

Submarine groundwater discharge around Taiwan

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Abstract

A preliminary study shows that the submarine groundwater discharge (SGD) exists around Taiwan even though groundwater overdrawing on the island is serious. Fifteen of the 20 sites studied for major anions and cations recorded a clear SGD signal with freshwater outflow. A total of 278 salinity and major ion measurements were made. Sixteen nearly freshwater SGD (salinity ≤ 1.0) samples were obtained, providing strong and direct evidence for the existence of fresh meteoric groundwater entering the ocean from Taiwan. The total SGD flux is estimated to be 1.07×10^{10} t/a which is about 14% of the annual river output. The freshwater component of the SGD is 3.85×10^9 t which is about 5.2% of the annual river discharge in Taiwan. The collected SGD has a composition similar to seawater with an addition of Ca, CO₃ and HCO₃ due to dissolution of calcareous rocks. Some samples with high Cl/(Na+K) may indicate pollution.

Key words: submarine groundwater discharge, Taiwan, flux, major components, seawater intrusion

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1 Introduction

The coastal zone is marked by rich biodiversity and is of great importance for fisheries, agriculture and human settlements. For islands, the groundwater is a particularly important freshwater resource (Aris et al., 2013). Yet, the groundwater in coastal zones faces many threats; of which, seawater intrusion is a notable example. In order to deal with potential threats to this critical resource it is therefore important to understand the freshwater-seawater interface. The seawater intrusion mentioned above involves the penetration of seawater landward. On the other hand, the submarine groundwater discharge (SGD) involves the flow of groundwater and associated dissolved material seaward (the conceptual model is depicted in Fig. 1 of Moore (2010)). SGD, in a way, is a waste of the freshwater resource, and is the subject of this study.

The subtropical island of Taiwan has an area of 35 873 km² which is mostly mountainous with abundant rainfall which averages 2 515 mm or 90×10^9 m³/a. The alluvial plains with elevation of less than 100 m cover an area of just 37%. The mountainous regions store about 125×10^8 – 165×10^8 m³ of groundwater while the alluvial plains store about 45×10^8 – 58×10^8 m³ groundwater. The annual groundwater recharge is about 4×10^9 – 5×10^9 m³ yet the pumping of groundwater is as much as 7×10^9 m³/a. In some areas of Taiwan, seawater intrusion has occurred due to the over-pumping of groundwater (Central Geological Survey (CGS), 2002;

Peng et al., 2008; Chiang et al., 2013). Nevertheless, Chen et al. (2005) obtained fresh meteoric groundwater with a seepage meter at a water depth of 7.8 m off Southwest Taiwan. Based on a hydraulic model with the help of salinity, deuterium and oxygen-18, Peng et al. (2008) came to the conclusion that, although some coastal areas in Taiwan are experiencing seawater intrusion, some coastal plains still show a surplus of groundwater moving downstream. Lin et al. (2010) and Zaviyalov et al. (2012) also found some evidence of SGD off Southwest Taiwan based on oceanic chemistry data. The total SGD flux for Taiwan, however, is not known.

The definition of SGD is any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force (Burnett et al., 2003). Basically, SGD is composed of the terrestrial freshwater and circulated seawater driven by various forces (e.g., density, tides and waves). Thus SGD occurs at land-ocean interface at every moment. Here the total flux of SGD around Taiwan is estimated for the first time. Since part of the aim is to study the components of the SGD we relied on the use of seepage meters to collect samples for further analyses.

2 Methods

Preliminary sampling of the SGD was performed from 2004 to 2016. Twenty sampling sites around the coasts of Taiwan are

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shown in Fig. 1. SGD samples for chemical analysis were drawn by a device designed by Zhang and Satake (2003), and either a Lee (1977) type or a conductivity based (Peng et al., 2008) seepage meter (Fig. 2) was used to measure the SGD flux at various tidal ranges. Preserved samples, with saturated HgCl₂ added except for salinity and Cl samples, were brought back and Ca, Mg, K, Na, total alkalinity (TA), SO₄ and Cl were measured in the laboratory following the methods described in Chen et al. (2008). A total of 278 salinity and major ion measurements were made.

