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Analysis on the characteristics of a pollutant dispersion in river environment

Ki-Chul Kim [a], Geon-Hyeong Park [a], Sung-Hee Jung [a], Jung-Lyul Lee [b], Kyung-Suk Suh [a,*]

[a] Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, Daejeon 305-600, Republic of Korea
[b] Sungkyunkwan University, 300 Cheonchenondong, Janan, Suwon 400-746, Republic of Korea

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ABSTRACT

A tracer experiment using a radioisotope was carried out to investigate the characteristics of pollutant transport and to estimate the dispersion coefficients in a river system. A well-known radioisotope tracer technique was applied to measure the dispersion coefficients in Daejong river which is located in the southeast area in Korea. The dispersion coefficients were determined by moment, routing and analytical methods based on the measured radioisotope data. Two-dimensional numerical models were used to simulate the flow fields and the concentration distributions of the radioisotope injected into the river. The calculated results were compared with the measurements. As a comparative study, the computed concentration distributions agreed well in the case of the usage of the dispersion coefficients determined by the moment method.

1. Introduction

The transport of a pollutant in a river is carefully investigated and evaluated in the aspects of the conservation of water resources and aquatic ecosystems. The movement of a conservative pollutant entered into the river is mainly dependent on the advection and dispersion. Conservative pollutants in a river are transported in a dissolved form by the advection and dispersion processes without any interactions with suspended and bed sediments (Raul, 2005). Considerable research for dispersion of pollutants in the river has been applied to its conceptual and analytical modeling (Caplow et al., 2004; Smedt, 2007). Hydrodynamic dispersion, commonly known as the dispersion coefficient, indirectly includes the combined effects of molecular diffusion, turbulent mixing, and mixing due to transverse and vertical shear (Singh and Beck, 2003). Determination of the longitudinal and transverse dispersion coefficients is one of the important factors to evaluate the characteristics of a pollutant's behavior in a natural river.

There are several methods to determine the dispersion coefficients such as moment, routing and analytical approximations. The moment method is based on the moments of the measured concentration profiles (Fischer et al., 1979). The routing method is used to determine the dispersion coefficients by routing the temporal concentration profile from one section to the other (Fischer, 1968). The analytical method uses the solution of the advection–dispersion equation with trial and error (Smedt et al., 2005).

In this study, a field tracer experiment using a radioisotope was performed to understand the process of the pollutant transport and to determine the dispersion coefficients in the river. A short half-life radioisotope was injected instantaneously into a flow as a point source by an underwater glass-vial crusher. The detection was made with 2 in. NaI (Tl) scintillation detectors bound to the transverse lines at a downstream position. The radiotracer method is a useful tool for investigating the pollutant dispersion and a description of the mixing process taking place in natural streams. The main advantage is that tracer detection remains unaffected by such factors as variations in chemical composition of a labeled medium and the presence of deposits (Filip, 1971; Pujol and Sanchez-Cabeza, 1999). The radioisotope tracer is a conservative material which does not adsorb to sediments. The longitudinal and transverse dispersion coefficients were determined by moment, routing and analytical methods using the measured radioisotope data. Also, two-dimensional numerical models were used to simulate the flow patterns and the concentration distributions of the radioisotope injected into the river. The calculated results using the dispersion coefficients obtained from the radioisotope data were compared with measured concentrations by statistical and graphical methods.

2. Numerical models

A two-dimensional hydrodynamic model (RMA2) is used to simulate the velocity fields. RMA2 is a two-dimensional depth-averaged finite element hydrodynamic model (King, 1990). It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA2 solves the depth-averaged equations of fluid mass and momentum conservation in two horizontal directions. These equations can be written as follows:

* Corresponding author. Tel.: +82 42 8684788; fax: +82 42 8688943.
E-mail address: kssuh@kaeri.re.kr (K.-S. Suh).

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$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right)+\frac{gun^2}{\left(1.486h^{\frac{1}{6}}\right)^2}(u^2+v^2)^{\frac{1}{2}}-\delta v_a^2\cos\varphi-2hv\omega\sin\phi=0 \quad (1)$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right)+\frac{gvn^2}{\left(1.486h^{\frac{1}{6}}\right)^2}(u^2+v^2)^{\frac{1}{2}}-\delta v_a^2\sin\varphi+2hu\omega\sin\phi=0 \quad (2)$$

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \quad (3)$$

where, h is depth, u, v are velocities in the Cartesian directions, ρ is density of fluid, E is eddy viscosity coefficient, g is acceleration due to gravity, n is Manning's roughness, δ is empirical wind shear coefficient, v_a is wind speed, φ is wind direction, ω is rate of earth's angular rotation and ϕ is local latitude.

Two-dimensional dispersion model (RMA4) is also used to calculate concentration distributions. RMA4 is designed to simulate the depth-averaged advection–dispersion process in an aquatic environment (King and Rachiele, 1989). RMA4 is a finite element water quality transport numerical model in which the depth concentration distribution is assumed as uniform. The depth-averaged form of the two-dimensional advection–dispersion equation for a non-conservative material can be written as follows:

$$h\left(\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}-\frac{\partial}{\partial x}D_L\frac{\partial c}{\partial x}-\frac{\partial}{\partial y}D_T\frac{\partial c}{\partial y}-\sigma+kc+\frac{R(c)}{h}\right)=0 \quad (4)$$

where c is concentration, h is depth, u, v are velocities, D_L, D_T are dispersion coefficients in x and y direction, k is first order decay of pollutant, σ is source or sink term and $R(c)$ is rainfall or evaporation rate. The velocity fields are calculated in the hydrodynamic model and they can be supplied with the basic input in the dispersion model.

