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Special Issue

Effects of sluice gate operations on water quality, sediment conditions, and benthic invertebrates in Cih Lake, Kinmen

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ABSTRACT: Cih Lake is an important habitat for numerous aquatic organisms. However, since the construction of a dike in 1969, the lake has become a closed reservoir, relying solely on sluice gates for water exchange. This limited exchange has led to significant deterioration in water quality. In response, the Kinmen National Park Headquarters began operating the sluice gates in 2017 to enhance seawater exchange. This study evaluates the effects of three different sluice gate operation modes: no seawater exchange (current operation), seawater exchange once per month, and seawater exchange twice per month. Water quality, sediment conditions, and benthic invertebrate communities were surveyed after each operational mode to assess the impact. Results showed that seawater exchange effectively diluted nutrient concentrations within the lake. However, the impact on sediment was not significant. Polychaete abundance appeared to increase following the water exchange operations, whereas mollusks and crustaceans did not exhibit notable changes. Based on these findings, we recommend conducting seawater exchange operations at least once per month to improve water quality and enhance polychaete abundance.

KEY WORDS: Benthic macroinvertebrates, sediment condition, sluice gate operation, water quality.

INTRODUCTION

Cih Lake, an important wetland located in Kinmen National Park, was once an open lagoon with natural tidal rhythms. However, after the construction of a dike in 1969 to prevent enemy landings, the lake became a closed reservoir (Fig. 1). Currently, seawater exchange in the lake relies entirely on two sluice gates located in the south. The construction of the dike has led to several negative effects, including a reduction in seawater exchange and an increase in wastewater inputs from nearby villages (Chiu, 2015). These factors have resulted in excess nutrient accumulation, deteriorating water quality, hypoxia, and negative impacts on aquatic biota.

The detrimental effects of dike construction on water quality and benthic communities have been well-documented in other studies. For example, in Japan's Isahaya Bay, eutrophic and hypoxic conditions developed due to low seawater-exchange rates following dike construction in 1997 (Hodoki and Murakami, 2006). Similarly, dissolved oxygen levels decreased, and the number of taxa, abundance, and biomass of macrofauna significantly dropped in inner bay stations at Chinhae Bay and Youngsan River estuarine bay in Korea (Lim *et al.*, 2006).

These adverse effects can be mitigated with well-designed gate management. For instance, Matsuda and Kokubu (2016) found that promoting tidal exchange by opening wet gates in dikes improved sediment quality and macro-benthos conditions inside the dikes. However, the effectiveness of gate openings heavily depends on operational procedures. In another study, Hayami and Hamada (2016) modeled the effects of gate-opening procedures on currents, hydrography, and sediment transport in Isahaya Bay. They observed that full gate openings generated strong currents, enhanced vertical mixing, and reduced hypoxia, stratification, and the average residence time compared to restricted gate openings, suggesting that full-opening was more effective in improving water quality.

To improve water quality in Cih Lake, the Kinmen National Park Headquarters (KNPH) began increasing seawater exchange through sluice gate operation in 2017. The gates were manually opened during spring tides each month to increase seawater input. An ecological survey conducted between 2016 and 2018 reported an increase in gastropod abundance and a decrease in nutrient levels following periodic gate operations (Lin and Jiang, 2018). This indicates that seawater input from sluice gate operations is crucial for maintaining water quality and supporting benthic fauna in Cih Lake.

Before the present study, there was no systematic management of gate operations, and the optimal procedure for gate opening remained unknown. Therefore, the main objective of this study is to evaluate the effects of different gate operation modes by monitoring changes in water quality, sediment conditions, and the benthic community. We hypothesize that, compared to the current gate operation of the KNPH, the operation scenario designed in the present study will increase the rate of water exchange, which, in turn, will dilute pollutant levels, improve sediment conditions, and enhance the diversity of benthic organisms. Finally, we will provide management recommendations to the KNPH.

