

Temporal changes of zooplankton in the detention pond closed off in 1997 from Isahaya Bay, Kyushu, in relation to desalination

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Abstract: Zooplankton surveys were made from May, 1997, to July, 2000, in the detention pond closed off from Isahaya Bay, an inlet of Ariake Sound, to follow changes in the zooplankton community concomitant with desalination after the closing of the dike in April, 1997. Mean salinity at the surface decreased from 27 to 3.9 psu in the four months after closing. Mean density of zooplankton (excluding protozoans) increased from 11.71 l^{-1} in May, 1997, to 225.71 l^{-1} in August, 1997, mainly due to increases in copepod nauplii and the rotifers *Brachionus plicatilis* and probably *B. rotundiformis*. Copepods consisted mostly of *Oithona davisae* (86%) and *Acartia pacifica* (10%) in May, 1997, but these had been completely replaced by brackish-water species, *Sinocalanus tenellus* (44%), *Pseudodiaptomus inopinatus* (35%), and *Paracyclopina nana* (19%) by August, 1997. With further desalination, the proportion of freshwater copepods, consisting mostly of *Thermocyclops* spp., increased. Zooplankton densities in the pond were comparable to those in other brackish waters until one year after closing. However, densities in the summers of 1998 and 1999 were significantly lower ($<10\text{ l}^{-1}$) than in 1997 and 2000; food-limitation and the extremely low salinities (<1.0 psu) are discussed as possible causes of the low densities in 1998 and 1999. Occurrences of marine copepods and the appendicularian *Oikopleura* sp. in 2000 suggest inflow of seawater through the gates of the dike.

Key words: zooplankton, copepods, rotifers, Isahaya Bay, desalination

Introduction

Isahaya Bay, an inlet of Ariake Sound, where there is a large tidal range (more than 6 m during spring tide) in the inner part, used to have one of the largest Japanese intertidal mudflats. On 14 April 1997, the upper third of the bay (35.55 km^2) was closed off by a 7 km long dike in order to reclaim 15 km^2 for agricultural land and as protection against floods and high tides. The water inside the dike, henceforth referred to as the detention pond, has been kept at a level 1 m lower than mean sea level by preventing inflow of seawater at high tide and discharging water through two drainage gates at low tide. In consequence, the mudflat inside the dike dried up quickly and most of the benthic animals there died out.

Azuma (2000a, b) and Sato et al. (2001) studied temporal changes of benthic animals in the detention pond. The number of species of gammarids decreased from 16 to

seven by 40 days after closing due to the disappearance of marine forms. In August, 1997 (four months after closing), the gammarid fauna was comprised almost exclusively of *Corophium sinense*, with a maximum density of 2000 m^{-2} ; however, its density decreased to 300 m^{-2} or less in April, 1998, and the species was not found in the pond in August, 1998, when only a few freshwater gammarid species were observed at low densities ($50\text{--}60\text{ m}^{-2}$) in the river mouth. Marine bivalves were abundant in the mudflat before closing, but they became almost entirely extinct there by August, 1997 (Sato et al. 2001). Instead, a freshwater bivalve, *Potamocorbula* cf. *laevis*, which had never been observed in Isahaya Bay before closing, occurred in the river mouth in August, 1997, and expanded its range throughout the pond, with a maximum density of 8317 m^{-2} by April 1998 (Azuma 2000b). Other benthic marine forms in the pond also went nearly extinct there in the first four months after closing. In contrast to the quick disappearance of marine benthic animals, phytoplankton in the pond continued to be dominated by marine forms for a longer time. For example,

