Analysis of two-dimensional flow and pollutant transport induced by tidal currents in the Han River

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ABSTRACT

We simulated two-dimensional pollutant transport in the tidal reach of the Han River and examined the mixing induced by reversed flow. We used the downstream water surface elevation to reflect the tidal constituents of the Yellow Sea when modeling the flow characteristics. We found that reversed flows were repeatedly created and destroyed as the tide varied. The reversed flow affected the spatial variation of the dispersion coefficients and caused the lateral fluctuations of the dispersion coefficient to increase. The change in the flow direction was related to oscillatory variations in the concentration–time curves, and the horizontal recirculation zone at the front of the reversed flow became a storage area where the pollutant cloud was trapped. The concentration–time curves showed oscillatory changes that corresponded with the temporal variations of the flow direction, and the amplitude of the oscillations gradually decreased. The increases in the time for which the polluted water was retained at the riverine parks can be explained by the oscillations on the falling limb of the concentration curves.

Key words | 2D pollutant mixing, retention time, reversal flow, riverine park, tidal trapping

INTRODUCTION

Waterfronts are important spaces for recreational activities, and many rivers that cross urban areas have riverine parks that host water-friendly activities. Therefore, to ensure public safety, the water quality in urban rivers needs special consideration and management. There are many riverine parks along the Han River, the main channel and many tributaries of which flow through urban areas of Seoul, South Korea, where residents use the river water directly and indirectly. Sewage treatment plants in Seoul treat the large amounts of domestic wastewater that are generated in the residential areas and are responsible for discharging approximately 5.3 million m$^3$ of treated water into the tributaries of the Han River every day (Lee & Seo 2007). As well as receiving discharges from treatment plants, the tributaries are vulnerable to pollution from several nonpoint sources such as rainwater and runoff from roads and waste thrown directly into the channels. It is therefore useful to study contaminant transport in urban streams to generate information that can be used to support the development of disaster prevention plans that provide for unexpected incidents of water pollution (Guozhen et al. 2016). Numerical models that can simulate the concentrations of pollutants in aquatic environments are increasingly used when developing management plans and implementing water quality regulations (Cea et al. 2016).

The Han River flows into the Yellow Sea, which is between mainland China and the Korean Peninsula and has the second largest tidal range in the world. Because there is no sea barrage, the estuary of the Han River is directly affected by the tidal currents of the Yellow Sea, and numerical simulations have shown that tidal water can intrude as far as 19.4 km upstream from the river mouth in high tide conditions (Seo et al. 2008b). The tidal constituents of the Yellow Sea therefore affect both the
flow and water quality in the Han River. Park & Park (2000) analyzed temporal variations in water quality caused by tidal currents where the Han River flows into the Yellow Sea in Kyeonggi Bay, and reported that large inflows of freshwater at high tide changed the water quality. Park et al. (2002) numerically simulated a range of tidal conditions in Kyeonggi Bay, and found that the inflows of freshwater from the Han River increased during normal flow conditions. Previous studies of river flows have shown that the flow patterns and mixing properties of the Han River are affected by the tidal currents in the Yellow Sea. Seo et al. (2014a) analyzed the flow characteristics of the tidal reach of the Han River, and reproduced the construction and destruction of reversal flow by changing the tidal conditions. Lee & Seo (2007) compared pollutant mixing patterns in the Han River to determine how tidal flow influenced contaminant transport. Furthermore, Lee & Seo (2010) numerically simulated accidental pollutant spills, and obtained oscillatory breakthrough curves that were caused by the tidal conditions.

Dead zones induced by tidal flows have been defined as trapping mechanisms that increase the retention time of polluted water (Fischer et al. 1979). The trapped water is dispersed further by the backwards and forwards oscillatory flow, causing increases in the one-dimensional longitudinal dispersion coefficient in the tidal region. Okubo (1973) therefore derived a one-dimensional longitudinal dispersion coefficient that comprised the steady and unsteady terms from the oscillatory flow. Wolanski & Ridd (1986) reported the ecological implications of tidal currents from their analysis of tidal trapping phenomena in mangrove swamps of the Ducie-Wenlock River in northeast Australia. Ridd et al. (1990) used a two-dimensional numerical model to study the relationship between the retention time and tidal currents at a river mouth, and reported that the residence time increased as the distance to the head of the river decreased. Through simulations, Hellweger et al. (2004) also demonstrated how a dead zone caused by a lag phase of the tidal cycle affected tracer transport in the Hudson estuary. MacVean & Stacey (2011) considered the strength of tidal advection when deriving their one-dimensional longitudinal dispersion coefficient to quantify tidal trapping.