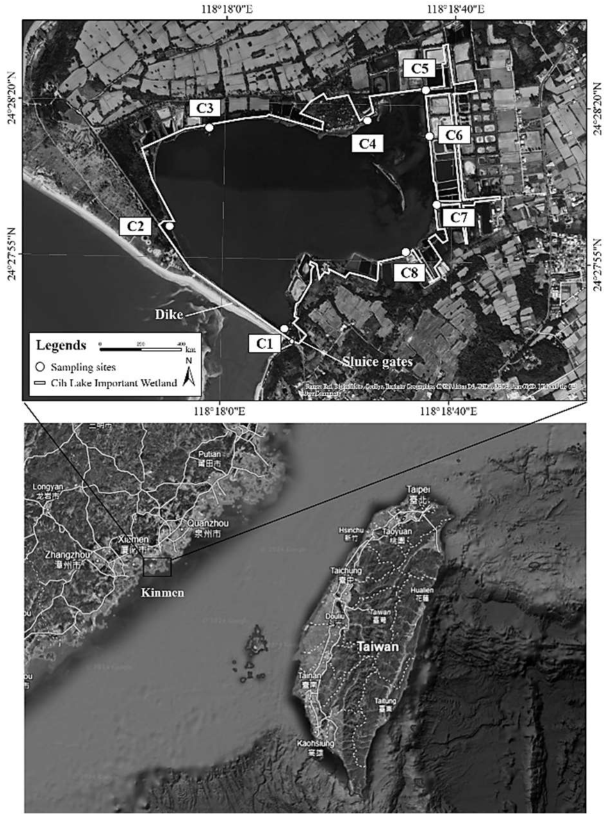

Fig. 1. The maps illustrate the relative positions of Taiwan, Kinmen Island, and Cih Lake. The study area and sampling points were located around the lake.

MATERIALS AND METHODS

Study Area

Cih Lake is located in Jinning Township, Kinmen County, covering an area of approximately 99 hectares. The lake is characterized by shallow waters, with depths ranging between 0.60 and 1.03 meters (Lin and Jiang, 2018). Eight sampling sites (C1~C8) were established around the lake (Fig. 1). Two drains at C5 and C7 discharge agricultural runoff into the lake. Sampling was conducted at the end of each gate operation mode in January, March, May, July, August, and October of 2022. Environmental and biological factors were monitored at each site, and automatic water loggers were installed at C1 and C6 to track water levels throughout the study period.

Sluice Gate Operation

The seawater exchange in Cih Lake is regulated by two gates: a flood gate with three slots located on the dike (Fig. 2A) and a scouring sluice in a culvert beneath the dike (Fig. 2B). Three sluice operation scenarios were implemented: the current operation mode of the KNPH (control operation) and two water exchange modes where the "water exchange operation" was executed once and twice per month, respectively.

In the current operation mode, water levels were maintained at a constant level (approximately 0.84 m). Seawater was only introduced when water levels dropped below this threshold, and only the middle slot of the flood gate and the scouring sluice were opened at heights of 20 cm and 40 cm, respectively. In contrast, the water exchange operation in the study involved opening all three slots of the flood gate to a height of 30 cm, discharging lake water, and then refilling the lake with seawater through full openings (flood gate slots at 30 cm and the scouring sluice at 180 cm) to enhance water exchange. The frequency of water exchange operations was constrained by tidal rhythms, as seawater could only be introduced when tidal heights exceeded 180 cm, limiting the maximum frequency of exchanges to twice per month. Compared to current operation mode, water exchange operation created stronger currents which could propel seawater further into the lake, and increase the amount of water exchanged.

Because the season affects nutrient input to the lake, we scheduled all three operation modes (control operation, and water change modes of once and twice per month) during both dry and wet seasons, as defined according to the historical precipitation records for Kinmen (2004–2021). Originally, we intended to test all operation modes at least once in both seasons. However, there was a difference in actual rainfall between the historical records and those of 2022. Therefore, we redefined the dry season (December 2021 to January 2022, and August to October 2022) and the wet season (March to July 2022) based on the rainfall data from 2022. During the wet season, two twice-water exchange operations and one single-water exchange operation were conducted, while two control operations and one single-water exchange operation were performed during the dry season. Each operational mode lasted approximately two months to allow enough time to observe its effects.

