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ORIGINAL ARTICLE

Seasonal Variations of Water Temperature and Salinity in the Vicinity of the Nakdong River Estuary

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Abstract

We described the time-series and seasonal variations in water temperature and salinity in the Nakdong River estuary from 2016 to 2022 using field observations. In addition, we also utilized precipitation, air temperature and freshwater discharge data from the Korea Meteorological Administration's open meteorological data portal and MyWater from the Korea Water Resources Corporation. The relationship between freshwater discharge, precipitation, and salinity at the observation stations near the floodgates showed a stronger correlation in the Nakdong River mainstream compared to the Seonakdong River. Salinity concentrations near the western floodgates of the mainstream showed a strong correlation with freshwater discharge, indicating that salinity decreased as freshwater discharge increased, unlike the pattern observed at the other floodgates. Seasonal variations in the Nakdong estuary had a substantially impacted both water temperature and salinity. During the spring and summer flood seasons, water temperatures increased, while the increase in freshwater discharge from floodgate openings reduced salinity concentrations. However, during the autumn and winter dry seasons, water temperatures decreased, and the reduction in freshwater discharge, along with the inflow of high-salinity water from the open sea, led to relatively higher salinity concentrations. The salinity concentrations near the floodgates of the Nakdong River mainstream were lower compared to those in the Seonakdong River, where stagnant water was caused by the closed floodgates. The eastern region of the Nakdong River mainstream showed relatively higher salinity concentrations than the western region due to the influence of high-salinity water inflowing from the open sea as a result of the regular floodgate openings. The spatial distribution of salinity showed low concentrations near the floodgates and around sandbars during the flood season, while high salinity concentrations were observed in coastal areas. In particular, a strong haline front formed near the sandbar during this period, although its structure weakened in the autumn and winter.

Key words : Nakdong estuary, Seasonal variation, Temperature, Salinity, Freshwater discharge

1. Introduction

The Nakdong River, which has a well-formed delta and sandbars, has a unique hydrological feature in Korea. This River is divided into the Seonakdong River and the mainstream of the Nakdong River as it passes through Daedong floodgate near Mulgeum-eup, Yangsan-si. Within the mainstream, the river divided into eastern and western branches around Eulsukdo Island, where it interfaces with coastal seawater. This river has a flow path extension and a watershed area of 521.5 km and 23,717 km^2, respectively. This region is a watershed with a high potential for water pollution caused by various pollutants with more than 800 small rivers (Park et al., 2008; Cho, 2011). In particular, this estuary is a representative estuarine regions where freshwater

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and salinity are mixed with each other, and is closely related to the lives of local residents by fishing, supplying agricultural, industrial, and domestic water, and preventing flood damage. The dynamic interactions between freshwater and seawater in this estuarine environment foster diverse ecological habitats, making it a focal point for both ecological studies and resource management.

With the completion of the Nakdong River estuary dyke project in July 1987, the surrounding region's topography and marine environment have undergone significant changes. This large-scale project, intended to control flooding and provide a stable water supply, has led to notable changes in sedimentation patterns, water salinity, and ecological dynamics in the estuarine region. Along with these environmental changes, many studies have been conducted to understand physical oceanography such as water temperature, salinity, and seawater circulation around the Nakdong River estuary (Kim and Ha, 2001; Kim, 2005; Jang and Kim, 2006; Oh et al., 2010; Song et al., 2014; Park et al., 2016; Yoon et al., 2017; Kim and Youn., 2019).

The Nakdong River was largely divided into the mainstream and the Seonakdong River. Within the mainstream, the flow splits into eastern and western branches around Eulsukdo Island, where it interfaces with coastal seawater. In this region, the flow created unique hydrological conditions where the river's freshwater interacted with the coastal seawater. Furthermore, the complex interactions between the river flows and the tidal effects from the sea play an important role in the formation of environmental and ecological characteristics in the estuary. On the other hand, Seonakdong River was originally the mainstream of Nakdong River, but its flow was controlled by the floodgates at Daejeo in the upstream area and Noksan in the downstream area. This place was a stagnant river caused by closed floodgates, which led to severe water pollution due to inadequate management. And the outflow was not significantly different between the flood season and the non-flood season (Kang et al., 2013; Kim and Kim, 2013).

The estuary has a very high economic value such as increasing biodiversity due to the combination of seawater and freshwater environments. Water temperature and salinity play an important role in understanding marine environmental characteristics in these regions (Chen et al., 2000; Lerczak et al., 2006; Fagherazzi et al., 2015; Heo et al., 2016; Sherin et al., 2020; Matsoukis et al., 2023). The Nakdong River estuary is affected by salinity rather than water temperature due to the amount of discharge caused by the supply of freshwater such as rivers. Yoon et al.(2005) suggested that the areas most sensitively affected by freshwater discharge were Jangja-do, Backhap-deung, Dadae, and Jinwoo-do in the mainstream of the Nakdong River. The characteristics of these area were greatly affected by the inflow of fresh water from rivers, tidal waves, topography, and density differences between freshwater and seawater. The artificial discharges of freshwater following the opening of the estuary barrier results in the formation of salinity stratification as the surface freshwater rapidly meets seawater in the form of plume (Chang et al., 1981; Yu et al., 1993; Yanagi, 1994; Kim et al., 1996; Han et al., 2011; Song et al., 2014; Matsoukis et al., 2023). Here, the salt wedge phenomenon occurs in the high salinity water of the bottom on the coast, which penetrates upstream of the estuary. On the other hand, in stagnant rivers like the Seonakdong River, the influence of high-salinity water from the open sea can cause relatively high-salinity water to stagnate and appear in the bottom layers of this region. (Lee and Yoon, 2003; Kim and Kim, 2013; Kang et al., 2013; Song et al., 2014).

Until now, a number of studies have been conducted on the marine environment and numerical models around the Nakdong River estuary (Yu et al., 1993; Kim et al., 1999; Lee and Yoon, 2003; Yoon et al., 2005; Cho, 2011; Woo et al., 2022). However, studies on the spatial distribution of marine environments based on long-term field observations are still lacking. Therefore, in order to understand the changes in the marine environment of the Nakdong River estuary, this study aims to reveal the time-series and seasonal variations of water temperature and salinity in the Nakdong River mainstream, the Seonakdong River, and the brackish waters where rivers and seawater interact.

2. Materials and Methods

In this study, we investigated the time series and seasonal variations of water temperature and salinity in regions such as the freshwater discharge region of the Seonakdong River and the Nakdong River's mainstream, as well as the brackish water zones where freshwater and seawater interact (Fig. 1). For regional classification in the Nakdong River estuary, the area was divided into the inner estuary region (stations T-1 to T-9) and the coastal region (stations T-10 to T-15).

2.1. Freshwater discharge, precipitation, and air temperature data

To investigate the relationship between freshwater discharge and precipitation in the Nakdong River by year, the relationship between the two factors was examined with data from winter (February), spring (May), summer (August), and autumn (November) for 6 years (2018-2023) provided by the MyWater of the Korea Water Resources Corporation. In addition, the relationship between the discharge of freshwater from each floodgate and the amount of precipitation was analyzed using the

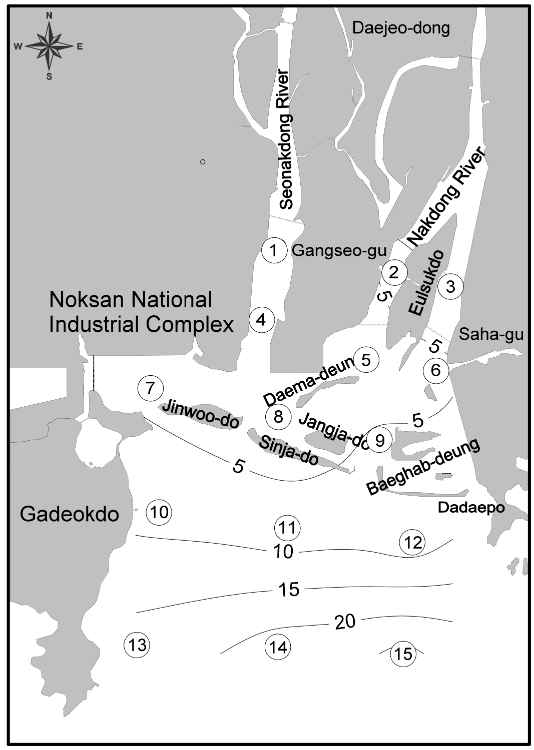

Fig. 1. Study area is the Nakdong River estuary. Observations of water temperature, salinity were conducted at 15 stations. Here, the contour lines represent the average water depth during the period of 8-year (2016-2023).

cumulative amount from 7 days before the survey date to the day.