The oscillatory flow patterns of rivers are related to tidal currents and affect the pollutant transport mechanisms and the retention time. In this study, we simulated two-dimensional flow and pollutant transport in the tidal reach of the Han River and investigated the effects of tidal trapping near riverine parks. We then: (1) reproduced the flow reversal in the Han River from measurements of the water surface elevation and the design tidal constituent; (2) analyzed spatial and temporal variations in the dispersion coefficients from the unsteady component of the reversed flow; and (3) analyzed the concentration–time curves for the riverine parks under flow reversal conditions. The results clearly showed that polluted water was trapped and the pollutant retention time increased because of the reversed flow, which shows that the reversed flow affected the advection of pollutants and the dispersion of the pollutant cloud.

MODEL DESCRIPTIONS

Pollutant mixing was simulated with the River Analysis and Modeling System, which comprises a two-dimensional hydrodynamic model (HDM-2D) and a two-dimensional contaminant transport model (CTM-2D) (Seo et al. 2014b). The HDM-2D is governed by the two-dimensional shallow water equations derived by depth-averaging the continuity and momentum equations, as below:

$$\frac{\partial h}{\partial t} + u_i \frac{\partial h}{\partial x_i} + u_i \frac{\partial u_i}{\partial x_i} = 0$$  \hspace{1cm} (1a)

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -g \frac{\partial (H + h)}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \nu \frac{\partial u_i}{\partial x_i} \right) - \frac{g n u_i^2}{h} \sqrt{u_i u_j}$$  \hspace{1cm} (1b)

where $t$ is the time, $h$ is the water depth, $u_i = (u, v)$ is the depth-averaged velocity vector, $g$ is the gravity acceleration, $H$ is the bottom elevation, $\nu$ is the kinematic viscosity, and $n$ is Manning’s roughness coefficient. The governing equations were discretized with the finite element method. The Galerkin method was used to discretize the continuity equation, and the Petrov–Galerkin method was used to deform the shape function of the momentum equation along the flow.
direction, as follows (Takase et al. 2010):

\[
\int_{\Omega} \Omega \left[ \frac{\partial h}{\partial t} + h \frac{\partial u_i}{\partial x_i} + u_i \frac{\partial h}{\partial x_i} \right] d\Omega = 0
\]  

(2a)

\[
\int_{\Omega} \left[ \Omega \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} + g \frac{\partial (H+h)}{\partial x_j} + \frac{g n^2}{H} u \sqrt{u_i u_j} \right) + v \frac{\partial w_j}{\partial x_i} \right] d\Omega + \sum_{e=1}^{n} \int_{\Gamma_e} \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} + g \frac{\partial (H+h)}{\partial x_j} + \frac{g n^2}{H} u \sqrt{u_i u_j} \right) d\Sigma = 0
\]  

(2b)

where \( p_i \) is the perturbation function (Hughes 1987). The series of algebraic equations were solved with the frontal solver and the Newton–Raphson method was used to solve the non-linear equation included in the discretized momentum equations. Detailed descriptions of the model construction can be found in Song et al. (2016).

In river mixing problems, the introduced pollutants are regarded to be well-mixed over the flow depth because of the large width-to-depth ratio (Fischer et al. 1979). The depth-averaged pollutant transport model has been used previously to analyze pollutant transport in natural streams (Piasecki & Katopodes 1999; King et al. 2005; Lee & Seo 2007, 2010; Seo et al. 2008a; 2010, 2016). The governing equation of the CTM-2D was derived by assuming complete vertical mixing, as below (Lee & Seo 2007):

\[
\frac{\partial h C}{\partial t} + \frac{\partial}{\partial x_i} \left( h u_i C \right) + k h C = \frac{\partial}{\partial x_i} \left( h D_{ij} \frac{\partial C}{\partial x_j} \right) + M \delta(x_k - x_{ki}) \delta(t)
\]  

