BENTHIC FORAMINIFERA AS BIOINDICATORS OF SALINITY VARIATION IN LAKE SHIHWA, SOUTH KOREA

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ABSTRACT

Lake Shihwa suffers from trace-metal pollution discharged from the Banweol stream and the Shihwa Industrial Complex. Installation of floodgates in 2001 increased water exchange and decreased trace-metal content, thereby improving the benthic environment within the lake. We analyzed surface sediments (including grain size, pH, trace-metal concentrations), water-quality data, and the assemblages of and, prevalence of deformities in, the benthic foraminifera, to understand the effects of recent changes in salinity variability. Since spatial and temporal distributions of benthic foraminifera are known to vary in response to both abiotic and biotic environmental variables, they are useful indicators of environmental change.

Since the installation of floodgates, surface-sediment composition coarsened from silt to sandy mud/muddy sand in response to increased water flow. Trace-metal contaminants (Ni, Cu and Zn) have decreased and are close to the Effect Range-Low (ER-L) designation. We identified 15 species of benthic foraminifera (3 agglutinated, 10 calcareous-hyaline, and 2 calcareous-porcelaneous). Buccella frigida and Elphidium albiumbilicatum were dominant, but seven sampling localities formed a nearly abiotic zone. Although trace contaminants have decreased, a high prevalence of test deformities (up to 65%) was observed, mostly in E. albiumbilicatum. Our findings suggest these abnormalities may be strongly related to the effects of seasonal variation of salinity in Lake Shihwa.

INTRODUCTION

Coastal areas have traditionally been places of human settlement, with the accompanying development of cities, industries, and other human-related activities that commonly impact aquatic ecosystems. These impacts may take the form of pollution from industrial, domestic, agricultural, or mining activities; dredging and dredge-spoil dumping; salinization; sedimentation from land clearance, forestry, or building; and the introduction of alien plant or animal species (Frontalini & Coccioni, 2011). Characterizing the community structure of organisms is as necessary as analyzing the pollutants from the water column and sediments. Benthic infaunal taxa are generally preferred for bioassays and as bioindicators, because they are typically sessile or of limited mobility, and are therefore subject to natural or anthropogenic stresses in their environment (Bilyard, 1987). As such, biological monitoring of these communities provides a useful gauge of environmental health.

Foraminifera are found in virtually all marine ecosystems that support eukaryotic life (Goldstein, 1999) and have specific ecological niches. Populations of foraminifera react quickly to environmental changes (Hallock et al., 2003; Ward et al., 2003). Moreover, a few species are remarkably resilient to environmental stresses and are often among the last organisms found living in polluted sites (Schafer, 2000). Spatial and temporal distributions of benthic foraminifera vary in response to both abiotic and biotic environmental variables (Schafer, 2000; Arminot du Chatlet et al., 2004). Various factors, including water depth, sediment type, flux of dissolved nutrients and organic matter, availability of oxygen, seawater temperature, salinity, distance from the river mouth, and extent of bioturbation, have been proposed to affect benthic foraminiferal distributions in coastal regions (Mendes et al., 2004; Murray, 2007; Bouchet et al., 2009).

Among the many biological and physico-chemical factors that affect benthic foraminiferal distribution in marginal marine areas, salinity changes associated with freshwater runoff are especially influential (Horton & Murray, 2007; Eichler et al., 2008; Bouchet et al., 2009; Frezza & Carboni, 2009). Changes in abundance, species assemblage, size, and the number of dissolved and distorted benthic foraminiferal tests have been attributed to ecological parameters including salinity changes (Boltovskoy et al., 1991). How salinity changes affect benthic foraminifera is not well understood, as it is difficult in field studies to delineate the effect of a specific parameter. Kurtarkar et al. (2011) and Saraswat et al. (2015), however, showed the pronounced influence of salinity-induced pH changes on growth, survival and reproduction in the benthic foraminifera Rosalina globularis d’Orbigny, and Rosalina leei Hedley and Wakefield, through laboratory-culture experiments.

