPI, BQI, EQR, and M-AMBI, for those given the quality thresholds that tentatively suggested in previous papers (Blanchet et al., 2008; KORDI, 1995; Labrune

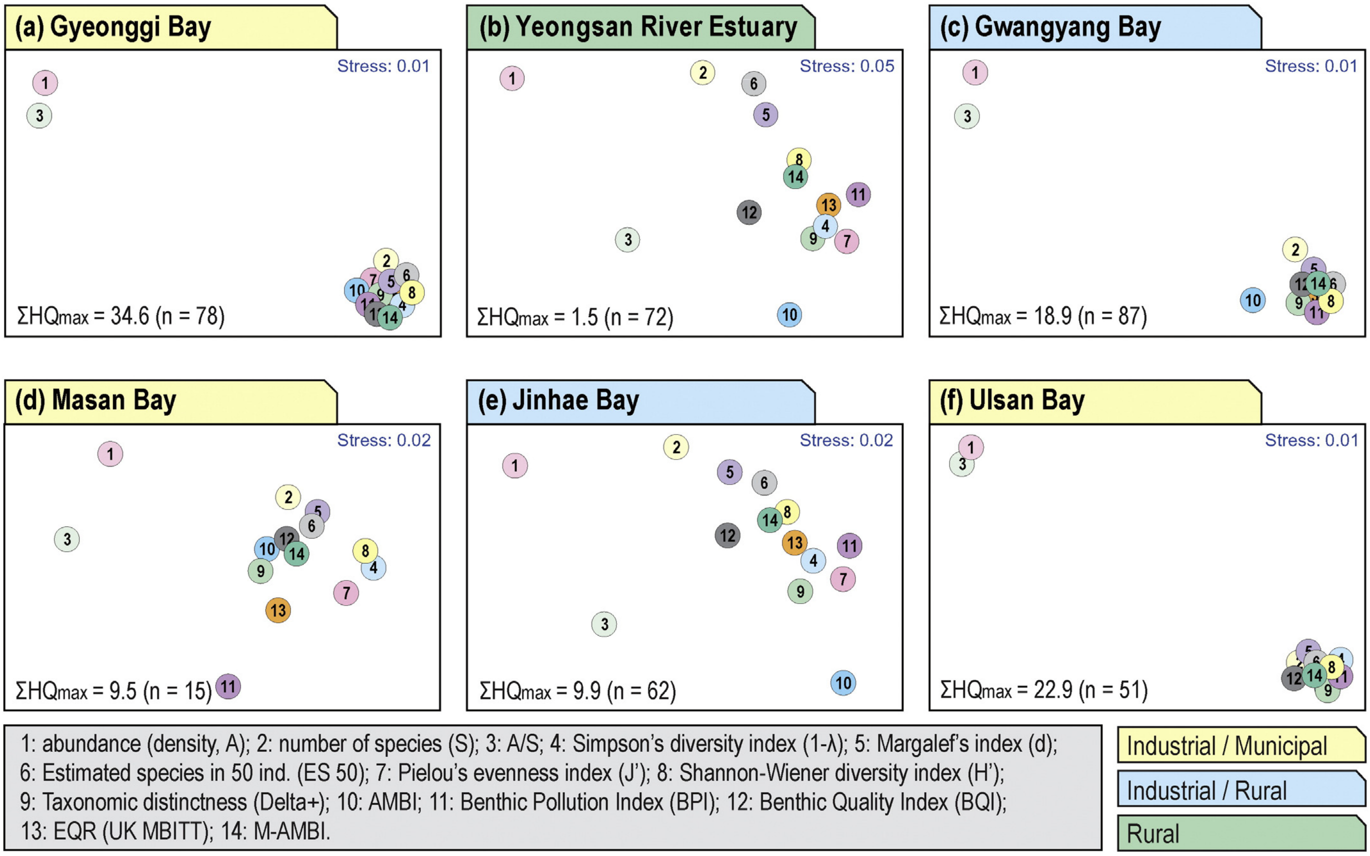


Fig. 3. MDS ordination results for 14 univariate and multivariate ecological indices and the maximum values of heavy metal hazard quotients (HQ_{max}) in six coastal areas of Korea.

et al., 2006; Rosenberg et al., 2004; Quintino et al., 2006). The European Water Framework Directive (WFD) proposed a guideline to assess EcoQ of water bodies and classify ecological status into five scales (high, good, moderate, poor, and bad). Here, EcoQ was assessed in each index based on the five scales as the WFD proposed: "High" if $H' > 4$, AMBI ≤1.2, BPI ≥ 60, EQR ≥ 0.80; "Good" if $3 < H' \le 4$, $1.2 < \text{AMBI} \le 3.3$, $40 \le \text{BPI} < 60$, $0.65 \le \text{EQR} < 0.80$; "Moderate" if $2 < H' \le 3$, $3.3 < \text{AMBI} \le 4.3$, $30 \le \text{BPI} < 40$, $0.43 \le \text{EQR} < 0.65$; "Poor" if $1 < H' \le 2$, $4.3 < \text{AMBI} \le 5.5$, $20 \le \text{BPI} < 30$, $0.20 \le \text{EQR} < 0.43$; and "Bad" if $H' \le 1$, AMBI > 5.5, BPI < 20, EQR < 0.20 (Blanchet et al., 2008). Conversely, the EcoQ assessed by BQI was determined by taking the highest BQI values as a reference value and by defining five classes of equal interval between 0 and the reference value (Rosenberg et al., 2004). M-AMBI determines the EcoQ based on pre-selected threshold values estimated from discriminant analysis, combining AMBI with the Shannon–Wiener diversity and the number of species (Muxika et al., 2007)..

A non-parametric Wilcoxon paired-sample test was used to assess (dis)agreement between the indices on the EcoQ status of locations statistically. A non-parametric Kendall's rank correlation coefficient between index-derived classifications was calculated and evaluated in assess whether the different indices displayed a similar tendency in the EcoQ classification of locations. A detailed description justifying the use of the Kendall's rank-correlation coefficient is provided by Blanchet et al. (2008). Kruskal–Wallis analysis was used to evaluate environmental differences between different EcoQ classes. The variables used in the analysis were mean grain size, organic carbon content, and heavy metals in the sediments. All three non-parametric statistical analyses were performed by SPSS 12.0.

3. Results and discussion

All study areas were located in shallow coastal zones of <30 m water depth. Sediment quality in the bays and adjacent socio-economic activities, such as population, industry and agricultural activities, were considered to classify the six bays into three groups; specifically, rural (Yeongsan River Estuary), rural/industry (Gwangyang Bay and Jinhae Bay), and municipal/industry (Gyeonggi Bay, Masan Bay, and Ulsan Bay) (Fig. 1). A total of 365 locations in the six bays were examined to identify the extent to which benthic indices showed (dis)agreement in assessing ecological integrity. Each area included >50 locations, except for the relatively small area of Masan Bay ($n = 10$ locations); thus, it was possible to make regional comparison between bays based on their size and/or geographical distribution. We considered stepwise analyses, say from general variables to simple and/or multivariate indices, whether site-specific indices may be used within the framework of an overall benthic quality assessment in the coastal areas of Korea.

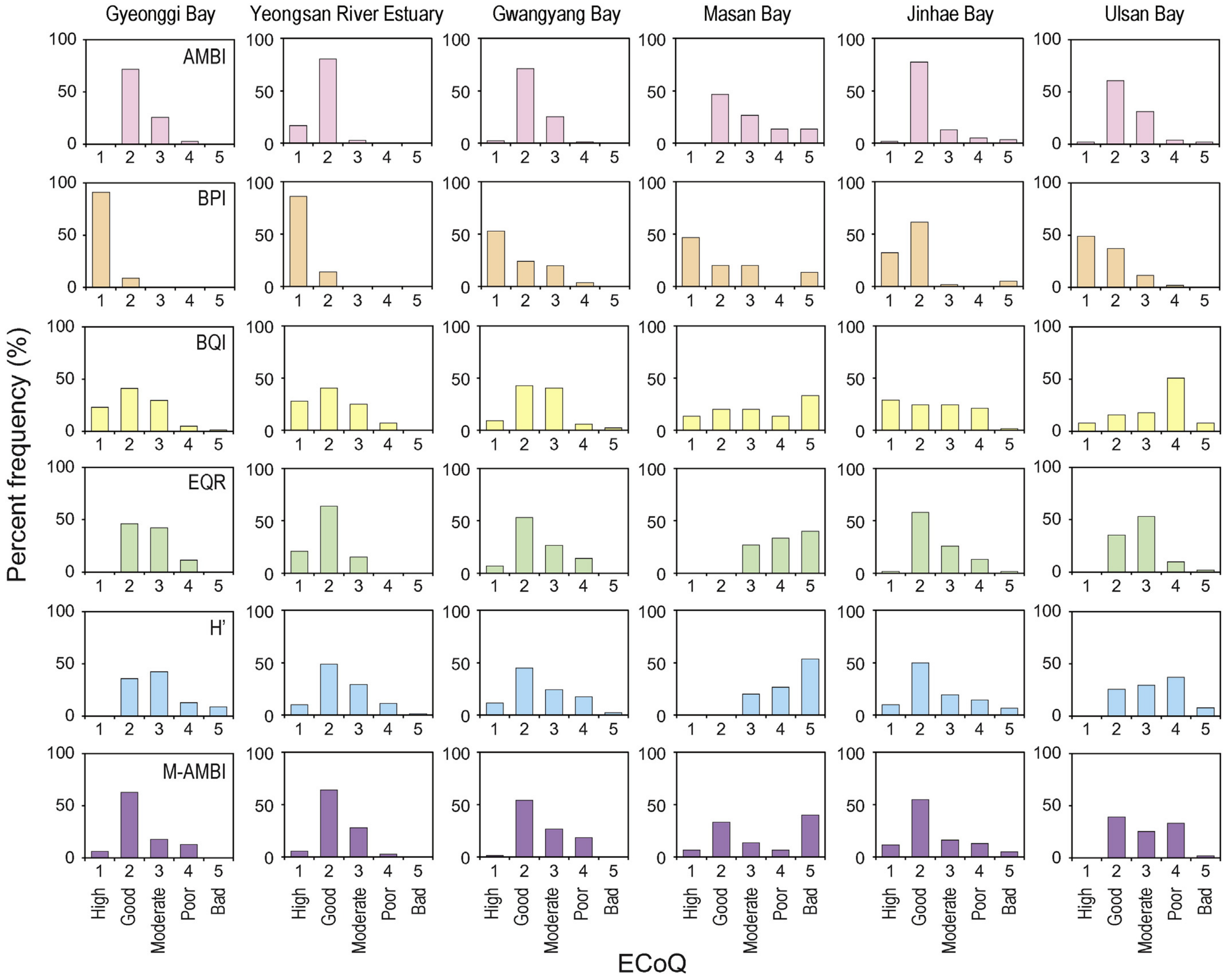


Fig. 4. Percent frequency (%) of ecological quality (EcoQ) status based on six selected benthic indices (AMBI, BPI, BQI, EQR, H', and M-AMBI) in six coastal areas of Korea..