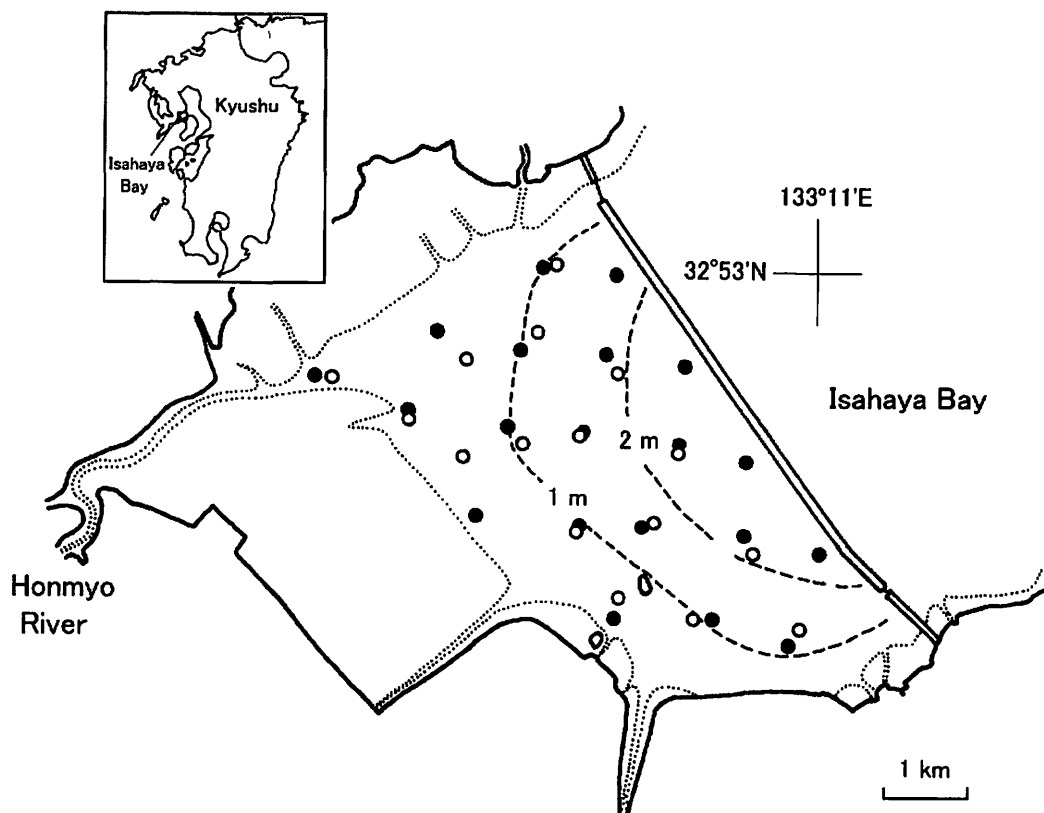


Fig. 1. Map showing sampling stations in the detention pond of Isahaya Bay. Open and solid circles indicate the stations on 24 May 1997 and on other dates, respectively. Dotted and broken lines show the margin of the mudflat and the depth contours, respectively.

Heterosigma akashiwo, a common causative organism of marine red tides in Japan, occurred abundantly even a year after closing (Ishizaka & Ueda 1998). As for the fish fauna in the pond, Azuma (2000a) reported that marine forms were replaced by freshwater ones, such as Japanese silver crucian carp *Carassius auratus langsdorfi*, but estuarine forms, such as the red lip mullet *Chelon haematocheilus*, continued to survive near the water gates.

The present study describes temporal changes of the zooplankton community in the detention pond of Isahaya Bay concomitant with desalination after the closing of the pond, compares zooplankton abundances, especially for copepods, with those previously observed in other brackish waters, and briefly discusses the factors that affected zooplankton abundance.

Materials and Methods

Zooplankton surveys were carried out at 16 to 20 stations (Fig. 1) in the detention pond on seven occasions, viz., on 24 May 1997 (40 days after the closing of the dike), 28 August 1997 (four months after), 9 April 1998 (one year after), 20 August 1998, 30 July 1999, 20 October 1999, and 26 July 2000. Zooplankton in the surface water were collected by throwing a plankton net (30 cm in mouth diameter and 0.1 mm mesh opening, without a lead) from an an-

chored boat to the full length of the attached 10-m long rope and immediately towing the net back to the boat by hand. The filtered volume per tow was estimated as 440 liters by assuming the filtering efficiency was 0.625, a value based on 10 tows conducted in the same manner using a net equipped with a flow meter. The samples were fixed immediately in ca. 5% seawater-formalin solution. Temperature, salinity, DO, pH, and turbidity of the surface and bottom (about 0.5 m above the bottom) waters were measured simultaneously with the plankton sampling by using a multi-parameter water quality meter (Alec Electronics Co. Ltd., ADR-1000), except for the DO on 26 July 2000, which was determined by Winkler's method because of trouble with the meter. Zooplankton excluding protozoans were counted under a microscope in 1/15 to 1/20 aliquots of each sample. Copepods (except for nauplii), cladocerans, and rotifers were identified at the species level as far as possible.