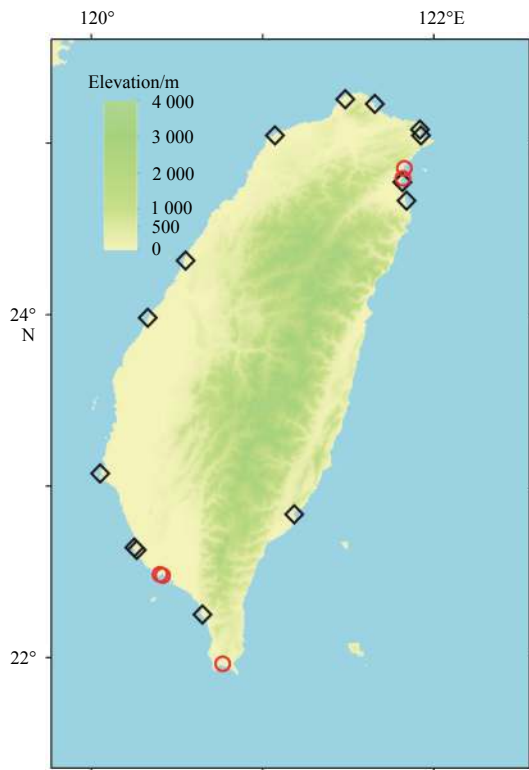


Fig. 1. Sampling sites around Taiwan. The five sites without the evidence of freshwater outflow are in open circles.

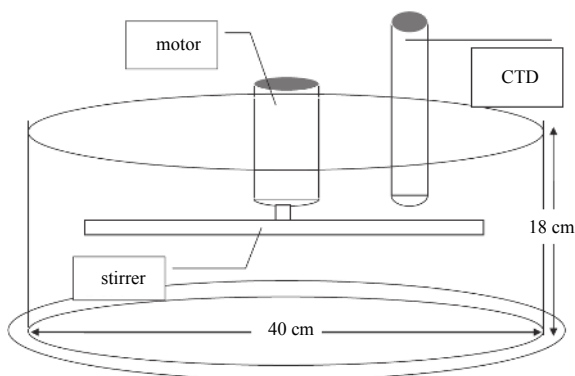


Fig. 2. Conductivity based SGD sampler.

3 Results and discussion

The salinity of 278 measurements varies over a wide range between 0.008 and 34.8 with an average of 21.92±11.43, reflecting seawater intrusion. Other ions also show a wide range. Of note is that 16 samples from five sites showed fresh (salinity ≤ 1.0) SGD. The SGD with a salinity of 0.2 was found at a distance of 350 m

and a water depth of 7.8 m off Southwest Taiwan. This is where Lin et al. (2010) and Zavalov et al. (2012) found low salinity seawater based on their measurements in the water column.

The average concentrations of the parameters measured are given in Table 1. Out of the 20 sampling sites, 15 showed evidence of some SGD. Five sites without the evidence of SGD are in areas known to be overpumping groundwater. Na and Cl are the dominating cation and anion, respectively (Fig. 3), followed by

Table 1. Concentrations of major ions measured in the SGD

	Range	Mean±SD	n
Salinity	0.008–34.8	21.92±11.43	278
Ca ²⁺ /mmol·L ⁻¹	0.028–36.8	7.98±5.04	116
Mg ²⁺ /mmol·L ⁻¹	0.051–62.5	32.5±16.50	116
K ⁺ /mmol·L ⁻¹	0.034–10.0	6.13±3.09	116
Na ⁺ /mmol·L ⁻¹	0.721–464	287±144	116
HCO ₃ ⁻ /mmol·L ⁻¹	0.54–8.25	3.00±1.34	123
CO ₃ ²⁻ /mmol·L ⁻¹	0.007–0.796	0.15±0.09	123
Cl ⁻ /mmol·L ⁻¹	7.814–623	364±177	100
SO ₄ ²⁻ /mmol·L ⁻¹	0.206–29.6	36.6±7.17	100

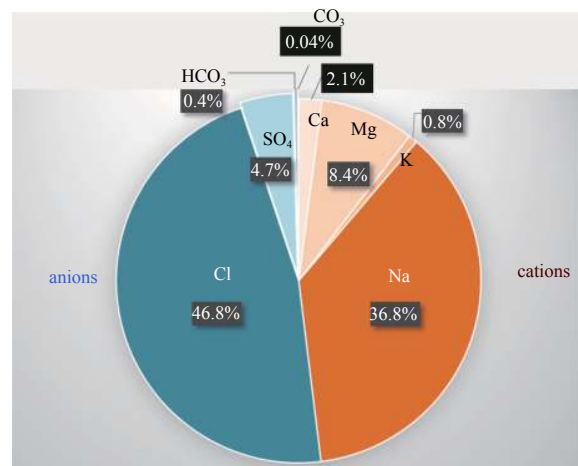


Fig. 3. Composition of major cations and anions.