Water Quality Monitoring and Sediment Sampling

Thirteen water quality parameters were measured, including water temperature (WT), salinity (Sal), pH, dissolved oxygen (DO), turbidity (TB), and concentrations of phosphate (PO4-P), nitrite (NO2-N), nitrate (NO3-N), ammonia (NH4-N), total suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand (COD), and phytoplankton chlorophyll a (Chl-a). In-situ measurements of WT, pH, Sal, and DO were taken using a water quality meter (AZ-86031, AZ Instrument Corp., Taiwan), while turbidity was measured with a turbidity meter (TU-2016, Lutron, USA) and Chl-a with a handheld fluorometer (AquaFluor 8000-010, AquaFluor, Taiwan). Water samples were collected in 500 ml brown bottles, transported to the laboratory, and kept at 4°C before analysis. Nitrate, nitrite, and ammonia were analyzed using brucine method (Jenkins and Medsker, 1964), Griess reagent method (Pai *et al*., 1990),

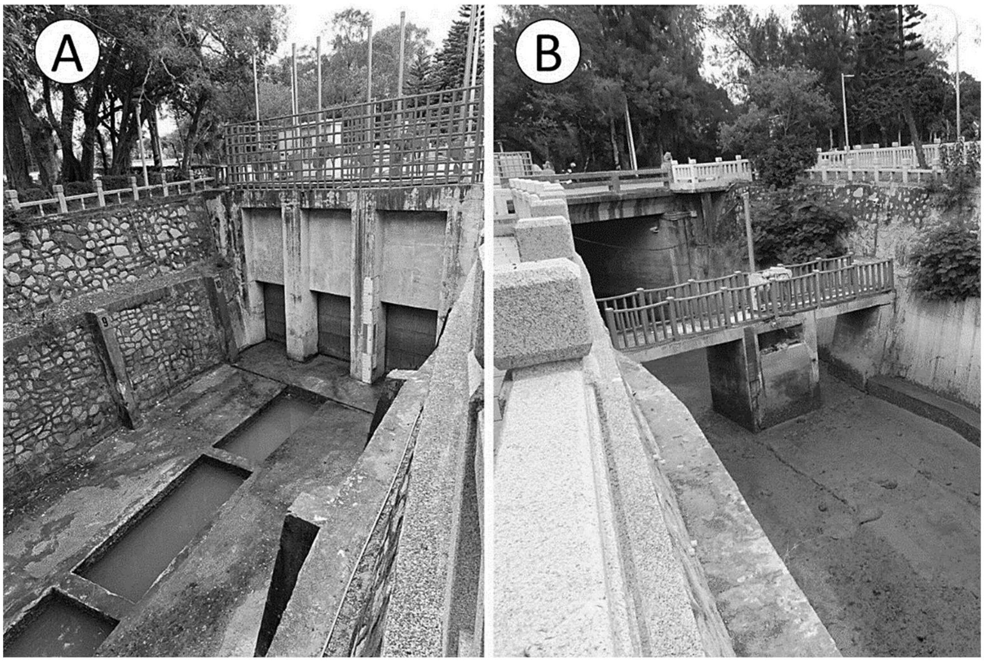

Fig. 2. Photos of the gates used to regulate seawater exchange in Cih Lake. **A.** Floodgate with three slots on the dike; **B.** Scouring sluice located in a culvert beneath the dike.

and indophenol blue spectrophotometric method respectively (Pai *et al.*, 2001), while phosphate was determined by Murphy-Riley method (Murphy and Riley, 1962). BOD and COD were measured according to the protocols established by the Taiwan Ministry of Environment. Sediment samples from the top 10 cm were collected at each site using a corer (4 cm in diameter). The pH and oxidation-reduction potential (ORP) of the sediments were measured at depths of 0, 5, and 10 cm using an ORP and pH meter (EZDO-8200, EZDO, Taiwan).

