

Submarine groundwater discharge and associated chemical input to a coastal sea

L. Li and D. A. Barry

School of Civil and Environmental Engineering and Contaminated Land Assessment and Remediation Research Centre, University of Edinburgh, Edinburgh

F. Stagnitti

School of Ecology and Environment, Deakin University, Warrnambool, Victoria, Australia

J.-Y. Parlange

Department of Agricultural and Biological Engineering, Cornell University, Ithaca, New York

Abstract. This paper presents a theoretical model of flow and chemical transport processes in subterranean estuaries (unconfined brackish groundwater aquifers at the ocean-land interface). The model shows that groundwater circulation and oscillating flow, caused by wave setup and tide, may constitute up to 96% of submarine groundwater discharge (SGWD) compared with 4% due to the net groundwater discharge. While these local flow processes do not change the total amount of land-derived chemical input to the ocean over a long period (e.g., yearly), they induce fluctuations of the chemical transfer rate as the aquifer undergoes saltwater intrusion. This may result in a substantial increase in chemical fluxes to the ocean over a short period (e.g., monthly and by a factor of 20 above the averaged level), imposing a possible threat to the marine environment. These results are essentially consistent with the experimental findings of Moore [1996] and have important implications for coastal resources management.

1. Introduction

Recently, Moore [1996] discovered that in a large coastal area, submarine groundwater discharge (SGWD) could amount to as much as 40% of the total river flow into the ocean. His estimate was inferred from a mass balance based on measurements of enriched radium 226 in the South Atlantic Bight. The new estimate, in contrast with previous estimates that range from 0.1 to 10%, may have important implications for coastal water management as discussed by Church [1996]. For example, estimates of land-derived pollutants into the coastal sea could well be underestimates. However, as Younger [1996] pointed out, the recharge to the coastal aquifer is not sufficient to sustain such a high rate of SGWD. The aquifer recharge alone can support only 4% of the estimated SGWD flux of $3 \times 10^7 \text{ m}^3 \text{ d}^{-1}$ to the South Atlantic Bight.

The definition of submarine groundwater discharge has been ambiguous in the literature. When used in the context of global water balance [Zektser *et al.*, 1983], it has the same meaning as the net groundwater discharge to the ocean, D_n , which essentially comes from the aquifer recharge. According to Church [1996], SGWD is defined as the direct groundwater outflow across the ocean-land interface into the ocean (Figure 1). Therefore the net groundwater discharge is only a part of SGWD. In a coastal aquifer, groundwater circulation driven by the potential gradient due to wave setup occurs between the upper and lower part of the beach face as shown in Figure 1 [Longuet-Higgins, 1983]. The outflow portion of the circulation, D_w , will contribute to SGWD. In addition, tides generate an

oscillating flow across the beach face and the resulting outflow component D_t likewise forms a part of SGWD. In summary, SGWD consists of the net groundwater discharge, the outflow due to wave-setup-induced groundwater circulation, and that due to tidally driven oscillating flow, i.e.,

$$D_{\text{SGWD}} = D_n + D_w + D_t. \quad (1)$$

Although these discharge components have been studied previously, the above conceptual model of SGWD is proposed for the first time.

D_n can be estimated using aquifer recharge data. It is normally small compared with the discharge due to river flows into the ocean, D_r ; the estimate of D_n as a percentage of D_r ranges from 0.1 to 10 [Younger, 1996]. Note that we are considering these discharges over a large coastal area (e.g., a few hundred kilometers in the alongshore direction) and a long period (e.g., seasonal). Although they contribute greatly to D_{SGWD} , the magnitudes of D_w and D_t have not been described in previous studies nor measured independently in the field. The recent field experiment by Moore [1996] in the South Atlantic Bight found that D_{SGWD} can be as much as 40% of D_r . Younger [1996] argued that only 4% of the D_{SGWD} estimated by Moore is due to D_n . According to (1), one can suggest that D_w and D_t may constitute 96% of the total SGWD, a very large portion indeed. However, the water involved in D_w and D_t is primarily of marine origin. Thus conclusions cannot readily be drawn with regard to the importance of these two discharges in transferring land-derived pollutants to the ocean and affecting the chemical mass balance in the marine environment.

The purposes of the present paper are: (1) to provide, for the first time, theoretical estimates of D_w and D_t and to compare these estimates with the experimental results of Moore

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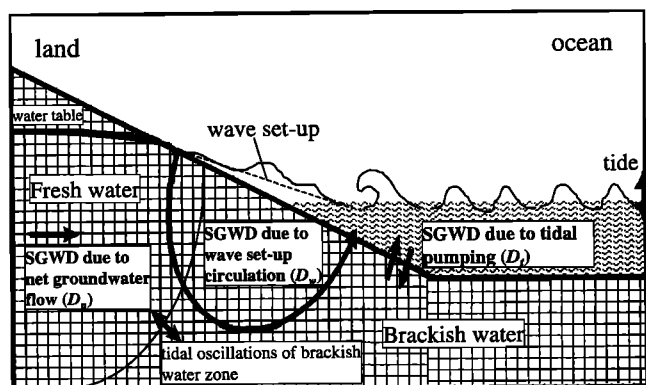


Figure 1. Schematic diagram of processes affecting submarine groundwater discharge (SGWD).

