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The Along-channel Salinity Distribution and its Response to River Discharge in Tidally-dominated Han River Estuary, South Korea

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Abstract

The Han River Estuary (HRE), located on the west coast of South Korea, is well known for its macro tidal characteristics with a tidal range more than 8.5 m. This estuary has a distinctive salinity distribution because its system consists of 3 main channels and 3 rivers, through which major tidal flow and river discharge meet each other. To determine the effect of change in external forcing (e.g., river discharge and tidal variation) on the salinity, a numerical model is established and verified with observation. Based on previous observation, the main channel of HRE shows well- and/or partially-mixed estuary during spring and neap periods, respectively. The vertical stratification during the neap period is stronger than that during the spring due to decreasing turbulent mixing. The numerical results show that the salinity distribution during high river flow condition can be temporally and spatially characterized by river discharge. The asymmetries of the salinity distribution response to increasing and decreasing river discharge are indicated in this estuary. During high river flow conditions, the front of Incheon Harbor is within the region of the freshwater influence.

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Keywords: salinity distribution; freshwater dishagre; numerical model; Han River Estuary; Gyeonggi Bay

1. Introduction

The salinity distribution is an important phenomenon in an estuary, and can constitute a serious problem to society due to the industrial, agricultural and residential needs for fresh water (Zhang et al. 2011). The salinity distribution and salt intrusion may be considered as major environmental factors affecting the existence and distribution of

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organisms in estuaries (Jassby et al. 1995; Attrill 2002). The estuarine salinity structure is caused by the effects of geometry, tidal variation, salinity difference between sea and river water, and freshwater discharge. Interactions of the various factors determine the mixing mechanism in an estuary and the salinity intrusion process (Dyer 1997).

Gyeonggi Bay (GGB), located along the central coast of the Yellow Sea, is a semi-enclosed region dominated mixed semi-diurnal tides (Fig. 1). The area consists of large and small islands and channels, with a complicated coastline, and a large tidal flat due to the large tidal range. The region has a very complicated spatio-temporal variability of tidal residual flow and volume transport due to variable tidal characteristics (Song and Woo 2011; Woo and Yoon 2011), seasonal variations in freshwater discharge (Park et al. 2002), mixing with seawater and the development of stratification (Jeong et al. 2007), and thermohaline circulation.

The Han River Estuary (HRE) in the GGB consists of three main channels (Yeomha, Seokmo, and Gyodong channel) and three rivers (Han, Imjin, and Yesung River). The mixing region, with freshwater from rivers and salty water from open sea, is located in two channels, one sited east of Ganghwa (Yeomha Channel) and the other channel sited west of Ganghwa (Fig. 1). Our research is focusing on Yeomha (YH) Channel. YH Channel is narrower (max 1.2 km wide near the mouth) and shallower (max < 12 m) than Seokmo Channel. The maximum tidal current is more 2 m/s and shows ebb-dominance characteristic (Yoon and Woo, 2013a). Because the amount of precipitation from the end of June to the end of September, the rainy season, accounts for 70% of the annual precipitation, seasonal variation of freshwater is distinct.

The salinity distribution in the HRE has been researched since the 1990s, using numerical models (Park et al. 2002; Jeong et al. 2007), analytical models (Yoon and Woo 2013b) and observation (Chang 1991; Park 2004). The HRE, which is one of the largest estuaries in the South Korea, has a complex topography with multiple channels. In generally, the analytical model focused on a single channel and for observation, access to the channel of north of Ganghwa is limited. Therefore, to assess the influence of combinations of the above factors on the salinity distribution in the estuary, numerical simulation is useful because it can provide more detail results in space and time. This paper applies a numerical model to the salt intrusion and salinity distribution process in the complex HRE system.