Benthic Invertebrate Sampling

Benthic invertebrates, including mollusks, crustaceans, and polychaetes, were sampled using appropriate methods. Mollusks were collected from three randomly selected quadrats (0.25 m^2) per site, and all individuals were identified and counted. Crustaceans were sampled using baited traps with sanma meat as bait. Three traps were placed at each site and checked daily over a three-day period, and captured crustaceans were recorded by species and number. Polychaetes were collected by digging 0.25 m^2 quadrats to a depth of 20 cm, followed by wet-sieving the samples through a 0.5-mm mesh. Polychaetes were extracted, preserved in 75% ethanol, and identified to family level under a microscope.

Data Analysis

Data were analyzed using R version 4.0.5 (R Core Team, 2021). Normality was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene's test. Continuous variables that met the assumptions of normality and homogeneity were compared using one-way ANOVA. For non-normally distributed data, the Mann-Whitney U test was employed. Post hoc pairwise comparisons were performed using the Dunn test. Benthic invertebrate abundance data were analyzed using generalized additive models (GAMs) to assess the effects of different gate operation modes on the abundance of mollusks, crustaceans, and polychaetes. Shannon diversity index and Pielou's evenness index were calculated to evaluate the diversity of benthic communities. Community composition of benthic invertebrates was assessed using cluster analysis based on the Bray-Curtis dissimilarity index. This analysis was conducted to evaluate similarities and differences among different sampling sites and operational modes. All analyses were considered statistically significant at $p < 0.05$.

RESULTS

Water Quality and Sediment Conditions

For in-situ water quality parameters, temperature varied with the season, ranging from 14.0°C to 37.6°C. Dissolved oxygen ranged from 2.5 to 11.21 mg/L, and no hypoxic conditions (< 2.0 mg/L) were observed during the study period. pH values ranged from 7.84 to 9.55, salinity between 1.51 and 41.9 PSU, and turbidity between 0 and 77 NTU. Chlorophyll-a (Chl-a) concentrations varied between 7.25 and 125.75 mg/L, with the highest values recorded in July and August. Biochemical oxygen demand (BOD) ranged from 2.6 to 17.2 mg/L, while chemical oxygen demand (COD) ranged from 11.6 to 55.6 mg/L. Nutrient levels varied, with nitrite concentrations ranging from undetectable to 0.13 mg/L, nitrate from 0 to 2.96

mg/L, ammonia from 0.02 to 0.42 mg/L, and phosphate from 0.03 to 1.49 mg/L.

The average amount of water exchanged under different operation modes was 42,434 m³ for the current operation, 55,669 m³ for the once-per-month exchange, and 62,809 m³ for the twice-per-month exchange. Water exchange operations led to a significant decrease in dissolved inorganic nitrogen (DIN) concentrations during the dry season (Mann-Whitney U Test, $p < 0.001$) but not during the wet season (Mann-Whitney U Test, $p = 0.481$) (Fig. 3A). Phosphate concentrations significantly decreased during the wet season (Mann-Whitney U Test, $p < 0.001$) but not during the dry season (Mann-Whitney U Test, $p = 0.878$) (Fig. 3B). BOD concentrations were significantly reduced during the dry season (Mann-Whitney U Test, $p < 0.001$), while COD concentrations were significantly lower after water exchange operations during the wet season (Mann-Whitney U Test, $p < 0.001$) (Fig. 3C, D).

For sediment conditions, average oxidation-reduction potential (ORP) values ranged from -294.33 to 132.83. One-way ANOVA indicated no significant differences in ORP values between gate operations ($p = 0.123$) (Fig. 3E). Sediment pH ranged from 7.00 to 8.44, and no significant differences were detected between gate operations ($p = 0.387$) (Fig. 3F).

Benthic Invertebrates

A total of 31 species from 23 families were recorded: 20 species of Mollusca, 15 species of Crustacea, and 10 families of Polychaeta. *Pirenella microptera*, *Batillaria zonalis*, and *Pirenella pupiformis* were the dominant species among Mollusca. *Penaeus chinensis* and *Palaemon orientis* were the dominant species among Crustacea, while Nereididae was the dominant family among Polychaeta. Generalized additive models (GAMs) revealed no significant effect of water exchange operations on the abundance of mollusks ($p = 0.681$) (Fig. 4A) or crustaceans ($p = 0.636$) (Fig. 4B). However, water exchange had a significant effect on polychaete abundance ($p = 0.021$), with higher abundance observed in the twice-per-month water exchange mode compared to the once-per-month mode (Fig. 4C). The Shannon diversity index ranged from 0.414 to 2.315, and Pielou's evenness index ranged from 0.257 to 1.0. No significant effects of water exchange were detected on either the Shannon diversity index ($p = 0.451$) (Fig. 5A) or Pielou's evenness index ($p = 0.754$) (Fig. 5B).

