Journal of Marine Science and Technology

Volume 25 | Issue 6 Article 6

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Recommended Citation
Lee, Seung Oh and Song, Chang Geun (2017) "NUMERICAL COMPUTATION OF THE TRANSIENT SALINITY DISTRIBUTION IN A MACRO-TIDAL ESTUARY," *Journal of Marine Science and Technology*: Vol. 25: Iss. 6, Article 6.
DOI: 10.6119/JMST-017-1226-06
Available at: https://jmstt.ntou.edu.tw/journal/vol25/iss6/6

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Acknowledgements

This work was supported by Incheon National University (International Cooperative) Research Grant in 2016.

Journal of Marine Science and Technology, Vol. 25, No. 6, pp. 666-670 (2017)
DOI: 10.6119/JMST-017-1226-06

NUMERICAL COMPUTATION OF THE TRANSIENT SALINITY DISTRIBUTION IN A MACRO-TIDAL ESTUARY

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Key words: macro-tidal estuary, flow reversal, salinity distribution, hydrodynamic model, advection-dispersion model, saline length.

ABSTRACT

In this study, the flow reversal and salinity distribution associated with tidal effects were investigated at a macro-tidal estuary located in tidal range of the Yellow Sea in South Korea. A 2-D hydrodynamic model (RMA-2) and a 2D advection-dispersion model (RAM4) were employed to simulate flow behavior and salinity distribution, respectively. The results showed that reverse flow occurred five times over 3-day period and the maximum reverse flow extended over 32.9 km upstream. Salinity distribution was obtained by estimating the salinity input with analytical solution of advection-dispersion equation. The total length of the saline wedge calculated from numerical simulation was in agreement with that obtained from an empirical formula.

I. INTRODUCTION

The tidal range in the Yellow Sea is about 9 m, and this wide range enables the water from the Yellow Sea to intrude into the main channel of the Han River in South Korea. Consequently, fluvial geomorphology and the brackish ecosystem are well preserved in this region. According to the survey of the National Institute of Environmental Research (2005), many endangered species such as *Platalea minor*, *Haliaeetus albicilla*, *Anser fabalis* and *Rana plancyi chosenica Okada* inhabit the estuary of Han River. Hydraulic analysis of the downstream of Han River is very important since it supplies the industrial and drinking water to the citizens in Seoul and Gyeonggi Province. Accordingly, the Ministry of Environment of Korea declared the estuary of Han River marsh to be protection zone in April, 2006. The flow characteristic of the estuary of Han River is very complex since there are many tributaries, including Im-jin River, and man-made structures such as bridges and submerged weirs. In addition, Pal-dang Dam and tidal water level are the two main factors controlling the flow behavior of water discharge.

The analysis of salinity distributions in estuaries is a significant issue in both marine science and estuary engineering. This is because salinity in water body exerts various influences on water movement, water quality and ecology. In hydrodynamic aspect, salinity changes the density of water and the movement of water body. It affects the quality of drinking water and the production of crops. Regarding ecosystem concerns, it is closely associated with the ecological health, landscape, and biodiversity. Consequently, the analysis of salinity distribution is a significant issue in terms of marine science and estuary engineering.

In this study, bathymetry of the lower Han River was produced based on the digital nautical charts. Salinity at the downstream boundary of the Han River was obtained by applying the analytical solution of a one-dimensional (1-D) advection-dispersion equation to the measurements obtained at Incheon tide gauge station. RMA-2, a two-dimensional (2-D) hydrodynamic model was used to analyse reverse flow under tidal effects in the Han River Estuary. The velocity and water depth outputs from RMA-2 were used as inputs into RAM4, a 2-D advection-dispersion finite element model, to analyse the characteristics of the salinity distribution.

II. DESCRIPTION OF NUMERICAL MODELS

RMA-2 is a two-dimensional depth-averaged finite element hydrodynamic model (Norton et al., 1973). It computes water surface elevation and horizontal velocity components for subcritical flow. It was originally developed by Norton, King and Orlob of Water Resources Engineers in 1973 for the Walla Walla District of the U.S. Army Corps of Engineering. The governing equations consist of one continuity and two momentum equations obtained by depth-averaging Navier-Stokes equations.