(3)

where \( C \) is the depth-averaged concentration, \( D_{ij} \) is the dispersion tensor, \( k \) is the reacting coefficient, \( M \) is the accidental released mass, and \( x_{ki} \) is the injection point of the mass pollutant. A source term was included in the CTM-2D, the third term on the right-hand side, to simulate accidental contaminant release, and the reaction term was also added to model non-conservative pollutant mixing (Seo & Lee 2007). Further, the spatially variable dispersion properties in natural streams were reproduced in the dispersion term using the tensor type dispersion coefficient, which was derived from the transformation of the coordinates, as below (Alavian 1986):

\[
D_{xx} = D_L \frac{u^2}{U^2} + D_T \frac{v^2}{U^2}
\]  

(4a)

\[
D_{xy} = D_{yx} = (D_L - D_T) \frac{uv}{U^2}
\]  

(4b)

\[
D_{yy} = D_L \frac{v^2}{U^2} + D_T \frac{u^2}{U^2}
\]  

(4c)

where \( D_L \) is the longitudinal dispersion coefficient, \( D_T \) is the transverse dispersion coefficient, \( U = \sqrt{u^2 + v^2} \); and \( D_{xx}, D_{xy}, D_{yx}, \) and \( D_{yy} \) are the components of dispersion tensor in the Cartesian coordinate. Using Equation (4), the CTM-2D model can describe the spatially variable mixing properties, so we do not have to use constant values of \( D_L \) and \( D_T \) and the model can be used to simulate pollutant mixing in complex flow structures (Lee & Seo 2010). We used the Streamline Upwind/Petrov–Galerkin (SU/PG) finite element scheme to discretize the governing equation of the CTM-2D model, as follows (Lee & Seo 2007):

\[
\int_{\Omega} \left[ \Omega \left( \frac{\partial (h C)}{\partial t} + \frac{\partial (h u_i C)}{\partial x_i} - \frac{\partial}{\partial x_j} \left( h D_{ij} \frac{\partial C}{\partial x_j} \right) + k h C - M \delta(x_k - x_{ki}) \delta(t) \right) \right] d\Omega = 0
\]  

(5)

The frontal solver was adopted to solve the algebraic equations. The CTM-2D model was coupled with the flow analysis model. The depth-averaged velocity field, used to calculate the advection of the pollutant cloud, was obtained from the results of HDM-2D.

**POLLUTANT TRANSPORT IN THE TIDAL REACH**

**Validating the flow analysis model**

We selected the middle part of the Han River between the Cheongdam Bridge and the Hang-ju Bridge as our study area (Figure 1). Upstream of the study reach, the channel meanders across the floodplain but then flows in a straight
line to the downstream boundary. The Hang-ju Bridge is about 40 km upstream of the Yellow Sea. The upstream discharge and the water level in the Han River are controlled by the Paldang Dam, which means that complex flow characteristics develop, resulting in reversal flow and periodic changes in velocity (Seo et al. 2014a). The two main tributaries in the study reach, the Jung-nang and the Anyang, which flow across the northeastern and southwestern parts of Seoul, discharge to the right and left banks of the Han River, respectively.

We validated the simulation results by comparing the results from the flow analysis in the HDM-2D model with the actual measurements of water elevation. We obtained upstream and downstream boundary conditions for the period from July 1 to July 3, 2015 from the Han River Flood Control Office. We used the flood season in South Korea as our study period because of the greater likelihood of contamination of the Han River. During this period the rainwater exceeds the maximum capacity of the sewage treatment plant and so can flow into the sewage systems. The time series of the upstream and downstream boundary conditions and of variations in the flow rates of the tributaries are shown in Figure 2. The boundary conditions show changes on a 24-hour cycle, during which there are two local maxima that correspond with the tide in the Yellow Sea. There was a time lag of 2 hours between the occurrence of the downstream maximum water surface elevation and the time taken for the flowrate at the upstream boundary to reach a maximum (Figure 2). The time series of the discharge in the tributaries show a step-wise function during the same period. The boundary conditions are summarized in Table 1. For the input parameters of HD-2M, we adopted the calibration results of Seo et al. (2014a), who studied flow characteristics in this tidal reach (Table 2). The Manning’s roughness coefficient was 0.025
in the main channel and 0.035 at the sidewall boundary. The eddy viscosity value was 4.0 m$^2$/s.