Lake Shihwa was a trace-metal-polluted, eutrophic lake with anoxic bottom waters. Installation of floodgates in 2001 increased water exchange and decreased trace-metal concentrations in the sediments, resulting in better water quality and positive changes in the benthic environment. However, these exchanges of freshwater and seawater in the lake have caused spatial and temporal variability of salinity, which has affected the distribution of benthic organisms. This study investigates the assemblages of benthic foraminifera inhabiting the lake environment, as well as the prevalence of deformed tests in those taxa, with

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the goal to understand the effects of the increased variability in salinity.

**STUDY AREA**

Lake Shihwa, which was called Banweol prior to 1994, is located on the west coast of Korea and has a macrotidal range (with a maximum range of ca. 9.5 m off the Incheon coast) and extensive tidal flats. Lake Shihwa is an artificial lake that was created by entrapment of the Yellow Sea with the construction of a 12.7 km long dike (Shihwa reclamation) in February 1994 (Fig. 1-A). The water depth is ~20 m in the center of the lake. The main channel has a gentle gradient, an average depth of about 6 m, and occurs toward the central area of the lake. Tidal flats are broadly distributed in the bordering areas (Fig. 1-B).

After the construction of the Shihwa reclamation, the tidal flats began to transition to a lake environment, which changed the surface geomorphology as well as the sediment and water quality. Lake Shihwa has been polluted by trace metals from waste discharged by a small stream located between the cities of Ansan and Hwaseong, and by creeks of the Banweol and Shihwa Industrial Complex (Lee et al., 1985; Ahn et al., 1995; Jung et al., 1996). Trace-metal concentrations in the sediment and lake water increased, especially copper (Cu) content, which increased four-fold.

*Figure 1. Sample station map (A) and bathymetric map (B) of Lake Shihwa, located on the west coast of South Korea. Note: area between stations 1–4: the stream inflow area, area between stations 5–7: the tidal flat, area between stations 8–12: central area.*
Choi et al., 1999). In addition to copper, zinc, cadmium, and mercury have accumulated in the inner part of the lake (Kim et al., 2009).

During desalination after the completion of reclamation, the restriction of water exchange with the open sea and the decline in creek water flowing into the lake resulted in serious deterioration of water quality. This resulted in the development of anoxic to suboxic environments in the highly saline bottom water, and highly eutrophic, brackish, surface water (Park et al., 1997). As a consequence, macrofaunal assemblages in polluted zones were characterized by the proliferation of opportunistic species under the influence of anthropogenic contaminants, with abiotic zones in some parts of the lake (Ahn et al., 1995; Hong et al., 1997).

Floodgates were constructed at the central area of the reclamation with the goal to improve water quality by increasing the water exchange rate, as well as for electric power production. Since 2001, metal concentrations in the lake, mainly associated with anthropogenic activities such as the production of industrial effluents, have decreased overall and show decreases with distance from the pollution sources (Ra et al., 2011).

The water quality (salinity, pH and DO) of Lake Shihwa, as monitored by the Ministry of Land, Transport and Maritime Affairs (MLTM) over eight years (May 2004–June 2011), is shown in Figure 2. For bottom waters, the average annual salinity ranges from 20.64–27.52 psu, average pH ranges from 8.08–8.70, and average DO from 8.08–11.4 mg/L. The overall average salinity is brackish at 24.24 psu. According to MLTM (2011), when the water-surface area of Lake Shihwa increased, annual salinity decreased, despite water exchange through the opening of floodgates at intervals of about 2–15 days/month. The salinity variation of Lake Shihwa is mainly controlled by the volume of freshwater entering from streams during the rainy season.

MATERIALS AND METHODS

SEDIMENT SAMPLING

Surface-sediment samples were collected from 12 stations in May 2011 (Fig. 1-A). Station locations were determined with a Global Positioning System (resolution: 3–5 m). Their positions were selected to detect potential sources of contamination and influence of the floodgates of the Shihwa reclamation.

A Van-Veen grab sampler was used to collect sediment over a surface of about 400 cm². The grab was carefully opened in a container into which sediments were deposited in their initial position. Three sets of subsamples at the uppermost sediment surface were taken at each station; one sample from each station was stored in a polyethylene jar for later analysis of the concentrations of trace elements.