3. Determination of dispersion coefficients

A number of methods are used to calculate the dispersion coefficients. The longitudinal and transverse dispersion coefficients based on the moment method can be calculated in the following manner respectively (Fischer et al., 1979).

$$D_L=\frac{1}{2}\bar{u}^2\frac{d\sigma_t^2}{dt}=\frac{1}{2}\bar{u}^2\frac{\sigma_t^2(x_2)-\sigma_{t1}^2(x_1)}{\overline{t_2}-\overline{t_1}},$$
$$D_T=\frac{1}{2}\bar{u}\frac{d\sigma_y^2}{dx}=\frac{1}{2}\bar{u}\frac{\sigma_{y2}^2-\sigma_{y1}^2}{x_2-x_1} \quad (5)$$

where D_L is longitudinal dispersion coefficient, D_T is transverse dispersion coefficient, $\bar{u}$ is average velocity in the longitudinal direction, σ_t^2 is variance of the temporal concentration profile at any section of longitudinal direction, $\overline{t_1}$ and $\overline{t_2}$ are time to centroids of temporal concentration profiles at section x_1 and x_2, respectively and σ_y^2 is variance of the concentration at the transverse direction. The moment method is valid within the diffusive period, in spite of the skewed distribution of the trace cloud. But the difficulty in the moment method is that the long tails on observed distributions make it difficult to compute a meaningful value of the variance (Fischer et al., 1979).

The routing method uses the frozen-cloud approximation for routing the temporal concentration profile from one section (x_1) to the other (x_2) (Fischer, 1968; McQuivey and Keefer, 1974). This method obtains the longitudinal dispersion coefficient using the measured concentration at upstream and downstream stations. For known $c(x_1, t)$ and $c(x_2, t)$, D_L can be optimized in a least square sense to match the observed and calculated concentration profiles at a downstream section.

$$c(x_2,t)=\int_{-\infty}^{\infty}\frac{\bar{u}c(x_1,\tau)}{\sqrt{4\pi D_L(\overline{t_2}-\overline{t_1})}}\exp\left\{-\frac{[\bar{u}(\overline{t_2}-\overline{t_1}-t+\tau)]^2}{4D_L(\overline{t_2}-\overline{t_1})}\right\}d\tau \quad (6)$$

where $c(x_2, t)$ is concentration at downstream, $c(x_1, t)$ is concentration at upstream, τ is dummy integration variable denoting time, $\overline{t_1}$ and $\overline{t_2}$ are time to centroids of temporal concentration profiles at section x_1 and x_2, respectively. The routing procedure can avoid the problem of the moment method by matching a downstream observation of passage of a tracer cloud to the prediction based on an upstream observation. But the numerical integration of Eq. (6) may be introduced errors in the estimate of the dispersion coefficients (Singh and Beck, 2003).

Analytical solution of the two-dimensional advection–dispersion equation can be used to determine the dispersion coefficients using the measured concentrations (Singh and Beck, 2003; Vilhena and Sefidvash, 1985). Analytical solution of the two-dimensional advection–dispersion equation is as follows:

$$c(x,y,t)=\frac{M}{4\pi ht\sqrt{D_LD_T}}\exp\left(-\frac{(x-ut)^2}{4D_Lt}-\frac{(y-vt)^2}{4D_Tt}\right) \quad (7)$$

where M is the total tracer amount, h is the water depth, u and v are the flow velocities. A least square method was used to obtain the best values for the dispersion coefficients in the longitudinal and transverse directions. Analytical procedure can obtain the longitudinal and transverse dispersion coefficients simultaneously based on the measured data. But some errors may introduce for the irregular shape of the river because it derives from the idealized rectangular shape.

4. Field tracer experiment

A field tracer experiment using a radioisotope was carried out on July 16, 2008 in Daejong river for the purpose of investigating the characteristics of a pollutant transport and to estimate the dispersion coefficients. The central area of the Daejong river located in the southeast part of the Korea was selected for the tracer experiment (Fig. 1). The average width of the river is about 18–30 m and the average depth is about 0.2–2.0 m. Measurements of the velocity and bathymetry before the tracer experiment were performed to select the sampling lines for the detection of the radioisotope. Two radiotracer injection experiments were performed in the morning (Exp-1) and afternoon (Exp-2). The release points and detection lines of the tracer were determined by GPS system (Fig. 2). Exp-1 and Exp-2 in Fig. 2 show the experimental sections in the morning and afternoon, respectively. Detectors in the transverse direction on lines 1 and 2 were deployed with the 7 and 8 ones, respectively. Average distance between each detection point in the transverse direction on lines 1 and 2 was about 2 m and 2.5 m, respectively. The measured concentration profiles of tracer in Exp-1 and Exp-2 presented in Figs. 3 and 4.

The radioisotope ^{99m}Tc which is a gamma emitter with a half-life of 6.02 h was used as the trace element. Technetium-99 m milked from a $^{99}Mo/^{99m}Tc$ generator fabricated for medical purpose has 0.141 MeV of gamma radiation. The nuclide is eluted with a 0.01 N HCl solution from a generator in the form of a TcO_4^- anionic ion which is so stable as to be one of the best radiotracers for an aqueous environment. Also, ^{99m}Tc is a conservative radioisotope which is suitable for this kind of experiments. The radioisotope