RAM4 is a depth-averaged advection-dispersion model (Seo et al., 2008). It can predict and estimate the transport of pollutant that has been injected continuously or instantaneously. The governing equation of this model is as follows:

$$\frac{\partial(hC)}{\partial t}+\nabla\left(\{q\}hC\right)-\nabla\cdot\left[D_c\right]\nabla\left(hC\right)-khC-Q\left(x,y,t\right)=0 \quad (1)$$

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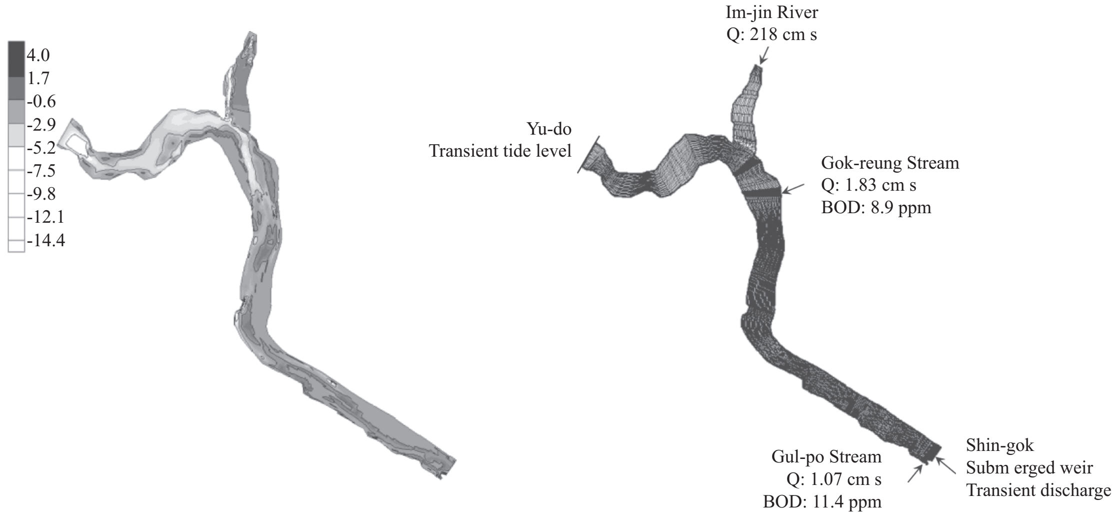


Fig. 1. Bottom elevation contour (left) and input conditions (right).

where h is depth, C is depth-averaged concentration, $\{q\}$ is depth-averaged velocity vector, k is first-order decay coefficient. $Q(x, y, t) = M\delta(x - x_s, y - y_s)\ \delta(t)$ is source term to handle pollutant injected instantaneously at the location (x_s, y_s). The dispersion coefficients $[D_c]$ in the above equation is defined in Seo et al. (2008). The horizontal 2-D finite element model is constructed by Streamline-Upwind/Petrov-Galerkin (SU/PG) scheme. Crank-Nicolson finite difference is used as the temporal discretization method. Numerical integration is carried out by Gauss quadrature in natural coordinates. Boundary conditions, such as instantaneous mass injection or concentration injections that are steady, pulsed or unsteady, can be assigned. More detailed descriptions on the model performance and applicability of RAM4 are available from (Lee and Seo, 2010; Park et al., 2016).

III. NUMERICAL SIMULATIONS

1. Study Reach and Input Conditions

From its confluence with the Gok-reung Stream, the Han River flows 13.7 km northwestward to the sea. However, owing to this area's proximity to the Military Demarcation Line, survey data, both along and across the river, are unavailable for this section of the river. Therefore, we constructed bathymetry of this area with the aid of digital nautical charts. Our study area spans from the Shin-gok submerged weir (representing the upstream boundary of the Han River in the finite element models) to Yu-do (representing the downstream boundary). It includes the Im-jin River and 36.8 km of the Han River. The finite element mesh of the study area contained 16,066 nodes and 5,920 elements. Fig. 1 shows the bathymetry, mesh layout and input parameters used in the numerical simulations. From the Shin-gok submerged weir downstream to the first meandering region, water depth on the right bank is greater than that on the left bank; but, downstream from the first meander, water depth on the left bank increases; and finally, below the confluence with the Gok-reung Stream, the entire channel deepens.