The pH was measured directly in the uppermost 2 cm of surface sediment at stations 1–10. The pH test used the Oakton pH Spear (Eutech instruments, Singapore), with a pH range of -1.00 to 15.00 pH, and resolution of 0.01 pH.

SEDIMENT ANALYSIS

Prior to grain-size analysis, organic matter and carbonates from each sample were eliminated by adding 10% hydrogen peroxide (H₂O₂) and 0.1 N hydrochloric acid (HCl) sequentially. Subsequently, the samples were subjected to a Sedigraph 5100 automatic particle size analyzer and sieve analysis. The weights of coarse and fine samples were recorded by weight percentage for each section (Folk, 1968).
Samples for trace-metal analysis were freeze-dried and reduced to a fine powder. Then 0.25 g of the sample was measured into a Teflon decomposition container with 6 ml of HNO₃ (65%), 1 ml of HClO₄ (65%), and 1 ml of H₂O₂ (30%; EPA Method 3052). The mixture was processed with the decomposition sequence of a microwave decomposition system (Ethos TC/Milestone/Italy). After cooling, the mixture was adjusted to 50 ml using 0.1% nitric acid, and was analyzed using Inductively Coupled Plasma Optical Mass Spectrometry (ICP-MS). Only the concentrations of Al, Fe, Mn, Zn, Cr, Ni, Cu, Co, As, Cd, Pb, and Hg were considered. The detection limits for each metal were: Al 51 mg kg⁻¹, Fe 51 mg kg⁻¹, Mn 2 mg kg⁻¹, Zn 1 mg kg⁻¹, Cr 2 mg kg⁻¹, Ni 1 mg kg⁻¹, Cu 0.5 mg kg⁻¹, Pb 1 mg kg⁻¹. Concentrations were compared to the ER-L (Effect-Range Low) and ER-M (Effect-Range Median) values reported for the sediment guidelines of USEPA by Long et al. (1995). Note, Sedi.: sediment, Sta. Para.: statistical parameters, Min.: minimum, Max.: maximum, Avg.: average.

Foraminiferal Analysis

An aliquot of 20 ml was taken from the uppermost 2 cm of sediment in each sample and added to a 4% formaldehyde solution with 1 g/l rose Bengal, to distinguish between stained (assumed to have been alive) and non-stained tests (Walton, 1952). Samples were oven-dried at 50°C, weighed (20 ml wet sample), and washed over a 63 μm sieve. After again drying, the samples were subdivided using a modified Otto micro-splitter. Foraminifera were counted wet under a binocular microscope from a known fraction, or the full sample was counted, to identify a minimum of 200 individuals per sample. The taxonomy of benthic foraminifera in this paper was based on the work by Asano (1950, 1951a, b, 1952), Matoba (1970), and Loeblich & Tappan (1994).

A scanning electron microscope was used to observe surface ornamentation and abnormalities in tests, and to assist with the identification of some smaller species using surface ultrastructural characteristics. Statistical analysis was carried out on the number of benthic foraminifera picked (B.F.), individuals/20 ml (no. B.F.), species diversity (H'), and evenness (J). Species diversity and evenness were calculated using the formulas of Shannon & Weaver (1963) and Pielou (1966), respectively. Planktic foraminiferal species were not identified. Pearson's correlation matrix was applied to grain-size and chemical results as a preliminary descriptive method to examine the relationships among the variables.

RESULTS

Sediment Analyses

The surface sediments were composed of very fine sand (average 53%) and mud (average 47%), and had a mean size of 5.37 phi (medium silt). The sediments were very poorly sorted (average 2.26 Ø), and the composition mostly ranged from sandy mud to muddy sand (Table 1). Sandy sediment, composed mostly of very fine sand, was distributed around creeks in front of the Shihwa Industrial Complex (stations 4, 5, 6, and 7) and on the tidal flat (Station 7). Silt and clay sediment (>, 63 μm) was found in the central area of the lake. The pH of the surface substrate (Table 2) ranged from a maximum of 7.26 at Station 5 to a minimum of 6.88 at Station 2 (mean 57.05).

