A New Focus on Groundwater–Seawater Interactions
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Submarine groundwater discharge under extreme rainfall events

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Abstract In coastal areas, it is recognized that seasonal variation of precipitation rates affects the hydraulic gradient of groundwater and thus submarine groundwater discharge (SGD) rates. In this study, we estimated the total outflux rate through the seepage face and seabed from the coastal aquifer by using the numerical code, FEFLOW. In particular, we focused on the effect of a localized pulse-type precipitation on SGD flux pattern. The calculated SGD flux with time-varying recharge rate shows a quite different pattern from the one with constant recharge rate and each type of the recharge yields a unique pattern of SGD. The results imply the dynamic boundary condition along the land side is significant and that SGD can be miscalculated when incorporating constant precipitation or recharge rate.

Key words submarine groundwater discharge (SGD); heavy rainfall effect; FEFLOW

INTRODUCTION

Submarine groundwater discharge (SGD) is one of the main processes which transfer contaminants and nutrients from inland to the sea; therefore, it has a significant effect on the estuarine environment and ecosystem. It being difficult to observe its existence and effects on the environment, scientific interest toward SGD has not occurred until recently. Even though numerous studies have been performed to identify SGD for several years, many components of it still exist that cannot be explained scientifically. In particular, recent studies of SGD mainly focus on the effect of dynamic oceanic conditions such as tide, waves and current, and show insufficiency in reflecting the dynamic hydrological conditions of inland areas (Taniguchi, 2002; Kim *et al.*, 2003; Li *et al.*, 2005). Michael *et al.* (2005) show the impact of seasonal oscillation of inland recharge rate with a sinusoidal shape to the SGD flux, but such a gradual change of recharge is not enough to represent rapid changes due to storms or heavy rainfall events. So in this study, we focus on the localized effect of a heavy rain event on SGD. Then, conducting the simulation for calculating outflux through the aquifer for several years with actual precipitation data, we investigated seasonal and annual variations of SGD.

METHOD

Conceptual model

A two dimensional vertical section of an unconfined coastal aquifer was constructed (Fig. 1). Then, a prescribed flux boundary condition, which considers the temporal

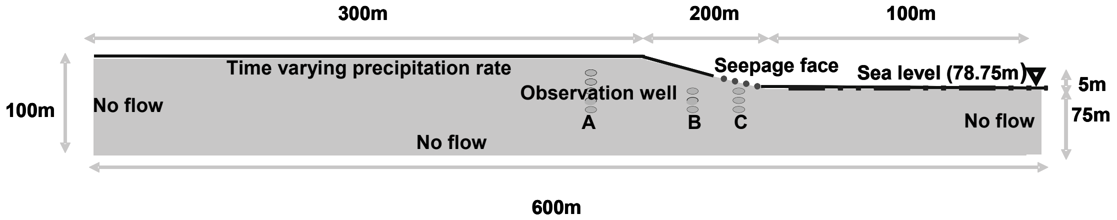


Fig. 1 Schematic representation of domain.

change of precipitation rate, is set on the top boundary and the time-varying SGD flux rate is calculated at each time. Also, three monitoring wells (A, B, C) are installed to investigate the variation of hydraulic head and salinity. Two different kinds of recharge rate are assigned: one is a sinusoidal curved type which emphasizes seasonal climate variation, and the other is a pulse type which focuses on the heavy rain effect in summer. For the heavy rainfall condition model, we pick the two days with the highest precipitation rate in a year. We also keep the average of the recharge rate the same as each other for the comparison. Finally, monthly averaged recharge rates for the last 10 years in Korea are assigned to the model and the SGD flux is calculated to demonstrate the relationship between the intensity of precipitation rate and SGD flux.

