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Temporal Variability of Velocity Structure According to Artificial Discharge in Yeoungsan Lake

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ABSTRACT

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An estuary dyke makes a closed environment in an artificial lake such as Yeoungsan Lake, thereby restricting material circulation. Because the artificial discharge serves as an external force with dominant effects on the internal material circulation of the lake, the effects of this discharge need to be investigated. This study analyzed the water temperature and velocity data for Yeoungsan Lake to identify the change in water temperature due to the discharge and the mechanism of the two-layer velocity structure found after the discharge. During the discharge, the downstream velocity and water temperature of the bottom layer of Yeoungsan Lake rapidly increased. After the discharge, a two-layer velocity structure repeatedly appeared, with flows in the downstream direction at the surface layer and upstream direction at the bottom layer. The water temperature, which rapidly increased at the bottom layer during the discharge, rapidly decreased after the water was completely discharged. Consequently, the water temperature after the discharge remained higher than that before the discharge. The inflow of water mass from the upstream area during the discharge led to a spatial density difference and generated the two-layer velocity structure after the discharge. The vertical mixing due to this two-layer velocity structure after the discharge increased the water temperature at the bottom layer and decreased stratification.

ADDITIONAL INDEX WORDS: *Thermal stratification, Yeoungsan Lake, artificial discharge, velocity structure.*

INTRODUCTION

Estuary dykes have been constructed in the downstream areas of Korean rivers such as Yeoungsan River, Geum River, and Nakdong River (but not the Han River) for measurement and irrigation. Artificial lakes have been established downstream of these rivers as a result of these estuary dykes, and fresh water is intermittently discharged according to the operation of the estuary dyke. A natural estuary is typically a transitional area connecting the land and sea, and an environmental change in the estuary zone significantly affects the adjacent estuaries. Because a constructed estuary dyke physically blocks the connection between a river and sea, it limits the fresh water flowing into the sea and prevents tidal wave propagation in the river's upstream direction. Therefore, the artificial discharges produced by the operation of estuary dykes lead to rapid changes in the environments of estuary zones and lakes (Jang and Kim, 2006).

Environmental problems such as a hypoxic layer and algal blooming occurred during the summer in Yeoungsan Lake after the construction of the estuary dyke. However, despite the significance of these issues, very few studies on Yeoungsan Lake have been carried out. The decreased water quality of Yeoungsan Lake is the main problem caused by the construction of the estuary dyke, and studies have focused on biochemical of the estuary dyke, and studies have focused on biochemical factors to identify the status of water pollution. When the water temperature at the surface layer of a closed water environment system such as Yeoungsan Lake increases during the summer, a thermocline layer is generated. This layer blocks most of the vertical material exchange and accordingly forms a hypoxic bottom layer (Ford, Boon, and Lee, 2002; Park, Park, and Shin, 2006). The dissolved oxygen concentration of Yeoungsan Lake is inversely proportional to the water temperature because of the changes in the amount of saturated dissolved oxygen with changes in the water temperature (Park, Cho, and Cho, 2008).

The hypoxic layer is formed downstream of Yeoungsan River during the summer, and the density stratification generated by both the water temperature and salinity also establishes this layer near the estuary dyke (Lee *et al*., 2009). The fresh water flowing from upstream into the inner lake has different properties than that of the existing water in the lake, and the circulation structure of the inner lake changes seasonally because of the difference in density (Carmack *et al*., 1979).

The hypoxic layer problem has frequently been reported for Yeoungsan Lake. However, although biogeochemical studies have been conducted as previously indicated, the effects of the physical, external force have not been sufficiently examined.