In order to see the change in freshwater discharge and salinity, the data on the mainstream of the Nakdong River and the Seonakdong River were analyzed as shown in Fig. 1. The data were analyzed in the Seonakdong River at T-1, T-4 stations, the west and east of the mainstream at T-2, T-5 stations and T-3, T-6 stations respectively. Here, the freshwater discharge in the Seonakdong River was mainly controlled by the Noksan floodgate, and in the mainstream of the Nakdong River, it was controlled according to precipitation and water reserve rates in the left and right floodgates. The discharge of the Noksan floodgate in the Seonakdong River was provided by

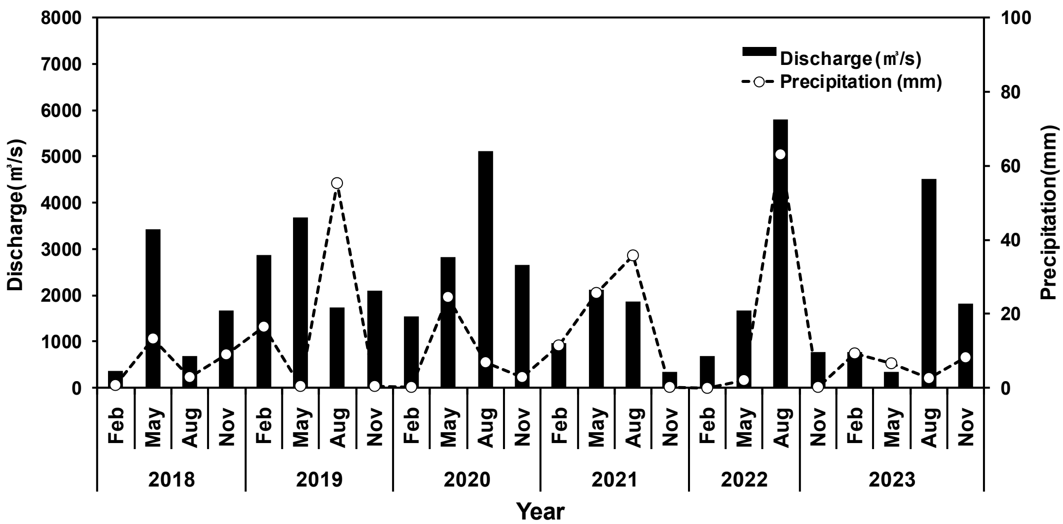

Fig. 2. Relationship between seasonal precipitation (mm) and freshwater discharge (m^3/s) at the Nakdong river during 2018-2023.

Gangseo-gu Office in Busan for 6 years (2018-2023). The amount of freshwater discharged from the left and right drains of the Nakdong River estuary provided by the MyWater of the Korea Water Resources Corporation at the same time as the Seonakdong River was analyzed with the salinity data from the field survey. Salinity concentrations were obtained by averaging data from the floodgate entrance and a nearby station to the south.

The air temperature data, used for analyzing the relationship with water temperature, was provided from the Open MET (METeorological) Data Portal of the Korea Meteorological Administration (KMA). Here, we used seasonal data (February, May, August, November) from the Busan Regional Meteorological Administration for 8 years (2016-2023).

2.3. Water temperature and salinity data

Water temperature and salinity data were collected from field observations conducted by Land & Ocean Environmental Engineering Corporation at 15 observation stations (T-1 to T-15) in the Nakdong River estuary in February, May, August, and November over an 8-year period (2016-2023) (Fig. 1).

The observations were carried out using a CTD (Ocean Seven 304 plus, Brugherio, Italy) provided by IDRONUAT, covering the range from the surface to the bottom. The observation stations were conducted at a total of 15 stations at 6 stations (T-1 to T-6) near the floodgates and river mouth, 3 stations (T-7 to T-9) in the sandbar region near Daema-deung, Jangja-do, and Baekhap-deung; 6 stations (T-10 to T-15) in the outer coastal region. The spatial distribution of water temperature and salinity was analyzed for the horizontal distribution at both the surface and bottom layers. In particular, the salinity and density data for August 2018 were excluded from the average values calculation in the time series analysis due to missing data. In addition, the impact of water temperature and salinity on density was analyzed to determine which factors were seasonally dominant over the 8-year period (2016-2023).

3. Results and Discussion

3.1. Relationship between precipitation and freshwater discharge

In this study, we analyzed the seasonal variations in precipitation and freshwater discharge near the floodgates of the Nakdong River from 2018 to 2023. Monthly cumulative data were examined for winter (February), spring (May), summer (August), and autumn (November). The results indicate that higher precipitation in spring and summer corresponds to increased freshwater discharge, while both precipitation and discharge are lower in winter and autumn (Fig. 2). Here, the correlation coefficient between freshwater discharge and precipitation was found to be about 0.4, indicating a low correlation between the two variables.

In this analysis, the relationship between freshwater discharge and precipitation, considering the influence of the floodgates, was examined using cumulative data from 7 days prior to the observation date up to the observation date. The analysis examined these relationships by distinguishing between the Noksan floodgate of the Seonakdong River and the western and eastern floodgates of the Nakdong River's mainstream (Fig. 3).

The correlation coefficients between freshwater discharge and precipitation for each floodgate were -0.08 for the Noksan floodgate in the Seonakdong River and 0.48, 0.46 for the floodgates on the western and eastern sides of the Nakdong River mainstream, respectively. In particular, it was found that there was almost no relationship between the two factors in the Noksan floodgate of the Seonakdong River. One of the reasons is that this area is a stagnant -controlled river where no national water level observatory is operated, making flow and water quality management difficult (SRRIC, 2005; Kang et al., 2013). Although the overall correlation was still weak, the correlation between the two factors was higher in the Nakdong River mainstream than in the Seonakdong River. The freshwater discharge in the mainstream was higher at the eastern floodgate compared to the western one, and this increase was also observed in August when precipitation was higher. However, in years when the correlation between the two factors was weak in this region, the eastern part of the mainstream recorded low precipitation amounts of about 7.0 mm in August 2020 and 2.6 mm in August 2023, while the discharge volume was high, at 3,676 m^3/s and 2,824 m^3/s, respectively. Therefore, it is thought that the seawater flow of the Nakdong River estuary was more influenced by the river plume resulting from the opening of the floodgates than by precipitation (Kim et al., 1999; Yoon et al., 2005; Ryu et al., 2011). The behavior of this runoff water was highly dependent on freshwater discharge from floodgate operations and influenced the seawater flow around estuaries in proportion to the discharge, regardless of the tide (Jang and Kim, 2006).

3.2. Relationship between freshwater discharge and salinity

The relationship between freshwater discharge and salinity was analyzed using data from the Noksan floodgate in the Seonakdong River and the floodgates on the west and east sides of the Nakdong River mainstream over six years (2018-2023). The salinity data were collected during field observations conducted simultaneously with the freshwater discharges (Fig. 4). In the correlation between freshwater discharge and salinity, the Seanakdong River showed a very weak negative correlation with a coefficient of -0.03. In contrast, the mainstream of the Nakdong River showed relatively stronger negative correlations, with coefficients of -0.75 and -0.69 in the west and east, respectively.