Governing equations

FEFLOW (Diersch, 2005) is used for solving coupled equations of variably saturated density-dependent flow and solute transport. Balance equations of fluid mass and momentum are given by:

$$[S_o \cdot s(\psi) + \varepsilon \cdot C(\psi)]\partial h / \partial t + \nabla \cdot \mathbf{q} = Q_h \tag{1}$$

$$\mathbf{q} = -K_r(s)\mathbf{K} \cdot \left[\nabla h + (\rho - \rho_o) / \rho_o \mathbf{e}\right] \tag{2}$$

where S_o is the specific storage coefficient, $C(\psi)$ is the relationship for the saturation dependent moisture capacity, $s(\psi)$is the empirical relationships for the capillary pressure head- saturation, ε is the porosity, h is the hydraulic head, t is the time, $\mathbf{q}$ is the Darcy flux vector, Q_h is the fluid source, $K_r(s)$ is the relative conductivity, $\mathbf{K}$ is the tensor of hydraulic conductivity, ρ is the fluid density, ρ_o is the reference fluid density and $\mathbf{e}$ is the gravitational unit vector.

And, the conservation equation for solute mass is given by:

$$s(\psi)\frac{\partial C}{\partial t} + \mathbf{q} \cdot \nabla C - \nabla \cdot [(\varepsilon \cdot s(\psi) D_d \mathbf{I} + \mathbf{D}) \cdot \nabla C] = 0 \tag{3}$$

where C is the concentration of solute in the fluid phase, D_d is the molecular diffusion coefficient, $\mathbf{I}$ is the identity tensor, $\mathbf{D}$ is the mechanical dispersion tensor.

The following equations are constitutive relations for the nonlinear coupling processes.

$$h = p / \rho_o g + z \tag{4}$$

$$\rho = \rho_o[1 + \alpha(C - C_o)] \tag{5}$$

where p is the fluid pressure, g is the gravitational coefficient, z is the elevation head, α is the fluid density difference ratio, C_o is the reference concentration of solute.

RESULTS

Hydrograph of SGD with different types of recharge rate

Figure 2 illustrates the relationship between recharge rate and SGD rate under a sinusoidal curved recharge rate. About 50 days of time lag between the maximum (and minimum) recharge rate and the maximum (and minimum) SGD rate exists. It is known that seasonal variation of recharge rate mainly controls the height of seasonal water table change and thus, the location of the freshwater–saltwater interface. This seasonal shift of interface makes the amount of recirculated seawater change with time (Michael *et al.*, 2005).

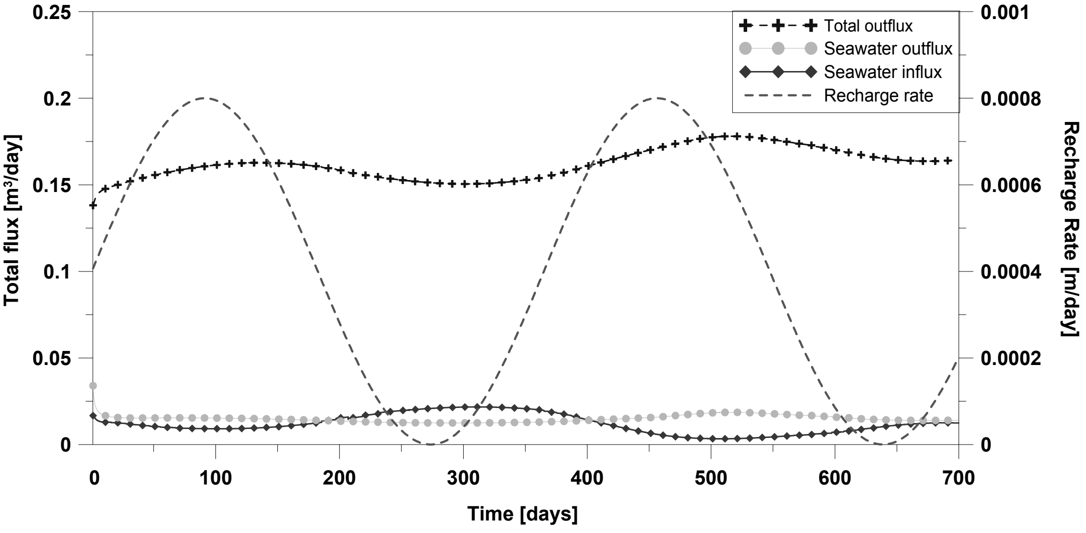


Fig. 2 Hydrograph of SGD with sinusoidal recharge rate.

