Quantify the Influence of the Ocean Current on the Submarine Groundwater Discharge

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ABSTRACT

In recent years, submarine groundwater discharge (SGD) is one of the important processes in the hydrological cycles. Previous investigations have recognized that many factors, such as the shoreline slopes, aquifer hydraulic conductivity, and tidal amplitudes might significantly control the SGD rates for an interested site. Ocean currents are common phenomena around the world that typically occur near coastal lines. The ocean currents may create pressure changes due to the current flows pass through interfaces of aquifers and seawater. This study employed HYDROGEOCHEM (Hydrologic Transport and Geochemical Reactions Model) numerical model to quantify the influences of ocean currents on output fluxes of SGD. A synthetic two-dimensional profile model is considered for illustration purpose. Based on the energy conservation equation (Bernolli's equation) for groundwater flow, the velocity heads influenced by ocean currents are not negligible in this study because the velocities of ocean currents are several orders of magnitudes greater than that of groundwater. With a variety of ocean current velocity values (from 0.2 m/s to 1.5 m/s) applied in the numerical model, we found that the ocean current leads to the increase the SGD rate up from 2.6 m/d to 6.3 m/d when the ocean current velocity was increased from 0.1 to 1.5 m/s. Such results suggest that the influences of ocean currents on SGD rates are significant, especially for coastal lines with high ocean current velocities.

INTRODUCTION

Submarine groundwater discharge (SGD) is defined as any upward flux of water from seabed sediment into the overlying marine water column (Smith 2004). Previous studies show that various factors impacts SGD, including terrestrial geometry (e.g., Konikow et al. 2013), tides (e.g., Li et al. 2009), waves (e.g., Nielsen 1990), density convection (e.g., Taniguchi et al. 2002), and seasonal recharge (e.g., Michael et al. 2005).

Despite of those factors impact on the SGD, interactions between aquifer surfaces have also studied for years (e.g., Cardenas and Wilson 2006). However, they often focused on the particle erosion or small scale relationship, little attention is paid for larger scale, such as the flux changed of SGD and the interaction between ocean current and aquifer.

This study went to employ HYDROGEOCHEM 4.0 to simulate SGD in two-dimensional unconfined coastal aquifer. Base on the measured velocity 92cm/s of Kuroshio around east coastline of Taiwan (Zhu et al. 2006). The influence of ocean current on SGD will be quantified with five velocities of ocean current 0.1, 0.5, 1.0, 1.5 m/s.

METHODS

HYDROGEOCHEM 4.0

HYDROGEOCHEM4.0 is a two dimensional numerical model coupled of water flow, thermal transport, solute transport, and mixed geochemical kinetic/ equilibrium reactions in a saturated/unsaturated porous media. This model is designed for a generic application to reactive transport problems controlled by both kinetic and equilibrium reactions in subsurface media (Yeh et al., 2004). HYDROGEOCHEM 4.0 was employed to simulate SGD in two-dimensional unconfined coastal aquifer in this study. Five velocities of ocean current 0.1, 0.5, 1.0, 1.5 m/s will flow through the aquifer in seaside, the current velocity result in pressure head reduced on seawater boundary due to Bernoulli's equation. The influence of ocean current on SGD can be quantified finally.

Flow equation

The flow equation of HYDROGEOCHEM is modified Richard equation that describes density dependent fluid flow in variably saturated media. It can be derived based on continuity of fluid continuity of solid, Darcy's law, consolidation of the media, and compressibility of water (Yeh et al., 2004):

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \cdot [\mathrm{K} \cdot (\nabla \mathrm{h} + \frac{\rho}{\rho_0} \nabla \mathrm{z})] + \frac{\rho^*}{\rho_0} q \tag{1}$$

in which F is the generalized storage coefficient (1/L), K is the hydraulic conductivity tensor (L/T):

$$F = \alpha' \frac{\theta}{n_e} + \beta' \theta + n_e \frac{\partial S}{\partial h} \tag{2}$$

$$K = \frac{\rho g}{\mu} k = \frac{(\frac{\rho}{\rho_0})}{(\frac{\mu}{\mu_0})} K_{so} K_r \tag{3}$$

where ρ is the fluid density (M/L^3), ρ_0 is the referenced fluid density (M/L^3), h is the pressure head (L), t is the time (T), z is the potential head (L), ρ* is the fluid density of either injection or with draw (=ρ) (M/L^3) and q represent the source or sink representing the artificial injection or withdraw of fluid [(L^3/L^3)/T]. In equation (2),α' is the modified compressibility of the media (1/L), θ is the effective moisture content (L^3/L3), n_e is the effective porosity (L^3/L^3), β' is the modified compressibility of the liquid (1/L) and S means the degree of saturation of water (dimensionless). For equation (3), μ_0 is the fluid dynamic viscosity at zero chemical concentration [M/(LT)], μmeans the fluid dynamic viscosity [M/(LT)], K_{so} is the referenced saturated hydraulic conductivity tensor (L/T) and $k_r=k/k_s$ represent the relative permeability or conductivity (dimensionless).