The relationship between the two factors

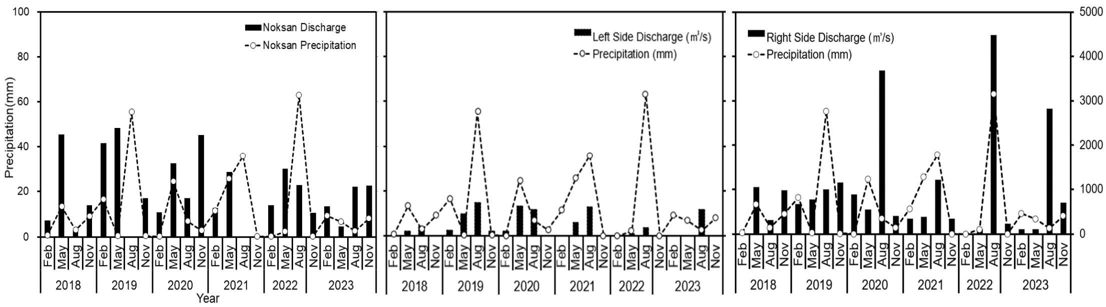

Fig. 3. Relationship between seasonal precipitation (mm) and freshwater discharge (m^3/s) near the Noksan floodgate of the Seonakdong River, and the left and right floodgates of the Nakdong river mainstream during 2018-2023.

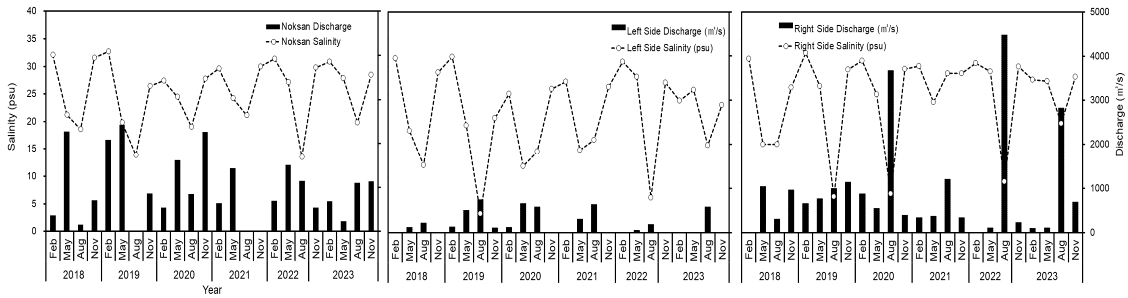

Fig. 4. Relationship between seasonal salinity (psu) and freshwater discharge (m^3/s) near the Noksan sluice of the Seonakdong river, and the left and right sluices of the Nakdong river mainstream during 2018-2023.

indicated that salinity tended to decrease as freshwater discharge increased, and vice versa. This correlation was stronger than that between freshwater discharge and precipitation, as previously described. In the case of the Seonakdong River, periods of high discharge from the Noksan floodgate, such as in May of 2018 and 2019, were associated with low salinity. However, during other times, the relationship between variations in discharge and salinity was not clear. Although the amount of freshwater discharge and salinity were not highly correlated in the Nakdong River mainstream, salinity tended to be low when discharge increased and high when discharge decreased. For example, freshwater discharged from the mainstream has been shown to have a significant effect on salinity levels. In August of 2020 and 2022, the freshwater discharge volumes at the eastern floodgate were 3,676 m^3/s and 4,476 m^3/s, respectively. During these periods, salinity concentrations noticeably decreased to 7.0 psu and 9.3 psu, respectively.

3.3. Station variations in annual average water temperature and salinity

To examine the annual variations in water temperature and salinity, we analyzed the results of field observations conducted at 15 stations across four seasons (February, May, August, and November) from 2016 to 2023 (Fig. 5).

Annual variations in water temperature by station were broadly categorized into two groups: stations T-1 to T-9, located from the floodgates to the sandbar as shown in Fig. 1, and stations T-10 to T-15, situated adjacent to the coast. The distribution of water temperature ranged from

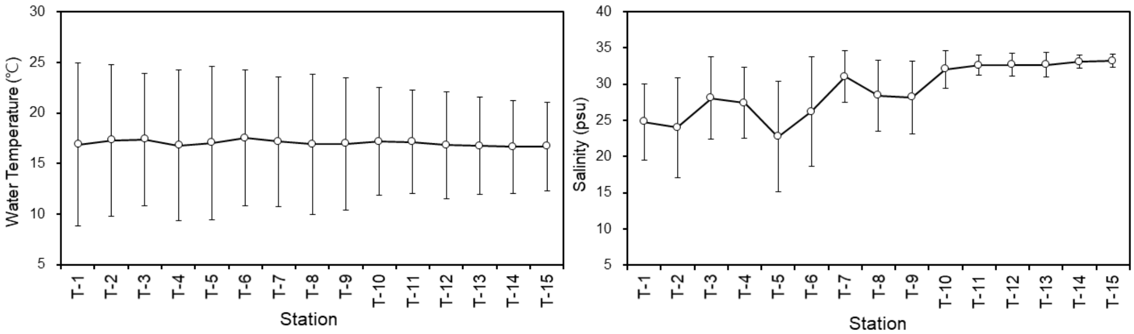

Fig. 5. Annual variation in water temperature (left) and salinity (right) for 15 stations during 2016-2023.

16.6℃ to 17.5℃, with stations T-1 to T-9 showing greater annual variation compared to stations T-10 to T-15. Here, stations T-1 to T-9 showed significant variation due to their shallow water depth and the direct influence of freshwater. The difference in water temperature between summer and winter also contributed to the observed annual variations.

Salinity, ranging from 22.73 psu to 33.23 psu, showed significant variation at stations T-1 to T-9 due to the strong influence of freshwater discharge. Similar to water temperature, salinity was higher in the coastal areas and lower near the floodgates and the sandbar, with significant variation observed in these regions. In particular, the salinity boundary was divided by stations T-9 and T-10, with distinct high and low salinity areas, except at station T-7. The T-7 station, located near the Noksan National Industrial Complex on the Seonakdong River, did not show a large variation in salinity. Although this station was in a region where low salinity was expected, relatively high salinity was observed. Moving from this station towards the floodgates, there was a large variation in salinity, and the concentration decreased. The salinity concentration at ST-2, located at the entrance of the western floodgate, decreases when freshwater is released through the floodgate but remains unaffected when the gate is closed. On the other hand, ST-5, located south of the gate, has a lower salinity concentration than ST-2 due to the convergence of freshwater from ST-2 and the freshwater discharge from ST-3 during the ebb tide. This suggests, as indicated by Yoon et al. (2005) and Yoo et al. (2007), that the discharge of river flow leads to increased sediment accumulation and deposition activity in the Nakdong River estuary, particularly around Jangja-do and Baekhap-deung.

3.4. Seasonal variations in water temperature and salinity

Water temperature and salinity were analyzed for the seasonal surface and bottom layers, averaged across 15 stations over an 8 years period (Fig. 6). In the surface layer, seasonal water temperatures and salinities ranged from 5.9 to 11.0℃ and 27.3 to 33.5 psu in winter, 15.3 to 18.6℃ and 18.5 to 33.2 psu in spring, 24.4 to 28.1℃ and 13.8 to 31.5 psu in summer, and 15.3 to 18.7℃ and 23.5 to 32.7 psu in autumn. In the bottom layer, seasonal water temperatures and salinities ranged from 6.1 to 11.3℃ and 28.8 to 33.8 psu in winter, 14.4 to 18.4℃ and 23.2 to 34.0 psu in spring, 17.6 to 27.8℃ and 18.6 to 33.7 psu in summer, and 15.4 to 18.5℃ and 26.3 to 33.4 psu in autumn.