Figure 3(a) and (b) illustrates the hydrograph of SGD when heavy rainfall events are included. For a pulse-type recharge event, the time lag between maximum precipitation and maximum SGD is about 2–3 days which is much shorter than that for the sinusoidal recharge. The high intensity of rainfall flux near the seepage face may cause this short lag. Modelling results indicate that a sudden increase of precipitation causes an increase of freshwater and seawater outflux to the ocean, while seawater influx through the seafloor decreases after the specific event. The increase of seawater outflux probably occurred not only as the freshwater–seawater interface moved backward to the seaside but also because of dispersive flushing due to the increased freshwater flux.

Figure 4(a) and (b) shows the equivalent hydraulic head and relative concentration of salinity change with time in the monitoring wells. The effect of heavy rainfall on the salinity and hydraulic head can also be observed.

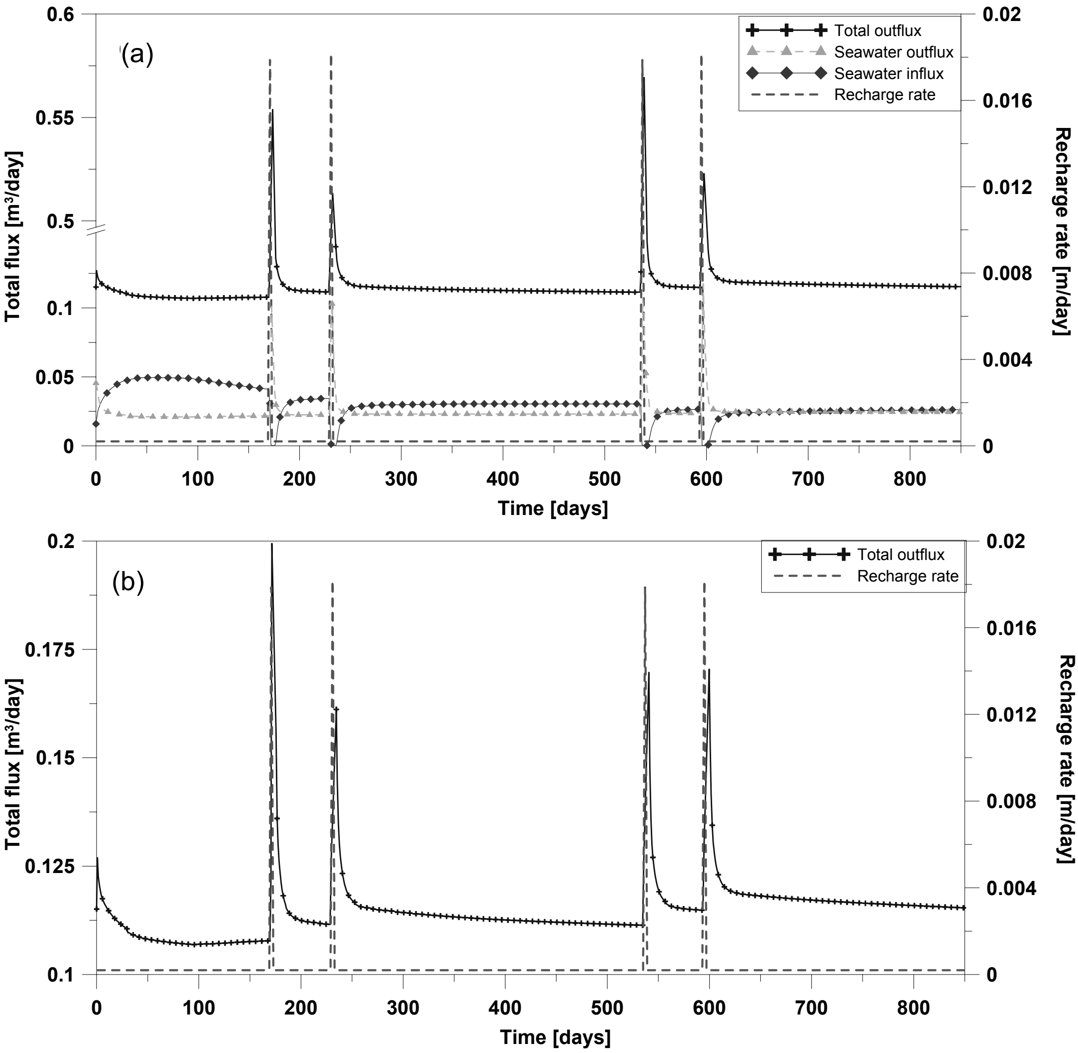
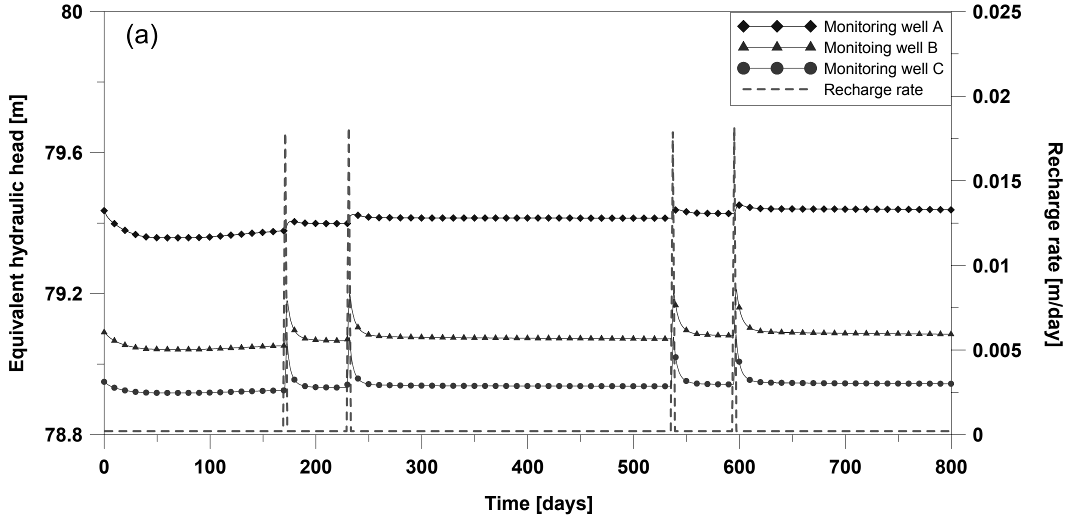