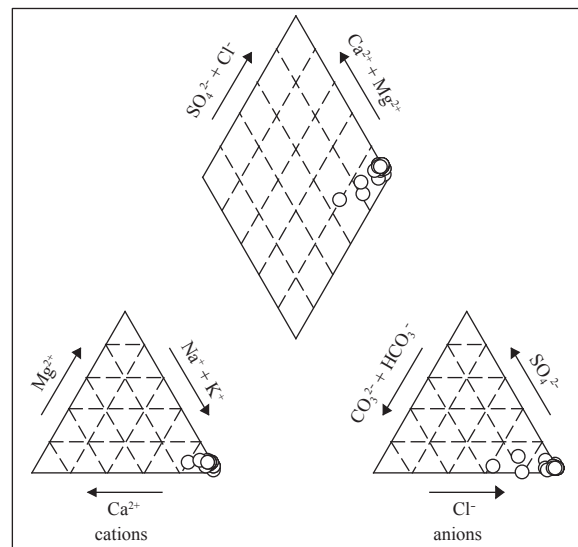


Fig. 4. Piper plot of SGD samples.

Mg and SO_4 . This is a clear initial indication that seawater is the major component of the SGD either coming directly through submarine intrusion or indirectly through sea spray with subsequent percolation into the groundwater. The Piper plot (Fig. 4) also reveals that the SGD is dominated by the Na(+K)-Cl type (seawater components) with small components of Ca-Cl (mixed seawater and freshwater components) and Ca- HCO_3 (+ CO_3) (freshwater components) types. This reflects the influence of seawater and the dissolution of calcareous rocks.

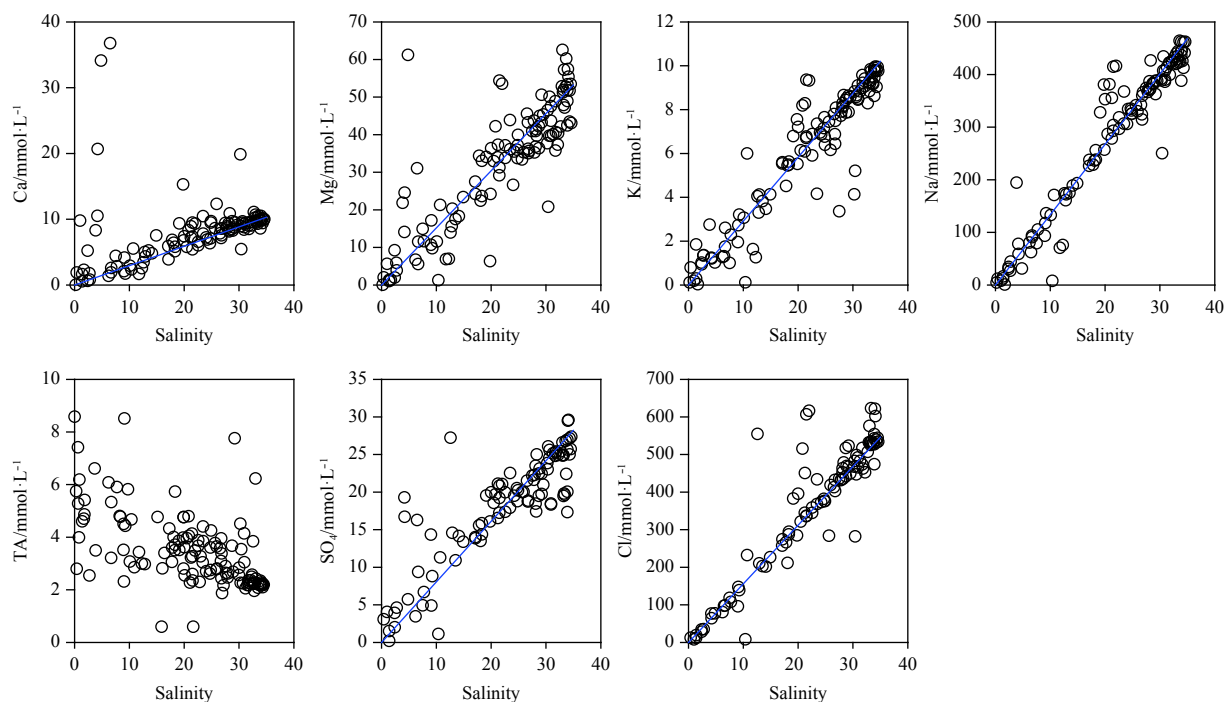


Fig. 5. Ca, Mg, K, Na, TA, SO_4 and Cl plotted vs. salinity.