Results

Environmental variables

Mean surface water temperature in the pond was higher than 25°C in summer (29.9°C on 28 August 1998, 30.6°C on 20 August 1998, 26.2°C on 30 July 1999, and 29.5°C on 26 July 2000) and lower than 20°C in spring and

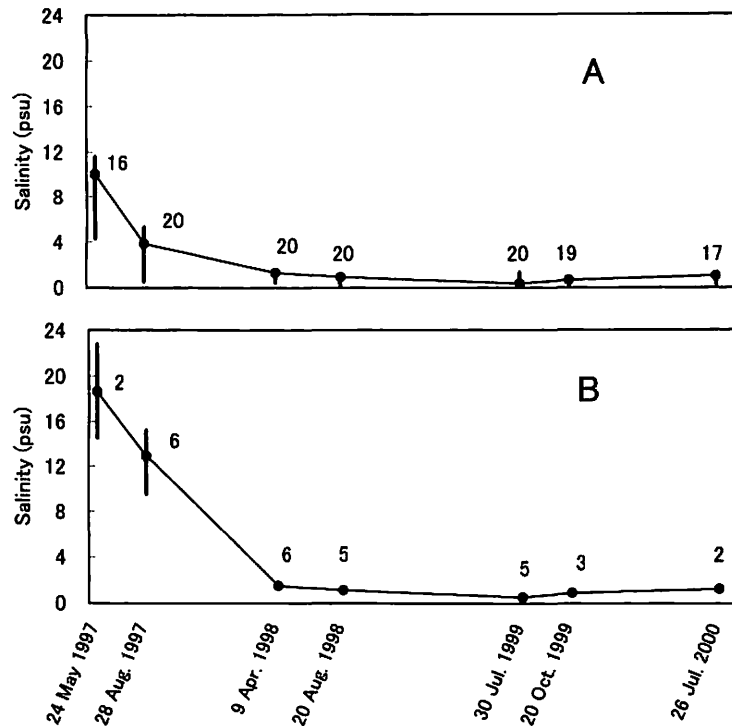


Fig. 2. Temporal change in salinity of the surface water at all stations (A) and of the bottom water at stations deeper than 2.0 m (B) in the detention pond of Isahaya Bay after closing the dike. Solid circles and vertical lines denote mean values and ranges, respectively. The figures by the solid circles indicate station number.

fall (17.8°C on 9 April 1998 and 17.9°C on 20 October 1999). Strong thermal stratification was observed at the deep stations on 28 August 1997 and 20 August 1998, where the mean vertical gradients at the stations deeper than 1.5 m were 0.6 and 0.9°C m⁻¹, respectively. Mean salinity of the surface water, which was about 27 psu just after closing the dike (Honda & Takeno 1997), steeply decreased to 3.8 psu on 28 August 1997, while at the bottom of the deep stations high-salinity waters (>15 psu) remained by the same date (Fig. 2). The salinity further dropped to less than 1 psu even at the deepest point by 30 July 1999, but then increased slightly. Low DO saturation (<30%) in the bottom water was observed at a few stations on 24 May 1997 and 28 August 1997, but these stations were not necessarily the deepest ones; on these dates the DO saturations at the bottom of the deepest (>2 m) stations were high (58–87%) with an exception of 26% on the latter date. Following this date, the DO saturation at the bottom was always high (83–184%) except for slightly lower values (65–78%) on 26 July 2000. The pH value was usually higher than 8.0 except on 30 July 1999, when the value was within 7.5–8.0 at most stations, and the highest mean value 8.6 was recorded at the surface on 28 August 1997. Although turbidity greatly varied from 0.3 to 351.2 ppm depending on date and station, the mean value in the surface water ranged between 100–200 ppm, except on 28 August 1997 (64.8 ppm) and 20 August 1998 (73.3 ppm). All these values were greater than the annual mean value (9.3–53.2

ppm) in the inner part of Ariake Sound (Shirota & Kondo 1985) and lower than the value (>500 ppm) in the inner part of Isahaya Bay before construction of the dike (estimated from the Landsat satellite image taken on 20 December 1972; Shirota 1982).