The physical mixing caused by the wind, tide, and thermal exchange exerts dominant effects on the distribution of the dissolved oxygen in water layers (Hull, Parrella, and Falcucci, 2008). Moreover, because Yeoungsan River is unlikely to be affected by the tides because of the constructed estuary dyke, the

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effects of the discharge and wind are expected to be significant. Thus, studies on the velocity structure changes produced by the discharge and wind should be performed to identify the mechanisms for the algal blooming and hypoxic layer generation. This study used velocity and water temperature data measured at each water layer over time to identify the changes in the velocity structure produced by the discharge and wind in the inner Yeoungsan Lake, as well as to understand the effects of the discharge on the vertical mixing and stratification.

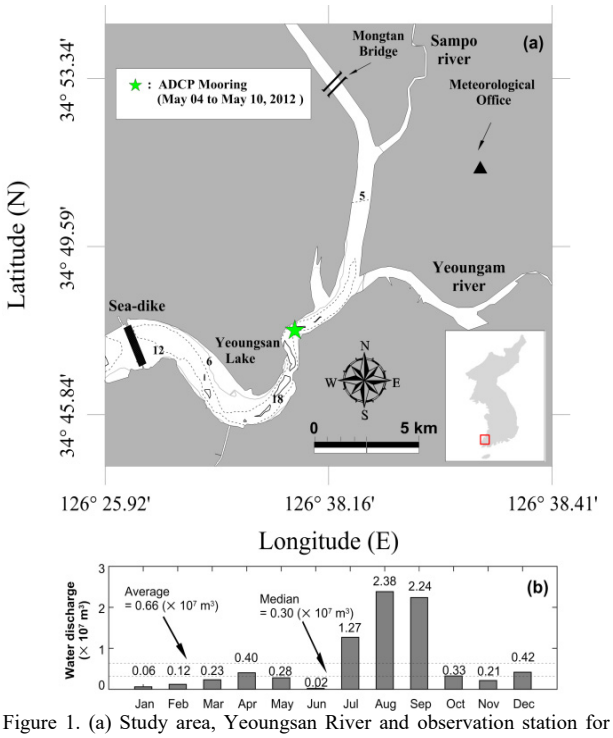


Figure 1. (a) Study area, Yeoungsan River and observation station for velocity (★ : 34°48'3.00" N, 126°31'25.20" E) and for wind (▲: 34°48'57.78" N, 126°27'46.56" E) at SJA. Gray dashed and black lines indicate 6, 12, and 18 m isobaths, respectively. (b) Monthly-mean freshwater discharge from Yeoungsan dyke.

METHODS

The flow velocity was simultaneously observed at fixed points to identify changes in the temperature and velocity of the water. The flow velocity observations were performed using an acoustic Doppler current profiler (ADCP) on the surface layer at a point on Yeoungsan Lake located approximately 10 km away from the estuary dyke of Yeoungsan River in the upstream direction from May 4th to 10th, 2012 (point ★ , see Figure 1a). The ADCP was fixed at a point 0.2 m below the water surface, and data on the flow velocity and direction by water layer were obtained at 10 min intervals.

Pre-processing was performed on the raw data extracted from the ADCP to increase the accuracy and reliability of the data. This pre-processing included (1) removing any abnormal data in the boundary between the surface and bottom layers, (2) eliminating data with acceptability values of less than 80 percent good value, (3) and performing a linear transformation process based on the true north coordinate system to correct for the difference between magnetic north and true north by 7° in this area.

The waterway in the area of the observation point had a width of approximately 370 m and showed narrow and straight topographic characteristics, as well as a significant flow velocity in the direction of the main waterway. In this regard, the components in the east–west and south–north directions were linearly transformed into those for a new coordinate system based on the direction of the main waterway and transverse direction by conducting a principal axis component. The linearly transformed data for the flow velocity in the direction of the main waterway were used to analyze the measured data (Preisendorfer and Mobley, 1988). To determine the flow velocity and identify the change in water temperature produced by the discharge at the bottom layer, the water temperature was simultaneously measured by installing the Conductivity-Temperature-Depth (CTD) 1 m from the bottom. In addition, the data for the discharge at the estuary dyke during the observation period (Korea Rural Community Corporation) were obtained and analyzed to examine the effects of the discharge. Sijong automatic weather station (SJA) data were used to analyze changes in the flow by the wind at Yeoungsan Lake.