Input parameters used in the numerical simulations were determined from existing literature. We adopted the roughness coefficient of 0.025 as suggested by the Ministry of Maritime Affairs and Fisheries (2001); this value was proposed for the Shin-gok-Wal-got section in the case of discharge below 2000 m^3/s. Since the study area is a restricted military area near the Military Demarcation Line, it is impossible to obtain values for the dispersion coefficients from field measurements. Therefore, we obtained estimates using the empirical formula of Elder and Fischer, which is accurate when applied to the estimation of longitudinal dispersion coefficients in 2-D advection-dispersion models (Fischer et al., 1979; Seo and Cheong, 1998). Since we were simulating a meandering channel where secondary flow was dominant, we adopted the coefficient of 0.6 in the computation of transverse dispersion. The estimated longitudinal (D_L) and transverse (D_T) dispersion coefficients were 7.47 and 0.75 m^2/s, respectively. Following Seo and Song (2007) and Seo et al. (2009), the Biochemical Oxygen Demand (BOD) decay coefficient was chosen to be 0.1/day.

A numerical simulation was carried out for a 3-day period, from 23 to 25 June 2006. This period was chosen because of favourable hydrologic conditions, including large tidal ranges measured at Incheon tide gauge station (Fig. 2). The flow rate from the Im-jin River into the main channel of the Han River was assumed to be 218 m3/s, which was the average value for this period.

2. Salinity Distribution

Salinity distribution in the lower Han River is determined by freshwater inflow discharge and tidal range. The Han River Development Project took place from 1982 to 1986. Since its completion, water quality observations carried out for periods of more than 13 hours regularly indicate the absence of salinity

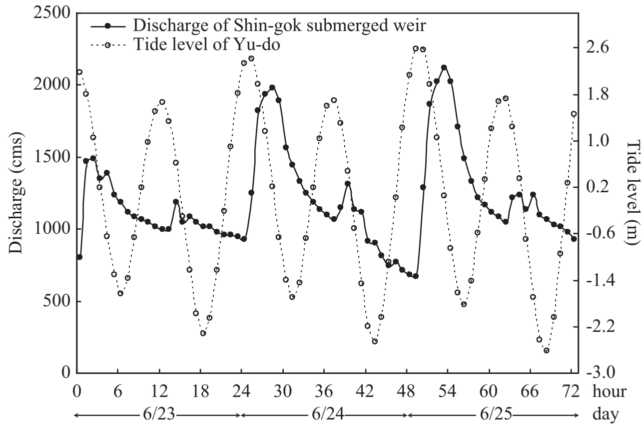
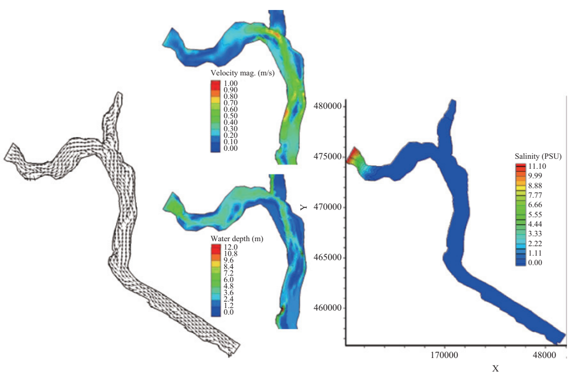
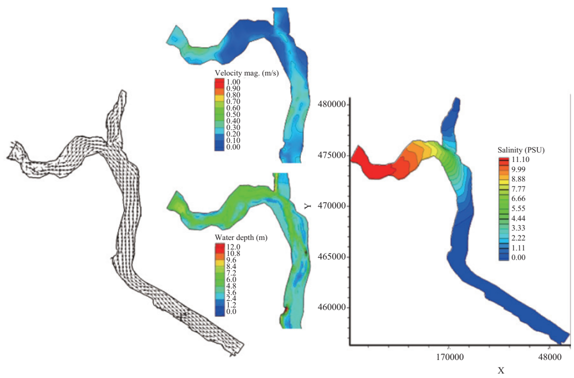