Transport Equation

The transport equation for species i consider advection, dispersion, diffusion, source/sink, radioactive decay and biogeochemical reaction. The equation was derived based on the continuity of mass and Fick's laws (Yeh et al., 2004):

$$\frac{\partial \theta C_i}{\partial t} + (\theta \alpha' \frac{\partial h}{\partial t} + \frac{\partial \theta}{\partial t}) \mathrm{C}_i = (\mathcal{L}(\mathrm{C}_i) - \mathrm{QC}_i) + M_i + \theta r_i \big|_R , i \in \{N\} \tag{4}$$

in which $\mathcal{L}$ is the advection-dispersion operator denoting:

$$\mathcal{L}(\mathrm{C}_i) = -V \cdot C_i + \nabla \cdot (\theta \mathrm{D} \cdot \nabla \mathrm{C}_i) \tag{5}$$

$r_i\big|_R$ denotes production rate r_i due to R reactions, which is described by:

$$r_i\big|_R = \sum_{i=0}^{R} (\nu_{ik} - \mu_{ik}) R_K \tag{6}$$

where {N} = {1, 2,...,N} in which N is the number of species. In equation (4), C_i is the concentration of the i- th species in units of chemical mass per water volume [M/L^3] and M_i means the external source/ sink rate of the i- th per unit medium volume [(M or L^3)/T]. For equation (5), V means the Darcy's velocity [L/T] and D represent the dispersion coefficient tensor [L^2/T]. In equation (6), ν_{ik} and μ_{ik} are the reaction stoichiometry of the i-th species in the k- th reaction associated with the products and reactants respectively.

Since seawater intrusion is often considered as density-dependent problem, in HYDROGEOCHEM, the density of groundwater is a function of chemical concentration as (Cheng, 1995) :

$$\rho = \rho_w + \sum_{i=1}^{M_a} c_i m_i (1 - \frac{\rho_w}{\rho_i}) \tag{7}$$

In this study, the temperature is considered as a constant 25℃, and the activity coefficient of ion is neglected.

Conceptual model

The conceptual model is shown in Figure 1. The left hand side of the domain is land boundary, and right hand side is sea boundary. The length of the simulation domain is 200 m, and the depth is 33 m. Beach slope 10 % started from distance 120m to 180m from land boundary. In simulation domain, it contains 1573 nodes and 3000 elements.

The tide waveform used in the sea boundaries with amplitude 1 m, and the frequency is 2 times per day. It was divided in 64 equal stress periods to capture the tide above the beach face during simulation time 8 days.

Constant head 31 m is used for the land side flow boundary conditions, and sea boundaries is sets as no flow. This study considers seawater as a density-dependent liquid with constant concentration 0.59 mole/L, mean sea level locates with Z=30 m. Following Robinson et al. (2007), longitudinal dispersivity is sets as 0.5m, the transverse dispersivity is 0.05 m, the porosity of the aquifer is set 0.25, and diffusion coefficient is 6.6E-2 m^2/day. Note that the aquifer is assumed homogeneous and isotropic, which the hydraulic conductivity is 10 m/day.