[1996], and (2) to examine the effects of D_w and D_t on transfers of land-derived chemicals to the ocean. In the following, we shall describe the theoretical models of SGWD and the associated mass transport, and discuss the results from model simulations.

2. Theoretical Model of SGWD

Longuet-Higgins [1983] studied near-shore groundwater circulation due to wave setup, this term referring to the tilt in the mean sea level due to an onshore gradient of radiation stress (dashed line in Figure 1). The groundwater circulation is driven by the hydraulic head gradient that results from the wave setup. It was shown that the circulation extends below the beach face to depths that are comparable with the width of the surf zone. On natural coasts, this width is typically of the order of 10^1 – 10^2 m. Using equations (4.6) to (4.8) of Longuet-Higgins [1983], one can derive:

$$D_w = Ks_w L, \quad (2)$$

where D_w is the discharge rate per unit alongshore distance, K is the hydraulic conductivity of beach sand, s_w is the slope of wave setup, and L is the distance between the breaker line and run-up line. Both s_w and L can be calculated according to the local wave conditions and beach slope [e.g., Dean and Dalrymple, 1991],

$$s_w = \frac{3\sigma^2 s_b}{8 + 3\sigma^2}, \quad (3)$$

$$L = \frac{H_b}{\sigma(s_b - s_w)}, \quad (4)$$

where σ is the breaking index, H_b is the breaker height (breaking wave height) and s_b is the beach slope. The breaking index σ is related to the wave conditions and beach slope [Dean and Dalrymple, 1991],

$$\sigma = \frac{1.56}{1 + \exp(-19.5s_b)} - 43.8[1 - \exp(-19s_b)] \frac{H_b}{gT_w^2}, \quad (5)$$

where g is the magnitude of the gravity acceleration and T_w is the wave period.

Tidal oscillations induce oscillating flows in the aquifer, contributing to the water exchange between the aquifer and the ocean. SGWD due to the tide (i.e., D_t) can be estimated by

integrating the difference between the highest water table and the mean water table. Using equation (31) of Nielsen [1990], we get

$$D_t = \frac{n_e A}{\kappa T_t} \exp(-\alpha)[\cos(\alpha) - \sin(\alpha)] + \frac{\sqrt{2}n_e A^2}{s_b T_t} \exp(-\sqrt{2}\alpha) \cos(\sqrt{2}\alpha) + \frac{n_e A^2}{s_b T_t}, \quad (6a)$$

with

$$\kappa = \sqrt{\frac{n_e \omega}{2KH}}, \quad (6b)$$

$$\alpha = \kappa A/s_b, \quad (6c)$$

where D_t is the discharge rate per unit alongshore distance; A , T_t , and ω ($2\pi/T_t$) are the tidal amplitude, period, and frequency, respectively; n_e is the effective porosity of the beach sand; and H is the averaged aquifer thickness.

As an example, we shall apply the model to Moore's [1996] field study in the South Atlantic Bight. This study provided an estimate of the SGWD based on the enrichment of ^{226}Ra in the coastal sea. In the application, we would usually divide the coastline of the study area into sections within which the wave, tide, and beach conditions may be taken as uniform. For the present, we wish to investigate the magnitude of SGWD caused by the wave setup and tide. Thus, for simplicity, we shall neglect the alongshore variability. Also, since the study area is so extensive (320 km in the alongshore direction), local variability may not affect the magnitude estimates significantly so long as representative parameter values are chosen in the calculation. A realistic set of parameter values applicable to a natural coast is shown in Table 1. Using these data, we find that for the entire coast, D_w is $1.65 \times 10^7 \text{ m}^3 \text{ d}^{-1}$, which is roughly 55% of the SGWD rate inferred by Moore ($3 \times 10^7 \text{ m}^3 \text{ d}^{-1}$). The corresponding estimate for D_t is $1.11 \times 10^7 \text{ m}^3 \text{ d}^{-1}$, or 37% of $3 \times 10^7 \text{ m}^3 \text{ d}^{-1}$. Therefore ~92% of the total SGWD may have resulted from the wave setup and tide. We do not suggest that our calculated quantities are particularly accurate. However, they seem to be of the right order of magnitude when compared with field observations.