The concentrations of each trace metal varied greatly among the sampling stations (Table 1). Station 1 at the sewage entrance exceeded the ER-Ls in concentrations of Zn, Cr, Ni, Cu, Pb and Hg. Most notably, the concentration of Cu (152 mg kg⁻¹) was 448% of the ER-L. Stations 2...
and 3 exceeded the ER-Ls in concentrations of Zn, Ni, Cu, and Ni, Cu, respectively. At stations 4–7, 10 and 12, no trace-metal concentrations exceeded the ER-Ls. Stations 8 and 9 exceeded ER-Ls in concentrations of Zn, Ni and Zn, Ni, Cu, As, respectively. At Station 11, only Ni exceeded the ER-L.

### Benthic Foraminifera

Fifteen species (3 agglutinated, 10 calcareous-hyaline, and 2 calcareous-porcelaneous) were identified, belonging to 10 genera (Appendix 1). A total of 45,180 benthic foraminiferal specimens were identified. Very few specimens (≤22 per 20 ml of sediment) were recorded at four of the twelve sampling sites (stations 1, 3, 9, and 11). Specimens were also relatively sparse at stations 2, 4 and 8 (<146). In contrast, foraminiferal specimens were extremely abundant at Station 5, where 90% of all specimens were found. Foraminiferal tests were abundant at stations 6, 7 and 10, ranging from 1200–1360 per 20 ml of sediment. Calcareous-hyaline taxa comprised 88% of all foraminifera identified. The assemblage was dominated by *Bucella frigida* (Cushman) and *Elphidium albiumbilicatum* (Weiss) (Fig. 3.1–3.4), with median relative abundances of 46% and 12%, respectively. *Ammonia beccarii* (Linnaeus) and *Trochammina hadai* Uchio were relatively abundant in a few samples; notably *A. beccarii* made up 50% of the foraminiferal specimens at Station 12. Species diversity was very low at 0.5–1.8. Stained specimens were found only at Station 5, and only as <1% of the total specimens in that sample.

Test abnormalities were primarily found in specimens of *E. albiumbilicatum* at all localities where the species occurred. The percentage of abnormalities varied widely among samples (Table 3). Percent abnormalities at stations 5 and 6, the two samples with the most specimens, were particularly pronounced at 65.5% and 60.5%, respectively. Tests with a broken last chamber were found at seven stations (2, 4–8, and 10).

In *E. albiumbilicatum* eight different types of abnormalities were recognized: (1) reduced chamber size (Fig. 3–5–3–7); (2) abnormally protruding chamber(s) (Fig. 3–8, 3–9); (3) aberrant chamber shape (Fig. 3–10–3–12); (4) aberrant and abnormal additional chambers (Figs. 3–13–3–16, and 4–1); (5) complex form (Fig. 4–2–4–13); (6) conjoined twins (Figs. 4–14–4–16, and 5–1–5–2); (7) distorted chamber arrangement or change in coiling (Fig. 5–3–5–4); and (8) non-developed tests (Fig. 5–5–5–6). In addition, taphonomic features included tests with a dissolved surface or broken last chamber (Fig. 5–7–5–13), and tests with a star shape due to the loss of chamber walls (Fig. 5–14–5–16).

### DEPOSITIONAL ENVIRONMENT AND WATER EXCHANGE

The depositional environment of Lake Shihwa can be subdivided into three categories: the stream inflow area (stations 1–3), represented by mud to muddy-sand facies and experiencing influx of anthropogenic contaminants; the tidal flat (stations 4–6), with muddy-sand to sandy facies; and the central area of the lake (stations 7–12), ranging from sandy-mud to slightly gravelly, muddy-sand facies, at depths over 10 m. This last region is directly affected by the tidal currents through the floodgates.

The depositional environment changed from a tidal flat, prior to the construction of the dam, to a lake nearly unaffected by seawater, and, with construction of the floodgates, to a brackish lake influenced by tidal currents. The surface sediments of Lake Shihwa changed from tidal silts prior to the construction of the dam, to silty sediments resuspended by wind-driven waves and currents after the construction of the dam (Choi et al., 1999) and then, following the construction of floodgates, to mixed facies with very fine sand (average 53%) and mud (average 47%).