Community analysis identified two distinct benthic community groups using the similarity profile test (SIMPROF) (Fig. 6), confirmed by ANOSIM ($R = 0.049$, $p = 0.091$). One group comprised only C4-1, while all other samples formed the second group. Pearson's correlations showed that Thiaridae was positively correlated with BOD ($r = 0.410$), phosphate ($r = 0.322$), and Chl-a ($r = 0.439$), and negatively correlated with salinity ($r = -0.335$). Veneridae ($r = 0.362$) and Nassariidae ($r = 0.377$) were positively correlated with ORP, while Penaeidae abundance was associated with higher temperatures ($r = 0.294$). Varunidae was positively correlated with BOD ($r = 0.587$), nitrite ($r = 0.355$), phosphate ($r = 0.332$), and temperature ($r = 0.309$), but negatively with salinity ($r = 0.487$).

DISCUSSION

Effects of Gate Operations on Environmental Factors

Most in-situ water quality parameters varied with seasons and weather conditions, such as wind and water flow. Nutrient and organic matter concentrations were compared across different gate operation modes during both dry and wet seasons. During the dry season, dissolved inorganic nitrogen (DIN) and phosphate concentrations decreased by 81% and 64%, respectively, after once-per-month water exchange operations. In the wet season, phosphate concentrations decreased by 78% after twice-per-month exchanges, though DIN concentrations did not significantly change. The relatively small difference in the amount of water exchanged between the once- and twice-per-month modes may explain the smaller dilution effect. Concentrations of BOD and COD decreased by 13% to 50% across different gate operation modes. High concentrations of nutrients and organic matter can deteriorate water quality (El-Adawy *et al.*, 2013), indicating that water exchange operations effectively dilute these pollutants, though the extent of the effects depends on the amount of water exchanged.

No significant differences in sediment ORP or pH were detected, suggesting that water exchange operations had limited effects on sediment condition. It is possible that the positive effects on sediment conditions are more pronounced immediately after the water exchange but diminish over time, thus no significant effects can be observed. However, sediment conditions showed some improvement after water exchange operations began. While ORP values were negative across all sites before the first water exchange, some sites displayed positive values after the first operation. These results suggest that water exchange operations may increase sediment oxidation, though the effects did not reach statistical significance.

Effects of Gate Operations on Benthic Invertebrates

Water exchange operations significantly increased polychaete abundance when conducted twice per month but had no significant effect on mollusks or crustaceans. No differences in Shannon diversity or Pielou's evenness indices were observed across gate operation modes, and community analysis suggested similar species composition between the different operations. These results indicate that the benthic community was relatively stable during the study period, with no strong response to