In the relationship between water temperature and salinity with seasonal variations, it was found that the surface layer showed a wider range of salinity throughout the year compared to the bottom layer (Fig. 6). In particular, the temperature difference between the surface and bottom layers in summer was more pronounced than in other seasons. In the relationship between the two factors, during the dry seasons of winter and autumn, an increase in salinity concentration was associated with an increase in water temperature. However, during the flood seasons of summer and spring, lower salinity due to increased precipitation and freshwater discharge was associated with higher water temperatures caused by insolation, while higher salinity, due to the influence of the open sea, was related to lower water temperatures. Moreover, the shallow regions within sandbar areas respond more quickly to increases in water temperature due to rising air temperatures. This is because these regions have a lower heat storage capacity compared to the deep open sea (Kim et al., 2015). In addition, the water temperature around the river estuary was lower in winter and higher in summer compared to coastal waters, which is consistent with the results presented by other researchers (Moon and Choi, 1991; Kim et al., 1999; Yoon et al., 2017; Kim and Youn, 2019). The range of salinity variations was relatively larger in the surface layer than in the bottom layer, with the lowest salinity observed in summer and the highest salinity in winter. Low salinity concentrations in summer were primarily influenced by increased precipitation and freshwater discharge. In contrast, high salinity concentrations in winter were mainly affected by coastal water observed at stations T-10 to T-15.

The air temperature showed clear seasonal variations, which were reflected in the surface water temperature of the Nakdong River. As shown in Fig. 7, the surface water temperature responded to the seasonal changes in air temperature, following the order of winter, autumn, spring, and summer. That is, the surface temperature is lowest in winter and gradually increases (decreases) through spring (autumn), reaching its peak in summer. This pattern implies the significant effect of air temperature on the thermodynamics of the river. Air temperature and water temperature showed a positive correlation with a determination coefficient (R^2) of 0.89, indicating a strong seasonal pattern(Kim and Youn, 2019). Conversely, salinity showed a negative correlation with air temperature (R^2 = 0.67), decreasing as air temperature increased. This relationship was more influenced by precipitation or freshwater discharge than by air temperature, as shown in Figs. 3 and 4.

3.5. Time-series variations in water temperature

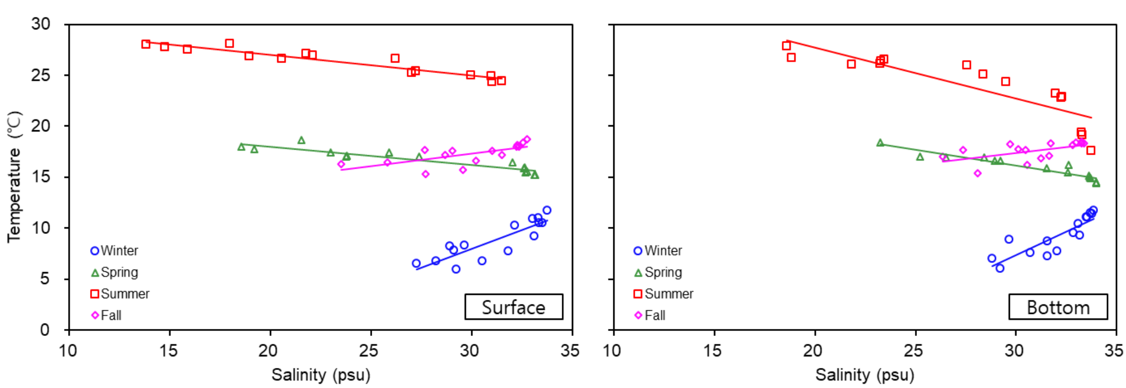

Fig. 6. Seasonal variations of water temperature and salinity in the surface (left) and bottom (right) during 2016-2023.

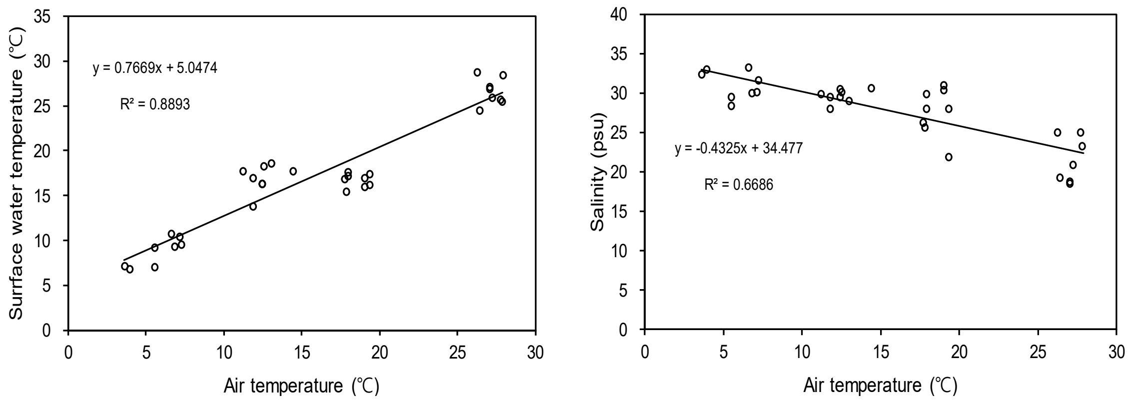

Fig. 7. Relationship between seasonal mean of air temperature and that of water temperature and salinity in the surface layer around the Nakdong River estuary during 2016-2023.

and salinity

The time series variations in water temperature, salinity, and density for both surface and bottom layers over an 8-year period (2016-2023) in the study area are showed in Fig. 8. The data analyzed seasonal variations and deviations by year.

The interannual variations in water temperature and the timing of seasonal increases and decreases were analyzed. In winter, the surface water temperature ranged from 6 to 11. 0℃. The years with an increase of more than 1℃ were 2019 to 2021, while the years with a decrease were 2016, 2018, and 2022. The surface salinity ranged from 20.0 to 34.2 psu. It decreased by 1.0 to 2.0 psu in 2016, but increased by 1.0 to 2.0 psu in 2018-19 and 2022. In spring, the surface water temperature ranged from 15 to 1 8℃. The years with an increase of less than 1℃ were 2016 and after 2020, while the year with a decrease of more than 1℃ was 2018. The surface salinity ranged from 5.11 to 34.02 psu. The decrease in salinity was over 4.0 psu in 2016 and below 1.0 psu in 2018 and 2021. However, it increased by over 2.0 psu in 2017 and 2022-2023. In summer, the surface water temperature ranged from 24 to 29℃. The years with an increase in water temperature of more than 1℃ were 2018 and 2021, while the years with a decrease were 2022-2023. Surface salinity ranged from 2.55 to 31.92 psu. It decreased by 2.0 psu in 2017-2019 and 2022, and increased by more than 1.0 psu in 2016 and 2021. In particular, the changes in summer salinity, as shown in Fig. 3 and Fig. 4, were influenced by higher precipitation and freshwater discharge in August of 2019 and 2022 compared to other years, which contributed to the reduction in salinity. Although the precipitation in August 2021 was not lower than in other years, the relatively small amount of freshwater discharge is thought to be related to the increase in salinity. The surface water temperature in autumn ranged from 16℃ to 19℃. It increased slightly in 2017, 2019, and 2021 compared to other years, which generally saw a decrease. The surface salinity ranged from 18.0 to 34.0 psu, with decreases and increases showed around 2020.

