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Seawater-groundwater Exchange in a Silty Tidal Flat in the South Coast of Laizhou Bay, China

Lijia Hou[†], Hailong Li^{†#}, Chunmiao Zheng[†], Qian Ma[†], Chaoyue Wang[†], Xuejing Wang[†], and Wenjing Qu[†]

[†] MOE Key Laboratory of Groundwater Circulation & Environment Evolution and School of Water Resources and Environment China University of Geosciences-Beijing Beijing 100083, P. R. China

[‡] School of Environmental Science and Engineering South University of Science & Technology of China Shenzhen, Guangdong 518055, P. R. China





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ABSTRACT

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There were few studies about seawater-groundwater exchange in silty, low-permeability tidal flats with very gentle slopes. This paper reports the monitoring data and preliminary analytical results on a typical transect in a silty tidal flat with large-scale seepage faces at the south coast of Laizhou Bay, China. The "pair-wells method", which was an improvement of the single-well method used by Ma *et al.* (2015) was used to estimate the seawater-groundwater exchange rate. We selected 14 locations along a typical transect in the intertidal zone, with a slope of 0. 4‰ and cross-shore length of 3514 m, to install pair-wells for monitoring the groundwater head, salinity and temperature at two different depths simultaneously once per hour from 20:00 August 10th to 23:00 September 12th, 2014. The vertical hydraulic conductivity measured in situ ranges from 5. 4×10^{-7} to 1.1×10^{-5} m s⁻¹. The salinity of the underground brine ranges from 25 to 56 g l⁻¹. Based on the observed data and the generalized Darcy's law, the submarine groundwater discharge (SGD) and inflow along the entire transect were estimated to be 164. 0 and 6. 5 m²d⁻¹, respectively. It is found that 80. 4% of the total SGD occurred between W7 and W10, where the hydraulic conductivity is one or two orders of magnitude greater than that at other wells; and 64. 6% of the total inflow occurred between W2 and W4. The single-well method, on the other hand, yields a SGD value of 223. 0 m²d⁻¹ and inflow value of 13. 3 m²d⁻¹. Neglecting the density effect may lead to an overestimation of the SGD by 25. 6% and underestimation of the inflow by 27. 4%.

ADDITIONAL INDEX WORDS: silty beach, seawater-groundwater exchange, pair-wells, seepage face, Laizhou Bay.

INTRODUCTION

With the new technologies and methods developed, the study of seawater-groundwater exchange has been a hot spot of hydrogeology and oceanography. Submarine groundwater discharge (SGD) has significant impacts and implications on ecological environment due to its important role in transport of nutrients, contaminations and other chemicals (Li and Jiao, 2013; Li et al., 1999; Slomp and Cappellen, 2004). An increasing number of scholars have paid attention to SGD estimation.

Many different methods have been developed to estimate SGD. Since 1996, natural radioactive isotopes Ra and Rn were widely used as tracers to estimate SGD in large scale areas (Gu *et al.*, 2012; Lee *et al.*, 2012; Moore, 1996, 2007; Moore and Oliveira, 2008; Wang *et al.*, 2015; Xu *et al.*, 2014). Seepage meters were also used to estimated SGD at local area, such as manual seepage instrument developed by Cable *et al.* (1997), heat pulse seepage meter developed by Taniguchi and Fukuo (1993) and ultrasonic flow meter developed by Paulsen *et al.* (2001). Numerical simulations usually focused on limited coastal transect, such as Guo *et al.* (2010), Robinson *et al.* (2007), Xia and Li (2012), Xia *et al.* (2010).

In comparison with many existing studies in gravel or sand beaches, there were few studies of seawater-groundwater exchange in silty beaches. A series of experiments conducted in gravel beaches of Prince William Sound, Alaska, indicated that the two-layered structure of a high-permeability surface layer underlain by a low-permeability layer had significant impacts on the persistence of spilled oil (Guo *et al.*, 2010; Li and Boufadel, 2010; Xia *et al.*, 2010). Xia and Li (2012) made a comparative study

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^{*}Corresponding author: hailongli@ cugb. edu. cn

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between a bald beach and a mangrove beach with similar topography and tidal actions in the intertidal zones of Dongzhaigang in Haikou City of Hainan Province, indicating that the inland freshwater recharge and the mud-sand two-layered structure played key roles in the development of mangrove and their spatial distribution.

Ma *et al.* (2015) developed a simple method ("single-well method") for estimating seawater-groundwater exchange rate in a silty beach, taking into account the effects of seepage face and density and based on field measurements of groundwater hydraulic head, temperature and salinity. The exchange rate can be calculated by the generalized Darcy's law, the observed tidal level and the hydraulic head in the observation well, Their case study in a silty beach at Haimiao of Laizhou Bay indicated that the SGD and inflow were 8.8 and 15.3 m³d⁻¹m⁻¹, respectively. A freshwater discharge tube was also identified near the low-tide line. Riedel *et al.* (2010) quantified SGD in a tidal sand flat margin with a seepage face in the German Wadden Sea using the numerical code SUTRA, and found that the magnitude of SGD was controlled by the maximum hydraulic gradient during low tide.

In this paper, "pair-wells method" is used to improve the single-well method used by Ma *et al.* (2015) to investigate the seawater-groundwater exchange rate in a typical cross-shore siltybeach transect in the intertidal zone of Qingxiang Town (Liutuan Town), Laizhou Bay. Fourteen pair-wells were used to monitor the pore water pressure, salinity and temperature at two different depths simultaneously along the entire transect. Based on these observed data, we quantitatively estimated the seawater-groundwater exchange rate. The impacts of density and groundwater pumping for salt production on SGD and inflow were discussed quantitatively. The difference between the results of this study and those of Ma *et al.* (2015) were analysed. Comparisons were made between the single-well and pair-wells methods. The advantages of the pair-wells method over the single-well one are discussed.