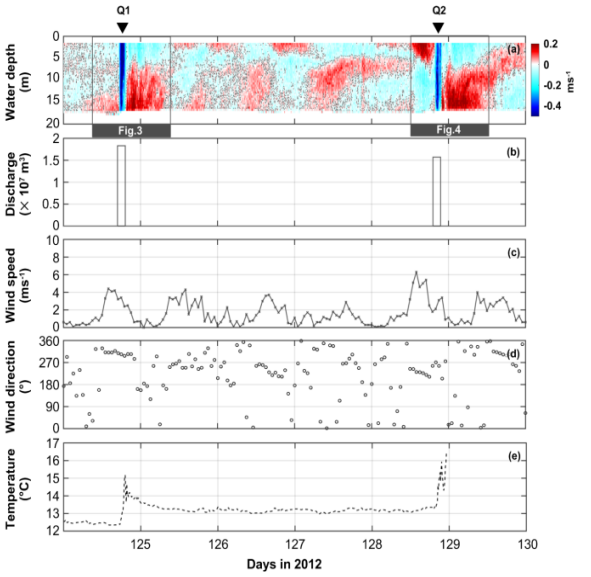


Figure 2. (a) Along channel velocity from ADCP, (b) freshwater discharge rate from the Korea Rural Community Corporation, (c) wind speed by SJA, (d) wind direction, and (e) bottom water temperature. Dashed lines indicate 0 m/s velocity. Red color represents upstream direction and blue color represents downstream direction. Q1 and Q2 (▼) indicate freshwater discharge event, respectively.

RESULTS

Flow Velocity and Discharge by Water Layer

The variation in the flow velocity in Yeoungsan Lake was clearly affected by the discharge (Figure 2a). Discharges occurred twice (Q1, Q2) during the observation period, with amounts of 1.83×10^7 m^3 and 1.57×10^7 m^3, respectively. The discharge period was defined as beginning when the floodgate of the estuary dyke was opened and ending when it was completely closed. Each discharge lasted approximately 2.4 h. During each discharge, the flow velocity in the downstream direction occurred approximately 30 min after opening the floodgate. The maximum velocity was 0.6 m/s during the Q1 discharge and 0.62 m/s during the Q2 discharge. The flow velocity in the downstream direction was observed for all of the water layers at the beginning of the discharge, and a two-layer velocity structure repeatedly appeared immediately after the discharge. Typically, the flow velocity in the downstream direction occurred at the surface layer, with that in the upstream direction found at the bottom layer, both of which lasted for approximately 12 h.

Direction and Speed of Wind

The SJA wind data were analyzed to examine the effects of wind, which is an external force that significantly affects lakes (Figure 2c,d). The analysis results indicated that a wind of approximately 4 m/s was repeatedly generated at an interval of one day. When a strong wind of 4 m/s blew, the velocity at the surface layer clearly changed, and the two-layer velocity structure was formed by the wind.

Change in Water Temperature at the Bottom Layer

The water temperature at the bottom layer was clearly changed by the discharge (Figure 2e). The water temperature at the bottom layer was constant at approximately 12.5℃ before the discharge, but rapidly increased during the discharge to approximately 15℃ at the beginning of the Q1 discharge and then gradually decreased to approximately 13℃ after the end of the discharge. It rapidly increased to approximately 16.5 ℃ during the second discharge (Q2). Further data were not obtained because of the insufficient battery capacity of the measurement equipment used.