Throughout the entire season, salinity increased in both the surface and bottom layers during the years when water temperatures decreased, but this trend did not necessarily match across all years. However, a significant difference between the variations of the surface

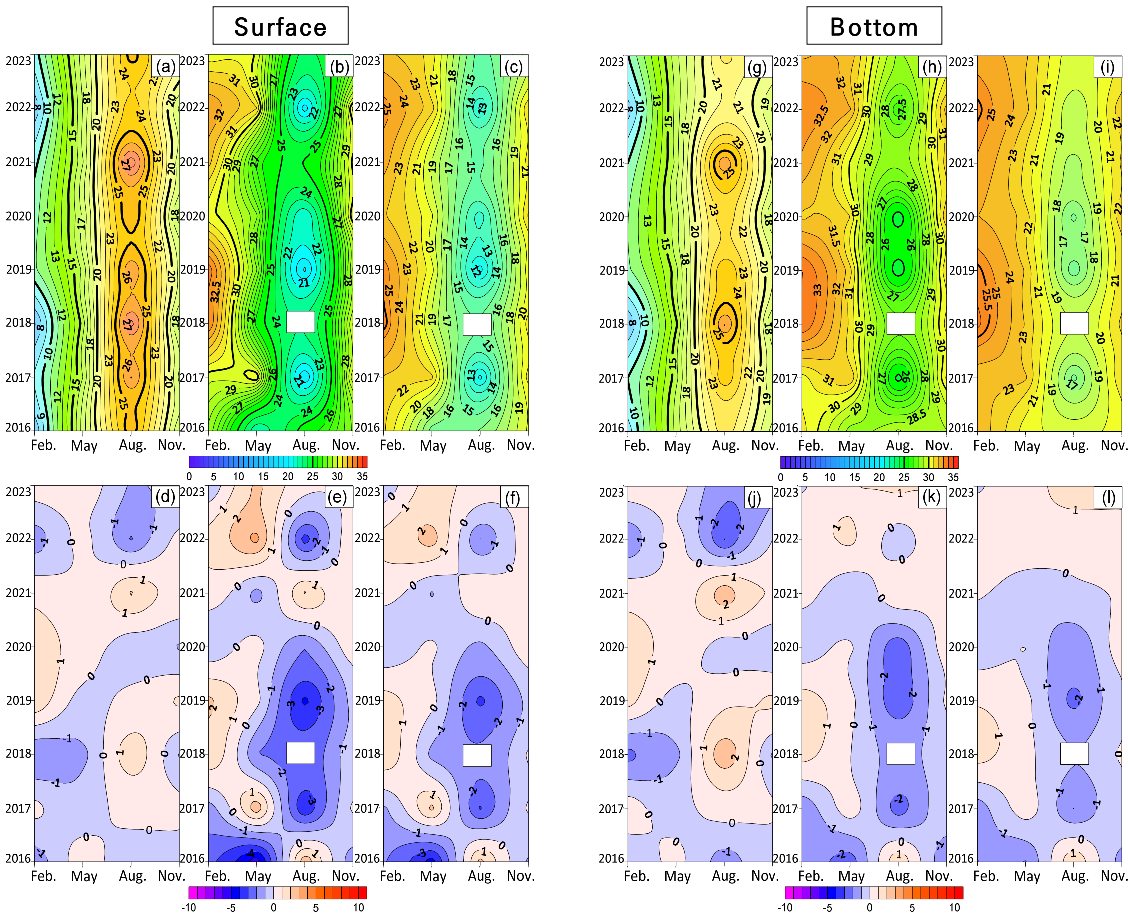

Fig. 8. Seasonal means of temperature (a, g), salinity (b, h), density (c, i), and anomalies of temperature (d, j), salinity (e, k), density (f, l) of surface (left) and bottom (right) in the study area during 2016-2023. Blank boxes represent missing data.

and bottom layers was observed during spring and summer after 2021. On the other hand, the time series variation in density is more similar to the variability of salinity than to that of water temperature, indicating that salinity is a more dominant factor than water temperature. The time-series characteristics of water temperature and salinity variations can be summarized as follows. Although there were differences in annual variations by station between the surface and bottom layers as shown in Fig. 6, salinity increased during the winter and autumn when water temperatures decreased, while it decreased during the spring and summer when water temperatures increased.

3.6. Mean and standard deviation of water temperature and salinity

The horizontal distribution of the mean and standard deviation of water temperature and salinity from the surface to the bottom of the Nakdong River estuary over 8 years (2016-2023) is shown in Fig. 9.

The mean values of water temperature ranged

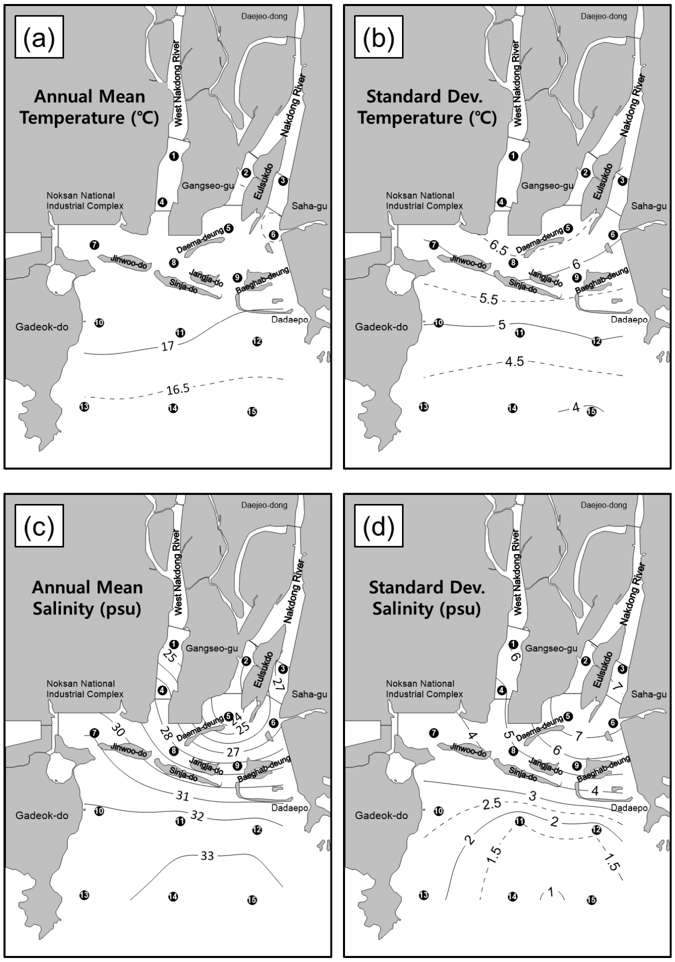

Fig. 9. Mean (a, c) and standard deviations (b, d) of water temperature and salinity, and in the Nakdong river over an 8-year period.

from 16℃ to 18℃, while salinity ranged from 22.9 psu to 33.3 psu. Water temperature was higher near the coast and decreased towards the vicinity of the floodgates, while salinity showed the opposite trend. The spatial range of the standard deviation was 3.9 to 7.6℃ for water temperature and 0.9 to 7.8 psu for salinity, with greater variations observed from the coastal region to near the floodgates. As shown in Figs. 4 and 6, salinity was more strongly influenced by summer compared to other seasons.

Regions with significant water temperature deviations showed variations greater than 6.0℃, extending from the floodgates of the Seonakdong River and the Nakdong River mainstream to near the sandbars, particularly around Jinudo, Jangjado, and Baekhapdeung. Salinity deviations showed significant fluctuations exceeding 5.0 psu, ranging from the vicinity of the floodgates west and east of Eulsuk-do in the Nakdong River mainstream to the regions in front of Daemadeung, Jangjado, and Baekhapdeung. These salinity variations were pronounced from near the floodgates to around the sandbar, with these regions being most sensitive to the effects of freshwater discharge during periods of high temperatures and low evaporation and sunshine hours, such as in spring and summer (Kim et al., 1999; Yoon et al., 2005; Jang and Kim, 2006; Park et al., 2008; Song et al., 2014, Kim and Youn, 2019).