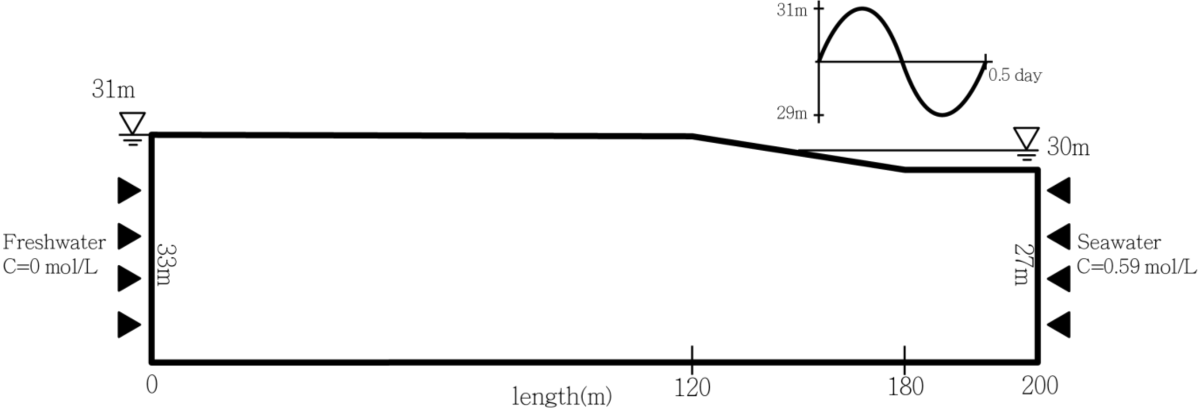

Figure 1. The conceptual model of simulation domain

To simply the situation when ocean current flows upon the aquifer, this study assumed seawater is constant concentration and frictionless, considered the Bernoulli's equation, which is:

$$\frac{P}{\rho g} + \frac{V^2}{2g} + z = H \tag{8}$$

where P is pressure [F/L^2], H is total head in aquifer[L] , z means height of considered point [L]. g is gravitational acceleration [L/T^2], V is velocity of ocean current [L/T], which is often neglected in groundwater problems. Following Bernoulli's equation, the ocean current will reduce the pressure gradient in aquifer with $\frac{V^2}{2g}$.

RESULTS AND DISCUSSION

Figure 2 illustrates the saline concentration distribution with and without ocean current in simulation time 8 days. In Figure 2, except the seawater freshwater interface, similar to previous studies, tide fluctuation makes an upper saline plume (USP) on the beach slope. Figure 2b shows that due to pressure head decreased by ocean current, the seawater/ freshwater interface moved more closed to seaside than the situation without ocean current. However, ocean current also increase the influences of tide on beach slope, it makes the range of USP bigger. Figure 3 shows that freshwater in aquifer discharged into ocean due to ebb tide, which is one of physical processes in seawater circulation (Santos et al., 2012). Compare to Figure 2a and 2 b, ocean current increases hydraulic from land to sea, it makes more freshwater discharge to the sea.

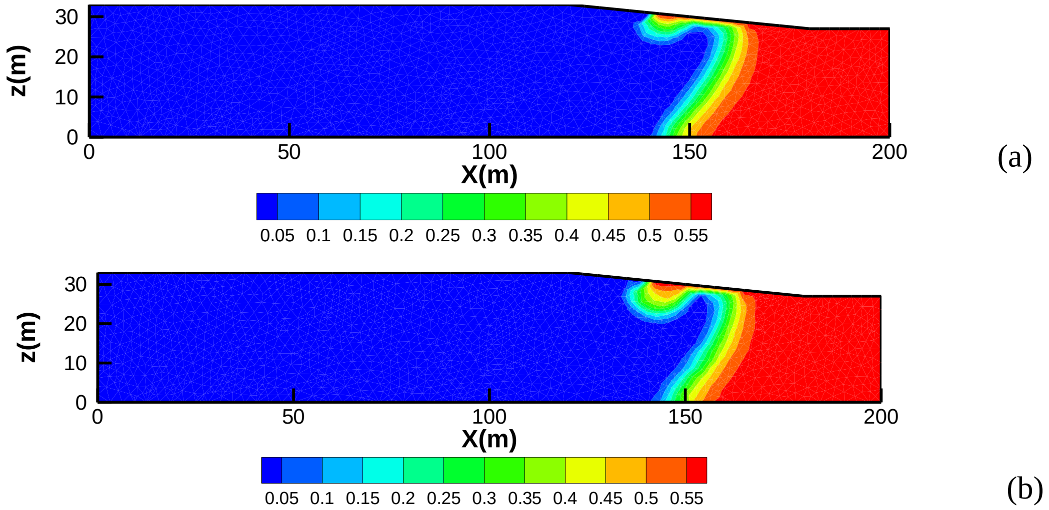

Figure 2. Saline concentration distribution at ebb tide in time=8 day (a) without ocean current and with ocean current V=1.5m/s (mole/L)