Zooplankton

During the course of the rapid desalination after the closing of the dike, the mean density of zooplankton in the detention pond increased greatly from 11.7 indiv. l⁻¹ on 24 May 1997 to 225.7 indiv. l⁻¹ on 28 August 1997 (Fig. 3). Thereafter, it decreased continuously to 2.4 indiv. l⁻¹ on 30 July 1999 with decreasing salinity, and then increased again up to 28.7 indiv. l⁻¹ on 26 July 2000 with increasing salinity. The high abundance of zooplankton on 28 August 1997 was accounted for mainly by rotifers and copepod nauplii, with mean abundances of 60.3% and 18.6% of total zooplankton, respectively. Rotifers were also the most important component of the zooplankton on 20 August 1998 and 26 July 2000, when they constituted 39.5% and 44.5%, respectively. On the other dates copepodids were the dominant zooplankton, comprising from 58.6% (20 October 1999) to 87.4% (9 April 1998). Cladocerans were abundant only on 28 August 1997 (mean 18.9 indiv. l⁻¹).

Five species of calanoid copepod, *Acartia pacifica* Steuer, *Paracalanus parvus* (Claus) s.l., *Pseudodiaptomus marinus* Sato, *Ps. inopinus* Burckhardt, and *Sinocalanus*

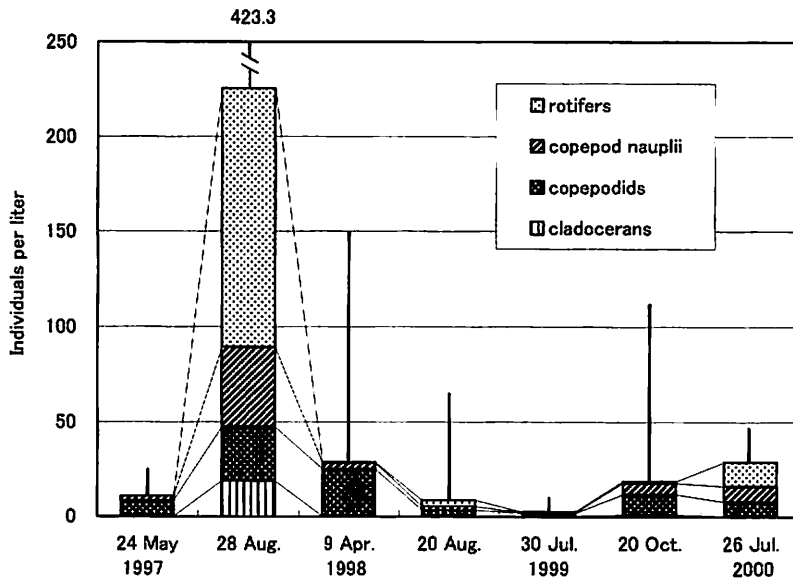


Fig. 3. Temporal change in mean densities of zooplankton (excluding protozoans) in the detention pond of Isahaya Bay. Vertical lines indicate the maximum densities of total zooplankton.