FIELD DESCRIPTION AND METHODS

Field Description

Laizhou Bay, an important fishing and salt production base of China (Figure 1), is located in the south of Bohai Sea, north of Shandong Peninsula. The beach in the southern coast of Laizhou Bay (from Hutouya to Yangjiaogoukou) is very flat, and the width of the intertidal zone in the cross-shore direction is about 4000 m. The tidal flat in the study area consists of silty-muddy sediments, and the aquifers are mainly composed of late Pleistocene to Holocene sediments. Brine in Quaternary aquifers is mainly distributed within 10 km of the shoreline (Han *et al.*, 2014; Zhang and Peng, 1998). There are three layers containing brine in the sediments (Xue *et al.*, 2000), which has resulted from a combination of past and recent processes, including a number of phases of regression, transgression, brine formation and mixing (Han *et al.*, 2014; Li *et al.*, 2000; Xue *et al.*, 2000).

The weather in Laizhou Bay belongs to sub-humid monsoon climate, with an annual average temperature of 11.9° (Han *et al.*, 2014). The annual mean precipitation is 660 mm, and 60–70% of the precipitation generally concentrates in June-August. The annual average potential evapotranspiration, approximately 1774 mm, is much greater than the precipitation (Bi *et al.*, 2012; Han *et al.*, 2014). Under natural conditions, the unconfined aquifer is recharged by precipitation and groundwater from south (Han, Wu, and Zhang, 2011; Han *et al.*, 2014). The area is exposed to semi-diurnal tides, and the average durations for both rising and falling tides are about 6 hours.



Figure 1. Location of the study area: (a) Bohai Sea; (b) Laizhou Bay; (c) 14 pair-wells (numbered W1, ..., W13, and W14 sequentially seaward) were set along the cross-shore transect. The white patch areas in the lower part of (c) are saltpans



Figure 2. Vertical cross-section of the studied transect and locations of transducers. A pair-wells, with two LTC-Divers, was installed at every pit of W1, W2, ..., and W14 for monitoring pore water pressure, electrical conductivity and temperature

The typical transect that we selected in the intertidal zone is located in Qingxiang Town (Figure 1). Along the entire transect, we dug 14 pits to install pair-wells, which are numbered as W1, W2, \cdots , and W14 sequentially seaward (Figure 2). The beach surface elevations of the pair-wells were surveyed by an electronic total station (TS-800, Johanna). These data and the elevations of each pressure transducer installed at the 14 observation pair-wells were given in Table 1. There were several times of raining during the monitoring period (from 20:00 PM August 11th to 23:00 PM September 12th, 2014, almost 33 days), with the precipitation ranging from 28.3 mm to 51.6 mm.

Field Methodology

Each of pair-wells consists of two LTC-Divers (Level, Temperature and Conductivity Diver: Levelogger Junior, Solinst, Canada), inner and outer PVC pipes, and a plexiglass rod linking the two LTC-Divers together (Figure 3a). The pipes were slotted uniformly with holes about 5.0 mm in diameter to keep a good hydraulic connection around the pair-wells. Furthermore, to prevent holes from being blocked by silty-muddy sediments generally occurring in the silty beach, fine stainless-steel meshes were screened outside the two pipes, and the room between the two pipes was filled with coarse sands (diameter of 0.5 - 2.0 mm). Then, a LTC-Diver was placed in each inner pipe (Figure 3b). In each pit, a pair of wells were installed to record the pore water pressure, temperature and conductivity hourly at two different depths (Table 1). At the same time, a LTC-Diver was installed in the sea to monitor the tidal fluctuation; and a Baro-Diver (Schlumberger) was placed above the ground surface to obtain the air pressure and temperature once an hour.

Based on the definition of salinity given by UNESCO (1966), the electrical conductivity measured by a LTC-Diver can be transformed into salinity. More details can be seen in Cox, Culkin, and Riley (1967); Ma *et al.* (2015); and, Wooster, Lee, and Dietrich (1969). Then, the observed pressures of air and ground-water, and elevations of each LTC-Diver, were transformed into freshwater-equivalent hydraulic head (Figure 4).

 Table 1. Elevations of beach surface and each LTC-Diver at the 14

 observation wells

Location	X (m)	Beach Surface Elevation Z (m)	Up LTC-Diver Elevation (m)	Low LTC-Diver Elevation (m)	
W1	0	1.43	1.36	0.84	
W2	277	1.42	1.31	0.78	
W3	554	1.40	1.23	0.70	
W4	841	1.38	1.28	0.75	
W5	1133	1.32	1.25	0.72	
W6	1422	1.19	1.10	0.57	
W7	1687	1.02	0.89	0.36	
W8	1951	0.82	0.77	0.24	
W9	2211	0.69	0.54	0.02	
W10	2493	0.61	0.50	-0.03	
W11	2735	0.45	0.34	-0.19	
W12	2989	0.33	0.22	-0.31	
W13	3254	0.25	0.15	-0.38	
W14	3514	0	-0.08	-0.61	

The in-situ multiple diameter falling-head method (Wang *et al.*, 2014) was used to measure the vertical hydraulic conductivity K_v (Table 2) of intertidal sediments at the locations of some pairwells (W2, W4, W6, W8 and W12). More details about the apparatus and method can be found in Li *et al.* (2010), Ma *et al.* (2015), and Wang *et al.* (2014).