In order to assess the reliability of the estimates, in Figures 2 and 3 we show the dependence of the estimated D_w and D_t , respectively, on the physical parameters involved. These plots show the sensitivity of the estimates to the uncertainties in the parameters. The parameters ranges are representative for natural coasts. It is evident that in all simulations, the estimated SGWD due to wave setup and tide are considerable.

Table 1. Model Parameter Values Used in the Calculations

Parameter	Value
H_b , m	1.5
T_w , s	8
s_b	0.05
K , m s^{-1}	0.001
n_e	0.45
A , m	1.5
ω , rad s^{-1}	7.27×10^{-5}
H , m	30

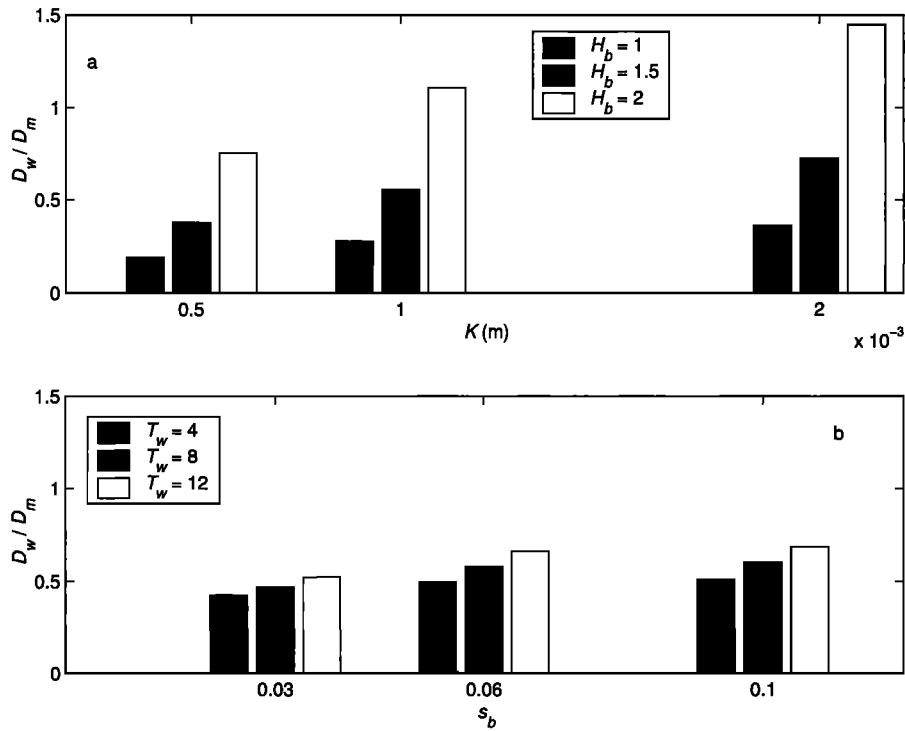


Figure 2. Sensitivity analysis. (a) Ratio of D_w to Moore's [1996] estimate of the total SGWD (D_m) varying with the breaking wave height and hydraulic conductivity, $T_w = 8$ s and $s_b = 0.05$. (b) Ratio of D_w to D_m as it varies with the wave period and beach slope, $H_b = 1.5$ m and $K = 0.001$ m s $^{-1}$.