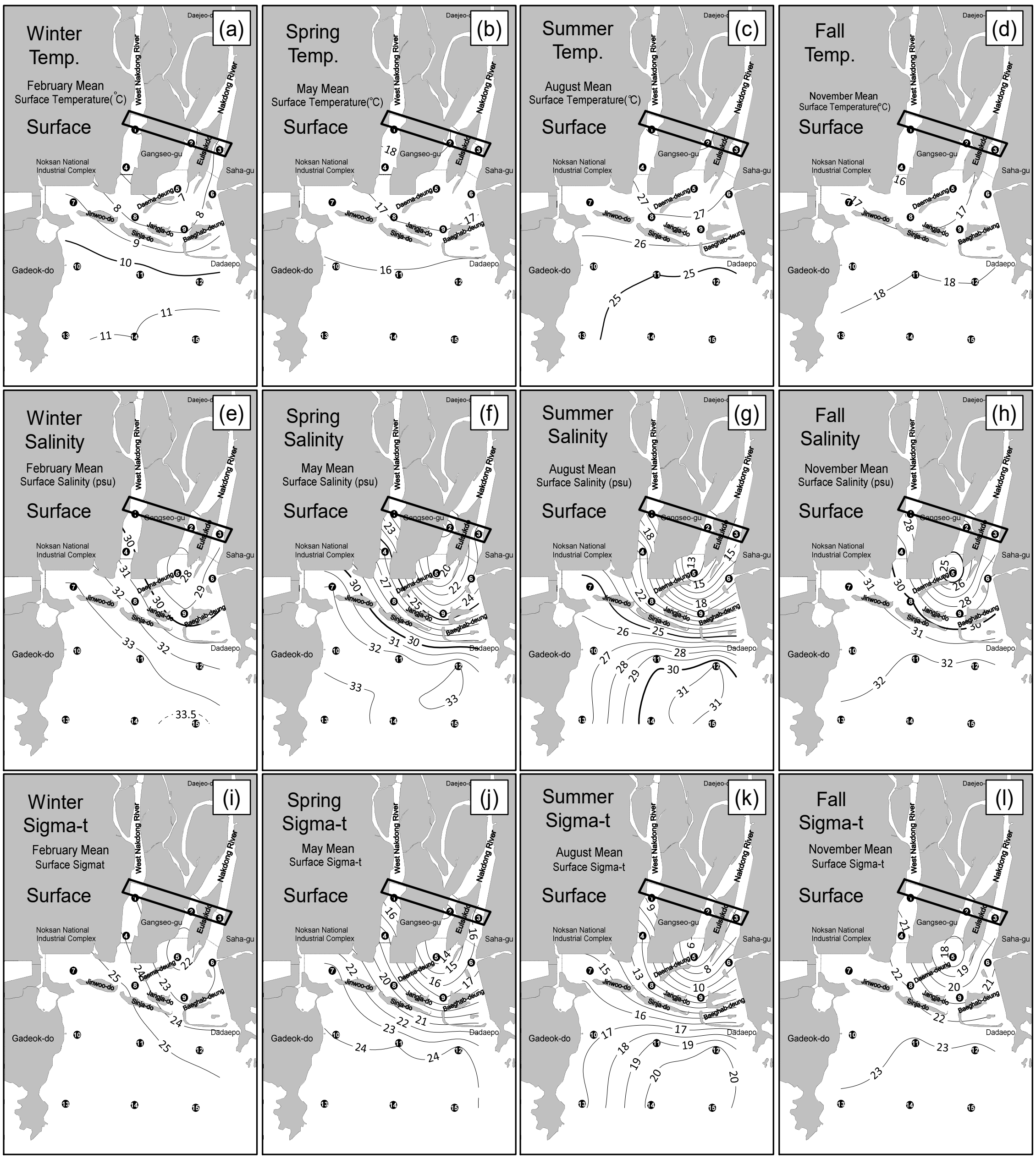

Fig. 10. Horizontal distribution of seasonal water temperature, salinity, and density in the surface layer during 2016-2023.

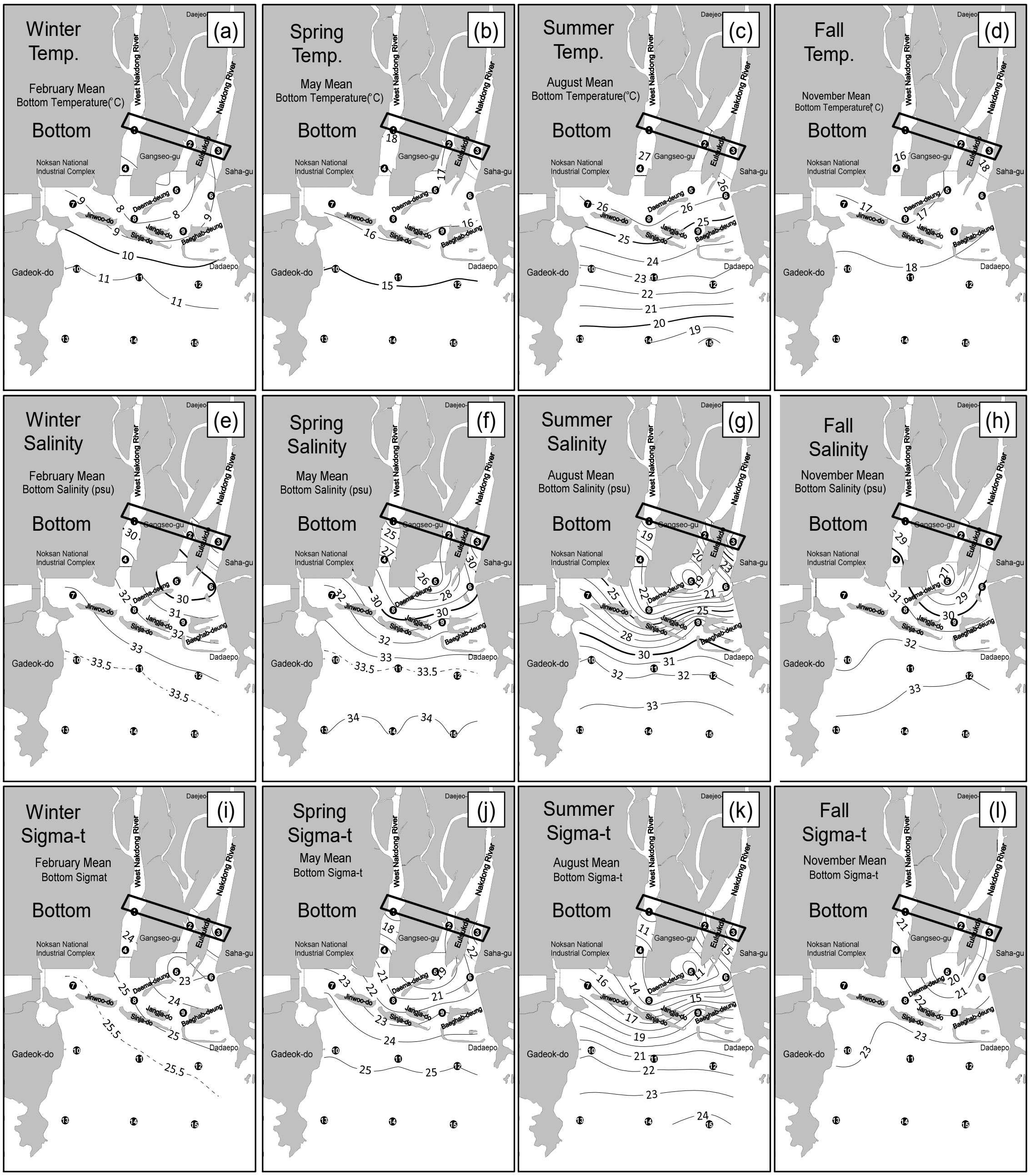

Fig. 11. Horizontal distribution of seasonal water temperature, salinity, and density in the bottom layer during 2016-2023.