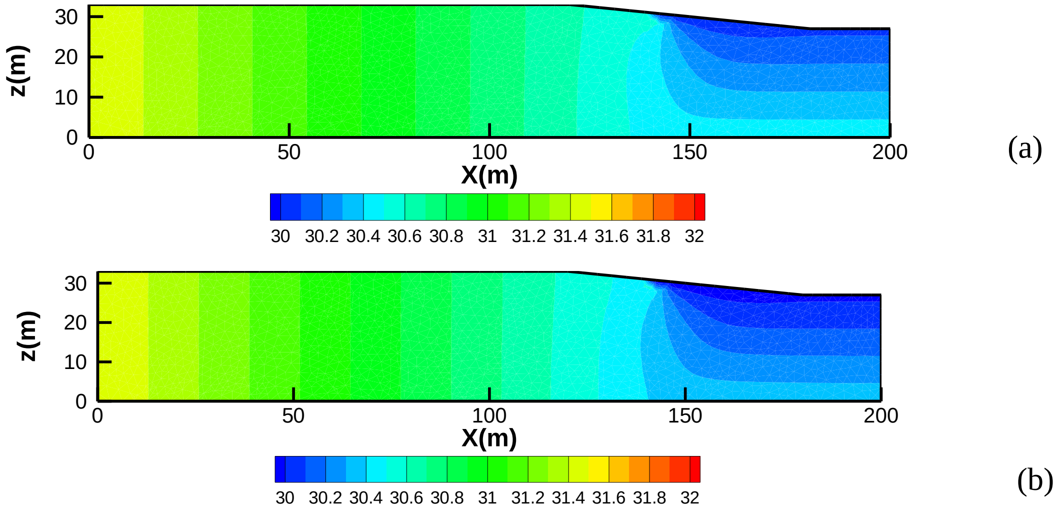

Figure 3. Total head at ebb tide in time=8 day (a) without ocean current and with ocean current V=1.5m/s (mole/L)

Freshwater discharge velocity on beach slope was employed to quantify the influences of ocean current in this study. In Figure 4, it shows that ocean current have significant effect on the discharge velocity, in V=1.5 m/s case, the output velocity can increase from 2.6m/d to 6.3m/d when the ocean current velocity was increased from 0.2 to 1.5 m/s.

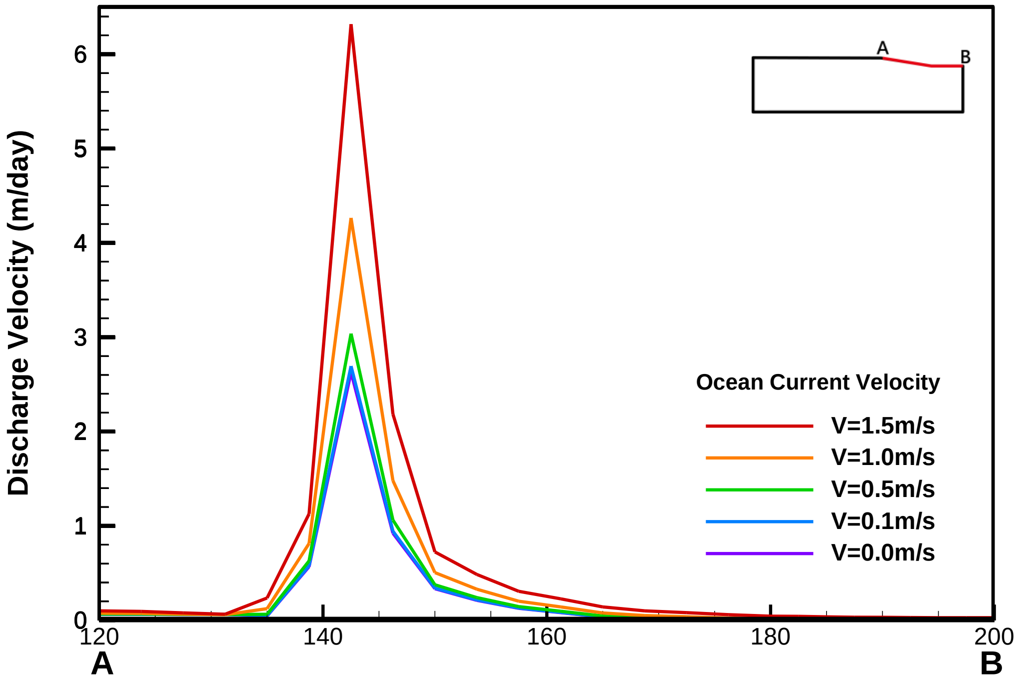

Figure 4. Freshwater discharge velocity on the beach slope

CONCLUSIONS

This study simulated the influence of ocean current on beach slope by using Bernoulli's equation, simulation results show that the ocean current effect will: (1) reduce the penetrate distance of seawater/freshwater interface; (2) increase the range of upper saline plume. Moreover, ocean current makes more freshwater discharge into to the sea, the output velocity can increase from 2.6m/d to 6.3m/d when the ocean current velocity was increased from 0.2 to 1.5 m/s.

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