Figure 3. (a) Schema of pair-wells. Not to scale. (b) A LTC-Diver was placed in each inner pipe, and the distance between the two LTC-Divers is a constant of 52.8 cm









Figure 4. The tidal head (50% - gray line), observed hydraulic heads at the up LTC-Diver (*black dots*) and low LTC-Diver (40% - gray dots) are shown in the primary axis, salinity (g l⁻¹) at the up LTC-Diver (*black line*) and low LTC-Diver (40% - gray line) are shown in the secondary axis, of W1, ..., W13, W14 in the intertidal zone. The elevations of each LTC-Diver and beach surface are shown as well

Seepage Face Development Condition

The presence/absence of seepage face development is defined by the characteristics of tidal actions and tidal flat face in the study area (Turner, 1995).

$$\Sigma = \frac{\pi R_T}{T} \cdot \frac{n}{K_H \sin^2 \beta} \tag{1}$$

where, Σ is the seepage face parameter: if $\Sigma > 1$, there will be seepage face development during low tide; if $\Sigma \leq 1$, no seepage face development. The parameter R_T denotes the tidal range [L]; T refers to the tidal period [T]; n denotes the effective porosity of sediment [-]; K_H refers to the horizontal hydraulic conductivity [LT⁻¹]; β is the beach slope [-].

In our study area, $R_T = 0.25 - 1.6$ m, T = 12 h, $K_H = 1.1 \times 10^{-5}$ m s⁻¹(Table 2), $\beta = 0.4\%$, n = 0.03 - 0.35. Considering that the horizontal hydraulic conductivity is greater than or equal to the vertical one ($K_H \ge K_V$) generally, a maximum value of the vertical hydraulic conductivity (1.1×10^{-5} m s⁻¹) was used for conservative estimation. No measurements were conducted for the effective porosity of the silty beach sediments. According to Fetter (1994), the porosity of silt, silt sands, fine sands and sandy clay ranges from 0.03 to 0.35, which is used here for conservative estimation. According to these parameters and Equa-

tion (1), the seepage face parameter ranged from 10^8 to 10^{10} , much greater than 1. Therefore, seepage faces will develop during low tides in the gentle silty tidal flat.

Table 2. K_{v} -values obtained by the method in Wang et al. (2014)

Location	Hydraulic conductivity K_v (m s ⁻¹)
W2	5.4×10 ⁻⁷
W4	3.6×10^{-6}
W6	5.1×10 ⁻⁶
W8	1.1×10^{-5}
W12	2.4×10^{-6}

Direct Estimation of Water Exchange Rate

The observed data and preliminary analysis (Figure 4) indicated that the beach surface between W2 and W14 was saturated during the entire monitoring period. The generalized Darcy's law considering the density effect can be used to estimate the vertical flow rate by the following equation (Ma *et al.*, 2015):

$$q_n \approx -\delta K_v \left(\frac{h_{\rm up} - h_{\rm low}}{\Delta L} + \frac{\varepsilon (c_{\rm up} + c_{\rm low})}{2} \right)$$
(2)

where q_n is the vertical flow rate [L T⁻¹]; K_v is the vertical hy-

draulic conductivity [L T⁻¹]; h_{uv} and h_{low} denote the freshwater-equivalent hydraulic head [L] at the up and low LTC-Divers, respectively; ΔL is the distance between the up and low LTC-Divers (52.8 cm) ; $c_{\rm up}$ and $c_{\rm low}$ denote the salinity [g l⁻¹] of the pore water at the up and low LTC-Divers, respectively; δ is the ratio of the dynamic viscosity of freshwater to saltwater [-]:

$$\delta = \frac{\mu_0}{\mu} = 1 - \xi c \tag{3}$$

W7

where, μ_0 and μ denote the dynamic viscosity [M L⁻¹T⁻¹] of freshwater and saltwater, respectively; ξ is a constant, equaling 1.566×10⁻³ m³kg⁻¹; c is the salinity of pore water [M L⁻³], which is the average of salinities at up and low LTC-Divers, considering that the salinity at the same location did not change much.

0.6

0.2

-0.2 -0.6 -1.0 -1.4 -1.8 (a)

0.3

0.2

0.1

0.0

Generalized hydraulic gradient

The parameter ε is a constant, equaling 7. $143 \times 10^{-4} \text{ m}^3 \text{kg}^{-1}$. which is used to describe the linear relationship between density and salinity, which is defined by

$$\rho = \rho_0 (1 + \varepsilon c) \tag{4}$$

where ρ and ρ_0 denote the density [M L⁻³] of saltwater and freshwater, respectively.

Therefore, the generalized hydraulic gradient J is defined as:

$$J \approx -\delta \left(\frac{h_{\rm up} - h_{\rm low}}{\Delta L} + \frac{\varepsilon (c_{\rm up} + c_{\rm low})}{2} \right)$$
(5)

2.0

27

2.0

The generalized hydraulic gradients J of the 12 pair-wells (W2 -W8, W10-W14) were shown in Figure 5.

If J > 0 (*i. e.*, $q_n > 0$), the groundwater flows upward (SGD); otherwise, it flows downward (inflow). Normally, the density effect leads to downward flow due to the positive parameter ε .

24

18

15

Time (d)

21



12

RESULTS

As shown in Figure 2, the beach surface of W1 is located in the high intertidal zone, and the low LTC-Diver was inundated only during 7.92–9.67 d, 17.25–19.54 d, and 21.92–23.67 d (Figure 4a). In other words, the LTC-Divers installed at W1 were above the water table and did not able to record the groundwater data during most of the observation time. Besides, the salinities at up and low LTC-Divers were 0 since no groundwater entered the inner pipe when the LTC-Diver were above the water table. Thus, the seawater-groundwater exchange estimation later did not include W1.

