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Brine discharges into shallow coastal waters with mean and oscillatory tidal currents

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Abstract

The development of a mathematical model on the cumulative effects due to brine discharges into shallow coastal waters with a flat seabed is conducted in this study. The model incorporates the effects of tidal currents, which are commonly encountered in the natural coastal environment. The tidal currents are represented by a small constant component, V (normally referred as residual or drift current), plus a periodic part, $U_0 \sin \omega t$. Anisotropic eddy dispersivities in the alongshore and cross-shore directions are also incorporated. The convergence to the quasi-steady state for the salinity excess due to the continuous brine input has been studied for the first time. The application of the mathematical model to assess a hypothetically practical discharge is also performed. Model predictions for representative velocity ratios of ν ($=V/U_0$) are obtained. In general, the placement of the outfall further offshore has been shown to reduce the shoreline impact as expected. A comparison of the results between constant and time-dependent dispersivities has been conducted.

Keywords: Brine discharges; Mathematical model; Salinity build-up; Tidal currents

1. Introduction

Desalination has become an increasingly viable option to supplement the water supply for many coastal cities due to the significant advancement of the relevant techniques and the reduction of cost. The size of the desalination plants has also grown substantially over the years. Meanwhile, the potential environmental impact caused by the desalting processes, particularly that from the desalination discharges has drawn growing attention from government agencies and desalination industries (Mabrook, 1994).

The operation of the desalination plants leads to a continuous discharge of brine, which is a highly concentrated saline water, as a by-product into the seawater. The discharges of the brine are normally through either surface outfalls at the shore or submerged outfalls at the seabed. Although the presence of salinity seems natural to seawater, an excessive input of salinity can adversely affect exposed marine organisms, particularly if the exposure lasts an extended period of time, which would be the case for continuous brine discharges (Iso et al., 1994). It is also recognized that an increase in the salinity of the ambient waters at the intake will impair the efficiency of salt removal and increase the operation cost in the long run. Another concern is the discharge of chemicals from the pretreatment processes into the seawater together with the brine releases.

Despite the significance of addressing this issue to meet the needs of the fast developing desalination industry, relevant work has been scarce in the literature. Purnama et al. (2003) studied the steady-state effect of brine discharges on local salinity. Thereafter, they extended their study to the effects of an oscillatory tidal flow in dispersing the brine discharge occurring in the Gulf of Oman (Purnama and Al-Barwani,

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2006). More recently they showed that the maximum shoreline salinity would remain constant throughout the tidal cycles and thus can be used as an indicator for regulatory purpose (Al-Barwani and Purnama, 2008). Despite these studies, the temporal evolution and the ultimately persistent fluctuation in salinity in the quasi-steady state are not reported in the literature so far.

In the following sections, we investigate the salinity build-up processes due to the continuous brine discharge, focusing particularly on the salinity fluctuations in the presence of the oscillatory tidal currents, as well as the effects of other relevant parameters including the anisotropy and possible time dependency of the dispersivities.

2. Development of mathematical model

We consider a desalination plant situated off an idealized straight shoreline in a costal region where the water depth, h_0, is assumed to be constant. During a tidal cycle, seawater flushes back and forth along the shore direction within a limited distance (normally referred to as the ‘tidal excursion’), and assists in spreading the salinity excess due to the brine discharges in the coastal region. We assume the presence of an alongshore tidal current, $U(t)$, which consists of a small constant residual or drift current, V, plus a periodic component, $U_0 \sin \omega t$, i.e.

$$U(t) = V + U_0 \sin \omega t \tag{1}$$

where U_0 is the amplitude of the oscillatory current and is typically much larger than the magnitude of the residual current V, $\omega = 2\pi/T$ (T is the tidal period) is the angular frequency of the oscillatory current, and t denotes time. In this study, U_0 is assumed to be invariant in the domain of analysis. x and y axes are taken to be perpendicular to and coincident with the shoreline, respectively. The brine outfall is deployed at a distance of x_0 offshore, and acts like a point source of concentrated brine injection.

For shallow coastal waters, the dispersion in the vertical direction occurs much faster than the horizontal directions. Hence, the transient salinity advection–diffusion equation can be derived in the following two-dimensional form,

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - U(t)\frac{\partial C}{\partial y}, \quad 0 \le x < \infty, \quad -\infty < y < \infty \tag{2}$$

where C denotes the salinity excess above the ambient level, and D_x and D_y are the eddy dispersivities in the x and y directions, respectively.

The boundary conditions applied herein are,

- Salinity excess tends to zero at great distances from the outfall, i.e.

$$C \to 0 \quad \text{as} \quad x \to \infty \quad or \quad y \to \pm\infty$$

- The shoreline acts as a solid boundary with a no-flux condition, i.e.

$$\frac{\partial C}{\partial x} = 0 \quad \text{at } x = 0, \quad \text{for all } y$$

Referring to the general solution of the one-dimensional advection–diffusion equation with time-varying flow and diffusivity derived by Holley (1969), the solution to Eq. (2) can be written in the form of a convolution integral as,

$$\begin{aligned} C_c(x,y,t) = \frac{C_0 Q}{4\pi h_0 \sqrt{D_x D_y}} \int_0^t \Bigg\{ & \exp\left[-\frac{(x-x_0)^2}{4D_x(t-t_0)} - \frac{\left[y - V(t-t_0) + \frac{U_0}{\omega}(\cos\omega t - \cos\omega t_0)\right]^2}{4D_y(t-t_0)} \right] \\ & + \exp\left[-\frac{(x+x_0)^2}{4D_x(t-t_0)} - \frac{\left[y - V(t-t_0) + \frac{U_0}{\omega}(\cos\omega t - \cos\omega t_0)\right]^2}{4D_y(t-t_0)} \right] \Bigg\} \frac{dt_0}{t-t_0} \end{aligned} \tag{3}$$

where C_0 is the volumetric solute concentration (i.e. salinity excess) at the source, Q is the brine discharge flow rate, C_c is the resulting volumetric solute concentration due to the continuous injection from time zero to time t, and t_0 is a dummy variable.

To facilitate the computation and presentation of results, dimensionless variables are defined as follows,

$$\begin{aligned} &\tau = \omega t, \quad \tau_0 = \omega(t - t_0) \\ &\xi = \frac{\omega x}{U_0}, \quad \xi_0 = \frac{\omega x_0}{U_0}, \quad \eta = \frac{\omega y}{U_0} \\ &C^* = C/\left(C_0 Q / 4\pi h_0 \sqrt{D_x D_y}\right) \end{aligned} \tag{4}$$

Substitution of these variables into Eq. (3) yields,

$$\begin{aligned} C_c^*(\xi,\eta,\tau) = \int_0^\tau \frac{d\tau_0}{\tau_0} & \left\{ \exp\left[-\lambda\alpha^2 \frac{(\xi-\xi_0)^2}{\tau_0} \right] + \exp\left[-\lambda\alpha^2 \frac{(\xi+\xi_0)^2}{\tau_0} \right] \right\} \\ & \cdot \exp\left[-\lambda \frac{[\eta - \nu\tau_0 + \cos\tau - \cos(\tau-\tau_0)]^2}{\tau_0} \right] \end{aligned} \tag{5}$$

where we have introduced three dimensionless parameters characterizing the advection–diffusion process, namely, the dispersivity ratio,

$$\alpha = \left(\frac{D_y}{D_x}\right)^{1/2} \tag{6}$$

which compares the longitudinal dispersivity to the lateral dispersivity, the velocity ratio,