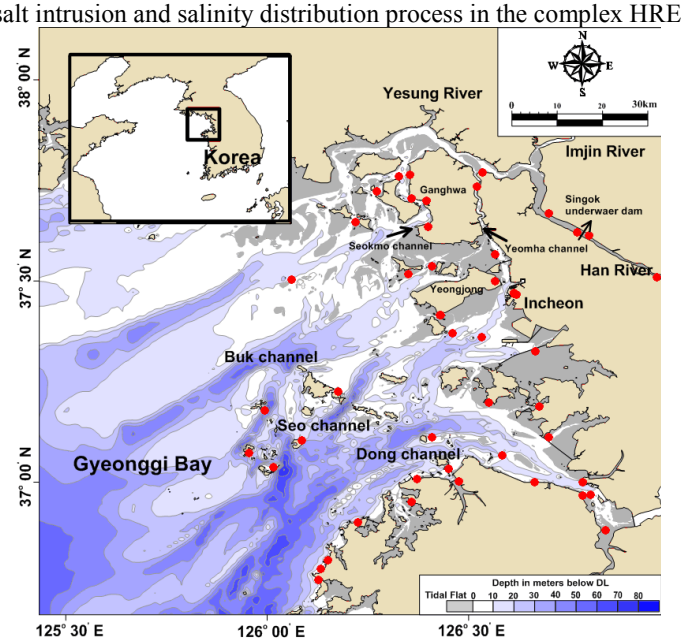


Fig. 1. Bathymetric map (unit: m) of study area and the tidal station for calibration of numerical model were collected: 50 points (red circles). The gray shaded areas indicate intertidal flats.

2. Numerical model

2.1. Model description

This study uses a three-dimensional hydrodynamic model, Environmental Fluid Dynamics Code (EFDC), which was developed by Hamrick (1996). EFDC has been successfully used in various water bodies such as coasts, estuaries, lakes, wetlands, and reservoirs by many researchers (e.g., Kuo et al. 1996; Shen et al. 1999; Park et al. 2005; Jin et al. 2000; Zuo et al. 2006; Yang and Hamrick 2003). The EFDC model comprises continuity equations, momentum equations, and conservation equations that include temperature, salinity, and sediments. The thermohaline conservation equation is related to the equation of motion by baroclinic forcing. The turbulent closure scheme level 2.5 of Mellor and Yamada (1982) is used, and the equation of Smagorinsky (1963) is used as the horizontal vortex coefficient to calculate every time step. The basic equations are expressed as the three-dimensional Reynolds average continuity equations, the equations of momentum, equation of state, and conservation equations. The structure of the basic model is similar to that of the Princeton Ocean Model (POM) of Blumberg and Mellor (1987), and a detailed explanation of the theoretical background and numerical technique is described in Hamrick (1994).

2.2. Model condition and application

The present numerical model is applied to the GGB which extends 130 km in the east-west direction and 126 km in the north-south direction (Fig. 2). The gridding system in this model uses orthogonal curvilinear coordinates (743 x 454 in x and y directions) in the horizontal direction and sigma coordinates (20 layers) in the vertical direction. A varying-size grid structure is used to better present estuary bathymetric and to resolve the complex shoreline. The size of grids varies, with relatively smaller cells near the main channel and the Han River (50~200 m) and increasingly larger cells seaward. The number of total water cells is 52,829 and the model time step is 4 s to satisfy the Courant-Friedrichs.-Lewy (CFL) condition. The open boundary conditions are specified using the harmonic constants of five major constituents (M_2, S_2, N_2, K1, and O_1) evaluated from the observation (Im, 1999) and the numerical model in Yoon and Woo (2012). An arbitrary condition of zero is used for the initial conditions for surface elevation and velocity (cold start). To estimate the initial salinity field, the model has a first spin-up period for 1 year with daily mean freshwater inflow (see Fig. 5).

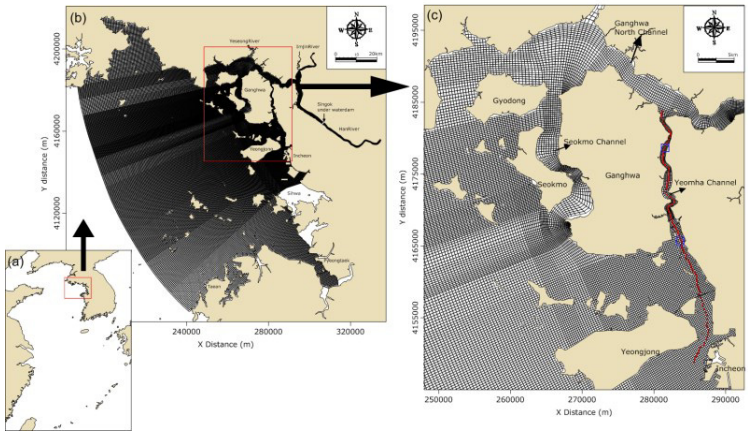


Fig. 2. Numerical model grid for the Han River Estuary (c) and Gyeonggi Bay (b), South Korea (a). River discharge was recorded at Paldang dam located from 60 km upstream from Singok underwater dam (b). Tidal current and salinity were measured at two stations (blue square). A line of red circles indicates salinity contour profile from ocean (Incheon Harbor) to upper estuary (north entrance of Yeomha Channel).