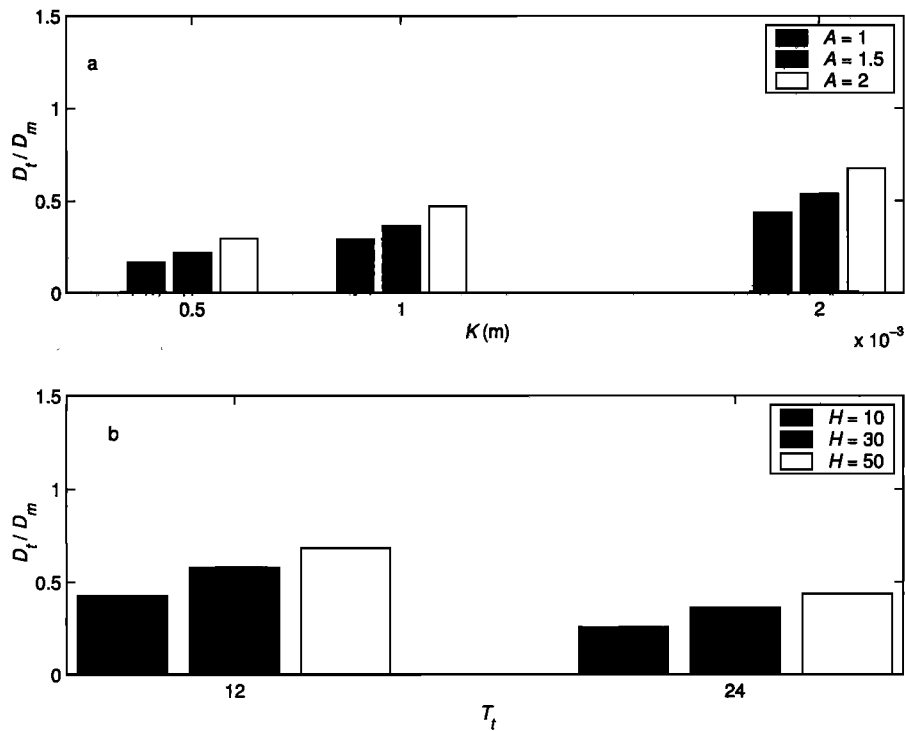


Figure 3. Sensitivity analysis. (a) Ratio of D_t to Moore's [1996] estimate of the total SGWD (D_m) varying with the tidal amplitude and hydraulic conductivity. Here $\omega = 7.27 \times 10^{-5}$ rad s $^{-1}$, $n_e = 0.45$, $H = 30$ m, and $s_b = 0.05$. (b) Ratio of D_t to D_m varying with the tidal period and averaged aquifer thickness. $A = 1.5$ m, $K = 0.001$ m s $^{-1}$, $s_b = 0.05$, and $n_e = 0.45$.

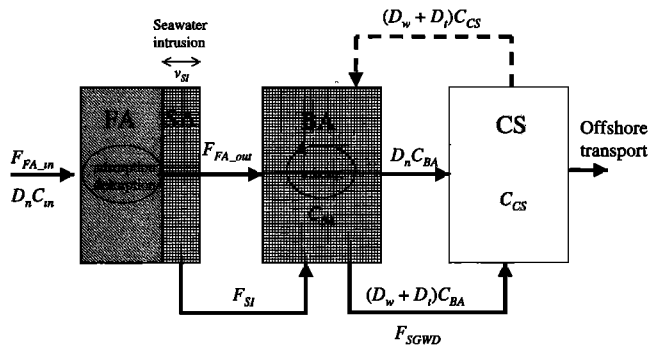


Figure 4. Schematic diagram of the "box" model for chemical transfers in a coastal aquifer.

3. Theoretical Model of the Mass Transport Associated With SGWD

As was discussed previously, since a large portion of the high rate of SGWD is of marine origin, questions remain as to how much the discharge contributes to the transfer of land-derived pollutants to the ocean. Using the "box" model described below, we will examine the importance of SGWD, especially D_w and D_t , to the process of chemical transfers from the aquifer to the ocean.

The model includes three water bodies: coastal sea (CS), brackish aquifer (BA), and freshwater aquifer (FA). Chemical transfers occur between the water bodies as shown by arrows in Figure 4. The chemicals are assumed to have similar geochemistry to that of ^{226}Ra , i.e., to be strongly adsorbed by sand particles in fresh groundwater and to desorb into brackish groundwater. Cesium, phosphate, ammonia, and cadmium are important constituents with this behavior [Moore, 1996].

The mass balance for FA can be described by

$$F_{\text{FA}_{\text{in}}} = F_{\text{FA}_{\text{out}}} \quad \text{if } S = S_{\text{eq}}, \quad (7a)$$

$$F_{\text{FA}_{\text{out}}} = 0 \quad \text{and} \quad V_{\text{FA}} \frac{dS}{dt} = F_{\text{FA}_{\text{in}}} \quad \text{if } S < S_{\text{eq}}, \quad (7b)$$

$$F_{\text{FA}_{\text{in}}} = D_n C_{\text{in}} \quad (7c)$$

$$S_{\text{eq}} = K_d C_{\text{in}}, \quad (7d)$$

where $F_{\text{FA}_{\text{in}}}$ and $F_{\text{FA}_{\text{out}}}$ are the input and output mass flux for FA, respectively (note that the calculations are performed per unit alongshore distance of the water body); S is the amount of adsorbed chemical, and the subscript eq denotes the equilibrium state; V_{FA} is the effective volume of the FA; K_d is the distribution coefficient (the dimensions of S have been changed to ML^{-3} and so K_d is nondimensional) and C_{in} is the input chemical concentration. Equation (7a) expresses an equilibrium state where the maximum adsorption has been reached and hence the output flux equals the input flux. In the nonequilibrium state, the output flux is reduced to zero due to adsorption, and S increases at a rate proportional to the input mass flux. Equation (7d) implies that adsorption occurs effectively instantaneously (i.e., large Damköhler number), a valid assumption for most chemicals under small groundwater flow rates in porous media [e.g., Barry and Li, 1994]. When applied to ^{226}Ra , (7) is based on the assumption that the regeneration of Ra from Th is negligible since the Th decay process is very slow [Moore, 1996].