3.1. General ecological qualities in six Korean coasts

From the entire six study areas, a total of 479 species of benthic invertebrates were identified. A full list of occurring species in the study areas are provided in the Table S1. In general, the bottom sediment in the bays was mostly mud-dominant habitat with >80% of mud content, on average, except for Gyeonggi Bay (49% mud) (Table 2). PCA ordination showed environmental gradient between regions, high in Ulsan and Masan Bays, intermediate in Jinhae and Gwangyang Bays, low in Gyeonggi Bay and Yeongsan River Estuary (Fig. 2). Despite low average contamination, Gyeonggi Bay showed the most extremely polluted locations near industrial harbors, such as Incheon North Harbor, known to be highly heavy metal polluted area (Ryu et al., 2011). The first two principal components accounted for 71.1% of the variability in environmental conditions over the regions, with 52.3% on axis 1 and 19.8% on axis 2. Zn, Cu, Ni, Co, and mud content were important determinants of differences between locations along the first axis, while Mn, Al, and Fe were influential along axis 2 (Table S2). The areas belonging to the industry/municipal regional group (e.g., Masan and Ulsan bays) were the most contaminated by heavy metals such as Cu, Zn, and Pb (Khim and Hong, 2014). Areas with moderate heavy metal pollution were found to be the bays adjacent to the industry/rural areas. Finally, the least heavy metal pollution was detected in the Yeongsan River Estuary that seemed to be due to the surrounding rural activities and high tidal currents of west coast of Korea. Overall, heavy metal contamination tended to reflect the geography and adjacent land use activities.

Macrozoobenthic biodiversity also tended to reflect the geographical setting and heavy metal pollution gradient between bays. For example, more benthic species (>200 species) were detected in areas adjacent to rural activity and/or open sea regions. In comparison, species numbers declined in the three areas, mostly semi-closed system, with high municipal activity (< 100 species). Given smaller sampling locations in Masan Bay compared to those in other areas, low number of species (n = 28) were observed, but the lowest density of individuals (182 ind. m^{-2}) was also found, reflecting the severe sedimentary pollution in the given area (Khim and Hong, 2014; Khim et al., 1999). In general, benthic organisms are influenced by sedimentary organic carbon contents, particularly in the species richness (Hyland et al., 2005). The smallest number of species of Masan Bay seemed to be associated with great organic carbon contents in sediments (0.8 to 4.1%). In addition, organic matter including toxic substances are accumulated greatly in sediments of the Masan Bay compared to the Gyeonggi Bay and Ulsan Bay, which reflected the general association of benthic community with the geographical setting in the semi-enclosed system given (Khim and Hong, 2014).

Table 3

Results of the non-parametric Wilcoxon paired-sample test between biotic indices derived ecological quality status classification (with the five EcoQ classes defined by the WFD), without considering tied ranking.

(a) Gyeonggi Bay (n = 78)

	BPI	BQI	EQR	H'	M-AMBI
AMBI	***	ns	***	***	ns
BPI		***	***	***	***
BQI			***	***	*
EQR				***	***
H'					***

(b) Yeongsan River estuary (n = 72)

	BPI	BQI	EQR	H'	M-AMBI
AMBI	***	*	ns	***	***
BPI		***	***	***	***
BQI			ns	**	ns
EQR				***	***
H'					*

(c) Gwangyang Bay (n = 87)

	BPI	BQI	EQR	H'	M-AMBI
AMBI	***	*	***	**	***
BPI		***	***	***	***
BQI			ns	ns	ns
EQR				ns	ns
H'					ns

(d) Masan Bay (n = 15)

	BPI	BQI	EQR	H'	M-AMBI
AMBI	**	ns	*	*	ns
BPI		ns	**	**	ns
BQI			*	**	ns
EQR				ns	*
H'					**

(e) Jinhae Bay (n = 62)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	***	ns	**	**	ns
BPI		**	***	***	***
BQI			ns	ns	ns
EQR				ns	ns
H'					*

(f) Ulsan Bay (n = 51)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	***	***	***	***	***
BPI		***	***	***	***
BQI			***	ns	**
EQR				***	*
H′					***

ns: not significant ($p > 0.05$).
* : Significant ($p < 0.05$).
** : Very significant ($p < 0.01$).
*** : Highly significant ($p < 0.001$).

The association of benthic faunal communities with the surrounding environment was also identified by NMDS analysis (Fig. 3). The MDS diagram clearly shows certain spatial patterns for ecological indices where two distinct groups (A and A/S vs. other indices) were consistently found. This trend was particularly strong for the industrial areas surrounding Gyeonggi, Gwangyang, and Ulsan bays. In general, the association of A and A/S gradually weakened as rural activities increased (i.e., as contamination declined). Meantime, certain indices (such as S, BQI, and AMBI) were dispersed in the rural areas but allocated together in the industrial and/or municipal areas, where contamination was greater. Such allocation change between indices was also observed for certain ecological indices, such as d and ES50, dispersed in rural areas such as the Yeongsan River Estuary and Jinhae Bay. All diversity indices ($1-\lambda$, J', H', and delta+) and certain multivariate indices (BQI, EQR, and M-AMBI), are located in center in a group and showed close association (located nearby) across each other. They appeared to be representative in an integrated manner. Compared to other indices, BPI was independent and/or inconsistent across the study areas. Of note, the NMDS plotting of ecological indices may not necessarily reflect the degree of pollution in a given area; rather, it may simply suggest (dis)similarity between indices. However, the close grouping between indices in contaminated areas with greater HQ_{metal}, in Gyeonggi, Ulsan, and Gwangyang Bays, implies potential pollution (Fig. 3).

The similarity analysis (ANOSIM) presented significant differences between the two areas with a significance level of 0.05, except Ulsan vs. Masan ($R = 0.013$, $p = 0.405$). Apparently 6 areas were found to be relatively similar in indices variation. This was confirmed by calculation of the percent of dissimilarity between the two areas and the contribution of specific indices to the very dissimilarity (SIMPER procedure) (Table S3).

3.2. EcoQ classifications

All of the indices used in this study, including multivariate indices, were useful for identifying the general benthic quality of the selected study areas. We also selected one ecological index (H') and five multivariate indices (AMBI, BPI, BQI, EQR, and M-AMBI) to quantify their site-specific utility in an ecological quality assessment. The percent frequency of the selected indices clearly showed regional differences in EcoQ, with this result being expected from the wide range of sedimentary pollution in the study areas (Fig. 4). Overall, the EcoQ results reflected the degree of pollution and nearby land use activity, with slight variation in patterns. Masan Bay had the lowest EcoQ status, with the greatest proportion of "Poor" to "Bad" quality locations (48%). This result was reflected in this site also having the smallest species numbers and abundance (Table 2). Yeongsan River Estuary had the healthiest benthic community, with >50% of locations being of "High" to "Good" quality.

Out of the six indices, the BPI seemed to be the most tolerant index with >90% of locations being classified as "High" to "Good," followed by AMBI (76%), M-AMBI (60%), and EQR (56%). More than 50% of locations were classified as a single specific EcoQ status for several indices, such as AMBI (72% "Good"), BPI (63% "High'), and M-AMBI (55% "Good"). This result indicates that these indices have relatively weaker resolution in classifying the specific range of EcoQ status. However,

Table 4
Results of the non-parametric Kendall's rank correlation coefficient test between biotic indices-derived ecological quality (EcoQ) status classifications.

(a) Gyeonggi Bay (n = 78)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	ns	ns	0.632***	0.460***	0.425***
BPI		ns	ns	ns	ns
BQI			0.529***	0.635***	0.660***
EQR				0.686***	0.627***
H′					0.707***

(b) Yeongsan River estuary (n = 72)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	0.306**	ns	0.453***	ns	ns
BPI		ns	0.230*	ns	0.287*
BQI			ns	0.382***	0.392***
EQR				0.526***	0.576***
H′					0.681***

(c) Gwangyang Bay (n = 87)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	0.693***	0.273**	0.749***	0.565***	0.706***
BPI		0.256**	0.691***	0.517***	0.604***
BQI			0.368***	0.470***	0.526***
EQR				0.704***	0.778***
H′					0.779***

(d) Masan Bay (n = 15)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	0.850***	−0.652**	ns	−0.556*	−0.581*
BPI		−0.696**	ns	−0.636**	−0.577*
BQI			0.611**	0.767**	0.905***
EQR				0.733**	0.719**
H′					0.832***

(e) Jinhae Bay (n = 62)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	0.375**	0.490***	0.673***	0.570***	0.672***
BPI		ns	0.302*	ns	0.352**
BQI			0.746***	0.730***	0.739***
EQR				0.853***	0.845***
H′					0.908***