As shown in Figure 4, the observed hydraulic heads at the up and low LTC-Divers of observation wells W2-W14 decreased with the falling tide when the tidal level was higher than the beach surface, and became almost constant when the tidal level fell near the beach surface until the next rising tide coming. Note that during the exposure of beach surface, the hydraulic heads of the two divers were higher than the beach surface. Furthermore, the hydraulic head of the low LTC-Diver was always higher than that of up LTC-Diver, especially at W2, W4 — W8, and W13. The generalized hydraulic gradient between the up and low LTC-Divers was positive (except W11) in most time which is about 0.2 at W7 and W8 (Figure 5b), indicating considerable groundwater discharge.

The salinity difference between the up and low LTC-Divers was very small for W2-W14, and was less than 2 g l^{-1} at W10 and W11 (Figures 4j and 4k). Note that as shown in Figure 4, the salinities at low LTC-Diver at W2, W4, W7 and W8 were 0, probably because the pipe was blocked by fine sediments, which exist extensively in the silty tidal flat, or there were bubbles around the LTC-Diver preventing water from entering. The sudden decrease of hydraulic heads at W3 – W5 (Figures 4c, 4d, and 4e) after 18 d may be caused by the pumping of groundwater for

salt production nearby (Feng, Tan, and Liu, 2013; Yu, 2014).

At W9, the low LTC-Diver did not worked (Figure 4i), thus the seawater-groundwater exchange estimation at W9 was not included. As shown in Figure 4i, the hydraulic head at up LTC-Diver was about 0.15 m higher than the beach surface, indicating that the groundwater discharge from the seepage face developed here and might be significant.

Evaluation of SGD and Inflow

The exchange rate q_n given by Equation (2) was averaged over the entire monitoring period for the outflow q_{out} and inflow q_{in} at each well using the following equations:

$$q_{\text{out}} = \frac{1}{t_e - t_0} \int_{t_0}^{t_e} \max_{t} \{0, q_n(t)\} dt$$
(6)

$$q_{\rm in} = \frac{1}{t_{\rm e} - t_{\rm 0}} \int_{t_{\rm 0}}^{t_{\rm e}} \max_{t} \{0, -q_{\rm n}(t)\} dt$$
(7)

where t_0 is the calculated initial time ($t_0 = 0$ h was set at 0:00 on August 17th, 2014, 5–6 days after the installation of the pairwells to eliminate the disturbance to groundwater table); t_e is the calculated end time ($t_e = 640$ h, at 15:00 on September 12th, 2014). Let W1 be the origin of the *x*-axis ($X_1 = 0$), and the coordinates of W2, \cdots , W13, W14 be X_2 , \cdots , X_{13} , X_{14} , correspondingly (Table 3), then the total SGD and inflow could be evaluated by the integral along the *x*-axis, namely:

SGD =
$$\sum_{i=2}^{15} \left(\int_{x_i}^{x_{i+1}} q_{out} dx \right)$$
 (8)

Inflow =
$$\sum_{i=2}^{15} \left(\int_{X_i}^{X_{i+1}} q_{in} dx \right)$$
 (9)

The values of q_{out} (or q_{in}) between X_i and X_{i+1} are determined by linear interpolations of their values at X_i and X_{i+1} ($i=2, \dots, 8, 10, \dots, 12, 13$).

Table 3. Exchange rate q_{in} , q_{out} of every well (except W1 and W9), and corresponding inflow and SGD between the adjacent wells estimated by the pair-wells method along the entire transect; and those (Inflow-s and SGD-s) obtained by the single-well method

Location	<i>X_i</i> (m)	$q_{ m in} \ (10^{-4} { m m d}^{-1})$	q_{out} (10 ⁻⁴ m d ⁻¹)	Inflow $(m^2 d^{-1})$	$\frac{\text{SGD}}{(\text{ m}^2\text{d}^{-1})}$	Inflow-s $(m^2 d^{-1})$	$\frac{\text{SGD-s}}{(m^2 d^{-1})}$
W2	277	0.1	1.7	1.9	2.4	2.7	3.2
W3	554	1.3	0.0	2.3	2.6	2.6	7.7
W4	841	0.3	1.8	0.6	8.5	1.3	16.8
W5	1133	0.1	4.0	0.2	8.4	1.0	16.3
W6	1422	0.0	1.8	0.0	29.9	0.5	31.1
W7	1687	0.0	20.9	0.0	51.4	0.1	60.7
W8	1950	0.0	18.1	0.0	50.5	1.4	74.6
W10	2493	0.0	0.5	0.7	0.7	1.4	2.3
W11	2735	0.6	0.0	0.7	0.7	1.4	2.5
W12	2989	0.0	0.3	0.8	0.4	1.4	2.3
W13	3254	0.0	3.0	0.0	4.4	0.5	4.3
W14	3514	0.0	0.7	0.0	4.8	0.3	3.7
Total				6.5	164.0	13.3	223.0

The estimated results of the seawater-groundwater exchange rate at each well are shown in Table 3. The calculated SGD along the entire transect was 164. 00 m²d⁻¹ and inflow was 6.5 m²d⁻¹. As shown in Figure 6, the inflow concentrating between W2 and W4, accounted for about 64. 6% of the total inflow. The SGD concentrated between W7 and W10 (Figure 6), accounting for about 80. 4% of the total SGD, which is probably due to the high-permeability (10^{-5} m s⁻¹ there, one or two orders of magnitudes greater than those of other pair-wells locations) nearby (Table 2). Under the rainfall condition, the SGD and inflow are season-dependent. It would be different in the wet and dry season with varying inland freshwater recharge, and it still needs further research.