The mass balance for BA is more complicated. The chemical input to BA includes $F_{\text{FA}_{\text{out}}}$, F_{CS} (mass flux due to the in-

coming seawater), and F_{SI} resulting from seawater intrusion. As was mentioned previously, the chemical adsorbed on sand particles tends to desorb in seawater. Thus seawater intrusion produces an input flux to BA, and the magnitude of this flux is related to the rate of seawater intrusion and the amount of adsorption, S . The output mass flux is due to SGWD. The governing equations are listed below:

$$V_{\text{BA}} \frac{dC_{\text{BA}}}{dt} = (F_{\text{FA}_{\text{out}}} + F_{\text{SI}} + F_{\text{CS}}) - F_{\text{SGWD}}, \quad (8a)$$

$$F_{\text{SGWD}} = (D_n + D_w + D_t) C_{\text{BA}}, \quad (8b)$$

$$F_{\text{CS}} = (D_w + D_t) C_{\text{CS}} \quad (8c)$$

$$F_{\text{SI}} = S \frac{dV_{\text{SI}}}{dt}, \quad (8d)$$

where V_{BA} is the volume of BA and C_{BA} is the average chemical concentration in BA. V_{SI} is the volume of intruded seawater. C_{CS} is the chemical concentration in the ocean and, for the contaminants considered, is usually small compared with C_{BA} . In the following simulations, we will therefore neglect F_{CS} for the purpose of simplicity.

3.1. Intrusion Rate Required to Achieve a High C_{BA}

Moore [1996] found the C_{BA} of ^{226}Ra to be 700 disintegrations per minute (dpm) per 100 L, significantly higher than C_{in} (<66 dpm per 100 L) and C_{CS} (~14 dpm per 100 L). Moore assumed that the high concentration of ^{226}Ra in BA was caused by seawater intrusion. Using the model described above, we will estimate the intrusion rate required in order to achieve the high C_{BA} .

For simplicity, we consider only the steady solution of (8), i.e., $dC_{\text{BA}}/dt = 0$, and assume $F_{\text{FA}_{\text{out}}}$ negligible (C_{in} small). In other words, F_{SI} is in balance with F_{SGWD} , and thus

$$v_{\text{SI}} = \frac{C_{\text{BA}} D_{\text{SGWD}}}{S H}, \quad (9)$$

where v_{SI} is the constant intrusion rate in terms of the salt wedge's movement, i.e., the displacement rate of the salt wedge. S can be estimated to be 2.6×10^5 dpm per 100 L for Moore's [1996] experiment. Substituting the values of C_{BA} and S into (9) and taking $(D_w + D_t)/D_n = 24$ based on Moore's data, we get $v_{\text{SI}} = 0.067 D_n/H$. Since the net groundwater flow rate D_n/H is small in reality, this result indicates that only a small rate of seawater intrusion is necessary to produce a high chemical concentration in the brackish groundwater. The model's prediction of a low intrusion rate is consistent with the fact that seawater intrusion at a natural coast is a slow process. In other words, this result implies that the model describes the behavior of the processes and thus gives us a degree of confidence in it.

3.2. Importance of D_w and D_t in Aquifer-Ocean Chemical Transfer

We shall consider a BA with an initial concentration C_0 and assume that, from $t = 0$ to $t = t_{\text{SI}}$, the aquifer undergoes seawater intrusion at a constant rate. The concentration in the BA, varying with time, is described by the analytical solution to (8) as follows

$$C_{\text{BA}}(t) = \frac{F_{\text{SI}}}{D_{\text{SGWD}}} + \left(C_0 - \frac{F_{\text{SI}}}{D_{\text{SGWD}}} \right) \exp \left(- \frac{D_{\text{SGWD}} t}{V_{\text{BA}}} \right), \quad (10a)$$