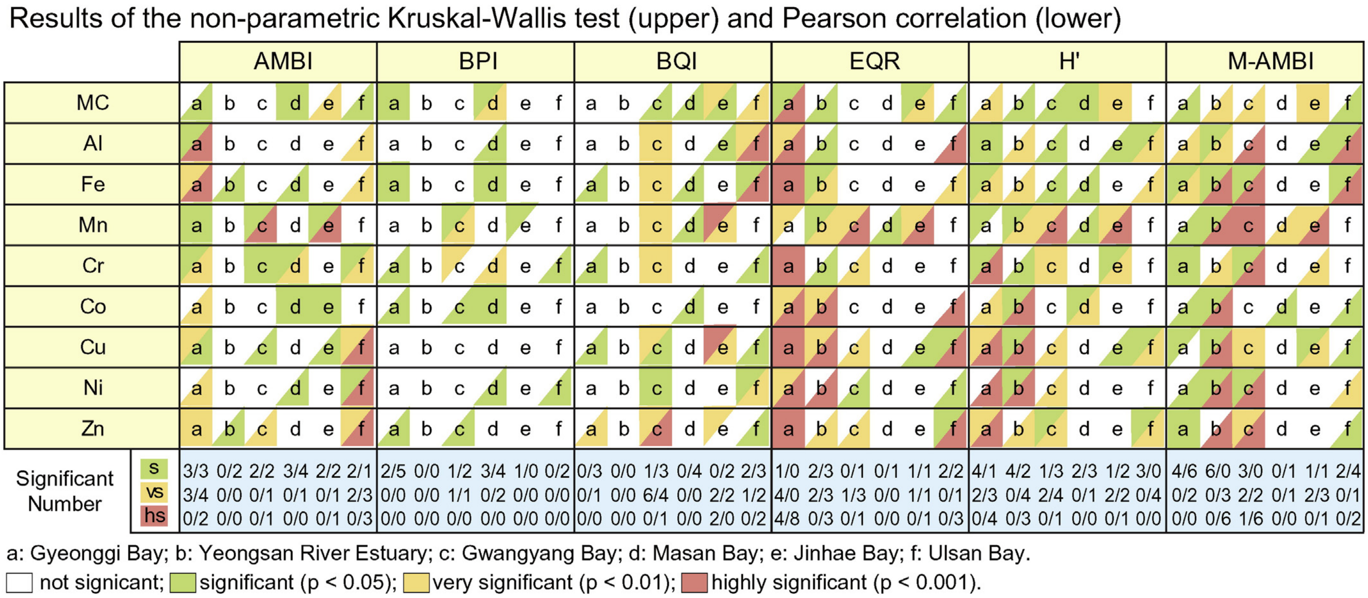
(f) Ulsan Bay (n = 51)

	BPI	BQI	EQR	H′	M-AMBI
AMBI	0.260*	0.272*	0.566***	0.325**	0.320*
BPI		ns	0.296*	ns	ns
BQI			0.533***	0.550***	0.648***
EQR				0.654***	0.736***
H′					0.831***

ns: not significant (p > 0.05).
* : Significant (p < 0.05).
** : Very significant (p < 0.01).
*** : Highly significant (p < 0.001).

the EcoQ across locations tended to be comparable within a given area, regardless of all selected indices. Overall, the EQR provided the clearest classification (see Masan and Yeongsan cases) across the range of EcoQ status (Fig. 4). Therefore, at present, EQR appears to present an appropriate index for regional grouping and/or the comparison of benthic quality assessments.

The WFD establishes a framework for the protection and improvement of all European surface and ground waters. Its final objective is to achieve at least ‘good water status’ for all water bodies by the year 2015. The WFD provides a guideline to assess ecological quality status based on EQR, including biological, hydromorphological, and physico-chemical quality elements (Borja et al., 2007). Similar to this effort, the Korean government proposed the Marine Ecological Quality Map (MEQM) in 2014 based on a great amount of monitoring data, classifying ecological quality of coastal water bodies into three classes (I, II, & III). Four criteria have been considered to the Korean EcoQ assessment, such as 1) endangered species, 2) ecological superiority (DO of bottom water, sediment pollution, biomass and ecological index of macrozoobenthos, harmful algae, and phytoplankton density), 3) biodiversity, and 4) designation of marine protected areas. However, assessment criteria for the first MEQM failed to be accepted with respect to scientific consensus and conflict with other legislation, accordingly the management objectives have been pending at present. Taking into account great amount of work to be carried out in the WFD process,


Results of the non-parametric Kruskal-Wallis test (upper) and Pearson correlation (lower)

Significant Number		AMBI						BPI						BQI						EQR						H'						M-AMBI					
	s	3/3	0/2	2/2	3/4	2/2	2/1	2/5	0/0	1/2	3/4	1/0	0/2	0/3	0/0	1/3	0/4	0/2	2/3	1/0	2/3	0/1	0/1	1/1	2/2	4/1	4/2	1/3	2/3	1/2	3/0	4/6	6/0	3/0	0/1	1/1	2/4
	vs	3/4	0/0	0/1	0/1	0/1	2/3	0/0	0/0	1/1	0/2	0/0	0/0	0/1	0/0	6/4	0/0	2/2	1/2	4/0	2/3	1/3	0/0	1/1	0/1	2/3	0/4	2/4	0/1	2/2	0/4	0/2	0/3	2/2	0/1	2/3	0/1
	hs	0/2	0/0	0/1	0/0	0/1	0/3	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	0/0	2/0	0/2	4/8	0/3	0/1	0/0	0/1	0/3	0/4	0/3	0/1	0/0	0/1	0/0	0/0	0/6	1/6	0/0	0/1	0/2

a: Gyeonggi Bay; b: Yeongsan River Estuary; c: Gwangyang Bay; d: Masan Bay; e: Jinhae Bay; f: Ulsan Bay.
☐ not signicant; 🟩 significant (p < 0.05); 🟨 very significant (p < 0.01); 🟥 highly significant (p < 0.001).

Fig. 5. Results of the non-parametric Kruskal–Wallis test and Pearson correlation to determine the relationship between environmental parameters and EcoQ status in six coastal areas of Korea.

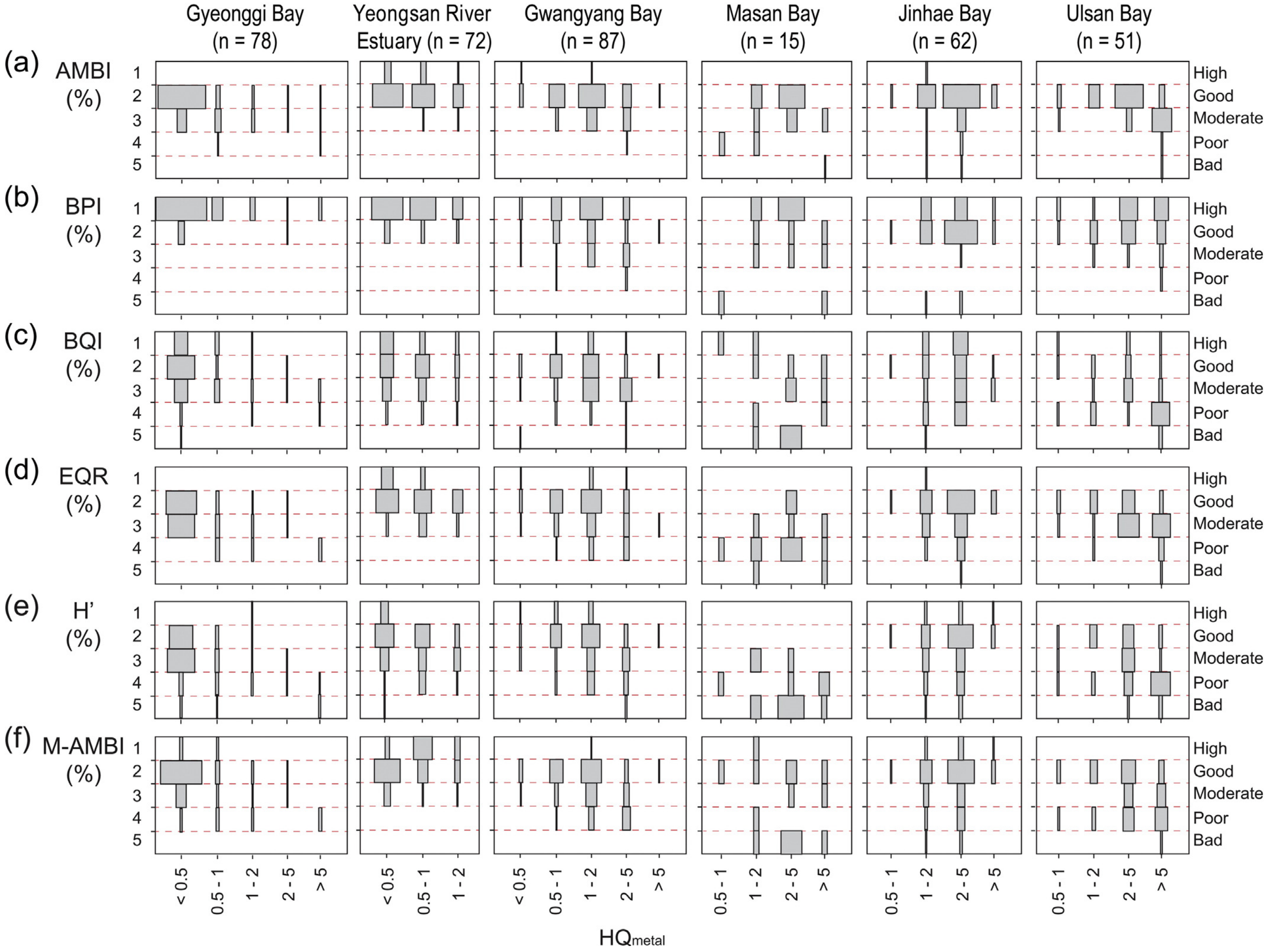


Fig. 6. Proportion of ecological quality (EcoQ) status against the degree of heavy metal hazard quotients (ΣHQ_{metal}) in six coastal areas of Korea.

the Korean MEQM needs further revision process, including complimentary researches, to achieve wide agreement from scientific community as well as managers with long-term perspectives.