Enhanced water exchange through opening of the floodgates, which occurs irregularly at intervals of about 2–15 days/month (MLTM, 2011), has occurred since 2001 to improve the sediment quality with regard to metal contamination (Ra et al., 2011). The depositional environment of the inner lake is influenced by strong tidal currents (tidal range is ~9 m) that occur when the floodgates are open. Kim et al. (2009) collected surface sediments in 2005 and reported high concentrations of metals, such as Ni, Cu and Zn, in the vicinity of the Shihwa Industrial Complex, exceeding the ER-Ms established by Long et al. (1995) for estuaries. Ra et al. (2011) reported that the average concentrations of Ni, Cu, and Zn between 2001 and 2009 were 39 µg/g, 131 µg/g, and 273 µg/g, respectively, where a creek discharges extremely polluted waters from the Shihwa Industrial Complex. These values were between the ER-L and ER-M for these metals, though Ra et al. reported that the metal concentrations have been decreasing gradually since 2001. The concentrations of Ni, Cu, and Zn in the present study (Table 1) are lower than those of Ra et al. (2011).

Trace metals tend to bind to muds and organic matter, and therefore bulk concentrations tend to be higher than in coarse-grained sediment (Bergamin et al., 2009; Coccioni et al., 2009). We found that trace-metal concentrations were positively correlated with the percentage of mud and were negatively correlated with sand (Table 4). Moreover, high correlation coefficients were seen among trace metals such as Zn, Cr, Ni, and As (Table 4). Because clays tend to complex and adsorb potentially toxic elements (PTEs), especially under oxidizing conditions (Luoma & Bryan, 1990), the concentration of PTEs in sediments tends to be inversely correlated with grain size (Green-Ruiz & Paez-Osuna, 2004). Thus, decreases in trace-metal concentrations in Lake Shihwa are likely associated with increased water exchange, which is changing the sediment composition from predominantly mud to mixed facies with sand and mud.
FIGURE 3. SEM micrographs of normal and abnormal specimens of foraminifera encountered in Lake Shihwa. 1: Trochamnia hadai, 2: Buccella frigida, 3: Ammonia beccarii, 4: Elphidium albumbilicatum. 5–16: SEM photomicrographs of Elphidium albumbilicatum bearing different morphological abnormalities, 5–7: reduced chamber(s) size, 8, 9: abnormally protruding chamber(s), 10–12: aberrant chamber shape, 13–16: aberrant and abnormal additional chamber.
Sediment acts as a major source for many natural and anthropogenic contaminants entering coastal systems, and can preserve a record of pollution sources and pathways (Degetto et al., 1997). The presence of these contaminants in sufficient quantities and under certain conditions may result in the sediments becoming toxic to benthic and epibenthic organisms, which spend a large part of their life cycle in the sediment, or on its surface. Therefore, the decrease of trace metal concentrations may contribute to the recovery the benthic ecosystem of Lake Shihwa.

**Benthic Foraminifera and Trace Metals**

Trace-metal concentrations were highest at Station 1, decreasing to lows at stations 6 and 7 on the tidal flat, then more variable in the central area of the lake (Fig. 6). The relatively high trace element concentrations (exceeding ER-L) at Station 1, where sediments are muddy sands (sand: 74%), indicates point-source pollution from the upper stream of Lake Shihwa (MLTM, 2009, 2010). The concentrations of Zn, Cr, Ni and Cu, the principal trace metals, decreased with distance from that source. The benthic foraminiferal abundances show a reverse trend to trace-metal concentrations (Table 4, Fig. 6). The area between stations 1 and 4, which had an average of 52 individuals per 20 ml of sediment (none live) and which was located in the stream inflow area, may represent an abiotic zone as described in a model by Alve (1995, fig. 23). The area between stations 5 and 7, where high foraminiferal abundances were observed, is the tidal flat in front of the creek area, and may represent a hypertrophic zone (Alve, 1995). The concentration of Zn, Ni, and Cu at stations 5, 6, and 7 were below the ER-Ls for those elements. Station 5, in particular, had 90% of the foraminiferal tests recovered in this study. The area between stations 8 and 12, with highly variable foraminiferal counts (17–1246 individuals per 20 ml of sediment), appears to be a mixing zone with both abiotic and hypertrophic zones. Supporting evidence for this hypothesis is that *A. beccarii*, which is known to be tolerant of hypoxic environments (e.g., Sen Gupta & Platon, 2006), was relatively abundant at stations 11 and 12, most notably 12, where it was 50% of the population.