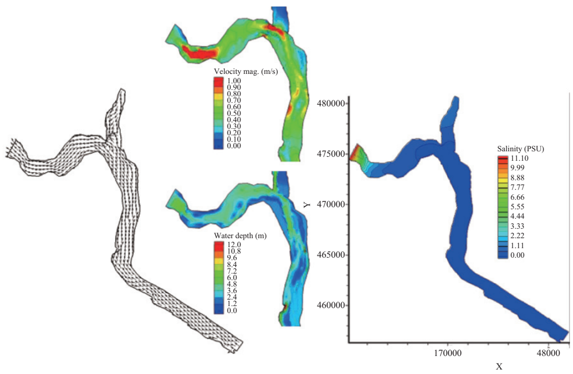
Fig. 2. Boundary conditions.



(a) t = 46.25 hr



(b) t = 51 hr



(c) t = 58.5 hr

Fig. 3. Salinity distributions with transient velocity fields.

intrusion at the Shin-gok submerged weir. However, 15.4 km downstream of the Shin-gok submerged weir, at Jeon-ryu station, a salinity of 1.0 PSU was recorded on 15 July 2003. On the same day, a maximum tide level of 919 cm was recorded at Incheon tide gauge station. On 8 July 2003, no salinity was recorded at Jeon-ryu, while a maximum tide level of 732 cm was recorded at Incheon. These results could be clear evidence of the influence of the Yellow Sea on the lower Han River. Depending on the tide level of Gyung-gi Bay, water from the Yellow Sea may extend up to Jeon-ryu station.

Under the assumption of a constant vertical salinity profile, RAM4, a 2-D finite element advection-dispersion model, was applied to delineate horizontal salinity distribution. Salinity at Yu-do was estimated by applying the analytical solution of a 1-D advection-dispersion equation to the measurements obtained at Incheon tide gauge station. The two sites are separated by 39.1 km and the distance is sufficiently large for the use of the following simplified equation:

Table 1. Variables for calculating the length of saline wedge.

Variable	Value	Variable	Value
Water temp.	24°C	Densimetric velocity (V_Δ)	1.24 m/s
Salinity	27 PSU	Velocity of river (V_r)	0.194 m/s
Density of sea water	1017.62 kg/m^3	Mean depth (H)	9 m
Kinematic viscosity (ν)	9.15×10^{-7} m^2/s		

$$C(x,t) = \frac{C_0}{2}\operatorname{erfc}\left(\frac{x-tu}{\sqrt{4Dt}}\right) \quad (2)$$

For the simulation period, mean salinity measured at Incheon tide gauge station was 27 PSU. The dispersion coefficient D was assumed to be 100 m^2/s, as D is generally higher in estuaries than in rivers. Using numerical analysis, we estimated a mean velocity u of 0.194 m/s. Hence, using Eq. (3), we estimated the depth-averaged salinity C at Yu-do to be 11.1 PSU. These parameters and the boundary conditions outlined in Fig. 2 were used as inputs into the RAM4 model. RAM4 simulations showed that the front of a saline wedge began to move upstream after the simulation of 46.25 hours (Fig. 3(a)). Maximum diffusion and transport of detritus occurred after the simulation of 51 hours. The upstream expansion of the saline wedge stopped at 2 km downstream from Jeon-ryu station (Fig. 3(b)). This is in line with Park's (2008) surveys, which indicated the absence of salinity at the station. After the simulation of 58.5 hours, the saline wedge retracted downstream under the dominance of the velocity field (Fig. 3(c)).