Of note is that many Ca, Mg, SO_4 and Cl values are clearly above the seawater slope. The higher Ca and Mg values are perhaps due to the dissolution of calcareous rocks or dolomite. The higher TA values at lower salinities support this suggestion. The higher SO_4 and Cl concentrations are, however, likely due to pollution to be discussed below.

The Mg/Ca ratio is shown in Fig. 6a. Most data follow the seawater ratio but some samples show an excess amount of Ca relative to Mg, suggesting dissolution of calcareous rocks. Ratios of Mg/Ca that exceeds 1.0 indicate that the dolomitization process may take place due to the presence of seawater in the groundwater (Pulido-Leboeuf, 2004). In the case for Taiwan, most SGD samples show a seawater Mg/Ca ratio of 5.14, with only a few having an Mg/Ca ratio below 1.0. The Na/Ca ratio (Fig. 6b) does not show a clear pattern except that the values fall around the seawater ratio. The Cl/ HCO_3 ratio increases with Cl (Fig. 6c). The SO_4 /Cl values mostly follow the seawater ratio (Fig. 6d) but there are some high values perhaps reflecting pollution. Figure 6e plots the non-sea salt SO_4 (nss- SO_4)/(Na+K) vs. Cl/(Na+K). The values above the seawater ratio reflect pollution of Cl from garbage incineration or petrochemical plants.

Altogether there are only 44 flux measurements with an average of (1 ± 0.7) L/($\text{m}^2 \cdot \text{h}$) for SGD and (0.37 ± 0.47) L/($\text{m}^2 \cdot \text{h}$) for the freshwater outflow. These small sample numbers are not sufficient to obtain a robust average because of the large seasonal and spatial variations. Besides, fluxes must be heavily influenced by

Figure 5 shows the concentrations of major components plotted vs. salinity. Needless to say, all but total alkalinity (TA) increases with salinity. TA is an exception as the values increase at lower salinities, reflecting the dissolution of calcareous rocks which contributes to HCO_3 and CO_3 , both major components of TA. Generally speaking, Ca, Mg, K, Na, SO_4 and Cl show a linear trend with respect to salinity (Fig. 4) and the slopes correspond to the seawater composition (Chen, 2007). This, again, is a clear sign of the seawater influence.

tidal phases due to different sea level responses (Liu et al., 2018). Since we measured the fluxes at various tidal phases the total SGD flux to be given below is subject to large uncertainties.

Assuming that the SGD exists in a 1 km wide band around Taiwan with a 1 200 km long coast line the first approximation of the SGD export results in a value of $(1.07 \pm 0.7) \times 10^{10}$ t/a; of which, $(0.38 \pm 0.48) \times 10^{10}$ t/a is the freshwater component. These values are, respectively, about 14% and 5.2% of the total river outflow from Taiwan, and fall within the ranges reported elsewhere (Zektser et al., 1983; Church, 1996; Moore, 1996; Cable et al., 1996; Burnett et al., 2001, 2003; Taniguchi et al., 2002, 2008). More specifically, Moosdorf et al. (2015) estimated the global average fresh groundwater discharge at $7\,050 \text{ m}^3/(\text{m} \cdot \text{a})$ with Taiwan having a value of $5\,486 \text{ m}^3/(\text{m} \cdot \text{a})$. Our freshwater SGD component translates to $(3\,200 \pm 4\,000) \text{ m}^3/(\text{m} \cdot \text{a})$. Considering the large uncertainty, the agreement is reasonable.

Across the Taiwan Strait the SGD has also been studied in the Jiulong River with its $14\,700 \text{ km}^2$ watershed falling in the same latitude as Taiwan (Fig. 1). The recent work of Wang et al. (2015) reported an SGD value in the Jiulong River Estuary as 8%–19% of the concomitant river discharge, compared with 14% obtained above for Taiwan (Fig. 1). In terms of the freshwater component of the SGD the Jiulong River Estuary exports about 2%–4.8% of the concomitant river discharge, compared to 5.2% for Taiwan. Considering the large uncertainties involved, these values can be considered similar.