2.3. Model calibration and verification

In order to examine the accuracy of numerical results, model calibration and verification were conducted according to observational data which include water level, tidal current, and salinity. To calibrate results of initial model, the tidal harmonic constants of water level (at 50 stations around GGB) were collected from Korean Hydrographic Oceanographic Administration and Han River Flood Control Office. The model was verified using the observation data (Yoon and Woo 2013a; Yoon and Woo 2013b) of tidal current and salinity during 2009 at two stations, at the northern and southern entrances of Yeomha channel. The model results, which were compared with the amplitudes and phase for 4 major tidal constituents, are presented in Fig. 3. The validity of the model results was further examined using time series measurements of tidal current (not showed) and salinity (Fig. 4). The model results show that the model generally reproduces the tidal and salinity variation of GGB.

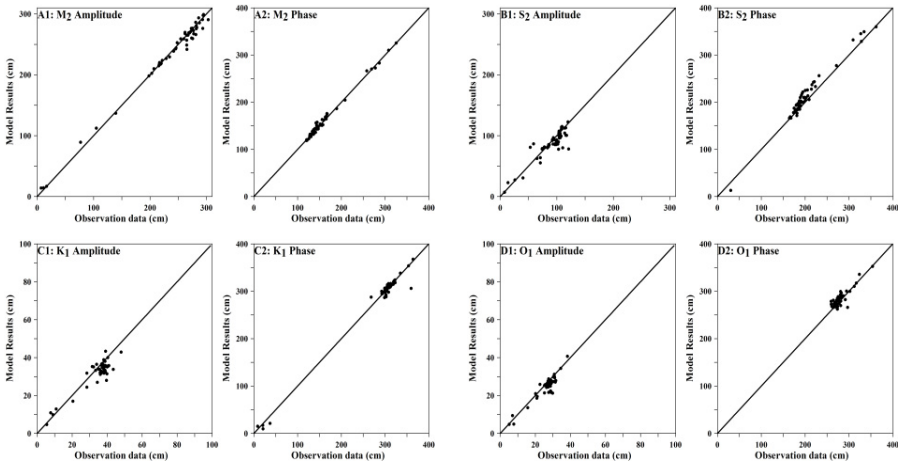


Fig. 3. One-to-one comparison between the observed and model results amplitude and phases for the four major tidal constituents (a) M_2, (b) S_2, (c) K_1, and (d) O_1

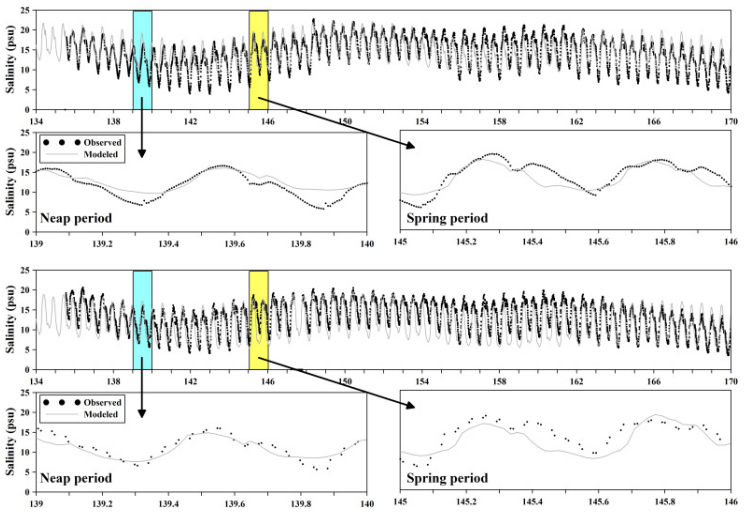


Fig. 4. Comparison between model results and observations for salinity at north (top panel) and south (bottom panel) entrances of Yeomha channel. The blue and yellow boxes indicate 24-hour observation periods during the neap and spring periods, respectively.