Figure 6. Outflow rates (*squares*, volume of groundwater discharging in unit area per day (q_{out} obtained by the pair-wells method (*solid line*) and q_{outs} obtained by the single-well (*gray dotted blue*))) are shown in the primary axis and inflow rates (*rhombus*, volume of seawater infiltrating in unit area per day (q_{in} obtained by the pair-wells method (*solid line*) and q_{ins} obtained by the single-well method (*gray dotted blue*))) are shown in the secondary axis averaged over the observation period between W2 to W14 (except W9)

When removing the observation periods of W3 to W5 influenced by groundwater pumping (*i. e.*, when the water pressure equaled essentially zero), the SGD and inflow along the entire transect were 170.7 and 5.6 m²d⁻¹, *i. e.*, the total SGD increased by 6.7 m²d⁻¹ (about 4.1%), and the total inflow decreased by 0.9 m²d⁻¹ (about 14.1%), respectively. Though groundwater pumping had little effect on the water exchange of the entire transect, it did have great impact on the zone between W3 and W5 (details will be given later).

The Impacts of Groundwater Pumping for Salt Production

As shown in Figures 4c-4e, the hydraulic heads and salinities of W3-W5 showed a sudden drop between 18.5 d ~ 20 d, even close to the elevations of LTC-Divers sometimes. This was most likely caused by groundwater pumping for salt production nearby. With pumping effect, the generalized hydraulic gradient changed from positive to negative suddenly, and gradually recovered to normal state after t=20 d (Figure 5a). Meanwhile, the hydraulic heads and salinities recovered gradually within two days. This phenomenon was not observed at W2 and W6, indicating that pumping only had an impact on local area.

The SGD and inflow between W3 and W5 were $6.9 \text{ m}^2 \text{d}^{-1}$ and

46.7 $m^2 d^{-1}$ during the pumping period, respectively. The SGD and inflow were 12.3 and 0.6 $m^2 d^{-1}$ when ignoring the pumping effects. The SGD decreased by 5.4 $m^2 d^{-1}$, and the inflow increased by 46.1 $m^2 d^{-1}$ with the pumping effects. During the pumping period, the maximum inflow between W3 and W5 increases to 217.3 $m^2 d^{-1}$. These results indicated that short-term high-rate pumping had great influence on the interactions of seawater-groundwater between W3 and W5.

DISCUSSION

Comparison with the Single-well Method

We also estimated the SGD and inflow using the data from low LTC-Divers and tidal level. The difference between the two estimation methods is how to calculate the vertical groundwater flow rate q_n . The vertical groundwater flow rate is calculated by the single-well method as following:

$$q_{\rm n} \approx -\delta K_{\rm V} \left(\frac{h_{\rm surface} - h_{\rm W}}{\Delta L} + \frac{\varepsilon(c_{\rm w} + c_{\rm sea})}{2} \right)$$
(10)

where, h_w and c_w represent the freshwater-equivalent hydraulic head [L] and salinity [g l⁻¹] of the pore water at low LTC-Diver; c_{sea} denotes the seawater salinity [g l⁻¹]; $h_{surface}$ depends on the surface elevation of the location of LTC-Diver and the tidal head when tide coming; δ , K_v and ε have the same meaning as those in Equation (2); ΔL is the depth of the low LTC-Diver from the beach surface [L] (Figure 2 and Table 1). The parameter $h_{surface}$ is defined as following:

$$h_{\rm surface} = \begin{cases} E_{\rm surface} & E_{\rm surface} > E_{\rm tide} \\ h_{\rm tide} & E_{\rm surface} \leqslant E_{\rm tide} \end{cases}$$
(11)

where, $E_{\rm surface}$ is the beach surface elevation [L], $E_{\rm tide}$ denotes the observed tidal level [L], $h_{\rm tide}$ refers to the freshwater-equivalent hydraulic head of the tidal level [L], and $h_{\rm tide} = (1 + \varepsilon c_{\rm sea}) \times E_{\rm tide}$. When the beach surface is submerged by seawater, $h_{\rm surface}$ equals the freshwater-equivalent hydraulic head of the tidal level; otherwise, it equals the beach surface elevation during the beach surface exposure. More details about the single-well method are shown in Ma *et al.* (2015).

The calculated seawater-groundwater exchange rates using the single-well method are shown in Figure 6. As shown in Table 3, the estimated SGD-s and inflow-s (SGD-s and inflow-s, the SGD and inflow calculated using the single-well method) are 223.0 and 13.3 m^2d^{-1} , much greater than those estimated by the pair-wells method. This might be related to the following aspects:

(1) The salinity difference between seawater and underground brine. As shown in Figure7, the underground brine salinities are between 30 and 40 g l⁻¹, up to about 56 g l⁻¹, which was much higher than the averaged seawater salinity about 23 g l⁻¹. When the averaged salinity between seawater and groundwater was used to estimate the vertical groundwater flow rate q_n , which will be less than the averaged salinity of pair-wells.

(2) The different tidal levels at different locations. The tidal level will decrease with the spread of tide landward (Lian and Zhao, 1995; Wang *et al.*, 1995), due to the influence of friction of beach surface (Kamphuis, 1978), and the coefficient of friction increases with decreasing depth (Yu and Li, 2002; Zhang, Lv, and Sun, 2012). But the differences of the tidal level at different locations are neglected in the single-well

method. What's more, the SGD and inflow estimation in the pairwells method used the hydraulic head at the up LTC-Diver, which is more close to the real hydraulic head at the observation well locations than the tidal level or beach surface here used in the single-well method.

Based on these reasons, the estimated results and errors of the single-well method would be greater than those by the pair-wells method.