3.3. Agreement and disagreement between ecological indices

The (dis)similarity between indices was shown by the regional assessment of EcoQ. Thus it might be necessary to address site-specific (dis)agreement across the selected indices. The non-parametric Wilcoxon paired-sample test showed that, there was significant disagreement between indices across (Table 3). In particular, the EcoQ significantly disagreed in Ulsan Bay, except BQI vs. *H′*. Gyeonggi Bay and Yeongsan River Estuary generally showed disagreement between indices, except for two (AMBI vs. BQI and AMBI vs. M-AMBI for Gyeonggi Bay) and three (AMBI vs. EQR, BQI vs. EQR, and BQI vs. M-AMBI for Yeongsan River Estuary) cases, respectively. Jinhae Bay showed the best agreement between indices, with no significant disagreement for seven cases of correlation out of 15 combinations, indicating the least variable index among tested. Gwangyang and Masan bays had the second best agreement between indices, with six cases significantly agreeing. The BQI and M-AMBI were found to be the most widely comparable indices in relation to all other indices in these areas, warranting lesser sensitive indices.

Most indices showed significant rank correlations (Kendall) with one another, except for the BPI (Table 4). This result indicates that rank-based regional classification based on AMBI, BQI, EQR, *H′*, or M-AMBI would be valid and reasonable. In particular, all correlations in Gwangyang Bay were significant. The observed significant rank correlation may be explained by “rank-shrinking” between indices. For instance, Gwangyang locations that were broadly classified as “High” to “Bad” by BQI and *H′* were narrowed down to mostly “Good” to “Moderate” or “Poor” by AMBI and M-AMBI (Fig. 4). Another explanation is the “rank-shift” phenomenon. For instance, the Gwangyang locations that were mostly classified as “High” or “Good” to “Moderate” by BPI or AMBI were delineated as “Good” to “Poor” by M-AMBI. However, significant disagreement was detected between BQI vs. AMBI, BPI vs. M-AMBI, and AMBI vs. M-AMBI (Table 3) from the paired-sample tests. Thus, it might be important to select appropriate indices or examine their relationships depending on the purpose of a given comparative assessment for regional EcoQ in management (Blanchet et al., 2008).

3.4. Relationship between ecological indices and metal pollutions

Regional variation in EcoQ classification and/or evidence of (dis)-agreement between indices may arise in coastal ecosystems because such systems are subject to continuous environmental changes (Blanchet et al., 2008; Labrune et al., 2006; Quintino et al., 2006). Strong association of such environmental changes to faunal responses would not be exception in the benthic environment, in particular certain sedimentary properties, such as mud or organic content, play a key role for macrofaunal distribution. Pollution may be a key factor

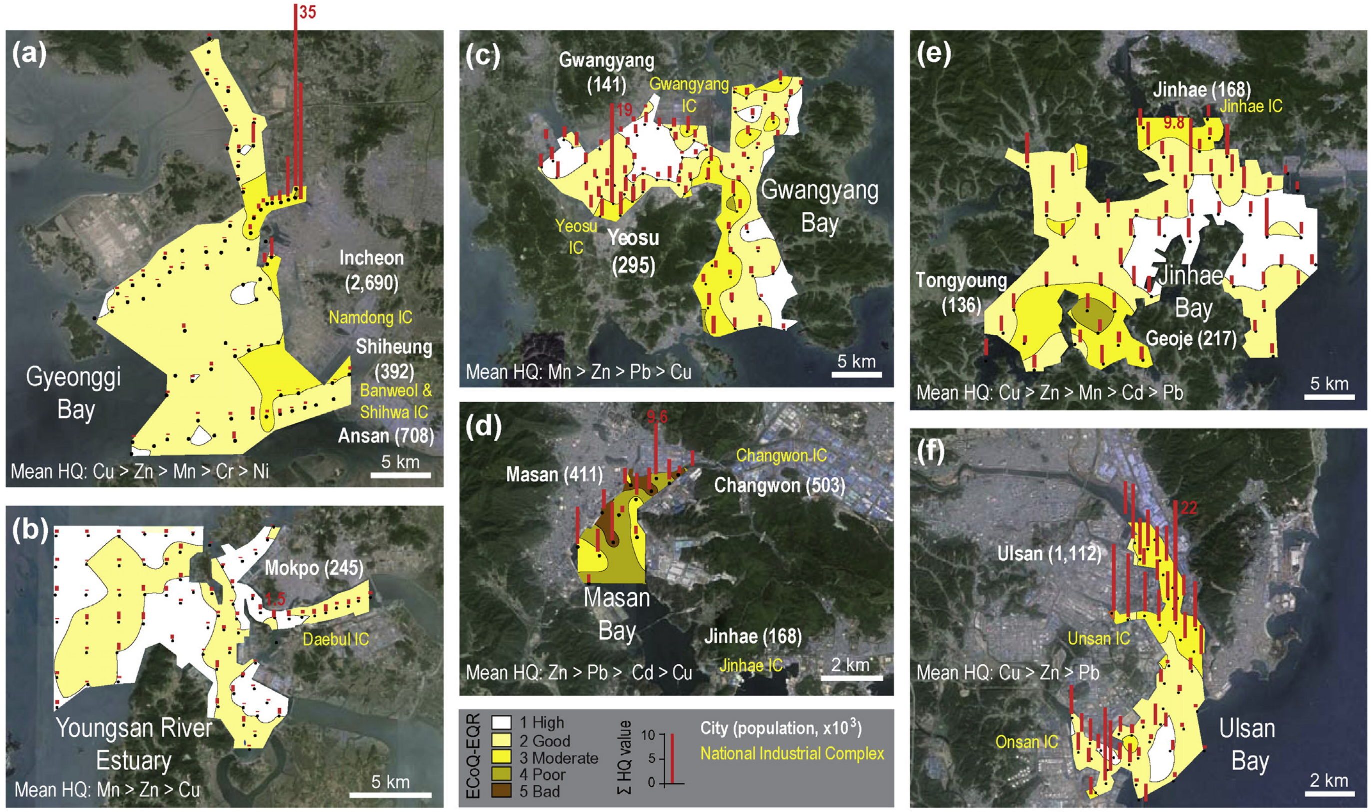


Fig. 7. Spatial distribution of ecological quality (EcoQ) status classes and heavy metal hazard quotients (ΣHQ_{metal}) values in six coastal areas of Korea.

controlling the health of the benthic community, particularly as pollutants tended to accumulate and sink to the bottom sediment layer (Ryu et al., 2011). To determine the relationship between environmental parameters and EcoQ status, we performed both non-parametric Kruskal–Wallis test and Pearson correlation analysis (Fig. 5 and Table S4). We found that mud content and heavy metal concentration were significantly associated with EcoQ class, particularly in major industrial areas (e.g., Gyeonggi and Ulsan bays). Interestingly, at least two indices, among six tested, were significantly associated with environmental parameters in each area, meantime some parameters (Fe, Mn, Cr, and Zn) were consistently associated with all six indices. However, the degree and spectrum of these associations differed between two statistics. In general, the Kruskal–Wallis test was more strict (less sensitive), because it considers the rank-based EcoQ status.

Among the six indices, the M-AMBI had the best fit with the EcoQ status for the tested environmental parameters with respect to region. Specifically, five of the six areas showed relatively high associations. However, the high proportion of strong associations might overestimate the specific association between EcoQ status and environmental condition; consequently, M-AMBI may not represent the most appropriate index. For example, the smallest heavy metal concentrations were found in Yeongsan River Estuary; yet, a strong association to EcoQ status was detected here. In comparison, the Masan Bay locations had relatively high and varying heavy metal concentrations, but with low correlations. This inconsistency between raw-data and statistical results would be masked by the other components and/or parameters, such as hypoxia, eutrophication, or trace organic contamination. Despite this issue, several heavy metals seemed to be strongly associated with EcoQ status, regardless of index. Significant metals for all six indices were Fe, Mn, Cr, and Zn in Gyeonggi Bay, Mn, Cr, and Zn in Gwangyang Bay, and Mn and Cr in Jinhae Bay.

To investigate how heavy metals are associated with EcoQ status, the proportion of EcoQ status against the degree of ΣHQ_{metal} was examined in each area (Fig. 6). As expected, Gyeonggi (EQR and M-AMBI) and Ulsan (BQI and EQR) bays showed a proportional gradient between these two parameters, supporting the Kruskal–Wallis test results. This result indicates that the EQR reflects the general pollution gradient of heavy metals, facilitating the effective separation of locations based on pollution status by each index (Fig. 4). EQR and ΣHQ_{metal} was also spatially associated in Gyeonggi and Ulsan bays, but not in any of the other areas (Fig. 7). In general, the EQR seemed to be more powerful for assessing hot spot locations and/or the spatial gradient of pollution in the study areas. Overall, this study demonstrated that the application of varying ecological indices was useful for quantifying ecological status in relation to sedimentary pollution in each area. In conclusion, we confirm that single or limited indices may over- or underestimate the ecological status of marine areas and thus strongly recommend the use of site-specific indices to specific areas and/or locations for objective pollution assessments.

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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.scitotenv.2015.10.016.

References

Ballesteros, E., Torras, X., Pinedo, S., García, M., Mangialajo, L., de Torres, M., 2007. A new methodology based on littoral community cartography dominated by macroalgae for the implementation of the European Water Framework Directive. Mar. Pollut. Bull. 55, 172–180.

Benyi, S.J., Hollister, J.W., Kiddon, J.A., Walker, H.A., 2009. A process for comparing and interpreting differences in two benthic indices in New York harbor. Mar. Pollut. Bull. 59, 65–71.

Blanchet, H., Lavesque, N., Ruellet, T., Dauvin, J.C., Sauriau, P.G., Desroy, N., et al., 2008. Use of biotic indices in semi-enclosed coastal ecosystems and transitional waters habitats — implications for the implementation of the European Water Framework Directive. Ecol. Indic. 8, 360–372.

Borja, A., Dauer, D.M., 2008. Assessing the environmental quality status in estuarine and coastal systems: comparing methodologies and indices. Ecol. Indic. 8, 331–337.