Figure 3 shows the time change in the streamlines, in which the reversed flow developed as the tide rose at the downstream boundary. After it decreased from the maximum discharge, the reversed flow also traveled upstream to beyond Seon-yu Island (Figure 3(b)) and then was destroyed when the upstream discharge began to increase and retreated downstream (Figure 3(c)). Also, because the increase in the second maximum flowrate was insufficient, reversed flow developed upstream of Banpo Park. Horizontal recirculation occurred at the interface between the forward and reversal flows, and created a dead zone where pollutants were trapped. The changes in the water surface elevation over time were compared with the actual measurements from the water level monitoring stations at the Hangang and Jamsu Bridges. Figure 4 shows that, even though there were some errors in the times of peak water level, the HDM-2D model adequately reproduced the rising and falling limbs of the changes in the water surface elevation. The mean absolute percentage errors at the Hangang and Jamsu Bridges were 2.18% and 3.19%, respectively.

**Pollutant transport in the tidal reach**

Even though the sewage from the urban area undergoes sewage treatment, the tributaries of the study reach

![Figure 3](https://iwaponline.com/jh/article-pdf/20/3/551/199954/jh0200551.pdf)
still contain pollutants. There are three riverine parks on the left bank of the study reach, Banpo, Yeouido, and Gangseo, and one, Ichon, on the right bank of the Han River. These riverine parks may be impacted by polluted water if the sewage treatment plants malfunction or if there are water pollution accidents. We assumed that there were water pollution accidents in the tributaries, and, from the distribution of polluted water near the riverine parks, investigated how the pollutants were mixed by the tidal flow.

The dispersion coefficient controls the mixing of the pollutant cloud by the shear flow (Fischer et al. 1979). The CTM-2D model calculates two-dimensional dispersion coefficients with Equation (4), and provides spatially variable dispersion coefficients (Seo et al. 2008a). Because the values of \( D_L \) and \( D_T \) vary to reflect the hydraulic properties of the river, it is important to input appropriate values so that the pollutant mixing is accurately predicted. When simulating pollutant transport in the Han River, Lee & Seo (2007) adopted the empirical formulas for \( D_L \) and \( D_T \) suggested by Elder (1959) and Fischer et al. (1979), respectively, as follows:

\[
D_L = 5.93 u' \\
D_T = 0.60 u'
\]

where \( u' = \sqrt{gRS_f} \) and is the shear velocity, \( R \) is the hydraulic radius, and \( S_f \) is the energy slope, calculated from the Manning’s formula. Figure 5 shows the spatial distributions of the dispersion tensor components, which were calculated using the depth-averaged velocity fields shown earlier. The spatial distribution of each component of the dispersion tensor (Figure 5) varied as the velocity field changed. The value of the \( D_{xy} \) component indicates dispersion of the pollutant cloud in positive or negative diagonal directions. Thus, when \( t = 33.7 \text{ hr} \), \( D_{xy} \) was positive in the forward flow, which means the pollutant cloud was stretched in the downstream direction in the upstream meandering section, but was negative downstream of the meanders. When \( t = 56.3 \text{ hr} \), \( D_{xy} \) was negative near the horizontal recirculation zone because of the reversal flow, and the pollutant cloud was rotated in this part by the combined effect of the dispersion tensor. The lateral variations in the constituents of the dispersion tensor, which were plotted at the boundary of the reversal and forward flows when \( t = 56.3 \text{ hr} \), are shown in Figure 6. The results show that each component of the dispersion tensor monotonically increased or decreased along the lateral direction when \( t = 33.7 \text{ hr} \), while the values of the dispersion tensor for a \( t \) value of 56.3 hr fluctuated laterally because of the flow reversal. It is noteworthy that \( D_{xy} = D_{yx} \) changed from positive to negative when the flow direction changed, which indicates that pollutants can be trapped by the tidal cycles.