To verify the RAM4 simulation result, 1-D empirical formula for determining the length of saline wedge was used. The applied variables are summarized in Table 1. The density of sea water is a function of water temperature and salinity and can be computed by σ_t method. Then, the densimetric velocity takes $V_\Delta = \sqrt{(\Delta\rho/\rho_m)gH} = 1.24$ m/s. Because Reynolds number $Re = V_\Delta H/\nu = 1.22\times10^7$ surpasses 10^7, the length of saline wedge is represented by Ippen (1966)

$$L = 6H\left(\frac{V_\Delta H}{\nu}\right)^{1/4}\left(\frac{2V_r}{V_\Delta}\right)^{-5/2} = 58{,}501 \text{ m} \quad (3)$$

As a result, the length of the saline wedge was estimated to be 58,501 m, as measured from Incheon tide gauge station. This is equivalent to the expansion of the salinity intrusion to 19.4 km upstream from Yu-do. This estimate is in agreement with the results from the numerical simulations (Fig. 3(b)).

IV. SUMMARY AND CONCLUSION

A 2-D hydrodynamic model (RMA-2) and a 2-D advection-dispersion model (RAM4) were applied to the Han River Estuary in South Korea to analyse the horizontal salinity distribution of the lower Han River. Flow characteristics of the lower Han River are mainly governed by the large tidal range of the Yellow Sea. A numerical simulation was carried out for a 3-day period, from 23 to 25 June 2006. This period was chosen because of favourable hydrologic conditions, including large tidal ranges measured at Incheon tide gauge station. The results showed that reverse flow occurred five times over a 72-hour period and the maximum reverse flow extended 32.9 km upstream. Further analysis was implemented to elucidate the transient salinity distribution. Salinity distribution was obtained from RAM4 simulations by estimating the salinity boundary conditions with the aid of the analytical solution of a 1-D advection-dispersion equation. The total length of the saline wedge calculated from the results of the numerical simulations showed good agreement with that obtained from an empirical formula.

The methodology and approach presented in this study are helpful for estimating the transient salinity distribution in estuaries with a long tidal reach, and where detailed input data for numerical simulation are lacking. Further studies are needed to verify model performance and to increase the accuracy in predicting the development of salinity intrusions.

ACKNOWLEDGEMENTS

This work was supported by Incheon National University (International Cooperative) Research Grant in 2016.

REFERENCES

Fischer, H. B., E. J. List, R. C. Y. Koh, J. Imberger and N. H. Brooks (1979). Mixing in inland and coastal waters, Academic Press.

Ippen, A. T. (1966). Estuary and coastline hydrodynamics, McGRAW-HILL.

Lee, M. E., and I. W. Seo (2010). 2D finite element pollutant transport model for accidental mass release in rivers. KSCE Journal of Civil Engineering 14(1), 77-86.

Ministry of Maritime Affairs and Fisheries (2001). Influence of tidal elevation on the basin of Han and Im-jin River.

National Institute of Environmental Research (2005). A Survey study on ecosystem of estuary.

Norton, W. R., I. P. King and G. T. Orlob (1973). A finite element model for lower granite reservoir. US Army Corp of Engineers.

Park, I., I. W. Seo, Y. D. Kim and C. G. Song (2016). Flow and dispersion analysis of shallow water problems with Froude number variation. Environmental Earth Sciences 75(2), 1-12.

Park, K. S. (2004). Salinity distribution and ecological environment of Han River Estuary. Journal Korean Wetlands Society 6(1), 14-31. (in Korean)

Seo, I. W. and C. G. Song (2007). Simulation of transport of BOD at the Han River using 2-D advection dispersion model. Journal of Korean Society of Civil Engineers 27(6B), 573-581. (in Korean)

Seo, I. W. and T. S. Cheong (1998). Predicting longitudinal dispersion coeffi-

cient in natural streams. Journal of Hydraulic Engineering 124(1), 25-32.
Seo, I. W., M. E. Lee and K. O. Baek (2008). 2D modeling of heterogeneous dispersion in meandering channels Journal of Hydraulic Engineering 134(2), 196-204.
Seo, I. W., N. J. Choi, I. O. Jun and C. G. Song (2009) Mixing characteristics of non-conservative pollutants in Paldang Lake. Journal of Korean Society of Civil Engineers 29(3B), 221-230. (in Korean)