$$t \leq t_{\text{SI}}$$

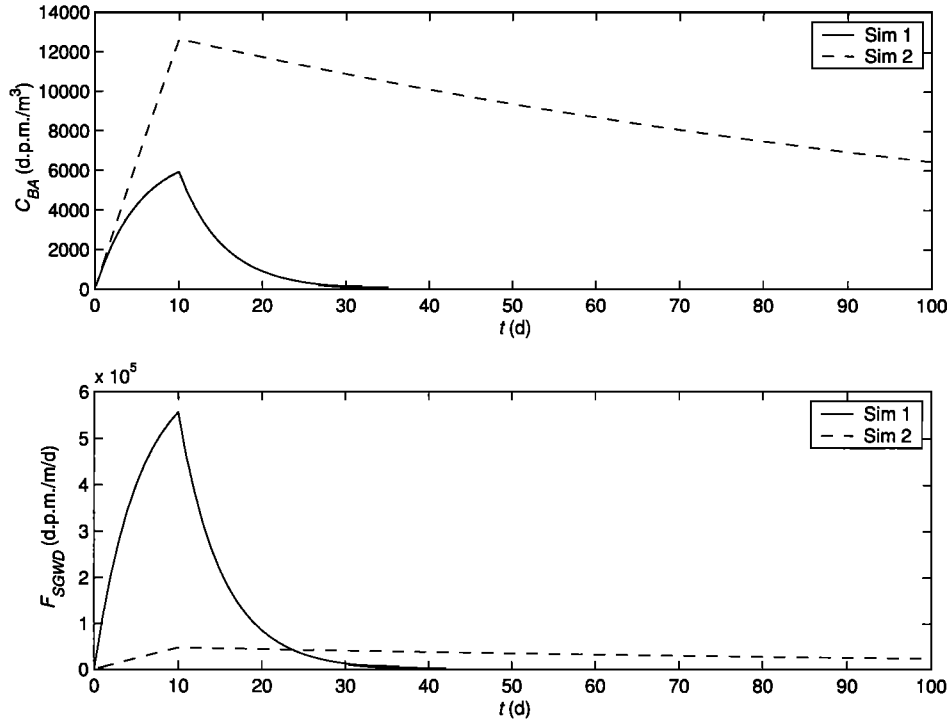


Figure 5. (top) Simulated chemical concentration in the brackish aquifer (BA), and (bottom) the rate of chemical transfer to the ocean.

$$C_{BA}(t) = C_{BA}(t_{SI}) \exp \left[-\frac{D_{SGWD}(t - t_{SI})}{V_{BA}} \right], \quad t > t_{SI}. \quad (10b)$$

The chemical input to the ocean is thus

$$F_{SGWD}(t) = F_{SI} + (C_0 D_{SGWD} - F_{SI}) \exp \left(-\frac{D_{SGWD}t}{V_{BA}} \right), \quad (11a)$$

$$t \leq t_{SI}$$

$$F_{SGWD}(t) = D_{SGWD} C_{BA}(t_{SI}) \exp \left[-\frac{D_{SGWD}(t - t_{SI})}{V_{BA}} \right], \quad (11b)$$

$$t > t_{SI}.$$

Two simulations were conducted with the same intrusion rate and $C_0 (= 0)$, but two different values of D_{SGWD} . For simulation 1 (denoted Sim 1), Moore's estimate of SGWD was used, i.e., $D_{SGWD} = 93.75 \text{ m}^3 \text{ m}^{-1} \text{ d}^{-1}$. Recall that we have shown that this high D_{SGWD} is largely due to D_w and D_t . In simulation 2 (denoted Sim 2), only D_n is considered, and $D_{SGWD} = 3.75 \text{ m}^3 \text{ m}^{-1} \text{ d}^{-1}$. For both simulations, $t_{SI} = 10 \text{ d}$, $V_{BA} = 500 \text{ m}^3 \text{ m}^{-1}$ (i.e., 10 m deep and 50 m in the cross-shore section) and $F_{SI} = 6.56 \times 10^5 \text{ dpm d}^{-1} \text{ m}^{-1}$, this value being calculated from (9) and (8d) using the data from Moore [1996].

The results of predicted C_{BA} and F_{SGWD} are shown in Figure 5. The concentration increased in both simulations as a result of seawater intrusion that provided a mass flux into the BA. Under a small rate of SGWD, the concentration in Sim 2 increased faster and to a greater extent prior to the end of the intrusion. Afterward, the concentration decreased slowly in Sim 2 while the reduction occurred more rapidly in Sim 1. In contrast, the chemical transfer rate in Sim 1 increased to a very high level and then decreased to the initial rate. Both the rising and falling phases occurred rapidly. The changes of the chem-

ical transfer rate in Sim 2 were small and relatively slow. This behavior of the chemical transfer from the BA to the ocean is consistent with the trends of the chemical concentration in the BA. The dynamics of the transfer processes in the BA bear much similarity to those in an estuary. In particular, a large D_n is analogous to a large river flow, and large D_w and D_t are analogous to large tidal currents in an estuary. All these large discharges will lead to high rates of chemical transfer to the ocean from the BA, as in the case of an estuary. In terms of the water quality in the BA, large rates of the local circulation and oscillating flows in the BA, as well as a large net flow rate from the FA, will lead to rapid flushing of the BA, resulting in low chemical concentration. This again is similar to what happens in an estuary [Ippen, 1966]. In parallel, one may define a BA as a "subterranean estuary" [Moore, 1999].

To demonstrate the importance of the local groundwater circulation and oscillating flows (i.e., D_w and D_t) in the chemical transfers from the aquifer to the ocean, we focus on the behavior of the transfer rates (Figure 5, bottom). It is clear that these local processes, contributing significantly to a high rate of SGWD, can rapidly increase the rate of chemical transfer to the ocean. Such an increase may lead to considerable degradation of the marine environment. It should be pointed out that the local processes do not change the total input of chemicals into the ocean. For example, the total chemical inputs to the ocean in the above simulations are both given by the product $F_{SI}t_{SI}$. Under a large D_{SGWD} (as a result of the local groundwater circulation and oscillating flows), the chemical transfer from the aquifer to the ocean occurs for a short period but at a relatively high rate.