We simulated pollutant transport in the study reach from the spatial and temporal variability in the dispersion tensor. When simulating the pollutant transport, we assumed that a conservative pollutant with a concentration of 50 ppm was continuously discharged from both the Jung-nang and An-yang streams for 12 hr because of a malfunction in the waste water treatment facilities. In this study, because we wanted to analyze the effect of shear dispersion
by flow characteristics without including the material properties of pollutants, we only considered soluble pollutants. Pollutants that flowed into the main channel from the Anyang mainly affected the left bank while those that flowed in from the Jung-nang affected the right bank (Figure 7). The pollutant cloud was trapped by a large horizontal circulation zone that developed at the interface of the flow reversal. Thus, the pollutant cloud receded near Bam and Seonyu Islands after 44.3 and 46.5 hr, respectively. We plotted the temporal evolution of the pollutant concentrations at each riverine park (Figure 8). The concentration–time curves show that the Ichon and Gangseo Parks, which are close to the tributary outlets, suffered most because of the polluted water. The maximum concentrations in the parks on the left bank (Yeouido and Banpo) were much lower, and were between 4% and 15% of the concentrations at Ichon Park. The falling limb of the concentration curve at Ichon Park was stretched because the pollutant cloud was transported upstream by the reversed flow. In addition, the concentration repeatedly peaked when reversed flows were created and destroyed. Water with high concentrations of pollutants remained in the

Figure 5 | Spatial variation in the dispersion tensor influenced by the velocity distributions.
Gangseo Park area near the outflow of the An-yang for about 24 hr because of changes in the flow direction.

POLLUTANT TRANSPORT IN THE DESIGNED TIDAL CURRENTS

We considered the downstream design tidal constituents when simulating the contaminant mixing in the study reach. Tides in the Yellow Sea are dominated by the principal lunar semi-diurnal tide, which is known as the M2 tidal constituent (Naimie et al. 2001; Kang et al. 2002). The downstream boundary elevations were reproduced as shown below:

\[ \eta(t) = A \cos(\omega t - G) \]  

(7)

where \( \eta \) is the water surface elevation, \( A \) is the amplitude, \( \omega \) is the frequency of the tide, and \( G \) is the time lag. Figure 9 shows the downstream surface elevations generated with Equation (7) for a discharge of 183.9 m\(^3\)/s, the
The tidal curve presented in Figure 6 shows that there was a difference of 1.20 m between the maximum water surface elevation of 3.98 m and the minimum elevation of 2.79 m. The Jung-nang and An-yang were also assumed to have normal flow conditions. The upstream and the downstream boundary conditions for the flow simulations are summarized in Table 1.

The simulation results of HDM-2D are shown in Figure 10, when the forward flow developed during the ebb tide \((t = 6 \text{ hr})\) and the reversed flow reached the confluence of the Jung-nang during the rising tide \((t = 9 \text{ hr})\). The interface of the reversed flow migrated to the area downstream of Bam Island when \(t\) was 12 hr, and a large horizontal recirculation zone was reproduced. Figure 11 shows the periodic variations in the flow patterns. The time changes of the dimensionless \(x\)-direction velocity component \((u/U)\) were plotted for each of the riverine parks. In Figure 10, the negative value of \(u/U\) indicates forward flow, and the positive value indicates a flow reversal. The results indicate that \(u/U\) was negative when the water surface elevation was decreasing, and changed to positive when the water surface elevation increased. The reversed flow arrived at Yeouido Park first, 70 min after the water surface elevation started to rise \((t = 6 \text{ hr})\), and then reached Ichon and Banpo Parks after 80 and 90 min, respectively. The reversed flow was therefore maintained at Yeouido Park for the longest time \((7.83 \text{ hr})\) and at Banpo Park for the shortest time \((6.83 \text{ hr})\).