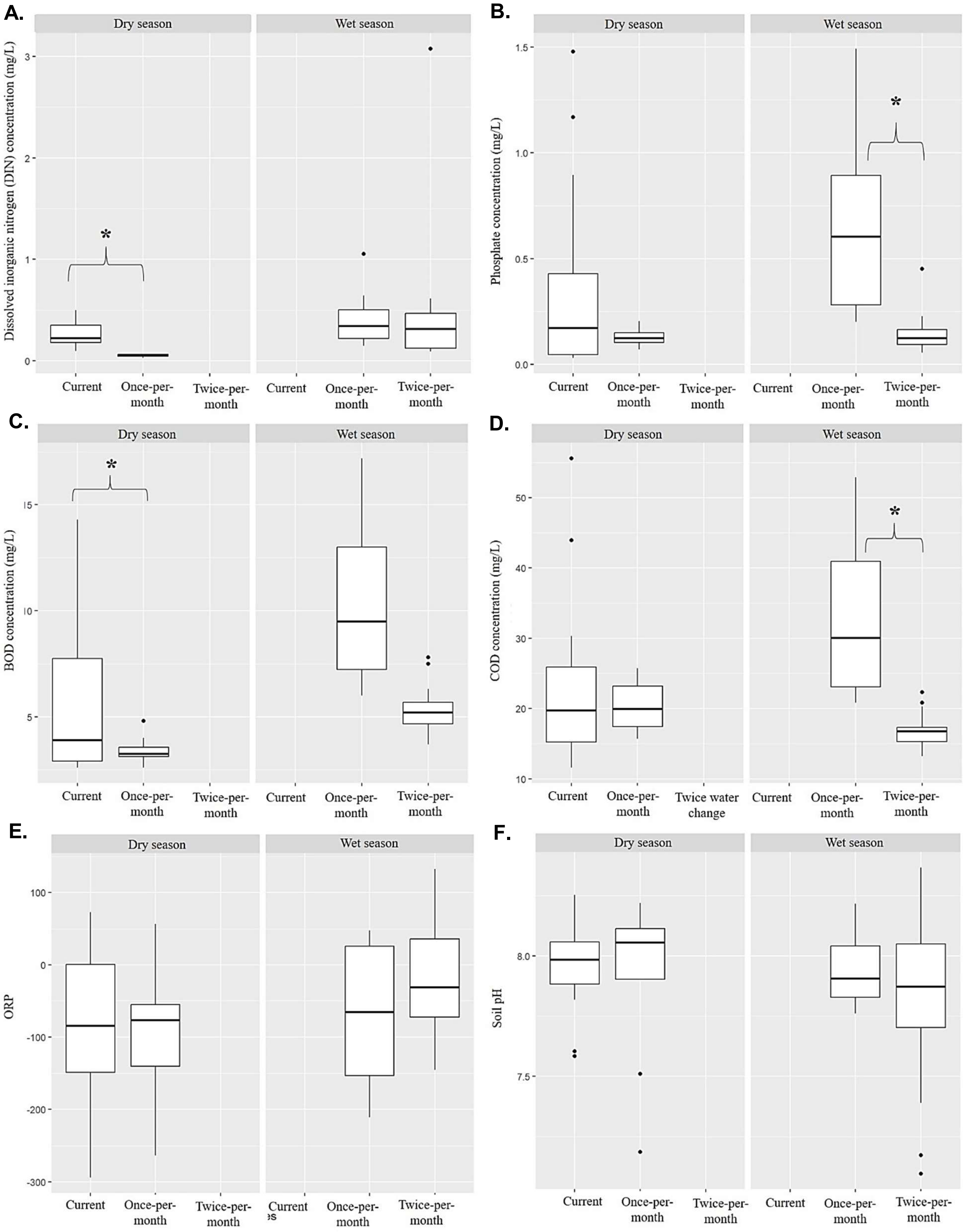

Fig. 3. Comparison of sediment conditions between gate operations during dry and wet seasons. **A.** Dissolved Inorganic Nitrogen (DIN); **B.** Phosphate; **C.** Biochemical Oxygen Demand (BOD); **D.** Chemical Oxygen Demand (COD); **E.** Oxidation-Reduction Potential (ORP); **F.** Soil pH.