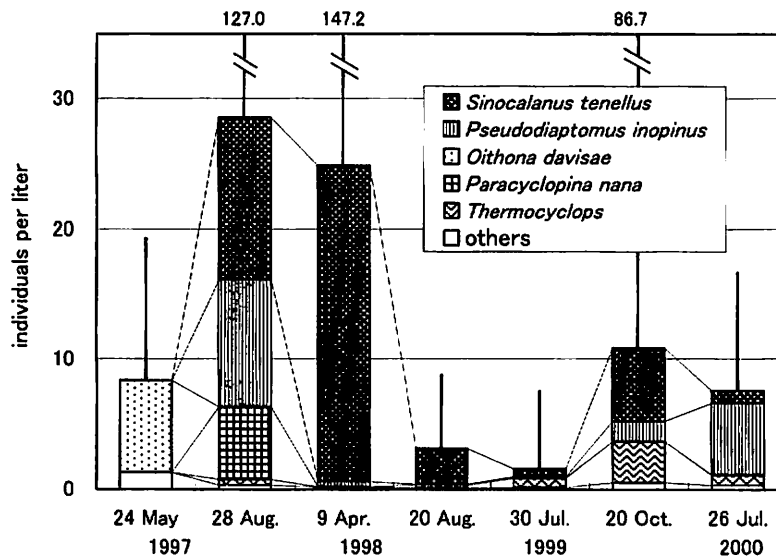


Fig. 4. Temporal change in mean densities of copepods (excluding nauplii) in the detention pond of Isahaya Bay. Vertical lines indicate the maximum densities of total copepods.

tenellus (Kikuchi), and seven species of cyclopoid copepod, *Oithona davisae* Ferrari & Orsi, *Paracyclops nana* Smirnov, *Halicyclops* sp., *Cyclops vicinus* Ulyanin, *Mesocyclops pehpeiensis* Hu, *Thermocyclops crassus* (Fischer), and *T. taihokuensis* Harada were identified. Temporal changes in the total number of copepodids were largely similar to those of total zooplankton, except that the increase on 28 August 1997 was not so extreme (Fig. 4). The mean densities of copepodids reached the maximum (28.5 indiv. l⁻¹) on 28 August 1997 and the minimum (1.5 indiv. l⁻¹) on 30 July 1999. On 24 May 1997, *O. davisae*, which is the most common copepod in Ariake Sound (Hirota & Tanaka 1990) and other eutrophic bays of Japan

(Ueda 1991), was the dominant copepod, comprising 62.9–98.6% (mean 84.7%) of the total copepodid numbers; *A. pacifica* (1.4–21.6%, mean 10.3%) and *Ps. marinus* (0–32.0%, mean 3.7%) were the next most abundant members. By 28 August 1997 the copepod fauna had almost completely changed to different species, viz., *S. tenellus* (11.7–67.8%, mean 43.6%), *Ps. inopinus* (4.2–70.5%, mean 34.5%), and *Paracyclops nana* (2.9–82.3%, mean 19.3%). In addition to these three species, a freshwater cyclopoid, *T. taihokuensis*, occurred at a density of 2.4–3.1 indiv. l⁻¹ (12.0–56.8% of total copepodids) at the stations with low salinities (0.5–1.7 psu) in and around the Honmyo River mouth, and an unknown *Halicyclops* species com-

prised 25.3% (5.4 indiv. l⁻¹) at a station near the river mouth. The copepods consisted almost exclusively of *S. tenellus* on the next two sampling dates, except at some stations in and around the river mouth, where the salinity was lower than 1.0 psu and *Halicyclops* sp. or *T. taihokuensis* were more abundant. The mean and maximum densities of *S. tenellus* on 4 April 1998 were 24.3 and 146.5 indiv. l⁻¹, respectively, and these decreased greatly to 2.8 and 8.5 indiv. l⁻¹ on 20 August 1998. On and after 30 July 1999 *S. tenellus* and *T. taihokuensis* were subsequently abundant, but *Ps. inopinus* outnumbered these two species on 26 July 2000. The marine copepod *O. davisae* occurred again on 26 July 2000 in small numbers (at most 0.4 indiv. l⁻¹ at a station near the dike).