DISCUSSION

Change in Velocity Structure by Water Discharge

Similar velocity structures were repeatedly found during and after discharges at the estuary lake of the Yeoungsan River. The flow velocity in the downstream direction was generated at the observation point 10 km away from the estuary dyke 30 min after the discharge began. This flow velocity in the downstream direction occurred at all of the water layers and was maintained during the discharge. A change in the velocity structure was clearly found during the discharge. To verify the vertical mixing by the discharge, a vertical velocity shear value was calculated using the flow velocity data, which were obtained at a water depth 2 m from the surface and bottom layers, as shown diagrammatically in Figures 3b and 4b. The flow velocity in the same direction occurred from the surface layer to the bottom layer at the beginning of the discharge.

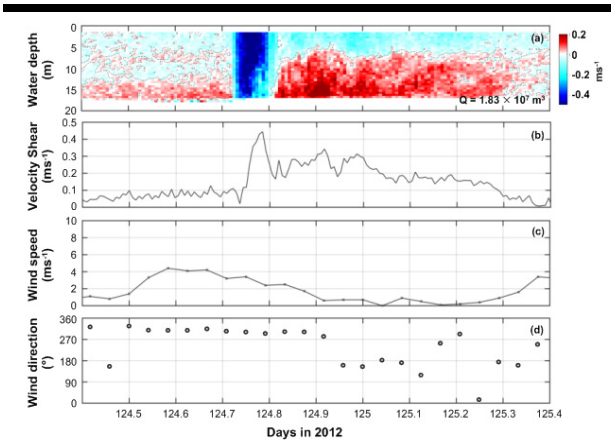


Figure 3. (a) Along-channel velocity during freshwater discharge conditions, (b) surface-bottom velocity shear, (c) wind speed, and (d) wind direction for Q1 discharge event.

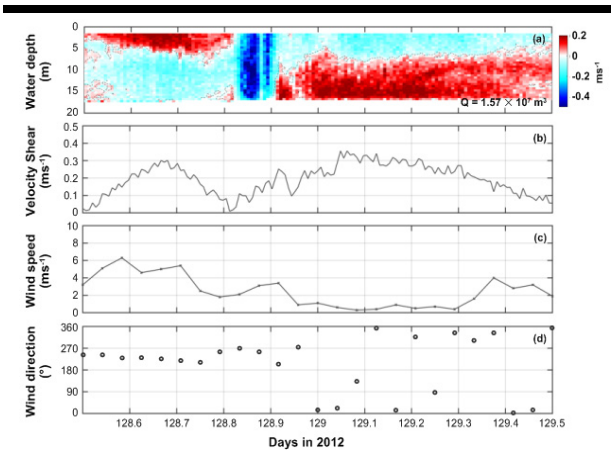


Figure 4. Same information as Figure 3, but for Q2 discharge event.

Because the velocity difference between the surface and bottom layers was insignificant, the vertical velocity shear value was also low. As the discharge proceeded, the velocity at the bottom layer rapidly decreased, and the vertical velocity shear value increased to 0.45 m/s (Figure 3b; Q1). After the end of the discharge, the flow velocity in the downstream direction sharply decreased, and a flow velocity in the upstream direction occurred at the bottom layer. Because flow velocities in opposite directions were generated at the surface and bottom layers, the vertical velocity shear value was maintained at 0.2 m/s or greater. Subsequently, the vertical velocity shear value gradually decreased as the flow velocity in the upstream direction at the bottom layer continued to decrease.

The difference of velocity shear pattern by Q1 and Q2 suggested that the velocity structures varied as a result of the effects of wind despite the fact that the discharges had similar scales. The two discharges, 1.83×10^7 m^3 and 1.57×10^7 m^3

as noted above, differed only insignificantly. The time durations of the Q1 and Q2 discharges were similar, at 2 h and 25 min and 2 h and 22 min, respectively. Although Q1 discharge was greater than Q2 discharge by approximately 0.26×10^7 m^3, the maximum flow velocity of Q2 (0.62 m/s) was higher than that of Q1 (0.6 m/s). This anomaly was attributed to the effects of strong southwest wind.