Figure 7. Observed salinity at the up LTC-Diver (*solid dots*) and low LTC -Diver (*hollow dots*) of W2, ..., W13, W14 and the seawater (*hollow dots*)

Density Effect and Salinity Distribution

The generalized Darcy's law used in both the pair-wells method and the single-well method above considers the density effect. The salinity along the entire transect is great, which will have significant impacts on the seawater-groundwater exchange.

Ignoring the density effect, the vertical groundwater flow rate q_n can be written as:

$$q_{\rm n} = -K_{\rm V}(\frac{h_{\rm up} - h_{\rm low}}{\Delta L}) \tag{12}$$

where, K_v is the vertical hydraulic conductivity of the sediment at observation well locations [LT⁻¹]; the parameters h_{up} and h_{low} denote the freshwater-equivalent hydraulic head at up and low LTC-Divers [L]; ΔL is the distance between the up and low LTC -Divers, equaling 52.8 cm.

The estimation of SGD by Equation (12) increased by 25.6% to 206.0 $\rm m^2 d^{-1}$, and inflow decreased by 27.4% to 4.7 $\rm m^2 d^{-1}$, compared to those estimated by pair-wells method. Due to the high salinity of underground brine, the influence of density effect can change the exchange rate by nearly 25%, indicating that much downward groundwater water flow driven by high density brine.

Considering that the salinity at every LTC-Diver was relatively

stable (Figure 4), the salinity observed at each LTC-Diver was averaged and the results were shown in Figure 7. One can see that along the entire transect the salinity decreased from 56.2 to 25.7 g l^{-1} seaward gradually, but all of them were higher than the seawater salinity, averaged 22.6 g l^{-1} (Figure 7). The reasons for this might include the following aspects: (1) evaporation (the exposure time of the tidal flat increases landward, leading to a landward increasing-evaporation and in turn a landward increasing of salinity), (2) human activities such as exploitation of the underground brine and construction of many salt pans, as shown in Figure 1c (such activities often discharge waste salt brines into the coastal areas, leading to the high salinity there), and (3) the inland fresh groundwater discharge near the low tide zone (Heiss and Micheal, 2014; Li, Boufadel, and Weaver, 2008; Robinson et al., 2007), which may lead to the decrease of salinity of the groundwater in the lower intertidal zone.

Comparison with Ma et al. (2015)

The estimated SGD by the pair-wells method in this study was 164.0 $\text{m}^2 \text{d}^{-1}$, much greater than the SGD about 8.8 $\text{m}^2 \text{d}^{-1}$ calculated in Ma *et al.* (2015); while the inflow along this transect was 6.5 $\text{m}^2 \text{d}^{-1}$, less than that nearly 15.3 $\text{m}^2 \text{d}^{-1}$ in Ma *et al.* (2015) (Table 4). The differences in SGD and inflow between the two results are significant since there are many differences between the two transects.

The length of the cross-shore transect in this paper is 3514 m, which is about nine times long of the transect (392 m) in Ma *et al.* (2015) (Table 4). There were six single-well along the entire transect in Ma *et al.* (2015), while 14 pair-wells were set along our transect in this paper (Figures 1 and 2). The selected cross-shore transect in Ma *et al.* (2015) has two distinct slopes, with the landward part of a relatively steep slope about 2%, and the seaward part of a gentle slope about 0.1%. The slope of the selected transect in this paper is about 0.4 ‰, which is much smaller than the slopes in Ma *et al.* (2015) (Table 4).

Field measurements were conducted from 11:00 September 9th to 15:00 September 14th, 2012, about 125 hours in Ma *et al.* (2015) (Table 4). The observation time from 20:00 August 10th to 23:00 September 12th, 2014, almost 800 hours in this paper, is very long compared with most previous studies (Table 4).

The selected transect in this paper is heterogeneous along the cross-shore direction. The permeability ranges from $10^{-7}-10^{-5}$ m s⁻¹, which is one or two orders of magnitude less than that about 10^{-5} m s⁻¹ in Ma *et al.* (2015) (Table 4). There are little water flowing downward due to the low-permeability surface sediments and the higher hydraulic head of the groundwater when surface was submerged.

Table 4. The comparison of the two typical transects in this paper and Ma et al. (2015)

Table 4. The comparison of the two typical transects in this paper and ma et al. (2013)							
No.	Transect length (m)	Transect slope	Monitoring period	Permeability (ms ⁻¹)	$\frac{\text{SGD}}{(m^2 d^{-1})}$	Inflow $(m^2 d^{-1})$	Publicaton
1	392	Landward 2% Seaward 0.1%	125 h (5.5 d)	10 ⁻⁵	8.8	15.3	Ma et al., 2015
2	3514	0.4‰	792 h (33 d)	$10^{-7} - 10^{-5}$	164.0	6.5	This paper

The salinity of groundwater along the transect in Ma *et al.* (2015) ranged from 16 to 27 g l⁻¹, which is less than the salinity of seawater. The transect in this study area is located in brine zones, and the salinity of groundwater at observation locations ranged from 25 to 56 g l⁻¹, which is greater than the seawater salinity averaged about 23 g l⁻¹ (Figure 7). The details of the salinity distribution have been discussed in the "Density effect and salinity distribution" section.

CONLUSIONS

This paper investigated the seawater-groundwater exchange in a silty tidal flat with a large-scale seepage face in the south coastal of Laizhou Bay. We selected 14 locations along a typical transect in the intertidal zone with the slope of 0.4% and the cross-shore width of 3514 m, to install observation pair-wells monitoring the groundwater head, salinity and temperature at two different depths simultaneously. The vertical hydraulic conductivity ranges from 5. 4×10^{-7} to 1. 1×10^{-5} m s⁻¹, and the salinity of the underground brine is from 25 to 56 g l⁻¹ along the selected transect. Basing on the observed data from 20:00 August 10th to 23:00 September 12th, 2014 and generalized Darcy's law, the submarine groundwater discharge (SGD) and inflow along the studied transect were estimated to be 164.0 and 6.5 $m^2 d^{-1}$, respectively; within 80.4% of the total SGD concentrated between W7 and W10 due to the high-permeability here, and 64.6% of the total inflow between W2 and W4.