High abundances of rotifers were observed on 28 August 1997 and 26 July 2000, when their mean densities were 136.0 and 12.8 indiv. l⁻¹, respectively. The dominant species on 28 August 1997 were *Brachionus plicatilis* (O. F. Müller) (48.7%), which probably included an allied species, *B. rotundiformis* Tschugunoff (A. Hagiwara, pers. comm.), and *B. calyciflorus* f. *anuraeiformis* (Brehm) (34.4%), and that on 26 July 2000 was a freshwater species, *Hexarthra mira* (Hudson) (80.8%). The dense population of cladocerans on 28 August 1997 consisted almost entirely of the single species *Moina macrocopa* (Straus), the mean abundance of which was 99.8% of the total cladoceran number, at a highest density of 100.5 indiv. l⁻¹. The marine cladoceran *Podon polyphemoides* (Leuckart) occurred at a density of 2.4 indiv. l⁻¹ only at a station near the dike on 26 July 2000, where the marine copepod *Paracalanus parvus* s.l. and the appendicularian *Oikopleura* sp. co-occurred. The number of larval plankton of benthic animals was very small as compared with holoplankton, and their mean density decreased from 0.9 indiv. l⁻¹ on 24 May 1997 to nearly zero on 9 April 1998, along with the decrease in salinity. The major components on 24 May 1997 were barnacle nauplii and polychaete larvae, which are marine forms and which almost completely disappeared on and after 28 August 1997.

Discussion

The copepod species occurring in the detention pond behind the Isahaya Bay dike can be classified into three ecological categories: "marine", "estuarine", and "freshwater" forms. The "marine" copepods include *Oithona davisae*, *Acartia pacifica*, *Pseudodiaptomus marinus*, and *Paracalanus parvus* s.l., which are found not only in estuaries but in high-salinity coastal waters and correspond to Jeffries' (1967) "euryhaline marine" and "estuarine and marine" forms. The "estuarine" copepods are represented by *Sinocalanus tenellus*, *Paracyclopsina nana*, and *Ps. inopinus*, which are known to prefer meso- and oligohaline waters such as Lake Shinji-ko and Lake Naka-umi in Shimane Prefecture (Harada et al. 1985; Ohtsuka et al. 1999) and correspond to Jeffries' "true estuarine" forms.

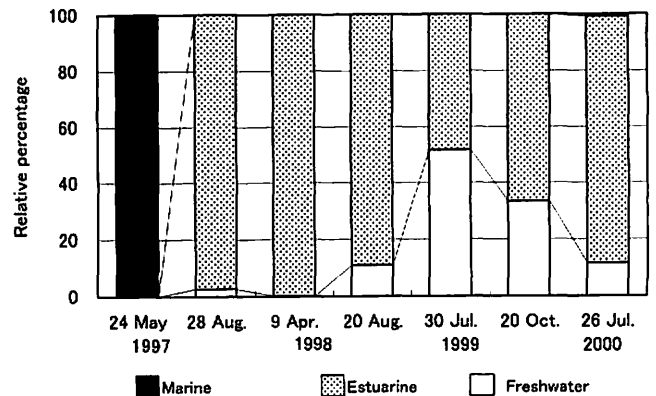


Fig. 5. Temporal change in relative percentages of three ecological categories of copepods, viz. "marine", "estuarine", and "freshwater" copepods. The species belonging to each group are listed in the text.

Cyclops vicinus, *Mesocyclops pehpeiensis*, *Thermocyclops taihokuensis*, and *T. crassus* are "freshwater" copepods. *Halicyclops* sp. is also considered to be a freshwater copepod because its distribution was most similar to that of *T. taihokuensis*; namely, it was confined to the lower salinity waters around the river mouth. Temporal change in the proportions of these categories (Fig. 5) indicates that the shift from marine copepods to estuarine ones was completed within four months after the closing of the dike and that the proportion of freshwater copepods was inversely correlated with the salinity. A drastic faunal change in the first four months was also observed in benthic molluscs, which were almost all marine forms on 24 May 1997 but had changed to estuarine and freshwater forms on 28 August 1997 (Sato et al. 2001). The same was true for gammarids, the marine forms of which disappeared in 40 days (Azuma 2000b). Thus the change in zooplankton with desalination was more similar to that of benthic animals than to that of phytoplankton, the dominant species of which were marine forms even a year after closing (Ishizaka & Ueda 1998). According to the monthly survey of water quality by Honda & Takeno (1997), chlorinity in the detention pond steeply declined after closing to about 1‰, even at the bottom, in July, 1997, when the monthly rainfall was 939 mm in Isahaya City (Nagasaki Marine Observatory). Chlorinity then recovered up to about 5‰ (=9 psu) in October and November, but again decreased to 1‰ (=1.8 psu) in January, 1998. These changes in chlorinity lead us to suggest the following scenario for the zooplankton changes in the first four months. The heavy rainfall in July almost entirely washed away the marine species from the pond, and in August, when the salinity had somewhat recovered, estuarine zooplankton such as *Brachionus plicatilis* and *S. tenellus*, which have higher growth rates than marine species (Uye 1997), propagated faster than marine forms and became the dominant components.