2.4. Experiment design

To understanding the salinity distribution of the study area, particularly along Yeomha channel, the model was conducted under different freshwater conditions. The freshwater conditions was calculated based on the resulting 36-year mean daily river discharge were estimated and used to specify the Han River daily mean discharge rates at the Paldang dam (60 km upstream from Singok underwater dam in Fig. 1). The averaged and median of freshwater discharge rate is 527 and 234 m^3/s, respectively. The period of 'dry', 'normal', and 'wet' condition of freshwater condition is January to March, April to June, and July to September, respectively (Fig. 5).

To find the along-channel salinity distribution at Yeomha channel response to short-term (flood and ebb tide) and long-term (spring-neap periods), the model was run for 1 year with constant normal freshwater discharge (378 m^3/s). To study the effect of wet freshwater discharge on salinity distribution, the freshwater rate of the model is a higher discharge (1332 m^3/s) during 10- days period of 140~150 days (Fig. 6). Although realistic freshwater data exist, the given constant freshwater rate for normal and wet conditions in the model simulation has the advantage of enabling simple interpretation of the salinity distribution.

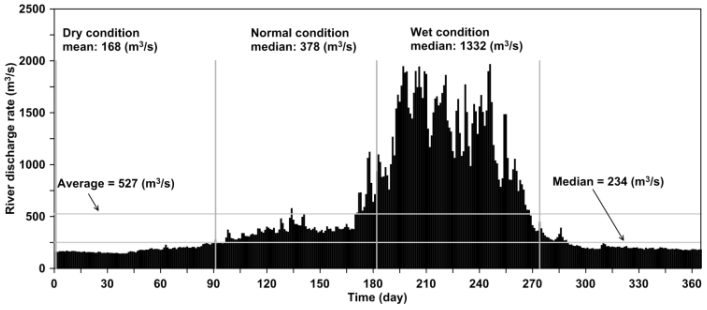


Fig. 5. Daily mean freshwater discharge at the Paldang dam in Han River averaged over 1974 ~ 2009.

3. Model results

The model results of salinity time series at surface layer of 3 station (front of Incheon Harbor, south and north entrances of Yeomha channel) and water level (southern entrance of Yeomha channel) under different freshwater conditions are presented in Fig. 6. The salinity range, at the station in front of Incheon Harbor, is from 24.3 to 31.2 psu. The salinity variation has relatively little change compared with the other station, but its magnitude varies more in freshwater than short- and long-term tidal periods. The freshwater discharge has a direct influence on the Incheon Harbor under the wet freshwater condition. These results of regions of freshwater influence coincide with previous studies (e.g., Park 2004; Yoon and Woo 2013b).

The variation in salinity shows a clear increase or decrease depending on the short- and long-term tidal period at the south and north entrances of Yeomha channel. The salinity decreased sharply when the freshwater discharge rate rapidly increased (i.e., 140 day in Fig. 6). The minimum salinity at the north entrance of Yeomha channel station is almost under 0.6 psu (i.e., 150 day in Fig. 6). This station may be a head of saltwater intrusion under the wet freshwater conditions. However, no field data are available to check, the head region of the salinity intrusion, because of its proximity to the maritime border between South Korea and North Korea.

For the varying river flow at the Han River, the salinity distribution recedes with increasing river flow and rebounds with decreasing river flow. The salinity decreases rapidly initially but then decreases gradually when the river discharge becomes constant (1332 m^3/s). With the river flow decreasing to the normal condition, the salinity rebounds gradually. The salinity reacts to an increase in river flow more quickly than to a decrease in river flow. This asymmetry has been explained by the nonlinear effect of bottom drag (Hetland and Geyer 2004). Gong and Shen (2011) showed a similar salinity variation to our results which they attributed to the salt transport balance. In addition, the salinity reacts more quickly from neap to spring tides than from spring to neap tides (Gong and Shen 2011).