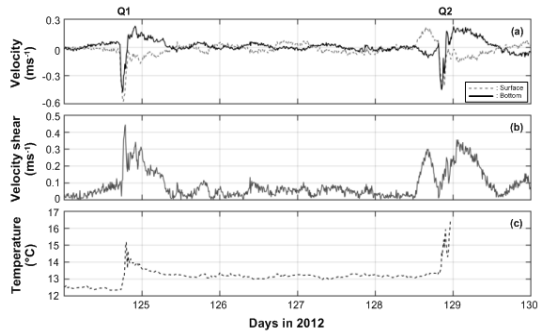


Figure 5. (a) Surface and bottom velocity, (b) the absolute value of vertical velocity shear time series, (c) bottom water temperature. Surface and bottom velocities are averages over surface and bottom layers, respectively, of 2 m thickness.

The SJA data for the wind magnitude and direction are presented diagrammatically to examine the variation in the flow velocity produced by the discharge and wind (Figure 4c,d). Before the discharge began, a strong southwest wind with a velocity of 4 m/s or greater blew. The flow velocity in the upstream direction was clearly observed at a water depth of 0–5 m from the surface layer (Figure 4a).

As previously indicated, this study verified that a strong wind and discharge exerted dominant effects on the velocity structure in Yeoungsan Lake, and that they also affected the velocity shear. Because the variation of the velocity shear was expected to produce a change in the water temperature at the bottom layer, it was comparatively analyzed, along with the water temperature data for the bottom layer.

Changes in Velocity Shear and Water Temperature at Bottom Layer Produced by Discharge

To identify the change in the water temperature at the bottom layer produced by the variation of the velocity shear, a comparative analysis was performed on the data for the flow velocity, vertical velocity shear, and water temperature at the bottom layer (Figure 5). The flow velocities at the surface and bottom layers tended to have opposite directions, except when the discharges were performed (Figure 5a). During no discharge, the vertical velocity shear was calculated to be 0.1 m/s or less, whereas it increased to 0.4 m/s during the discharges (Figure 5b). In addition, the water temperature at the bottom layer rapidly changed during the discharges. The water temperature at the bottom layer was maintained at approximately 12.5℃ before the Q1 discharge, but sharply increased to approximately 15℃ during the discharge, and then gradually decreased and was maintained at approximately 13℃ until the beginning of the Q2 discharge. This result verified that the water temperature after the discharge increased by nearly 0.5 ℃ compared to that before the discharge. The bottom temperature showed a pattern similar to that of the vertical velocity shear, which was attributed to active mixing by the vertical difference in velocity.

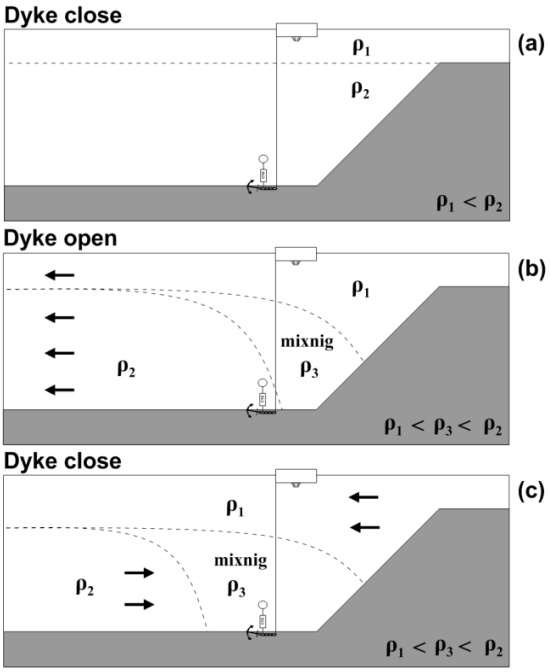


Figure 6. Schematic of two layer velocity structure induced by freshwater discharge in Yeoungsan Lake. (a) Before discharge, (b) during discharge, (c) after discharge. The parameter ρ indicates the water density.