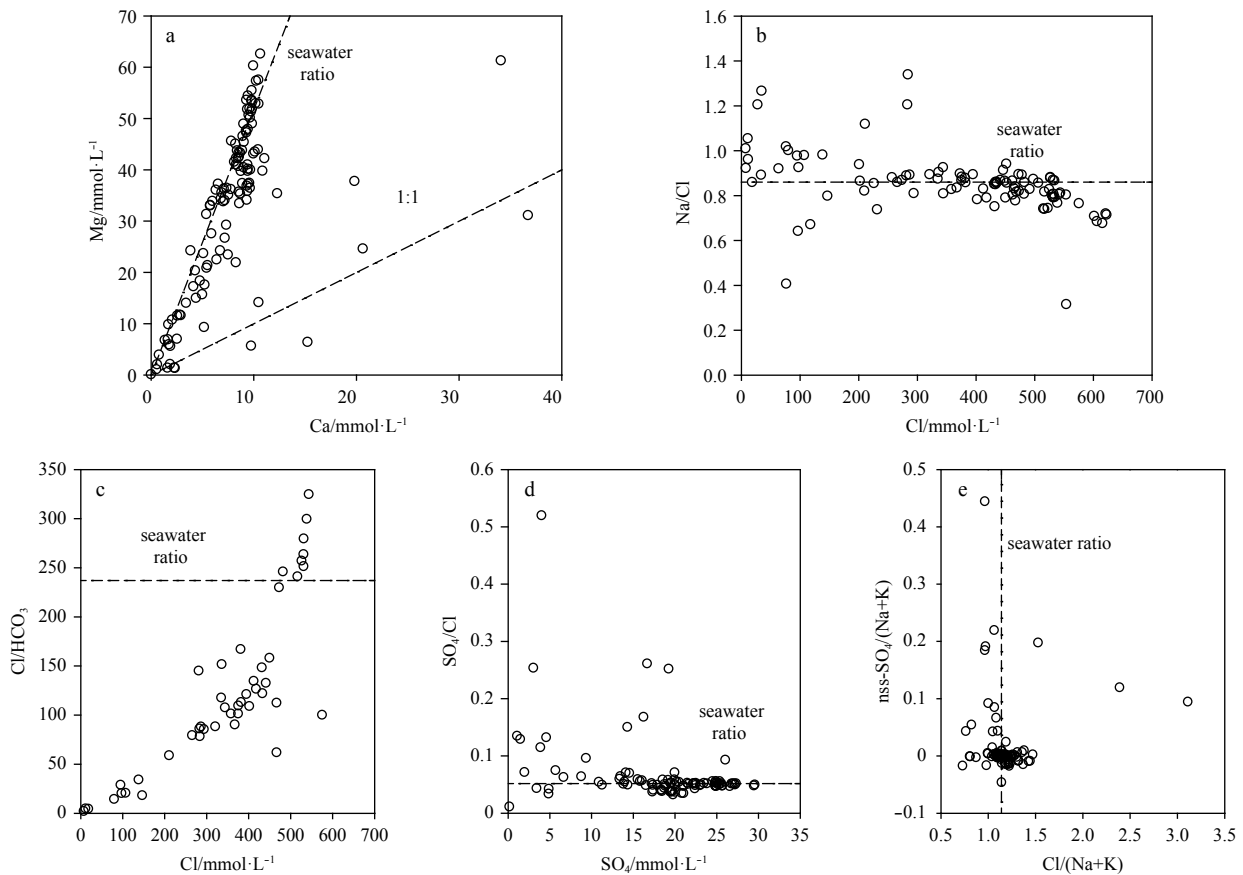


Fig. 6. Mg vs. Ca (a), Na/Cl vs. Cl (b), Cl/HCO₃ vs. Cl (c), SO₄/Cl vs. SO₄ (d) and nss-SO₄/(Na+K) vs. Cl/(Na+K) (e).

4 Conclusions

Two hundred and seventy-eight salinity and major ion measurements were performed on the SGD collected at 20 sites around Taiwan. Fifteen sites showed evidence of some freshwater outflow. The collected SGD has a composition similar to seawater with an addition of Ca, CO₃ and HCO₃ due to dissolution of calcareous rocks. Some samples with high Cl/(Na+K) may indicate pollution. Forty-four flux measurements reveal that the total flux of SGD from Taiwan amounts to 14% of the total river outflow.

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