The above simulations and discussion were based on the assumption that the aquifer underwent seawater intrusion. We

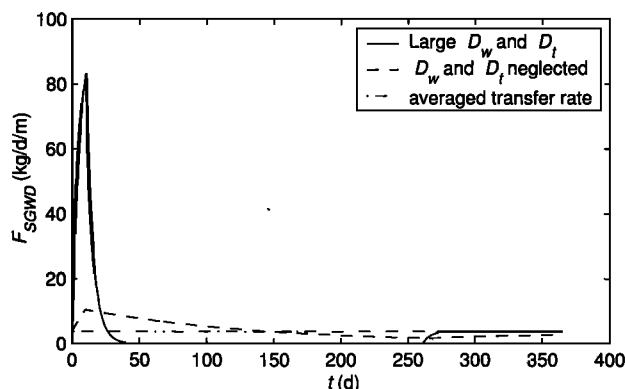


Figure 6. Simulated rates of the transfers of land-derived chemicals to the ocean.

have shown that a small rate of seawater intrusion can lead to a high chemical concentration in the BA and provide a substantial source of chemicals. Owing to fresh groundwater extraction and variations (e.g., seasonal) of the rainfall and sea levels, seawater intrusion is a common phenomenon in a coastal aquifer. Therefore, the situation considered here is likely more a norm than an exception. We note that (10) provides a method to detect and monitor the seawater intrusion.

3.3. Transfer Fluctuations of Land-Derived Pollutants to the Ocean Due to D_w and D_t

In the case of ^{226}Ra , the sediment in the freshwater aquifer is a primary source of the chemical. Chemicals such as phosphate and ammonia are more likely to be land-derived pollutants, for example, as a result of nutrient leaching from the agricultural fertilizers [e.g., Pakrou and Dillon, 1995]. Sediments in the freshwater aquifer, as a temporary storage for these chemicals due to high adsorption, become the immediate source of chemical to the brackish aquifer when seawater intrusion occurs and the chemical desorbs into the brackish groundwater from the sediment. In this section, we examine how the local groundwater circulation and oscillations affect the transfer of land-derived pollutants. A simulation was conducted for this purpose.

The simulation included the chemical transport and adsorption-desorption processes in the three water bodies as illustrated in Figure 4. In the simulation the distribution coefficient K_d was assumed to be 400. The FA is assumed to be in an equilibrium state initially, and seawater intrusion occurs between $t = 0$ and 10 days. The saltwater front retreats shoreward between $t = 10$ days and $t = 20$ days. The salt wedge moved at a constant rate, equal to 5% of the net groundwater discharge rate. The net groundwater discharge rate D_n was set to be $3.75 \text{ m}^3 \text{ d}^{-1} \text{ m}^{-1}$, and the sum of D_w and D_t is $90 \text{ m}^3 \text{ d}^{-1} \text{ m}^{-1}$ ($24D_n$). The inland chemical concentration (C_{in}) was 1 kg m^{-3} . The volume of the BA is $500 \text{ m}^3 \text{ m}^{-1}$. During seawater intrusion, the output mass flux from the FA is described by (7a) and during the retreat of the salt wedge, $F_{\text{FA_out}}$ is given by (7b). The time that it takes for the FA to reach the equilibrium state after the retreat of the salt wedge can be estimated using $F_{\text{SI}}t_{\text{SI}}/F_{\text{FA_in}}$.

The simulated rate of chemical transfer to the ocean is shown in Figure 6. Also plotted are the results from a comparison simulation with D_w and D_t neglected. It is clearly shown that a large increase of the transfer rate resulted from

the seawater intrusion and the local groundwater circulation/oscillating flows. The first factor, i.e., seawater intrusion, contributes to an extra and excessive source of the chemical. The second factor, i.e., the local groundwater circulation and oscillating flows, provides the mechanism for rapid flushing of the BA, resulting in increased chemical transfer to the ocean. Without the second factor, the large impulse of chemical input to the ocean would not occur as demonstrated by the comparison simulation (dashed curve in Figure 6). The increase of F_{SGWD} was substantial, more than 20 times as high as the averaged rate (inland chemical flux, $F_{\text{FA_in}}$). As the salt wedge retreated, the transfer rate decreased to zero, since the inland chemical was all adsorbed in the FA. Although the transfer rate varies, the local processes did not change the total amount of the chemical input to the ocean, which is determined by the inland source.