The benthic ecosystem of Lake Shihwa experienced an extreme change after construction of the dam (Ahn et al., 1995; Hong et al., 1997). Almost all marine macrobenthic infauna disappeared, and abiotic zones in areas of <6 m water depth developed due to the severe depletion in dissolved oxygen caused by organic loading (Hong et al., 1997). Following the construction of the floodgates that allowed entry of seawater, a brackish-water biota developed in response to the water exchange. Input of seawater into a brackish-water estuary typically results in density stratification, especially in deeper areas. Where there is substantial flux of nutrient or organic matter into the estuary, those deeper areas can quickly become hypoxic or even anoxic. Thus, a mixing zone with abiotic and hypertrophic areas has developed in the central area of the lake that is directly affected by tidal currents through the floodgates. Station 9, with only 22 foraminiferal specimens per 20 ml of sediment (essentially abiotic) had concentrations of Zn, Ni, Cu, and As that were over the ER-L. These trace-metal concentrations slightly increased in the central area due to the transportation of heavily polluted sediments through resuspension and tidal movements (Ra et al., 2011).

**Test Abnormalities and Salinity Fluctuation**

The very low species diversity, highly variable abundances of dead specimens, and dearth of live specimens in Lake Shihwa, all indicate that the foraminiferal populations are stressed (e.g., Schafer, 1973; Yanko et al., 1998). Sources of environmental stress include trace metals, other anthropogenic pollutants including dissolved nutrients and organic matter, and, possibly most importantly, strong fluctuations in salinity, oxygen and carbonate saturation, all of which can stress most foraminiferal taxa.

Enhanced water exchange increased flushing of Lake Shihwa and created a brackish estuarine environment. Between 2004 and 2011, the annual average salinity in April (the dry season) was 29.03 psu, and in August ~ October (the typhoon/rainy season) was 17.23 psu (Fig. 2). The salinity decreases rapidly during the rainy season by the inflow of freshwater from streams, especially in the vicinity of Station 1; this inflow also carries anthropogenic pollutants. Such a stressed environment may be either abiotic or hypertrophic (Alve, 1995), if tolerant taxa are able to exploit food and space resources (Martinez-Colon et al., 2009). *Buccella frigida* and *Elphidium albiumbilicatum* appear to be opportunistic species in Lake Shihwa.

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<td>67 (47.9)</td>
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FIGURE 4. SEM photomicrographs of *Elphidium albumbilicatum* bearing different morphological abnormalities. 1: aberrant and abnormal additional chamber; 2–13: complex form; 14–16: conjoined twins.
### Table 4: Correlation matrix (Pearson) showing the relationships among trace-metal concentrations, sediment characteristics, and benthic foraminiferal species. Significant correlations are shown by asterisks (*95%, **99%).

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<th>Pb</th>
<th>Hg</th>
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<th>Silt</th>
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<th>T. hadai</th>
<th>A. beccarii</th>
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<th>E. clavatum</th>
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FIGURE 5. 1–11: SEM photomicrographs of *Elphidium albiumbilicatum* bearing different morphological abnormalities. 1, 2: Conjoined twins; 3, 4: distorted chamber arrangement or change in coiling; 5, 6: non-developed test; 7–11: dissolved surface and broken last chamber; 12, 13: dissolved surface and broken last chamber of *Elphidium albiumbilicatum*; 14–16: star shape (extensive breakage or dissolution).
Stations 5, 6, 7, and 10 had a high relative abundance of benthic foraminiferal tests, and were located in the hypertrophic zone with low concentrations of trace metals. These stations were dominated by *E. albiumbilicatum* and *B. frigida*, co-occurring with *T. hadai* and *A. beccarii*. Moreover, test deformities were found in 16–56% of the *E. albiumbilicatum* specimens examined (Table 2). Abnormal tests have previously been observed in a number of *Elphidium* species (e.g., Alve, 1991; Burone et al., 2006; Frontalini et al., 2009).