3.7. Spatial distributions of water temperature, salinity and density

The seasonal variations in the surface and bottom layers, averaged over 8 years (2016-2023), to understand spatial variations in regions with significant deviations in water temperature and salinity, are shown in Figs. 10 and 11. In addition, factors influencing the spatial distribution of density, such as water temperature and salinity, were analyzed.

In the surface layer, the horizontal distributions of seasonal water temperature, salinity, and density are shown in Fig. 10.

In winter, water temperatures ranged from 6 to 12℃, increasing from near the floodgates to the coastal region. The spatial distribution showed similar intervals around the sandbar region but expanded as it extended toward the coast. Salinity ranged from 27.0 to 33.6 psu, with low salinity showed at 31.0 psu near the entrance of the Seonakdong River, and at 28.0 psu and 29.0 psu in the west and east of the Nakdong River mainstream, respectively. However, high salinity, exceeding 33.0 psu, appeared at the T-7 station near the Noksan National Industrial Complex, the T-11 station among coastal stations, and in the southwest between the T-12 and T-15 stations. In general, during winter, water temperature in regions influenced by floodgate discharge decreases due to the influx of cold river water. When discharge ceases, water temperatures in these regions tend to increase again. It is known that saltwater intrusion in the Nakdong River estuary during the dry season is influenced by seawater inflow during flood tides (Han et al., 2011; Ryu et al., 2011). Here, the vertical separation between freshwater and seawater becomes more pronounced with a smaller inflow rate due to density differences. Conversely, with a larger inflow rate, mixing between these two water masses occurs. Therefore, during the dry season, the spatial distribution of salinity is thought to be relatively high in the western area of the Nakdong River estuary due to the mixing of surface freshwater with low discharge before it reaches Gadukdo during flood tides.In addition, the high salinity in the western waters of the Nakdong River estuary can be attributed to the influence of higher salinity in the coastal region (Kim et al., 1999; Jang and Kim, 2006; Kim and Youn, 2019). In spring, the water temperature ranged from 15 to 19℃, which was approximately 5 to 9℃ higher than in winter, corresponding with the increase in air temperature. The horizontal distribution of water temperature was clearly segmented into areas ranging from the river mouth to the sandbar and the coastal regions, although spatial variability was minimal. Salinity ranged from 19.0 to 33.5 psu, with the low salinity distribution near the river mouth being similar to that observed in winter. Its concentration was 19.0 psu west of the Nakdong River mainstream, which was lower than that east of the river (22.0 psu) and in the Seonakdong River (24.0 psu). Compared to winter, the spatial distribution of salinity showed a steeper gradient from the floodgates to the sandbar, resulting in the formation of a salinity front (hereafter referred to as the haline front) where freshwater and seawater meet near the sandbar. In summer, the water temperature ranged from 24 to 28℃. The spatial distribution was similar to that in spring. However, the interior of the sandbar was about 2℃ warmer than the coastal area, with a boundary of 26℃ in the coastal region. Salinity ranged from 12.0 to 32.0 psu, and the spatial distribution from the floodgates to around the sandbar showed narrower isohaline intervals compared to spring. Low salinity concentrations near the river mouth were in the order of west (12.0 psu) and east (14.0 psu) of the Nakdong River mainstream and 16.0 psu in the Seonakdong River, similar to the patterns appeared in winter and spring. Salinity was divided into low-salinity regions within the estuary and high-salinity regions coast, with a boundary of 26 psu. Additionally, a stronger haline front developed around the sandbar compared to the spring season. In autumn, the sea surface temperature ranged from 15 to 19℃, showeding a decrease of about 8 to 11℃ compared to summer. The boundary between the estuary and coastal regions was appeared at 17℃. Salinity ranged from 24.0 to 33.0 psu, with a weak haline front showed compared to the strong haline front seen from the floodgates to the sandbar in spring and summer.

Freshwater and seawater flow into the estuary simultaneously, leading to the formation of density currents due to differences in density. These currents result in strong transport and diffusion effects on the material in both horizontal and vertical directions (Han et al., 2011). In the surface layer, the seasonal spatial distribution of density (σ_t, Sigma-t) in the Nakdong River estuary has been summarized. In winter, the density ranges from 21.0 to 26.0. It was higher southwest of the 25.0 contour, similar to the distribution of the 32.0 psu isohaline, and lower near the floodgates. The density in spring ranged from 13.0 to 25.0. Areas of lower density were observed in the Seonakdong River and the Nakdong River mainstream where high temperatures and low salinity were present. The spatial distribution formed density fronts similar to those of salinity, from the floodgate entrance to the region around the sandbar. In summer, the density ranged from 5.0 to 21.0, showing a pattern similar to the spatial distribution of salinity, as observed in winter and spring. In particular, densities below 16.0 were distributed in a tongue-shaped freshwater outflow pattern from the floodgates to the sandbar region. Meanwhile, high densities above 17.0, flowing from the offshore regions, formed a boundary with the lower densities below 16.0 around the Dadaepo area. In autumn, the density ranged from 17.0 to 24.0, and the strong density fronts formed during spring and summer had weakened. The seasonal spatial distribution of surface density was more similar to that of salinity than water temperature.

In the bottom layer, the horizontal distributions of water temperature, salinity, and density for each season are shown in Fig. 11. In winter, the bottom water temperature ranged from 7 to 12℃, and its spatial distribution was almost similar to that of the surface temperature, though the coastal region was about 1.0℃ higher than the surface. The salinity ranged from 29.0 to 33.6 psu. Bottom salinity, compared to the surface layer, was about 2.0 psu higher from the floodgate to the sandbar and about 0.5 psu higher in the coastal region. The bottom density ranged from 23.0 to 25.5 and was about 0.5 to 1.0 higher than in the surface layer. In spring, the battom water temperature ranged from 14 to 19℃. Although its spatial distribution was similar to that of the surface layer, it was about 1.0℃ lower than the surface layer. Salinity ranged from 24.0 to 34.1 psu. Compared to the surface layer, there was no significant haline front around the sandbar. Salinity concentrations were 2.0 to 7.0 psu higher near the floodgate entrance and 0.5 to 2.0 psu higher in the coastal region. The bottom density ranged from 23.0 to 25.5 psu. Compared to the surface layer, it was about 2.0 to 6.0 psu higher around the sandbar and about 1.0 to 2.0 psu higher in the coastal region. In summer, the bottom water temperature ranged from 17 to 2 8℃. It was about 1℃ lower near the floodgate entrance and 4 to 6℃ lower in the coastal region compared to the surface layer. The bottom salinity ranged from 17.0 to 33.5 psu, with concentration was more than 5.0 psu higher in the eastern waters of Gadeokdo compared to the surface layer. The density ranged from 9.0 to 24.1, which was about 4.0 to 5.0 higher near the floodgate to the sandbar and about 3.0 to 4.0

higher in the coastal region compared to the surface layer. In autumn, the water temperature ranged from 15 to 19℃. Although there were localized differences of about 1℃ compared to the surface layer, there were no significant overall variations. The salinity ranged from 26.0 to 33.5 psu, with concentrations 1.0 to 2.0 psu higher inside the sandbar and about 1.0 psu higher in the coastal region compared to the surface layer. The density ranged from 19.0 to 24.0, which was about 1.0 to 2.0 higher than in the surface layer. The density ranged from 23 to 25.5, which was about 0.5 to 1.5 higher than in the surface layer.