The comparative study between the pair-wells method and single-well method indicated that the pair-wells method is more suitable for the long transect with a very gentle slope than the single-well method, due to the pair-wells can monitor the groundwater head, salinity and electrical conductivity at two different elevations simultaneously. The fixed distance of the pairwells can avoid the uncertain errors of the single-well method.

The observed data indicated that pumping of groundwater has significant impacts on the exchange between seawater and groundwater. During the groundwater pumping period, the outflow decreased by $5.4 \text{ m}^2 \text{d}^{-1}$ and the inflow increased by $46.1 \text{ m}^2 \text{d}^{-1}$, even up to $217.3 \text{ m}^2 \text{d}^{-1}$ within the tidal zone from W3 to W5.

The density effect had great impacts on the seawatergroundwater exchange in the brine zones due to its high salinity ranging from 25 to 56g l^{-1} along the entire transect. Leaving out the density effect, the exchange rate can change 25%, indicating that much downward groundwater flow driven by the density effect.

The salinity decreased seaward gradually along the entire transect, probably because the evaporation, human activities such as exploitation of the underground brine and construction of many salt pans, and the inland fresh groundwater discharge near the low tide zone.

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LITERATURE CITED

- Bi, Y. F.; Yu, H. J.; Xu, X. Y., and Su, Q., 2012. Study on the groundwater hydrochemical characteristics in the southern Laizhou Bay. *Marie Science Bulletin*, 31(3), 241-248.
- Cable, J. E.; Burnett, W. C.; Chanton, J. P.; Corbett, D. R., and Cable, P. H., 1997. Field Evaluation of Seepage Meters in the Coastal Marine Environment. *Estuarine*, *Coastal and Shelf Science*, 45, 367–375.
- Cox, R. A.; Culkin, F., and Riley, J. P., 1967. The electrical conductivity/ chlorinity relationship in natural sea water. *Deep Sea Research and Oceanographic Abstracts*, 14 (2), 203 -220.
- Feng, S. T.; Tan, X. F., and Liu, G., 2013. Potentiality Analysis on Underground Brine Resources in Shandong Province. Shandong Land and Resources, 29, 69–73.
- Fetter, C. W., 1994. Applied Hydrogeology. New Jersey: Prentice Hall.
- Gu, H. Q.; Moore, W. S.; Zhang, L.; Du, J. Z., and Zhang, J., 2012. Using radium isotopes to estimate the residence time and the contribution of submarine groundwater discharge (SGD) in the Changjiang effluent plume, East China Sea. *Continental Shelf Research*, 35, 95–107.
- Guo, Q. N.; Li, H. L.; Boufadel, M. C., and Sharifi, Y., 2010. Hydrodynamics in a gravel beach and its impact on the Exxon Valdez oil. *Journal of Geophysical Research*, 115, C12077, doi: 10.1029/2010JC006169.
- Han, D. M.; Song, X. F.; Currell, M. J.; Yang, J. L., and Xiao, G. Q., 2014. Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China. *Journal of Hydrology*, 508, 12–27.
- Han, F.; Wu, J. C., and Zhang, Y. X., 2011. Numerical simulation for the salt/ brine water intrusion in a leaky aquifer: A case study of the southern beach of Laizhou Bay, eastern China. *Journal of Nanjing University*, 47(3), 281–290.
- Heiss, J. W. and Michael, H. A., 2014. Saltwater-freshwater mixing dynamics in a sandy beach aquifer over tidal, springneap, and seasonal cycles. *Water Resources Research*, 50(8), 6747-6766.
- Kamphuis, J. W., 1978. Attenuation of gravity waves by bottom friction. *Coastal Engineering*, 2, 111–118.
- Lee, C. M.; Jiao, J. J.; Luo, X., and Moore, W. S., 2012. Estimation of submarine groundwater discharge and associated nutrient fluxes in Tolo Harbour, Hong Kong. *Science of the Total Environment*, 433, 427–433.
- Li, D. G.; Zhao, M. H.; Han, M.; Jiang, A. X., and Zhang, Z. L., 2000. A study of the shallowly-buried paleochannel zones in the south coast plain of the Laizhou Bay. *Marine Geology & Quaternary Geology*, 20 (1), 23–29.
- Li, H. L. and Boufadel, M. C., 2010. Long-term persistence of oil from the Exxon Valdez spill in two-layer beaches. *Nature Geoscience*, 3(2), 96–99.
- Li, H. L.; Boufadel, M. C., and Weaver, J. W., 2008. Tide-induced seawater-groundwater circulation in shallow beach aquifers. *Journal of Hydrology*, 352, 211–244.
- Li, H. L. and Jiao, J. J., 2013. Quantifying tidal contribution to submarine groundwater discharges: a review. *Chinese Science Bulletin*, 58 (25), 3053–3059.
- Li, H. L.; Sun, P. P.; Chen, S.; Xia, Y. Q., and Liu, S., 2010.

A falling-head method for measuring intertidal sediment hydraulic conductivity. *Ground Water*, 48(2), 206-211.