Before the Q2 discharge, the two-layer velocity structure produced by the wind increased the velocity shear. The magnitude of the velocity shear before the Q2 discharge was similar to that during the discharge. It was expected that vertical mixing by the flow velocity difference would increase the water temperature at the bottom layer, whereas the two-layer velocity structure induced by the wind did not increase the water temperature at the bottom layer. During the Q2 discharge, the vertical velocity shear was calculated to be 0.3 m/s or less, whereas the bottom temperature rapidly increased to approximately 16.5℃. The magnitude of the velocity shear produced by the wind was similar to that produced by the discharge. But the water temperature variations at the bottom layer produced by the wind and discharge were different, which as attributed to the effects of vertical mixing due to the discharge, as well as advection.

It was estimated that the flow velocity in the downstream direction at all of the layers would move the entire water mass of

Yeoungsan Lake in the downstream direction, and that the water mass at the upstream area would flow into the area of the observation point. The inflow of surface water produced by the discharge was considered to have mixed the water masses at the middle and bottom layers, and to have increased their water temperature. In addition, as the discharge proceeded, fresh water flowing from the upstream area might have filled the observation area, and the water temperature at the bottom layer might have increased as a result of the advection.

Change in Water Circulation of Yeoungsan Lake Produced by Discharge

Therefore, it was found that the two-layer velocity structure was formed after the discharge as a result of the horizontal difference in the densities of the middle and bottom layers. Moreover, the water temperature at the bottom layer changed as a result of the vertical mixing and advection produced by the discharge, which subsequently led to the horizontal difference in density. The formation process for the two-layer velocity structure produced by the discharge can be described as follows:

(1) The thermal stratification in Yeoungsan Lake is maintained in the absence of a discharge (Figure 6a).

(2) As the discharge begins, the flow velocity in the downstream direction at all of the water layers leads to the advection of fresh water in the upstream area in the downstream direction (Figure 6b).

(3) As the discharge proceeds, the existing water mass is pushed in the downstream direction, water with a high temperature at the upstream area fills the middle-upstream area, and mixing simultaneously occurs (Figure 6b).

(4) After the discharge is finished, a water mass with a low temperature and high density is located at the middle and bottom layers in the downstream area. On the other hand, a water mass with a high temperature and low density is formed in the upstream area, which generates a horizontal difference in density. This spatial difference in density leads to the formation of a two-layer velocity structure (Figure 6c).

CONCLUSIONS

To understand the changes in water quality condition produced by two discharges at Yeoungsan Lake, we analyzed the two-layer velocity structure using velocity and bottom temperature observations. The velocity structure of Yeoungsan Lake and changes in the bottom temperature were analyzed by focusing on the effects of the discharges and wind, and the following conclusions were derived:

(1) The velocity structure was significantly affected by the artificial discharge in Yeoungsan Lake. The flow velocity in the downstream direction occurs at all of the water layers at the beginning of a discharge, and a two-layer velocity structure is repeatedly found after the discharge. The vertical velocity shear value rapidly increases during and after a discharge, and the water temperature at the bottom layer increases because of vertical mixing. A strong wind affects the surface flow velocity, as well as the velocity structure and maximum flow velocity during a discharge.

(2) It is considered that the bottom water temperature increases as a result of the vertical mixing produced by a discharge and advection. The vertical velocity shear produced by the wind showed a magnitude similar to that of a discharge, whereas the water temperature at the bottom layer did not increase. A rapid increase in the water temperature at the bottom layer cannot be described based solely on the vertical mixing, but the inflow of surface water by advection seems to simultaneously induce such an increase.

(3) A two-layer velocity structure appeared to be formed after a discharge as a result of a horizontal density difference produced by the discharge. The entire water mass of Yeoungsan Lake moves in the downstream direction at the beginning of a discharge, and a water mass of low density flows into the upstream area. It was also found that a water mass of low density produced by a discharge generates a spatial density difference at the middle and bottom layers and develops the two-layer velocity structure.

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