On 24 May 1997 *Oithona davisae* was the only abundant species of copepod in the pond and its mean density was

7.0 indiv. l⁻¹. This is comparable to densities of this species recorded from Ariake Sound in the same month using a plankton net of the same mesh size, for example, 2–42 indiv. l⁻¹ in shallow waters adjacent to mudflats in the mid-eastern region (Hirota & Tanaka 1985) and 15.0 indiv. l⁻¹ at a station off the Chikugo River mouth (Hibino 2000). On the next sampling date, 28 August 1997, rotifers occurred most abundantly with a mean density 136.0 indiv. l⁻¹, and most were *Brachionus plicatilis* and probably *B. rotundiformis*. Although this value apparently underestimates the true abundances because their size (about 0.12–0.13 mm in body width) is smaller than the diagonal length (0.14 mm) of the mesh opening of the plankton net used, it is greater than the maximum density (70 indiv. l⁻¹) of the same species in brackish Lake Naka-umi (Ohtsuka et al. 1999), which was obtained by monthly plankton surveys using a net of the same mesh size. The mean density of the dominant copepod *Sinocalanus tenellus* on the same date was 12.4 indiv. l⁻¹. This species is known to propagate more in the colder season (Hada et al. 1986, Ohtsuka et al. 1999). For example, the densities in a brackish-water pond constructed on reclaimed land in Hiroshima were less than 1.0 indiv. l⁻¹ from July to August in contrast to the highest recorded density of 330 indiv. l⁻¹ in November (Hada et al. 1986). The density of *S. tenellus* in the detention pond of Isahaya Bay on 28 August 1997 was thus rather high for summer. The mean and maximum densities (24.3 and 146.5 indiv. l⁻¹, respectively) of this species on 9 April 1998 were also at about the same level observed in the pond in Hiroshima (Hada et al. 1986, 40–100 indiv. l⁻¹, read from the figure) and Lake Shinji (Uye 1997, about 80 indiv. l⁻¹, idem) in April. Thus, the zooplankton densities in the pond were comparable to those in other estuarine and brackish waters until at least one year after the closing of the dike.

Zooplankton abundances in the summers of 1998 and 1999 were significantly lower than those in the summers of 1997 and 2000. One of the possible reasons is deficiency of phytoplankton as food for zooplankton. According to Ishizaka & Ueda (1998), the mean phytoplankton density in the pond was only 79 cells ml⁻¹ on 20 August 1998, which was about 17–20% of that in the summer of 1997. However, it is uncertain whether the zooplankton population was really food-limited, because there was a lot of suspended detritus in the detention pond. Some estuarine copepods are known to utilize detritus as supplementary food (e.g., Roman, 1984). Another possible cause for the low zooplankton abundance during the summers of 1998 and 1999 was the extremely low salinity. Kimoto et al. (1986) reported that the dominant copepod *Sinocalanus tenellus* showed its highest growth rate at 15 psu but could not develop to the first copepodid stage at 0 and 2.5 psu in the laboratory. Mashiko (1955) investigated the zooplankton fauna in 14 oligohaline water bodies and concluded that *S. tenellus*, *Pseudodiaptomus inopinus*, and *Brachionus plicatilis* occurred mainly in brackish waters where the

chlorinity was always more than 1‰ (equivalent to 1.8 psu). These studies suggest that the extremely low salinity (<1.0 psu) during 1998 and 1999 would be expected to reduce the abundance of these estuarine species.

Paracalanus parvus s.l. and *Oikopleura* sp. that occurred on 26 July 2000 were undoubtedly introduced from outside the detention pond, because these marine species could not have survived in the extremely low-salinity water that was present in 1998 and 1999. This suggests inflow of seawater to the pond probably by leakage through the gates or by reverse flow at the bottom when the gates opened to discharge pond water.

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