The period for which the reversed flow is maintained is related to the retention time of polluted water, as shown earlier. We compared the times for which the contaminants were retained at the riverine parks based on the pollutant transport simulation results from the M2 tidal constituent with normal flow conditions. We simulated the pollutant transport with the CTM-2D model, with water with soluble pollutant concentrations of 50 ppm flowing into the main channel from the Jung-nang and An-yang for 12 hr. The normal flow condition of the River Han (MOLIT 2012).
Dispersion coefficients for reproducing the spatially and temporally variable mixing properties were calculated with Equations (4) and (6). The concentration distributions and the changes in the water surface elevation are shown in Figure 12. In high tide, the reversed flow pulled the polluted water to the upstream (Figure 12(b) and 12(d)), and the contaminants from the An-yang reached Seon-yu Island. The pollutant clouds were then advected backwards and forwards as the downstream water surface elevations varied with time.

The breakthrough curves for each riverine park downstream of the Jung-nang Stream are plotted against time in Figure 13. The maximum concentrations in the parks on the left bank (Banpo and Yeouido) were between 58% and 50% of the concentration at Ichon Park because of their position relative to the Jung-nang. The concentration curve for Ichon Park shows that the leading edge of the pollutant cloud arrived when $t$ was 26.0 hr, and the polluted water was transported to the upstream 80 min after the tide started to rise ($t = 30.0$ hr), in line with the change in the flow direction shown in Figure 10(b). After 36.0 hr, the peak concentration at Ichon Park oscillated because the concentration curves were superimposed by the reversed and forward flows, and the amplitude of the concentration curve gradually decreased as the transverse dispersion

Figure 10 | Velocity distributions near the riverine parks for the M2 tidal constituents.

Figure 11 | Temporal variations in the x-dir. velocity components in the riverine parks.

Figure 12 | Temporal variations in the x-dir. velocity components in the riverine parks.
progressed. The mixing properties mentioned earlier, which show the oscillatory falling limb of the concentration curves, caused the retention time of the polluted water to increase. The concentration at Banpo Park first peaked about 3 hr after the highest downstream water surface elevation occurred whereas the concentrations at the other parks peaked when the downstream water level was at a minimum. Of all the parks, the reversed flow was maintained for the shortest time at Banpo Park, as shown in Figure 11.

Thus, the pollutants that were transported to the upstream by the reversed flow merged with the forward flow after 33.0 hr, resulting in increased pollutant concentrations; the oscillations in the concentration–time curve for Banpo Park were therefore different from those for the other parks.

**CONCLUSIONS**

In this study, we simulated unsteady flow and pollutant mixing in the tidal reach of Han River as follows:

1. The flow simulations showed that the construction and destruction of the reversed flow corresponded with the changes in the downstream water surface elevation, and the reversed flow meant that the flow direction changed repeatedly.
2. The dispersion coefficients varied both temporally and spatially in the study reach because of the development of the reversed flow. The pollutants can be trapped at the front of the reversed flow because of the change in $D_{xy} = D_{yx}$ over the width of the channel.
3. Changes in the flow direction were related to oscillations in the concentration–time curves, and the amplitude of
the concentration curve gradually decreased with time. Further, the retention time of the polluted water increased because of oscillations along the falling limb of the concentration curves.

The flow simulations were based on measurements of water surface elevation at the Hangju Bridge, and there were errors of between 2.18% and 3.19% in the simulations. We extended the flow analysis to include the principal lunar semi-diurnal tide, the major tidal constituent of the Yellow Sea. The simulation results showed that the flow direction changed repeatedly and that, of all the parks in the study reach, the reversed flow was maintained at Yeouido Park for the longest time. The reversed flow affected the temporal variations of the dispersion coefficients; of these, the diagonal component of the dispersion tensor caused a storage effect at the front of the reversed flow. The pollutant transport simulation results show that the concentration–time curves at these riverine parks had long tails, which indicate oscillatory falling limbs, and this means that the retention time of polluted water increases. We therefore need to establish response plans for water pollution accidents that consider the effects of tidal trapping in the tidal reach.

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REFERENCES


King, I., Letter, J. V. & Donnel, B. P. 2005 RMA4 Users Guide 4.5x. US Army, Engineer Research and Development Center, WES, CHL.


Seo, I. W., Kim, Y. D. & Song, C. G. 2014a Analysis of flow characteristics around islands due to semi-diurnal currents in the Han River, Korea. *KSCE Journal of Civil Engineering* 19 (6), 1905–1915.