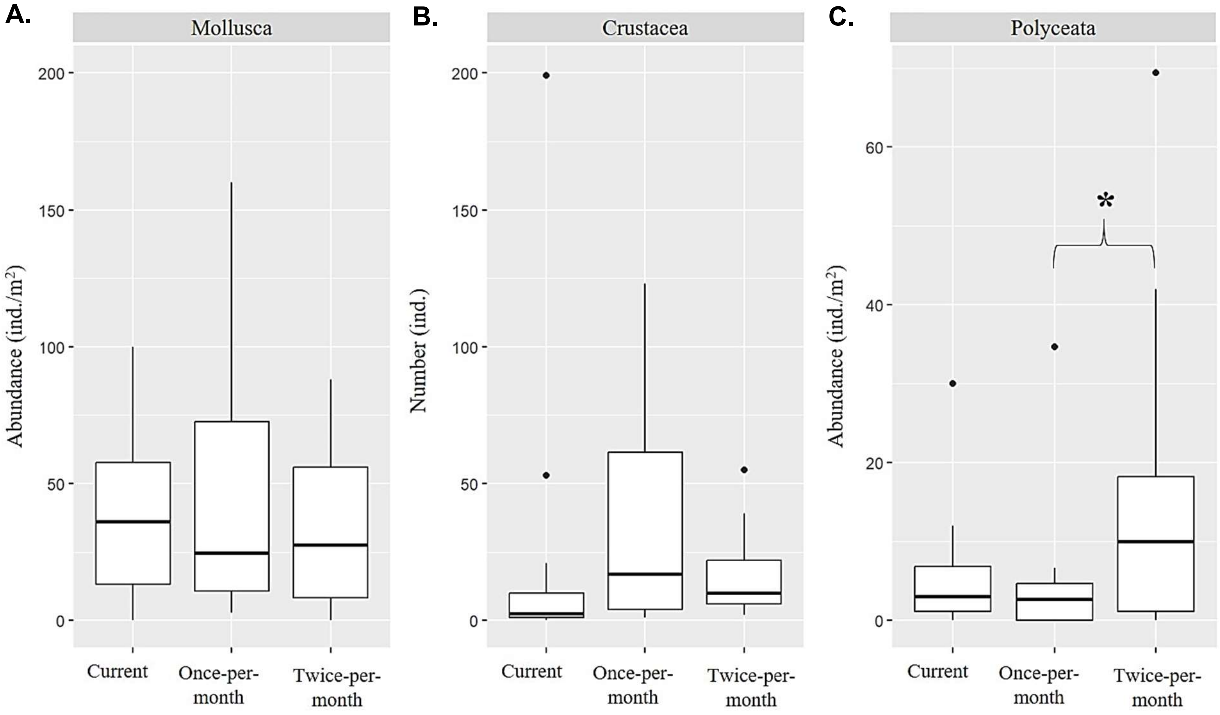

Fig. 4. Comparison of benthic fauna abundance between gate operations. **A.** Mollusca; **B.** Crustacea; C. Polychaeta. * indicates a significant difference between groups.

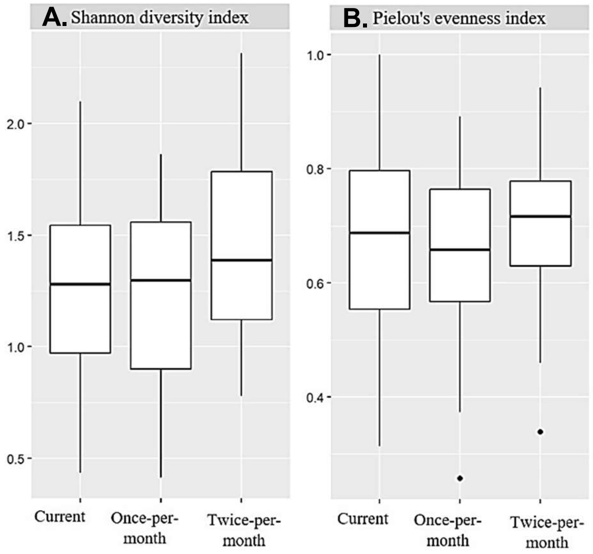

Fig. 5. Comparison of diversity indices between gate operations. **A.** Shannon diversity index; **B.** Pielou's evenness index.

water exchange operations, possibly due to the short duration of the experiment. Previous studies have shown that gastropods like *Batillaria cumingii* and *Cerithideopsilla cingulata* increased in abundance six months after water exchanges, while bivalves such as *Musculus senhousia* and *Ruditapes philippinarum* required more than 12 months to show a response (Matusda and Kokubu, 2016). In contrast, polychaetes like *Hediste* sp. responded within three months. This study only addresses short-term effects due to the one-year study period, but longer-term studies of at least one year are needed to capture more comprehensive patterns. Environmental factors influence the distribution of aquatic organisms (Protasov *et al*., 2019). For example, Thiaridae were more abundant in areas with lower salinity and higher concentrations of Chl-a, phosphate, and organic matter. In contrast, Batillariidae showed no significant patterns with environmental factors, indicating their ubiquitous distribution. It is worth noting that Veneridae and Nassariidae tended to increase in abundance with higher ORP values, suggesting that improved sediment conditions may enhance the abundance of these species.