Alve (1991) noted that the normal rate of abnormal tests in a non-stressed population is about 1%. In laboratory cultures of *Ammonia* under normal conditions, abnormalities were observed in 1% of the culture (Stouff et al., 1999). The high percentage of abnormalities of *E. albiumbilicatum* in the present study indicates a stressed population, which is not surprising given the range of possible stressors influencing their environment. These include: (1) changes in salinity and temperature, (2) the lack or overabundance of food, (3) strong fluctuations in dissolved-oxygen concentrations, and (4) anthropogenic pollutants, as previously observed by Boltovskoy et al. (1991) in other areas. The correlation matrix (Table 4) shows a correlation between trace-metal concentrations and the relative abundance of species. In particular, *B. frigida* has a negative correlation with all trace elements, while *E. albiumbilicatum* was positively correlated with Cu, although the correlation coefficient was low ($r = 0.33$). In laboratory cultures of *Ammonia* (Cadre & Debenay, 2006), increasing concentrations of Cu led to (1) an increasing delay before the production of new chambers, explaining dwarfism in polluted areas; (2) an increasing delay before reproduction and a decreasing number of juveniles, explaining low density; and (3) an increasing proportion of deformed tests.

Since the emplacement of the floodgates, Lake Shihwa has become a brackish estuary, with an annual average salinity of 24.24 psu from 2004–2011, with seasonal highs averaging 29.03 psu (Burone et al., 2006; Fig. 2). Test formation by benthic foraminifera is quite susceptible to salinity changes (e.g., Stouff et al., 1999; Saraswat et al., 2015) and fluctuations may disturb ontogenetic development. Saraswat et al. (2015) reported a maximum number of abnormal specimens at 20 psu salinity. Kurtarkar et al. (2011) stated that the benthic foraminifera are capable of recovering and rebuilding their shells after short-term exposure to low salinity and accompanying low pH. Armonyot du Chatelet & Debenay (2010), however, pointed out the difficulty in differentiating between the influence of salinity and the impact of pollution. We suspect that the high percentage of abnormalities in *E. albiumbilicatum* from Lake Shihwa is related to the low salinity and seasonal variation of salinity (difference: 11.8 psu).
Some specimens had dissolved test surfaces and broken chambers (Fig. 4-7-4-16). Breakage during sediment transport can be associated with tidal currents (Fig. 5-7-5-14-5-16). In some specimens, test surfaces and chamber walls were altered or destroyed by decalcification, which is consistent with the low pH values reported (Table 3). Dissolution of calcareous foraminiferal tests begins at pH > 7.8 (Boltovskoy & Wright, 1976; Cadre et al., 2003). The pH of normal seawater ranges between 7.8 and 8.3, with a mean value of about 8.1 (Copin-Montégut, 1996).

Low pH can result from eutrophication. In summer, microbial activity leads to the destruction of organic matter, causing anoxic-sulfidic conditions at the sediment-water interface, and the formation of ferrous sulphide minerals with carbonate saturation of the pore waters. In winter, cool temperatures slow down microbial activity, the ferrous sulphide minerals become oxidized, and the pH is lowered, causing carbonate dissolution (Reaves, 1986). These processes take place in the top few centimeters of the sediment, where most living foraminifera occur (Jorissen et al., 1995). Low pH conditions, which are known to change the assemblage composition by dissolving calcareous tests (Murray & Alve, 1999), may also act on foraminiferal morphology. The pH of surface sediments in Lake Shihwa averaged 7.05 psu (Table 3), much lower than the pH values of ~ 8 reported in Figure 2. Saraswat et al. (2015) stated that a significant drop in pH severely hampers the calcification capability of benthic foraminifera. Specimens of Rosalina globularis at 10 and 15 psu (pH 7.2 and 7.5, respectively) became opaque and began to dissolve within 2 days of lowering the salinity. Among specimens kept at 15 psu salinity, ~23% of specimen tests dissolved within 39 days of lowering the salinity. However, the rate of dissolution then increased, and within the next 11 days, ~93% of the tests dissolved. The low salinity (average of 17.23 psu), in the August–October rainy season, rapidly decreased the pH in Lake Shihwa, and may have caused the dissolution shown in the foraminiferal tests.