Borja, A., Dauer, D.M., Díaz, R., Llansó, R.J., Muxika, I., Rodríguez, J.G., et al., 2008. Assessing estuarine benthic quality conditions in Chesapeake bay: a comparison of three indices. Ecol. Indic. 8, 395–403.

Borja, A., Franco, J., Muxica, I., 2004. The biotic indices and the water framework directive: the required concensus in the new benthic monitoring tools. Mar. Pollut. Bull. 48, 405–408.

Borja, A., Franco, J., Pérez, V., 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Mar. Pollut. Bull. 40, 1100–1114.

Borja, A., Josefson, A.B., Miles, A., Muxika, I., Olsgard, F., Phillips, G., et al., 2007. An approach to the intercalibration of benthic ecological status assessment in the north Atlantic ecoregion, according to the European Water Framework Directive. Mar. Pollut. Bull. 55, 42–52.

Chang, W.K., Ryu, J., Yi, Y., Lee, W.-C., Lee, C.-W., Kang, D., et al., 2012. Improve water quality in response to pollution control measures at Masan bay, Korea. Mar. Pollut. Bull. 64, 427–435.

Clarke, K.R., Gorley, R.M., 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth.

Clarke, K., Warwick, R., 1998. A taxonomic distinctness index and its statistical properties. J. Appl. Ecol. 35, 523–531.

Clarke, K., Warwick, R., 1999. The taxonomic distinctness measure of biodiversity: weighting of step lengths between hierarchical levels. Mar. Ecol. Prog. Ser. 184, 21–29.

Coates, S., Waugh, A., Anwar, A., Robson, M., 2007. Efficacy of a multi-metric fish index as an analysis tool for the transitional fish component of the water framework directive. Mar. Pollut. Bull. 55, 225–240.

Cusack, C., O'Beirn, F., King, J., Silke, J., Keirse, G., Whyte, I., et al., 2005. Water Framework Directive – Marine Ecological Tools for Reference, Intercalibration and Classification. Environmental Protection Agency, Ireland.

Dauer, D.M., 1993. Biological criteria, environmental health and estuarine macrobenthic community structure. Mar. Pollut. Bull. 26, 249–257.

Dauvin, J.C., 2008. Effects of heavy metal contamination on the macrobenthic fauna in estuaries: the case of the Seine estuary. Mar. Pollut. Bull. 57, 160–169.

Dauvin, J.C., Ruellet, T., 2007. Polychaete/amphipod ratio revisited. Mar. Pollut. Bull. 55, 215–224.

Diaz, R.J., Solan, M., Valente, R.M., 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. J. Environ. Manag. 73, 165–181.

Fitch, J.E., Crowe, T.P., 2010. Effective methods for assessing ecological quality in intertidal soft-sediment habitats. Mar. Pollut. Bull. 60, 1726–1733.

Hennessey, J., Nichols, B., 2011. The State Ocean Caucus. Marine Spatial Planning in Washington: Final Report and Recommendations of the State Ocean Caucus to the Washington State Legislature. Washington Department of Ecology publication No. 10–06-027, WA: Olympia.

Hyland, J., Balthis, L., Karakassis, I., Magni, P., Petrov, A., Shine, J., et al., 2005. Organic carbon content of sediments as an indicator of stress in the marine benthos. Mar. Ecol. Prog. Ser. 295, 91–103.

Ingram, R.L., 1971. Sieve analysis. In: Carver, R.E. (Ed.), Procedures in Sedimentary Petrology. Wiley Interscience, New York, pp. 49–68.

Khim, J.S., Hong, S., 2014. Assessment of trace pollutants in Korean coastal sediments using the triad approach: a review. Sci. Total Environ. 470-471, 1450–1462.

Khim, J.S., Kannan, K., Villeneuve, D.L., Koh, C.H., Giesy, J.P., 1999. Characterization and distribution of trace organic contaminants in sediment from Masan bay, Korea. 1. Instrumental analysis. Environ. Sci. Technol. 33, 4199–4205.

Kitano, Y., Fujiyoshi, R., 1980. Selective chemical leaching of cadmium, copper, manganese and iron in marine sediments. Geochem. J. 14, 113–122.

Korea Ocean Research & Development Institute (KORDI), 1995. Marine Environment Assessment Based on The Benthic Faunal Communities. KORDI, Ansan, Korea (in Korean).

Labrune, C., Amouroux, J.M., Sarda, R., Dutrieux, E., Thorin, S., Rosenberg, R., et al., 2006. Characterization of the ecological quality of the coastal Gulf of Lions (NW Mediterranean). A comparative approach based on three biotic indices. Mar. Pollut. Bull. 52, 34–47.

Lee, C.-H., Lee, B.-Y., Chang, W.K., Hong, S., Song, S.J., Park, J., et al., 2014. Environmental and ecological effects of Lake Shihwa reclamation project in South Korea: a review. Ocean Coast. Manag. 102, 545–558.

Marques, J.C., Salas, F., Patricio, J., Teixeira, H., Neto, J.M., 2009. Ecological Indicators for Coastal and Estuarine Environmental Assessment – A User Guide. WIT Press, Southampton.

Maurer, D., Nguyen, H., Robertson, G., Gerlinger, T., 1999. The infaunal trophic index (ITI): its suitability for marine environmental monitoring. Ecol. Appl. 9, 699–713.

McBride, E.F., 1971. Mathematical treatment of size distribution data. In: R.E. C, Editor. Procedures in Sedimentary Petrology. 109–127. Wiley Interscience, New York.

Ministry of Oceans and Fisheries of Korea (MOF), 2013. Marine Environmental Quality Guideline. Ministry of Oceans and Fisheries of Korea, Seoul.

Muxika, I., Borja, A., Bald, J., 2007. Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European Water Framework Directive. Mar. Pollut. Bull. 55, 16–29.

Quintino, V., Elliott, M., Rodrigues, A.M., 2006. The derivation, performance and role of univariate and multivariate indicators of benthic change: case studies at differing spatial scales. J. Exp. Mar. Biol. Ecol. 330, 368–382.

Ranasinghe, J.A., Frithsen, J.B., Kutz, F.W., Paul, J.F., Russell, D.E., Batiuk, R.A., et al., 2002. Application of two indices of benthic community condition in Chesapeake bay. Environmetrics 13, 499–511.

Reiss, H., Kröncke, I., 2005. Seasonal variability of benthic indices: an approach to test the applicability of different indices for ecosystem quality assessment. Mar. Pollut. Bull. 50, 1490–1499.

Rosenberg, R., Blomqvist, M., Nilsson, H.C., Cederwall, H., Dimming, A., 2004. Marine quality assessment by use of benthic species-abundance distributions: a proposed new protocol within the European Union Water Framework Directive. Mar. Pollut. Bull. 49, 728–739.

Ryu, J., Khim, J.S., Kang, S.-G., Kang, D., Lee, C.-H., Koh, C.-H., 2011. The impact of heavy metal pollution gradients in sediments on benthic macrofauna at pollution and community level. Environ. Pollut. 159, 2622–2629.

Simboura, N., Zenetos, A., 2002. Benthic indicators to use in ecological quality classification of Mediterranean soft bottom marine ecosystems, including a new biotic index. Med. Mar. Sci. 3, 77–111.

Teixeira, H., Weisberg, S.B., Borja, A., Ranasinghe, J.A., Cadien, D.B., Velarde, R.G., et al., 2012. Calibration and validation of the AZTI's marine biotic index (AMBI) for southern California marine bays. Ecol. Indic. 12, 84–95.

Van Hoey, G., Degraer, S., Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian continental shelf. Estuar. Coast. Shelf Sci. 59, 599–613.

Weisberg, S.B., Ranasinghe, J.A., Dauer, D.M., Schaffner, L.C., Diaz, R.J., Frithsen, J.B., 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake bay. Estuaries 20, 149–158.

Wisconsin Department of Natural Resources (WDNR), 2003. Concensus Based Sediment Quality Guidelines. Recommendations for Use and Application. department of interior, washington DC, p. 17 20240.

Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Zettler, M.L., Schiedek, D., Bobertz, B., 2007. Benthic biodiversity indices versus salinity gradient in the southern Baltic sea. Mar. Pollut. Bull. 55, 258–270.

Appendix A. Supplementary data

Table S1. List of marine benthic invertebrates from six Korean coasts. The number of species belonging to each phylum and class given in parenthesis.

- Phylum Cnidaria (22)
  - Class Anthozoa (22)
    - Order Actiniaria
      - Family Actiniidae
        - ***Anthopleura kurogane***
        - ***Anthopleura nigrescens***
        - ***Dofleinia armata***
        - ***Epiactis japonica***
        - ***Epiactis* sp.**
        - ***Paracondylactis hertwigi***
    - Order Pennatulacea
      - Family Pennatulidae
        - ***Pennatula* sp.**
- Phylum Nemertina (8)
  - Class Anopla (8)
    - Order Heteronemertea
      - Family Lineidae
        - ***Euborlasia* sp.**
        - ***Lineus fuscoviridis***
        - ***Lineus* sp.1**
        - ***Lineus* sp.2**
        - ***Lineus* sp.3**
        - ***Lineus* sp.4**
        - ***Micrura* sp.**
      - Family Valenciniidae
        - ***Baseodiscus* sp.**
- Phylum Brachiopoda (4)
  - Class Rhynchonellata (4)
    - Order Terebellida
      - Family Dallinidae
        - ***Campages mariæ***
      - Family Terebrataliidae
        - ***Coptothyris grayi***
        - ***Terebratalia coreanica***
    - Order Rhynchonellida
      - Family Hemithirididae
        - ***Hemithiris psittacea***
- Phylum Sipuncula (10)
  - Class Phascolocomatidea (8)
    - Order Aspidosiphonida
      - Family Aspidosiphonidae
        - ***Aspidosiphon angulatus***
        - ***Aspidosiphon* sp.**
    - Order Mesogastropoda
      - Family Phascolosomatidae
        - ***Phascolosoma albolineatum***
        - ***Phascolosoma japonicum***
        - ***Phascolosoma kurilens***
        - ***Phascolosoma onomichianumi***
        - ***Phascolosoma scolops***
        - ***Phascolosoma* sp.**
  - Class Phascolocomatidea (2)
    - Order Golfingiida
      - Family Golfingiidae
        - ***Golfingia* sp.**
      - Family Themistidae
        - ***Dendrostomum* sp.**
- Phylum Mollusca (75)
  - Class Polyplacophora (2)
    - Order Chitonida
      - Family Ischnochitonidae
        - ***Lepidozona iyoensis***
    - Order Lepidopleurida
      - Family Leptochitonidae
        - ***Lepidopleura* sp.**
  - Class Gastropoda (12)
    - Order Cephalaspidea
      - Family Cylichnidae
        - ***Adamnestia japonica***
    - Order Caenogastropoda
      - Family Potamididae
        - ***Cerithidea rhizophorarum***
    - Order Cephalaspidea
      - Family Aglajidae
        - ***Philinopsis speciosa***
      - Family Philinidae
        - ***Philine orientalis***
    - Order Littorinimorpha
      - Family Calyptraeidae
        - ***Crepidula onyx***
      - Family Naticidae
        - ***Lunatia fortunei***
        - ***Neverita didyma***
    - Order Neogastropoda
      - Family Terebridae
        - ***Hastula* sp.**
      - Family Nessariidae
        - ***Nassarius castus***
        - ***Nassarius sulfflatus***
      - Family Buccinidae
        - ***Volutharpa ampullacea***
    - Order Vetigastropoda
      - Family Fissurellidae
        - ***Puncturella nobilis***
  - Class Bivalvia (60)
    - Order Anomalodesmata
        - ***Puncturella nobilis***
    - Order Anomalodesmata
      - Family Lyonsiidae
        - ***Agriodesma navicula***
        - ***Lyonsia ventricosa***
    - Order Arcoida