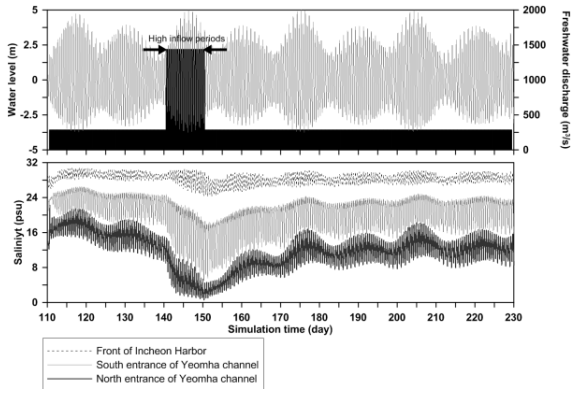


Fig. 6. The response of the salinity distribution to an ideally varying river discharge.

In the downstream portion (Incheon (IC) Harbor in Fig. 7) of Yeomha channel in the HRE, the salinity range is presented 30 psu during high tide in both spring and neap periods under normal river condition (Figs. 7b and 7d). The 20 psu line, during low tide in both spring and neap periods during normal river condition, is located 12~15km (Figs. 7a and 7c) from Incheon Harbor, compared to 20~28km during high tide. The vertical salinity profile shows more gradient during neap period than during spring period. During normal river flow condition, the 20 psu line is moved 20km upstream.

The model results show that overall salinity distribution is less under high river flow conditions than under normal flow (Figs. 7e and 7f). At high tide, the 30 psu line is located in Incheon Harbor (Fig. 3f). On the other hand, the 20 psu line is not presented in Fig 3e, which indicates that the salinity distribution is the least during low tide at the neap period under wet (high) river condition.

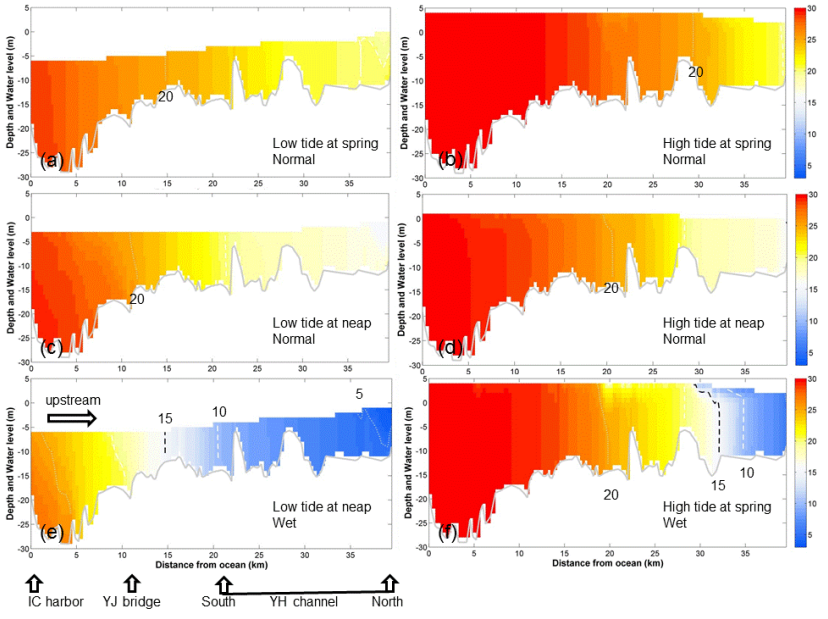


Fig. 7. Model results of vertical distributions of salinity along the main channel (Yeomha channel) of HRE under high (b, d and f) and low (a, c, and e) tides, spring (a, b, and f) and neap (c, d, and e) periods, and normal (a, b, c, and d) and wet (e and f) discharge conditions.

4. Summary

In this research, a numerical model using a high-resolution grid system was developed for studying the salinity distribution and its response to river flow in the tidally-dominated HRE in GGB, South Korea. The numerical model (EFDC) was calibrated and verified for water level, tidal current, and salinity. The important study finding is that the salinity distribution tends to be sensitive to change in the river discharge although the HRE is a tidally-dominated estuary compared to some other estuaries in South Korea. Freshwater discharge is the primary environmental factor controlling the salinity in the HRE during high river condition. The response time is shorter when river flow is increasing than when it is decreasing. To simulate the high river condition, the front of Incheon Harbor is an area which directly affected by freshwater discharge. Generally, sea level rise can cause saline water to migrate upstream in estuaries. Therefore, the distance of salinity intrusion in the HRE will be investigated using scenarios to simulate future sea level rises.

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