In the estuaries of the Nakdong River, factors influencing water temperature distribution include solar radiation, seawater inflow from the coastal area affecting water circulation and mixing due to tidal currents, and changes in seawater flow caused by wind. As a result of analyzing the spatial distribution of water temperature in the Nakdong River estuary, a distinct seasonal pattern was revealed, with water temperatures being lower in winter and higher in summer (Moon and Choi, 1991; Kim et al., 1999; Yoon et al., 2017; Kim and Youn, 2019). During autumn and winter of the dry season, water temperatures were nearly uniform between the surface and bottom layers due to sea surface cooling. The water temperature difference across the estuary was within 1℃, with the bottom layer being slightly warmer. On the other hand, in spring and summer, surface water temperatures increased compared to autumn and winter due to higher insolation. In particular, water temperatures from near the floodgates to the sandbar were 1 to 2℃ higher than those in the coastal region. The high water temperature within the estuary in summer is greatly influenced by insolation, changes in air temperature, and river discharge, leading to significant seasonal variations in water temperature (Kim et al., 1984). The increase in water temperature within the estuary is attributed to the shallower water depths in these regions, which are less than 5m, as shown in Fig. 1. Consequently, the water temperature in these regions responds more rapidly to increases in air temperature compared to coastal waters (Kim et al., 2015). In summer, the variation of bottom water temperature in coastal regions showed a different pattern compared to other seasons (Fig. 11). This pattern, as shown in Fig. 10, occurs because a large amount of freshwater does not flow out to the open sea but instead mixes with seawater, resulting in relatively lower water temperatures in the coastal region (Jang and Kim, 2006).

As a result of various studies, changes in salinity at the Nakdong River estuary have been mainly attributed to factors such as freshwater discharge, tidal variations, and changes in topography (Kim et al., 1999; Jang and Kim, 2006; Ryu et al., 2011; Song et al., 2014; Kim and Youn, 2019). In this study, it was found that salinity changes in the Nakdong River estuary are influenced by variations in freshwater discharge due to the opening and closing of floodgates in both the Seonakdong River and the Nakdong River mainstream, as well as by the mixing of freshwater with seawater entering the coastal region. Salinity concentration changes were distinctly observed from the floodgates near the Seonakdong River and the Nakdong River mainstream to the coastal sandbars, including Jinwoodo, Sinjado, Jangjado, Daemadeung, and Baekhapdeung, as well as the coastal region (Figs. 10 and 11). Salinity near the Seonakdong River floodgates showed relatively high concentrations throughout all seasons, although there were differences in concentration compared to the mainstream. In this region, the seasonal salinity near the floodgates was higher in autumn and winter than in spring and summer, similar to the trends observed in the Nakdong River mainstream. After the construction of the floodgate, the region's river flow became stagnant due to the floodgate blockage, and water quality pollution became very severe if the floodgate was not opened. In addition, there was little difference in discharge between flood and non-flood periods (Lee and Yoon, 2003; Kim and Kim, 2013; Kang et al., 2013; Song et al., 2014). Therefore, the higher salinity concentration in the Seonakdong River compared to the Nakdong River mainstream is attributed to the minimal impact of freshwater discharge due to the closed floodgates and the influence of high salinity in the coastal region. As a result, the high salinity water from the coastal region seems to have extended around Jinwoodo, reaching near the Seonakdong River. According to the model results presented by Yoo et al. (2007), the Seonakdong River appeared isolated with no flow variations, while part of the westward flow of the mainstream was shown to move toward the Seonakdong River. In the Nakdong River mainstream, the western part showed lower salinity levels compared to the eastern part. The low salinity was observed from the floodgate to the region around the sandbar throughout all seasons, while high salinity was observed in the coastal region. The salinity distribution in spring and summer, when evaporation is low, is largely influenced by the supply of freshwater from precipitation and rivers, as well as the influx of high salinity water from the open sea. The salinity concentrations at the estuary entrance located at the western floodgate of the mainstream were lower than those at the eastern side. This is because the freshwater released from the eastern floodgate converged with the discharge from the western floodgate, flowing into the vicinity of the western estuary entrance. In addition, the eastern estuary entrance showed relatively higher salinity than the western side due to the influence of seawater inflow caused by the constant opening of the floodgate. During this period, the haline front around the sandbar became progressively stronger from spring to summer due to the influence of freshwater discharge caused by increased precipitation. This haline front in summer was strongly formed around the sandbar. The regions where a strong front formed included Jangja-do, Baekhap-deung, and Jinwoo-do, which are particularly sensitive to freshwater discharge. These results closely align with the findings presented by Yoon et al.(2005) and Yoo et al.(2007). The behavior of the outflow from the Nakdong River's mainstream significantly influenced salinity changes in the surrounding sea regions, especially during high volumes of freshwater discharge. In addition, regardless of tidal timing, the outflow passed through the canal region in the form of a strong plume and affected the salinity of the surrounding waters. (Jang and Kim, 2006; Ryu et al., 2011). The spatial distribution of salinity during autumn and winter, the dry seasons, showed that the area around the east gate of the mainstream, where the floodgate is always open, is more affected by freshwater discharge and seawater inflow during flood tide periods compared to the west gate. The change in current velocity of the Nakdong River mainstream observed by Song et al.(2014) also showed that the velocity was slower in the western part compared to the eastern part, due to smaller freshwater discharge. During this period, the salinity gradient from the floodgate to the area around the sandbar was weak. In this study, the spatial analysis of density distribution showed that during the dry seasons of autumn and winter, the gradient of the isopycnal lines was weak. However, during the flood seasons of spring and summer, the density fronts formed strongly around the sandbar and were well consistent with the haline fronts.

4. Conclusions

In this study, we examined the time-series and seasonal variation characteristics by using field observations of water temperature and salinity over 8-year (2016–2023) around the Nakdong River estuary, along with precipitation, freshwater discharge, and air temperature data provided by the open meteorological data portal of the KMA and the MyWater of the Korea Water Resources Corporation. The relationship between freshwater discharge, precipitation and salinity at the observation stations near the floodgates showed a stronger correlation in the mainstream of the Nakdong River compared to the Seonakdong River. Here, salinity concentrations showed a relatively strong correlation with freshwater discharge near the western floodgates of the mainstream compared to other floodgates, indicating that salinity decreases as freshwater discharge increases.

Seasonal variations in the Nakdong estuary significantly affected both water temperature and salinity. During the spring and summer flood seasons, water temperatures increased, while higher freshwater discharge from floodgate openings lowered salinity concentrations. However, during the autumn and winter dry seasons, water temperatures decreased, and the reduced freshwater discharge, combined with the inflow of high salinity water from the open sea, led to relatively high salinity concentrations. The regional distribution of salinity was lower near the floodgates of the Nakdong River mainstream compared to the Seonakdong River, where stagnant water was caused by the closed floodgates. The eastern region of the Nakdong River mainstream showed relatively higher salinity concentrations than the western due to the influence of high salinity water inflowing from the open sea as a result of the regular opening of the floodgates. The spatial distribution of salinity showed low concentrations near the floodgates and around sandbars during the flood season, while higher salinity concentrations were observed in coastal areas. In particular, a strong haline front formed near the sandbar during this period, but its structure weakened in the autumn and winter.

The Nakdong River estuary creates a complex marine environment where the river meets the sea, which is expected to have a significant impact on the local marine ecosystem. This study found that salinity rather than water temperature was the primary factor influencing density in the Nakdong River estuary. Furthermore, it was confirmed that freshwater discharge due to floodgate operation and the influx of high salinity water from coastal areas significantly affect the marine environment of the estuary. Although data from the spring monsoon season were not included in this study, it is expected that the impact of salinity from river discharge due to precipitation would be similar during the monsoon. In addition, based on the results presented in this study, it is important to elucidate mechanisms such as the salt wedge phenomenon caused by high salinity inflows from the open sea, along with a temporal variation analysis that considers spatial patterns, such as empirical orthogonal function analysis. Finally, the marine environment of the Nakdong River estuary responds more sensitively to seasonal salinity variations than to water temperature, and these findings are expected to provide important information for future water resource management and environmental conservation policy development.

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