Table S1. (continued).

- Family Arcidae
- ***Anadara broughtonii***
- ***Anadara inaequivalvis***
- ***Anadara sativa***
- ***Arca boucardi***
- Family Glycymerididae
- ***Glycymeris munda***
- Family Parallelodontidae
- ***Porterius dalli***
- Family Noetiidae
- ***Striarca symmetrica***
- Order Euheterodonta
- Family Hiatellidae
- ***Hiatella arctica***
- ***Panopea japonica***
- Family Pharidae
- ***Phaxas attenuatus***
- ***Siliqua pulchella***
- Order Lucinoida
- Family Lucinidae
- ***Lucinoma annulata***
- ***Pillucina striata***
- Order Myoida
- Family Corbulidae
- ***Potamocorbula amurensis***
- Order Nuculanoida
- Family Yoldiidae
- ***Yoldia seminuda***
- ***Yoldia similis***
- Order Nuculida
- Family Nuculidae
- ***Acila divaricata***
- Order Pectinoida
- Family Pectinidae
- ***Chlamys nobilis***
- Order Pterioida
- Family Pinnidae
- ***Atrina pectinata***
- Order Veneroida
- Family Cardiidae
- ***Fulvia mutica***
- ***Laevicardium undatopictum***
- Family Kelliidae
- ***Kellia porculus***
- Family Mactridae
- ***Mactromeris polynyma***
- Family Mytilidae
- ***Arcuatula senhousia***
- Family Semelidae
- ***Theora lata***
- Family Tellindae
- ***Cadella lubrica***
- ***Ciliatocardium ciliatum***
- ***Gorbraeus kazusensis***
- ***Heteromacoma irus***
- ***Macoma incongrua***
- ***Macoma praetexta***
- ***Macoma sectior***
- ***Macoma tokyoensis***
- ***Megangulus*** **sp.**
- ***Moerella jedoensis***
- ***Moerella rutila***
- ***Pharaonella iridella***
- ***Tellina hokkaidoensis***
- ***Tellina iridella***
- ***Tellina*** **sp.**
- ***Tellina venulosa***
- ***Tellina vestalioides***
- ***Nitidotellina nitidula***
- Family Ungulinidae
- ***Cycladicama cumingii***
- ***Diplodonta sowerbyi***
- ***Felaniella usta***
- Family Veneridae
- ***Dosinorbis troscheli***
- ***Glycydonta marcia***
- ***Leukoma jedoensis***
- ***Mercenaria stimpsoni***
- ***Meretrix lamarckii***
- ***Paphia undulata***
- ***Perglypta fischeri***
- ***Ruditapes philippinarum***
- ***Ruditapes variegatus***
- ***Saxidomus purpurata***
- ***Venus cassinaeformis***
- Class Cephalopoda (1)
- Order Octopoda
- Family Octopodidae
- ***Octopus minor***
- Phylum Annelida (150)
- Class Polychaeta (150)
- Order Amphinomida
- Family Amphinomidae
- ***Amphinome*** **sp.**
- Order Canalipalpata
- Family Chaetopteridae
- ***Chaetopterus*** **sp.**
- Order Capitellida
- Family Arenicolidae
- ***Abarenicola*** **sp.**
- Family Capitellidae
- ***Capitella capitata***
- ***Heteromastus filiformis***
- ***Heteromastus*** **sp.**
- ***Mediomastus*** **sp.**
- ***Notomastus*** **sp.**
- Family Maldanidae
- ***Axiothella*** **sp.**

Table S1. (continued).

- ***Clymenella koreana***
- ***Clymenella* sp.**
- ***Maldane* sp.**
- ***Praxillella affinis***
- **Unidentified**
- Order Cossurida
  - Family Cossuridae
    - ***Cossura* sp.**
- Order Echiuroidea
  - Family Echiuridae
    - ***Anelassorhynchus mucosus***
    - ***Anelassorhynchus sabinus***
  - Family Urechidae
    - ***Urechis chilensis***
    - ***Urechis* sp.**
- Order Euheterodonta
  - Family Pharidae
    - ***Cultrensis attenuatus***
- Order Eunicida
  - Family Dorvilleidae
    - ***Dorvillea* sp.**
    - ***Parougia caeca***
  - Family Eunicidae
    - ***Leodice antennata***
    - ***Marphysa sanguinea***
    - **Unidentified**
  - Family Lumbrineridae
    - ***Lumbrineris heteropoda***
    - ***Lumbrineris japonica***
    - ***Lumbrineris latreilli***
    - ***Lumbrineris longifolia***
    - ***Lumbrineris nipponica***
  - Family Oenonidae
    - ***Arabella iricolor***
    - **Unidentified**
  - Family Onuphidae
    - ***Diopatra sugokai***
    - ***Nothria* sp.**
- Order Opheliida
  - Family Opheliidae
    - ***Armandia lanceolata***
    - ***Leitoscoloplos pugettensis***
    - ***Ophelina acuminata***
    - ***Phylo felix asiaticus***
    - ***Phylo fimbriata***
    - ***Phylo* sp.**
    - **Unidentified**
  - Family Paraonidae
    - ***Aricidea cerrutii***
    - ***Aricidea horikoshii***
    - ***Aricidea* sp.**
    - **Unidentified**
  - Family Scalibregmatidae
    - ***Oncoscolex* sp.**
- ***Travisia* sp.**
- **Unidentified**
- Order Phyllodocida
  - Family Aphroditidae
    - **Unidentified**
  - Family Glyceridae
    - ***Glycera chirori***
    - ***Glycera* sp.**
    - ***Glycera unicornis***
    - **Unidentified**
  - Family Goniadidae
    - ***Glycinde* sp.**
    - ***Goniada maculata***
    - ***Goniada* sp.**
  - Family Hesionidae
    - ***Oxydromus* sp.**
  - Family Nephtyidae
    - ***Aglaophamus sinensis***
    - ***Aglaophamus* sp.**
    - ***Inermonephtys inermis***
    - ***Neanthes* sp.**
    - ***Nectoneanthes oxypoda***
    - ***Nectoneanthes* sp.**
    - ***Nephtys caeca***
    - ***Nephtys ciliata***
    - ***Nephtys longosetosa***
    - ***Nephtys oligobranchia***
    - ***Nephtys polybranchia***
    - ***Nephtys* sp.**
    - ***Nereis* sp.**
    - ***Perinereis* sp.**
    - ***Pseudonereis* sp.**
    - ***Tambalagamia* sp.**
    - **Unidentified**
  - Family Phyllodocidae
    - ***Eteone* sp.**
    - ***Eulalia* sp.**
    - ***Phyllodoce koreana***
    - ***Phyllodoce* sp.**
    - **Unidentified**
  - Family Pilargidae
    - ***Sigambra hanaokai***
    - **Unidentified**
  - Family Polynoidae
    - ***Lepidasthenia* sp.**
    - **Unidentified**
  - Family Sigalionidae
    - **Unidentified**
  - Family Syllidae
    - ***Syllis elongata***
    - ***Syllis* sp.**
    - **Unidentified**
- Order Sabellida
  - Family Sabellidae

Table S1. (continued).