Other strategies can also be applied. On the mainland of Taiwan, similar cases can be found in Dapeng Bay and Qigu Lagoon. In Dapeng Bay, the principles of System Dynamics (SD) were applied to assess the impacts of tourism development on water quality and the environment (Chuang, 2010). Using numerical models, multiple scenarios were simulated to predict and estimate long-term effects. In Qigu Lagoon, habitat management strategies included the partial removal of mangroves on the mudflat, the construction of a tide pool, and the creation of several artificial tide ditches to enhance seawater exchange (Chiu *et al*., 2021). Therefore, we recommend that, in addition to sluice gate operations, theoretical models and habitat management strategies should also be considered to assist decision-makers in selecting the most appropriate management approaches for Cih Lake.

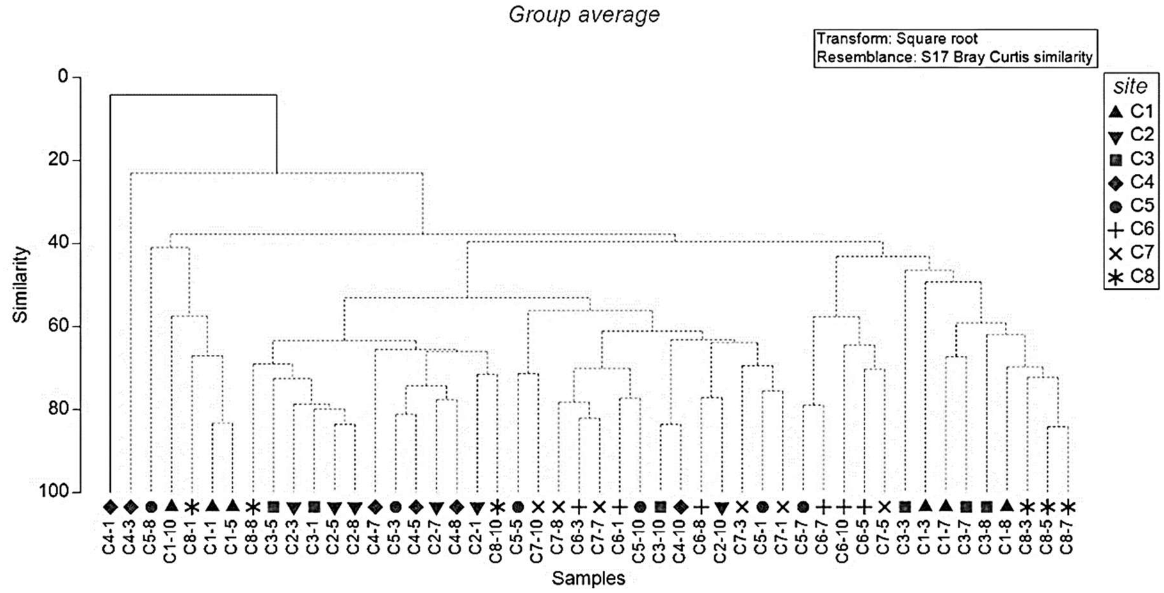

Fig. 6. Cluster analysis plot of the benthic community.

CONCLUSION

This study highlights the critical role of sluice gate operations in managing water quality and supporting benthic communities in Cih Lake. The findings indicate that regular seawater exchange significantly reduces nutrient concentrations and improves the abundance of polychaetes, while having a limited effect on mollusks and crustaceans. Although sediment conditions showed no significant changes in oxidation-reduction potential (ORP) or pH, the potential for improved sediment quality was observed after water exchange operations. Given the results, it is recommended that seawater exchange operations be conducted at least once per month to enhance water quality and promote the stability of benthic fauna in Cih Lake. Future studies should focus on longer-term monitoring to capture the broader ecological impacts of sluice gate management and to optimize operational procedures further.

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