Fig. 3 (a) Hydrograph of SGD with pulse type recharge rate. (b) An enlarged partial section of total outflux through the aquifer, increase of SGD after the heavy rainfall event is observed.

Long-term variation of SGD

Figure 5 shows the long-term relationship between the precipitation rate and the SGD flux. The simulation result indicates time-varying precipitation and its intensity has a formidable effect on SGD variation. The modelling results also indicate that there exist different patterns of SGD flux every year. This annual change of outflux represents the effect of precipitation rate of each year. Also, the volume of outflux is influenced by the recharge rate from the previous years. Figure 5 shows this effect in which the higher recharge rate between days 210 and 240 leads to the upper shift of the SGD flux till about 1000 day. This phenomenon is more evident in the latter part of the graph.



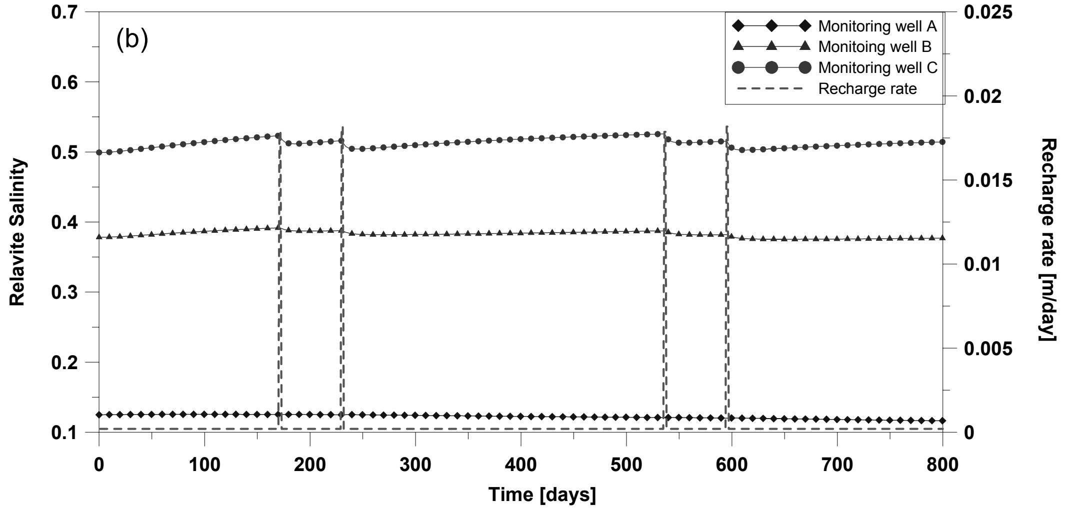


Fig. 4 (a) Equivalent hydraulic head and recharge rate. (b) Relative salinity and recharge rate. Monitoring depth from wells A, B and C are 50 m, 24 m, and 18 m below the surface respectively.

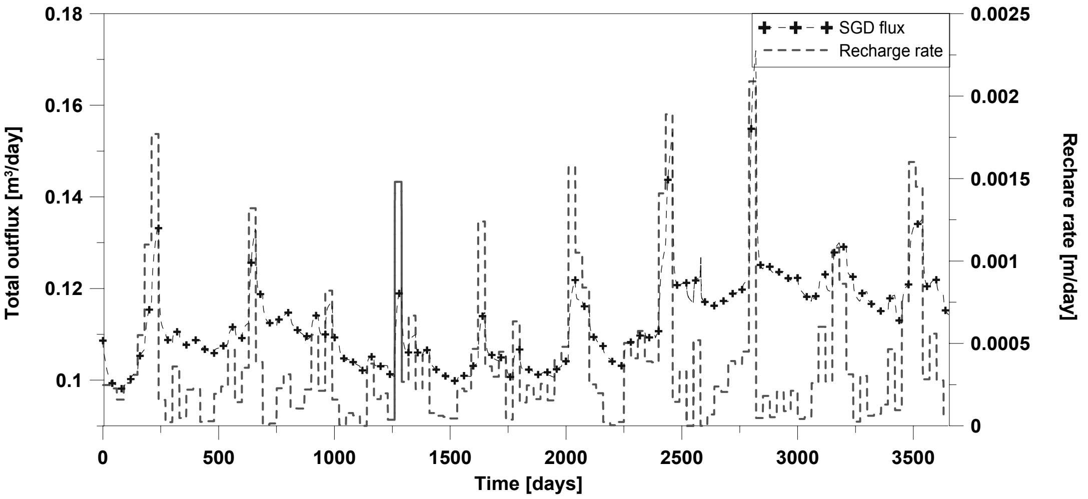


Fig. 5 Hydrograph of SGD with long-term precipitation rate variation.

DISCUSSION AND CONCLUSION

Our simulation results show that different patterns of recharge rate make unique patterns of SGD. When a gradual change of seasonal climate is emphasized, the outflux shows similar patterns to the recharge rate with a lag time. This phenomenon is caused by the oscillation of hydraulic head and interface. But when the heavy rain effect in the summer is emphasized, a periodic change of SGD cannot be observed. Rather, its variation is followed by the high intensity of precipitation for the long period. From this result, we can infer that unusually frequent storms or heavy rainfall events give rise to the increased outflux rate and flux of dissolved nutrients and contaminants to the sea, leading to unexpected eutrophication and contamination of the estuary environment. This research demonstrates that not only the change of oceanic conditions but also the change of precipitation rate should be considered when quantifying SGD flux to the ocean in transient condition.

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