Chone infundibuliformis
Chone sp.
Euchone sp.
Hydroides ezoensis
Hydroides sp.
Lygdamis giardi
Pseudopotamilla occelata
Pseudopotamilla sp.
Sabella sp.
Spirobranchus sp.
Unidentified
Order Spionida
Family Longosomatidae
Heterospio sp.
Family Magelonidae
Magelona japonica
Magelona sp.
Family Poecilochaetidae
Poecilochaetus johnsoni
Family Spionidae
Dispio sp.
Laonice cirrata
Paraprionospio pinnata
Polydora sp.
Pseudopolydora sp.
Prionospio sp.
Prionospio pinnata
Pygospio sp.
Spiophanes sp.
Unidentified
Order Terebellida
Family Ampharetidae
Amage auricula
Amage sp.
Ampharete sp.
Amphicteis gunneri
Amphicteis sp.
Amphisamytha japonica
Amphisamytha sp.
Melinna cristata
Melinna elisabethae
Melinna sp.
Family Cirratulidae
Chaetozone sp.
Cirratulus cirratus
Cirratulus sp.
Cirriformia sp.
Cirriformia tentaculata
Tharyx sp.
Unidentified
Family Flabelligeridae
Brada villosa
Daylithos parmatus
Pherusa plumosa
Family Pectinariidae
Amphictene japonica
Lagis bocki
Unidentified
Family Sternaspidae
Sternaspis scutata
Family Terebellidae
Amphitrite edwardsii
Amphitrite sp.
Loimia medusa
Pista cristata
Unidentified
Family Trichobranchidae
Terebellides horikoshii
Terebellides sp.
Trichobranchus sp.
Unidentified
Phylum Arthropoda (156)
Class Malacostraca (152)
Order Amphipoda
Family Ampeliscidae
Ampelisca brevicornis
Ampelisca cyclops
Ampelisca diadema
Ampelisca misakiensis
Ampelisca sp.
Byblis japonicus
Family Ampithoidae
Ampithoe lacertosa
Ampithoe sp.1
Ampithoe sp.2
Family Aoroidea
Grandidierella sp.1
Grandidierella sp.2
Family Caprellidae
Caprella acanthogaster
Caprella sp.
Family Eriopisidae
Eriopisella sechellensis
Family Isaeidae
Eurystheus sp.
Family Ischyroceridae
Cerapus tubularis
Ericthonius pugnax
Ericthonius sp.
Jassa falcata
Jassa sp.
Family Kamakidae
Kamaka kuthae
Kamaka sp.
Family Leucothoidae
Leucothoe sp.1
Leucothoe sp.2
Family Liljeborgiidae

Table S1. (continued).

Liljeborgia japonica
Liljeborgia **sp.**
Family Lysianassidae
Orchomene sp.
Family Maeridae
Maera **sp.**
Maeropsis cobia
Family Melitidae
Melita dentata
Melita koreana
Melita **sp.1**
Melita **sp.2**
Family Ochlesidae
Odius sp.
Family Oedicerotidae
Monoculodes **sp.1**
Monoculodes **sp.2**
Monoculodes **sp.3**
Pontocrates **sp.**
Family Photidae
Gammaropsis japonica
Gammaropsis **sp.1**
Gammaropsis **sp.2**
Gammaropsis utinomii
Photis longicaudata
Photis sp.1
Photis sp.2
Family Phoxocephalidae
Mandibulophoxus **sp.**
Family Stegocephalidae
Stegocephaloides **sp.**
Family Stenothoidae
Stenothoe **sp.**
Family Urothoidae
Urothoe **sp.1**
Urothoe **sp.2**
Order Cumacea
Family Bodotriidae
Bodotria similis
Eocuma hilgendorfi
Eocuma latum
Eocuma sp.
Iphinoe sagamiensis
Sympodomma diomedeae
Family Diastylidae
Diastylopsis **sp.**
Dimorphostylis **sp.1**
Dimorphostylis **sp.2**
Dimorphostylis valida
Paradiastylis longipes
Family Lampropidae
Lamprops sarsi
Family Leuconidae
Nippoleucon enoshimensis
Family Nannastacidae
Nannastacus **sp.**
Raphidopus **sp.**
Scherocumella japonica
Order Decapoda
Family Alpheidae
Alpheus bisincisus
Alpheus brevicristata
Alpheus brevicristatus
Alpheus japonicus
Alpheus rapax
Alpheus **sp.1**
Alpheus **sp.2**
Family Camptandriidae
Camptandrium sexdentatum
Family Chasmocarcinidae
Chasmocarcinops sp.
Family Corophiidae
Corophium japonica
Corophium **sp.1**
Corophium **sp.2**
Corophium uenoi
Crassicorophium crassicorne
Family Crangonidae
Crangon affinis
Family Diogenidae
Dardanus **sp.**
Diogenes edwardsii
Diogenes **sp.**
Paguristes ortmanni
Nobilum japonicum japonicum
Nobilum **sp.**
Paradorippe **sp.**
Family Epialtidae
Huenia **sp.**
Family Euryplacidae
Eucrate crenata
Eucrate **sp.**
Heteroplax dentata
Heteroplax **sp.**
Family Goneplacidae
Carcinoplax longimana
Carcinoplax **sp.**
Carcinoplax vestita
Goneplax **sp.**
Family Hexapodidae
Hexapus anfractus
Family Hippolytidae
Latreutes planirostris
Latreutes **sp.**
Lysmata vittata
Family Inachidae
Achaeus japonicus
Family Inachoididae

Table S1. (continued).

Pyromaia tuberculata
Family Leucosiidae
Philyra pisum
Family Macrophthalmidae
Macrophthalmus japonicus
Tritodynamia horvathi
Tritodynamia intermedia
Tritodynamia longipropoda
Tritodynamia rathbunae
***Tritodynamia* sp.**
Family Ogyrididae
Ogyrides orientalis
Family Palicidae
***Parapalicus* sp.**
Family Pandalidae
Pandalus danae
Family Pasiphaeidae
Leptochela aculeocaudata
Leptochela gracilis
***Leptochela* sp.**
Family Penaeidae
***Metapenaeopsis* sp.**
Family Pilumnidae
Pilumnopeus makianus
***Typhlocarcinus* sp.**
Family Pinnotheridae
Pinnixa penultipedalis
***Pinnixa* sp.**
Pinnixa tumida
Pinnotheres pholadis
***Porcellana* sp.**
Raphidopus ciliatus
Family Portunidae
Charybdis bimaculata
Charybdis japonica
Thalamita prymna
Thalamita sima
Family Sesarmidae
Nanosesarma gordoni
Family Upogebiidae
Upogebia major
Family Varunidae
Sestrostoma balssi
Family Xenophthalmidae
Xenophthalmus pinnotheroides
Order Euphausiacea
Family Euphausiidae
Thysanoessa longipes
Order Isopoda
Family Anthuridae
***Cyathura* sp.**
Family Chaetiliidae
Symmius caudatus
Family Cirolanidae
Cirolana harfordi
Metacirolana japonica
Natatolana japonensis
Family Holognathidae
Cleantioides japonica
***Cleantioides* sp.**
Family Idoteidae
***Cleantiella* sp.**
Family Paranthuridae
Paranthura japonica
***Paranthura* sp.**
Family Sphaeromatidae
Gnorimosphaeroma ovatum
Order Leptostraca
Family Nebaliidae
Nebalia bipes
Order Stomatopoda
Family Squillidae
Oratosquilla oratoria
Typhlocarcinus sp.
Family Pinnotheridae
Family Tanaididae
***Tanais* sp.**
Class Maxillopoda (3)
Order Sessilia
Family Balanidae
***Balanus* sp.**
Balanus trigonus
Unidentified
Class Pycnogonida (1)
Order Pantopoda
Family Ascorhynchidae
Ascorhynchus auchenicus
Phylum Echinodermata (44)
Class Asteroidea (2)
Order Forcipulatida
Family Asteriidae
***Distolasterias* sp.**
Order Valvatida
Family Asterinidae
Aquilonastra batheri
Class Crinoidea (1)
Order Comatulida
Family Antedonidae
Antedon serrata
Class Echinoidea (4)
Order Camarodonta
Family Temnopleuridae
Temnopleurus hardwickii
Temnopleurus toreumaticus
Order Spatangoida
Family Schizasteridae
Brisaster owstoni
Schizaster lacunosus

Table S1. (continued).

- Class Holothuroidea (9)
  - Order Apodida
    - Family Synaptidae
      - ***Protankyra bidentata***
  - Order Dendrochirotida
    - Family Sclerodactylidae
      - ***Eupentacta quinquesemita***
    - Family Cucumariidae
      - ***Neoamphicyclus problematica***
      - ***Ocnus* sp.**
    - Family Phyllophoridae
      - ***Phyllophorus hypsipyrga***
      - ***Phyllophorus ordinata***
    - Family Sclerodactylidae
      - ***Sclerodactyla multipes***
  - Order Molpadida
    - Family Caudinidae
      - ***Caudina similis***
- Class Ophiuroidea (28)
  - Order Ophiurida
    - Family Amphiuridae
      - ***Amphiodia craterodmeta***
      - ***Amphioplus japonicus***
      - ***Amphipholis sorbrina***
      - ***Amphipholis* sp.**
      - ***Amphipholis squamata***
      - ***Amphiura (Fellaria) sinicola***
      - ***Amphiura aestuarii***
      - ***Amphiura koreae***
      - ***Amphiura sinicola***
      - ***Amphiura* sp.**
    - Family Ophiacanthidae
      - ***Ophiacantha omoplata***
      - ***Ophiacantha* sp.**
    - Family Ophiactidae
      - ***Ophiactis affinis***
      - ***Ophiactis brachygenys***
      - ***Ophiactis macrolepidota***
      - ***Ophiactis profundi***
      - ***Ophiactis savignyi***
      - ***Ophiactis* sp.**
      - ***Ophiopholis mirabilis***
    - Family Ophiolepididae
      - ***Ophiolepis* sp.**
      - ***Ophiothrix exigua***
      - ***Ophiothrix* sp.**
    - Family Ophiuridae
      - ***Ophiura (Ophiuroglypha) kinbergi***
      - ***Ophiura leptoctenia***
      - ***Ophiura sarsii***
      - ***Ophiura* sp.**
      - ***Stegophiura* sp.**
      - **Unidentified**

Phylum Hemichordata (1)

- Class Enteropneusta (1)
  - Order Enteropneusta
    - Family Ptychoderidae
      - ***Balanoglossus* sp.**

Phylum Chordata (9)

- Class Actinopteri (7)
  - Order Perciformes
    - Family Gobiidae
      - ***Acanthogobius flavimanus***
      - ***Taenioides cirratus***
- Class Ascidiacea (2)
  - Order Pleurogona
    - Family Molgulidae
      - ***Molgula* sp.**
  - Order Stolidobranchia
      - ***Halocynthia hilgendorfi igaboja***
      - ***Herdmania mirabilis***
      - ***Herdmania momus momus***
    - Family Styelidae
      - ***Dendrodoa aggregata***
      - ***Polycarpa maculata***
      - ***Styela clava clava***

Table S2. PCA of environmental conditions in six coastal areas of Korea.