The values of the model parameters used in the simulation are typical for sandy beaches. The prediction of a high increase in the chemical transfer rate indicates that local processes in a coastal aquifer, i.e., groundwater circulation/oscillating flows and seawater intrusion, are important in determining the impact of groundwater contamination on the marine environment. On average, the chemical input from the aquifer is small. However, the input rate may fluctuate to a level significantly higher than the average as a result of the coastal groundwater processes. The resulting high impulse of the chemical input has the potential to cause serious degradation of the marine ecosystem.

4. Conclusion

We have developed a theoretical model for the submarine groundwater discharge and the associated chemical transfer to the ocean. Using the model, we demonstrate that the wave setup and tidal pumping may be the processes largely responsible for the high rate of SGWD as observed by Moore [1996]. The model also predicts that the local groundwater circulation and oscillating flows (due to wave setup and tidal pumping, respectively) can increase the rate of chemical transfers to the ocean greatly and thus represent a threat to the coastal sea environment.

With the limited field data available, a comprehensive model validation is yet to be conducted. However, the preliminary results from the model are found to be consistent with Moore's [1996] field observations. Moreover, the dynamics of the processes in the brackish aquifer (i.e., a subterranean estuary), as predicted by the model, have many similarities to those in a surface estuary. Since both water bodies are interacting zones between inland water and seawater, similarities in their behavior are to be expected.

While extensive studies have been conducted on the surface estuary dynamics, very little has been done with regard to subterranean estuaries. To fully understand and quantify the chemical fluxes to the ocean from the land, a more extensive knowledge base on subterranean estuaries is needed. The present paper, as a first attempt to model the processes in a subterranean estuary, serves this purpose. There are processes that have not been included in this study but should be examined in future investigations, for example, spring-neap tides, seasonal sea level changes, long-term rise of sea level, and density-driven groundwater circulation [Cooper, 1959].

Notation

A	tidal amplitude [L].
C_{in}	inland chemical concentration [ML^{-3}].
C_{BA}	chemical concentration in the brackish groundwater aquifer [ML^{-3}].
C_{CS}	chemical concentration in the coastal sea [ML^{-3}].
D_n	net groundwater discharge rate per unit alongshore distance [$L^3T^{-1}L^{-1}$].
D_w	groundwater discharge due to wave setup [$L^3T^{-1}L^{-1}$].
D_t	groundwater discharge due to tidal pumping [$L^3T^{-1}L^{-1}$].
D_{SGWD}	submarine groundwater discharge [$L^3T^{-1}L^{-1}$].
D_r	river discharge to the ocean [L^3T^{-1}].
$F_{FA_{in}}$	input chemical flux into the fresh groundwater aquifer per unit alongshore distance [$MT^{-1}L^{-1}$].
$F_{FA_{out}}$	input chemical flux from the fresh groundwater aquifer per unit alongshore distance [$MT^{-1}L^{-1}$].
F_{SI}	chemical flux to the BA due to seawater intrusion per unit alongshore distance [$MT^{-1}L^{-1}$].
F_{SGWD}	chemical flux to the ocean due to SGWD (i.e., the rate of chemical transfer to the ocean from the aquifer) [$MT^{-1}L^{-1}$].
g	magnitude of gravitational acceleration [LT^{-2}].
H	aquifer thickness [L].
H_b	breaker height (breaking wave height) [L].
K	hydraulic conductivity [LT^{-1}].
K_d	distribution coefficient.
L	width of the surf zone [L].
n_e	effective porosity.
S	the solid phase chemical concentration (same units as C) [ML^{-3}].
S_{eq}	equilibrium chemical concentration (same units as C) [ML^{-3}].
s_w	gradient of wave setup.
s_b	beach slope.
T_t	tidal period [T].
T_w	wave period [T].
t_{SI}	seawater intrusion period [T].
V_{BA}	volume of the brackish groundwater aquifer per unit alongshore distance [L^3L^{-1}].
V_{FA}	volume of the fresh groundwater aquifer per unit alongshore distance [L^3L^{-1}].
V_{SI}	volume of the intruded seawater per unit alongshore distance [L^3L^{-1}].

v_{SI}	displacement rate of the salt wedge [LT^{-1}].
σ	breaking index.
ω	tidal frequency [$rad T^{-1}$].

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- D. A. Barry and L. Li, School of Civil and Environmental Engineering and Contaminated Land Assessment and Remediation Research Centre, King's Buildings, University of Edinburgh, Edinburgh EH9 3JN, Scotland, United Kingdom. (a.barry@ed.ac.uk; ling.li@ed.ac.uk)
- J.-Y. Parlange, Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853-5701. (jp58@cornell.edu)
- F. Stagnitti, School of Ecology and Environment, Deakin University, Warrnambool, Victoria 3280, Australia. (frankst@deakin.edu.au)

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