Test abnormalities may have natural origins (rapid salinity change, chemical damage, temporary acidification leading to test dissolution, or physical damage followed by regeneration), and anthropogenic origins (e.g., pollutants; Boltovskoy et al., 1991; Alve, 1995). The numbers of abnormal specimens may increase dramatically in areas subjected to different types of pollutants, including trace elements (Yanko et al., 1994, 1998; Coccioni, 2000; Samir & El-Din, 2001; Scott et al., 2001; Geslin et al., 2002; Saraswat et al., 2004; Burone et al., 2006; Romano et al., 2008; Coccioni et al., 2009; Nigam et al., 2009). However, it is difficult to isolate any single specific cause as abnormalities may be a result of multiple effects (Boltovskoy et al., 1991; Alve, 1995).

Most studies of foraminifera in polluted environments have focused on linking the malformed tests to trace elements, without distinguishing the role played by the other stressors in those same environments, which might also contribute to the prevalence of abnormalities. While we have not been able to directly establish a relationship between variation of salinity and abnormal tests, we strongly suspect that the prevalence of test abnormalities are associated with the overall hyposaline waters, and especially the strong seasonal variations in salinity.

CONCLUSIONS

Ecological conditions in benthic foraminifera were investigated in Lake Shihwa, the environment of which changed from tidal flats to a eutrophic, nearly abiotic freshwater lake (in 1994), and presently, to brackish estuary (in 2001) as a consequence of human-controlled tidal mixing via floodgates. Following the construction of a dike in 1994, the area became a shallow lake with significant input of anthropogenic contaminants, including organic matter and chemicals. The result was eutrophication, anoxic sediments and elevated concentrations of trace metals (especially Zn, Ni and Cu) from nearby industrial activity. To mitigate the pollution, floodgates were installed in 2001, allowing exchange between the lake and the Yellow Sea. Strong tidal currents have increased sediment grain size thereby reducing pollutant-sediment binding in previously fine mud. As a result, concentrations of trace metals have declined.

Assessment of foraminiferal assemblages from sediment samples collected in 2011 revealed very few live specimens and very high variability among sampling stations in the abundances of dead tests in the sediments. Very few tests were found at sites closest to the Shihwa Industrial Complex, where trace-metal concentrations were high, which is interpreted as an abiotic zone. Foraminiferal tests were abundant in samples collected from the tidal flat, where trace-metal concentrations were low; this area is interpreted as a hypertrophic zone. In the central, deeper area of the lake, test abundances were highly variable, likely resulting from a combination of strong currents when the floodgates are open and possibly the development of hypoxia when gates are closed.

The foraminiferal assemblage is characterized by low diversity of stress-tolerant taxa. Test abnormalities were prevalent, especially in specimens of E. albiumbilicatum. While a variety of environmental stressors are present in the lake, the high incidence of test abnormalities could be largely the consequence of hyposaline waters, including the substantial variations in salinity between the rainy and dry seasons. Consistent monitoring of ecological conditions at Lake Shihwa may enhance understanding of the relationship between salinity variability and anthropogenic contaminants, and their effects on benthic foraminifera.

ACKNOWLEDGMENTS

This study was financially supported by the Post Innovation Program of the Fisheries Science Institute at Chonnam National University. H. J. Woo was partially supported by coastal environment studies funded by KIOST (PE98927).

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APPENDIX 1. Numbers, relative abundance (%) and statistical data for benthic foraminifera from Lake Shihwa.

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