	PCA axis	
	1	2
Eigen value	4.706	1.697
Relative inertia (%)	52.3	18.9
Cumulative inertia (%)	52.3	71.1
Eigen vectors		
Mud content	0.61	0.46
Al	0.31	0.88
Cr	0.46	0.40
Co	0.76	-0.04
Cu	0.84	0.09
Fe	0.44	0.83
Mn	-0.19	0.88
Ni	0.81	0.39
Zn	0.87	0.20

Table S3. Comparisons of 14 ecological indices at six coastal areas of Korea. Probabilities resulting from pair-wise analysis of similarity (ANOSIM) tests for indices similarities between areas are given above the diagonal (shaded). Values on the diagonal are percent similarity within habitat (SIMPER). Values below the diagonal are percent dissimilarity between areas (SIMPER).

Areas	Gyeonggi Bay	Yeongsan River estuary	Gwangyang Bay	Masan Bay	Jinhae Bay	Ulsan Bay
Gyeonggi Bay	87.77%	0.001	0.001	0.003	0.001	0.001
Yeongsan River estuary	13.41%	89.39%	0.001	0.002	0.001	0.001
Gwangyang Bay	14.07%	14.03%	86.43%	0.003	0.012	0.001
Masan Bay	16.45%	14.47%	17.42%	85.70%	0.006	0.405
Jinhae Bay	14.01%	13.15%	13.76%	16.82%	86.69%	0.001
Ulsan Bay	15.36%	15.01%	16.02%	16.16%	16.06%	83.76%

Table S4. Results of the non-parametric Kruskal-Wallis test comparing the environmental characteristics of locations between EcoQ classes derived from the six biotic indices in six coastal areas of Korea.

(a) Gyeonggi Bay (n=78)

	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	ns	*	*	*	**	*	*	*	ns	**	ns	**	-	-	-
BPI	*	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns	-	-	-
BQI	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-	-	-
EQR	*	***	***	**	***	**	**	***	**	***	**	***	-	-	-
H’	ns	**	**	*	*	*	ns	*	ns	**	ns	**	-	-	-
M-AMBI	ns	*	*	ns	*	ns	ns	*	ns	*	ns	*	-	-	-

(b) Yeongsan River estuary (n=72)

	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	ns	-	-	ns	ns	ns	-	ns	ns	ns	ns	ns	*	ns	-
BPI	ns	-	-	ns	ns	ns	-	ns	ns	ns	ns	ns	ns		-
BQI	ns	-	-	ns	ns	ns	-	ns	ns	ns	ns	ns	ns	ns	-
EQR	ns	-	-	ns	*	*	-	ns	**	**	**	ns	ns	*	-
H’	ns	-	-	ns	ns	*	-	ns	*	*	*	ns	**	ns	-
M-AMBI	ns	-	-	*	*	*	-	ns	*	*	*	ns	*	*	-

(c) Gwangyang Bay (n=87)

	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	ns	-	ns	ns	ns	*	-	*	ns	ns	ns	ns	ns	-	-
BPI	ns	-	ns	ns	ns	*	-	**	ns	ns	ns	ns	ns	-	-
BQI	ns	-	*	**	**	**	-	**	ns	**	*	**	ns	-	-
EQR	ns	-	ns	ns	ns	**	-	ns	ns	ns	ns	ns	ns	-	-
H’	ns	-	ns	ns	ns	**	-	**	ns	ns	ns	*	ns	-	-
M-AMBI	ns	-	ns	ns	*	***	-	*	ns	**	*	**	ns	-	-

(d) Masan Bay (n=15)

	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	*	-	ns	ns	ns	ns	-	*	*	ns	ns	ns	ns	ns	ns

BPI	*	-	ns	ns	*	ns	-	ns	*	ns	ns	ns	ns	ns	ns
BQI	ns	-	ns	ns	ns	ns	-	ns	ns	ns	ns	ns	ns	ns	ns
EQR	ns	-	ns	ns	ns	ns	-	ns	ns	ns	ns	ns	ns	ns	ns
H’	*	-	ns	ns	ns	ns	-	ns	*	ns	ns	ns	ns	ns	ns
M-AMBI	ns	-	ns	ns	ns	ns	-	ns	ns	ns	ns	ns	ns	ns	ns
(e) Jinhae Bay (n=62)															
	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	ns	-	-	ns	ns	*	-	ns	*	ns	ns	ns	ns	*	ns
BPI	ns	-	-	ns	*	*	-	ns	ns	ns	ns	ns	ns	ns	ns
BQI	**	-	-	ns	ns	***	-	ns	ns	***	ns	**	ns	***	ns
EQR	*	-	-	ns	ns	**	-	ns	ns	ns	ns	ns	ns	***	ns
H’	**	-	-	ns	ns	**	-	*	ns	ns	ns	ns	ns	***	ns
M-AMBI	**	-	-	ns	ns	**	-	ns	ns	*	ns	ns	ns	**	ns
(f) Ulsan Bay (n=51)															
	MC	LOI	TOC	Al	Fe	Mn	V	Cr	Co	Cu	Ni	Zn	Pb	Cd	As
AMBI	ns	-	-	ns	ns	ns	-	*	ns	**	*	**	ns	ns	-
BPI	ns	-	-	ns	ns	ns	-	ns	ns	ns	ns	ns	ns	ns	-
BQI	ns	-	-	**	*	ns	-	ns	ns	ns	*	ns	ns	ns	-
EQR	ns	-	-	ns	ns	ns	-	ns	ns	*	ns	*	ns	ns	-
H’	ns	-	-	*	ns	ns	-	ns	ns	*	ns	*	ns	ns	-
M-AMBI	ns	-	-	*	*	ns	-	ns	ns	ns	ns	ns	ns	ns	-

- : not analyzed.
ns: not significant ($p > 0.05$).
*: significant ($p < 0.05$).
**: very significant ($p < 0.01$).
***: highly significant ($p < 0.001$).

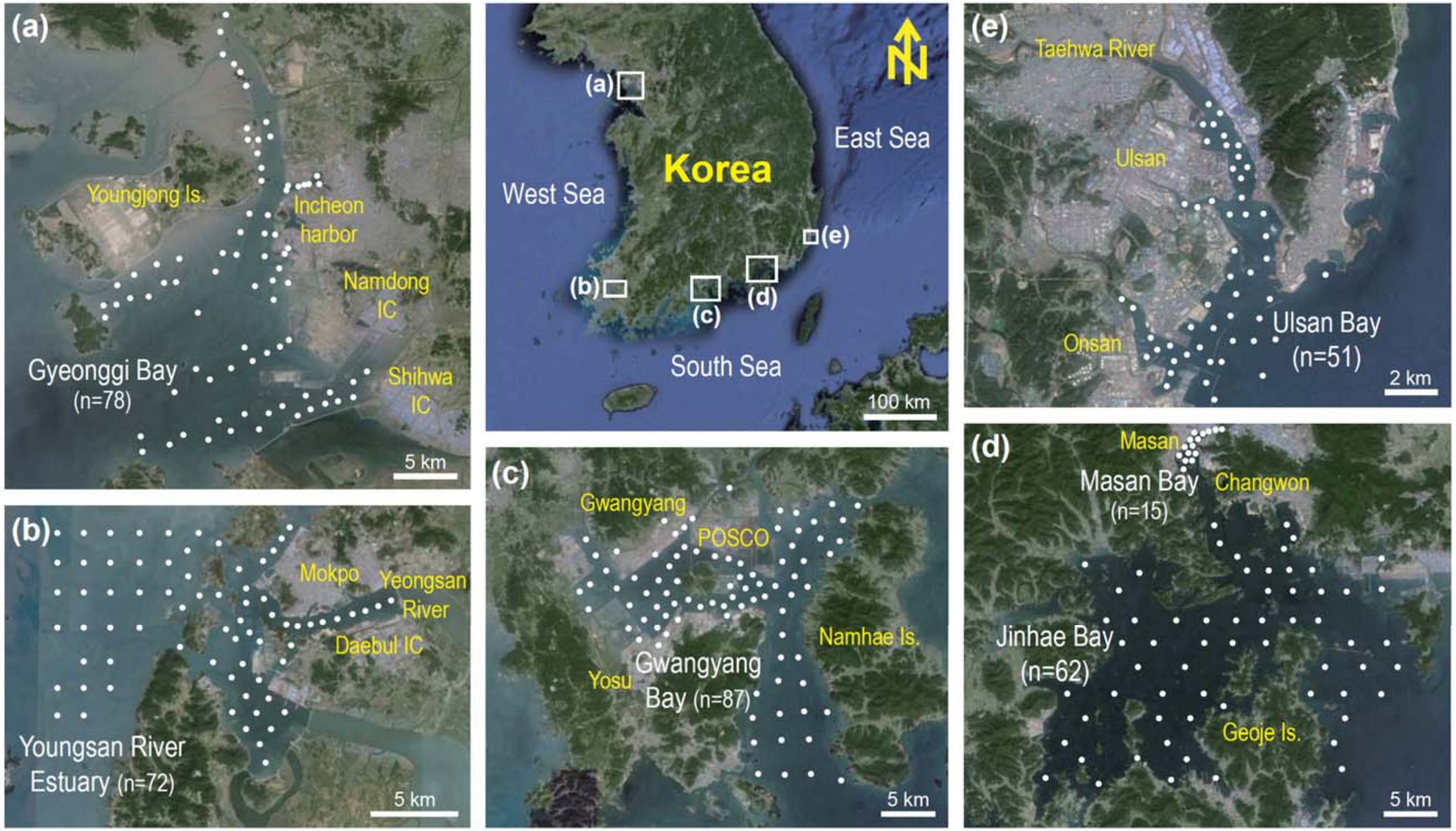

Fig. S1. Map showing the coastal geography and sampling locations (total n = 365) in six target study areas (a–e, two areas in d panel); (a) Gyeonggi Bay (n = 78), (b) Yeongsan River Estuary (n = 72), (c) Gwangyang Bay (n = 87), (d) Masan Bay (n = 15) and Jinhae Bay (n = 62), and (e) Ulsan Bay (n = 51).