- Li, L.; Barry, D. A.; Stagnitti, F., and Parlange, J. Y., 1999. Submarine groundwater discharge and associated chemical input to a coastal sea. *Water Resource Research*, 35 (11), 3253-3259.
- Lian, J. J. and Zhao, Z. D., 1995. Interactions between wavecurrent and muddy sea-bed. *Journal of Sediment Research*, 3, 40-50.
- Ma, Q.; Li, H. L.; Wang, X. J.; Wang, C. Y.; Wan, L.; Wang, X. S., and Jiang, X. W., 2015. Estimation of seawatergroundwater exchange rate: case study in a tidal flat with a large-scale seepage face (Laizhou Bay, China). *Hydrogeology Journal*, 23(2), 265-275.
- Moore, W. S., 1996. Large groundwater inputs to coastal waters revealed by²²⁶Ra enrichments. *Nature*, 380, 612–614.
- Moore, W. S., 2007. Estimating submarine groundwater discharge in the range 10¹ to 10⁸ km² using Ra isotopes. *Geochimica Et Cosmochimica Acta*, 71(15), A684-A684.
- Moore, W. S. and Oliveira, J. D., 2008. Determination of residence time and mixing processes of the Ubatuba, Brazil, inner shelf waters using natural Ra isotopes. *Estuarine Coastal* and Science, 76(3), 512–521.
- Paulsen, R. J.; Smith, C. F.; O'Rourke, D., and Wong, T. F., 2001. Development and Evaluation of an Ultrasonic Ground Water Seepage Meter. *Groundwater*, 39(6), 904–911.
- Riedel, T.; Lettmann, K.; Beck, M., and Brumsack, H. J., 2010. Tidal variations in groundwater storage and associated discharge from an intertidal coastal aquifer. *Journal of Geophysical Research*, 115, C04013, doi: 10.1029/2009JC005544.
- Robinson, C.; Gibbes, B.; Carey, H., and Li, L., 2007. Saltfreshwater dynamics in a subterranean estuary over a springneap tidal cycle. *Journal of Geophysical Research-oceans*, C9 (112), C09007, doi: 10.1029/2006JC003888.
- Robinson, C.; Li, L., and Barry, D. A., 2007. Effect of tidal forcing on a subterranean estuary. Advances in Water Resources, 30(4), 851-865.
- Slomp, C. P. and Cappellen, P. V., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *Journal of Hydrology*, 295 (1-4), 64-86.
- Taniguchi, M. and Fukuo, Y., 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. *Ground Water*, 31(4), 675-679.
- Turner, I. L., 1995. Simulating the influence of groundwater seepage on sediment transported by the sweep of the swash zone across macro-tidal beaches. *Marine Geology*, 125(1-2), 153-174.

- Wang, L.; Jin, Y.; Li, Y., and Ding, J., 1995. Approact to Characteristics of Wave Breaking. *The Ocean Engineering*, 13 (3), 81-89.
- Wang, X. J.; Li, H. L.; Jiao, J. J.; Barry, D. A.; Li, L.; Luo, X.; Wang, C. Y.; Wan, L.; Wang, X. S.; Jiang, X. W.; Ma, Q., and Qu, W. J., 2015. Submarine fresh groundwater discharge into Laizhou Bay comparable to the Yellow River flux. *Science Reports.* doi:10.1038/srep08814.
- Wang, X. J.; Li, H. L.; Yang, J. Z.; Wan, L.; Wang, X. S.; Jiang, X. W., and Guo, H. M., 2014. Measuring in-situ vertical hydraulic conductivity in tidal environments. *Advances in Water Resources*, 70, 118–130.
- Wooster, W. S.; Lee, A. J., and Dietrich, G., 1969. Redefinition of salinity. *Limnology and Oceanography*, 14 (3), 437–438.
- Xia, Y. Q. and Li, H. L., 2012. A combined field and modeling study of groundwater flow in a tidal marsh. *Hydrology and Earth System Science*, 16(3), 741–759.
- Xia, Y. Q.; Li, H. L.; Boufadel, M. C., and Sharifi, Y., 2010. Hydrodynamic factors affecting the persistence of the Exxon Valdez oil in a shallow bedrock beach. *Water Resources Re*search, 46(10), W10528, doi: 10.1029/2010WR009179.
- Xu, B. C.; Xia, D.; Burnett, W. C.; Dimova, N. T.; Wang, H. J.; Zhang, L. J.; Gao, M. S.; Jiang, X. Y., and Yu, Z. G., 2014. Natural²²²Rn and ²²⁰Rn indicate the impact of the Water-Sediment Regulation Scheme (WSRS) on submarine groundwater discharge in the Yellow River estuary, China. *Applied Geochemistry*, 51, 79–85.
- Xue, Y. Q.; Wu, J. C.; Ye, S. J., and Zhang, Y. X., 2000. Hydrogeological and Hydrogeochemical Studies for Salt Water Intrusion on the South Coast of Laizhou Bay, China. *Ground Water*, 38 (1): 38-45.
- Yu, Y. and Li, Y. C., 2002. Dissipation of wave energy on very mild slope. *Journal of Hydrodynamics*, 17 (5), 553–564.
- Yu, Y. H., 2014. The development of salt industry on south of Laizhou Bay in northern Shandong. Salt Industry History Research, 2, 8-16.
- Zhang, J. C.; Lv, X. Q., and Sun, L. Y., 2012. Study on bottom friction parameterizations for two-dimensional tidal models using data assimilation. *Chinese Journal of Computational Mechanics*, 29(1), 49–54.
- Zhang, W. H.; Cai, Y. Q., and Wu, C. C., 2002. A research into some environmental aspects of beach erosion. *Journal of Safety and Environment*, 2 (3), 8–12.
- Zhang, Z. L. and Peng, L. M., 1998. The groundwater hydrochemical characteristics on seawater intruded in eastern and southern coasts of Laizhou Bay. *China Environmental Science*, 18 (2), 121–125.