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INVESTIGATION AND ASSESSMENT OF SUBMARINE GROUNDWATER DISCHARGE OF PING-TUNG NEARSHORE AREA IN SOUTHWESTERN TAIWAN†

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ABSTRACT

Submarine groundwater discharge (SGD) is a potential pathway for nutrients and anthropogenic pollutants that flow from the land into the coastal ocean, and probably influences the aquatic ecosystem in tidal areas. This paper focused on surveying possible groundwater locations around the coastal area. The possible location, pathway and discharge of SGD in the Ping-Tung Shelf of southwestern Taiwan were described by oceanographic measurements. During the field surveys of the study area, onboard surface to bottom CTD (conductivity, temperature, depth) profiling, ADCP (Acoustic Doppler Current Profiler) measurements, and fluorescence profiling were carried out at 25 different stations. The collected hydrographic data were used to identify a suspected SGD site in the central part of the study area, where a local drop of salinity by up to 0.06 psu has been observed in the lowermost 0.2 ~ 1.5 m of the water column. Thanks to explicit evidence for a possible pathway and locations, seepage meters were deployed on the sea bed to measure the SGD rate at about 6.0 ml h^{-1} m^{-2} in the dry season. Based on the surveyed data, the likely locations of the SGD sources in the study area were specified, all of which were restricted to the inner shelf at a depth less than 8 m. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: submarine groundwater discharge; Ping-Tung; conductivity; temperature; depth; Acoustic Doppler Current Profiler; Taiwan

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RÉSUMÉ

La décharge d'une nappe souterraine en milieu sous-marin (SGD) est une voie potentielle pour que des nutriments et des polluants anthropiques d'origine terrestre influencent l'écosystème aquatique dans les zones de marée. Ce document est axé sur la reconnaissance des nappes souterraines autour de la zone côtière de Ping-Tung (sud-ouest de Taiwan). L'emplacement possible, les voies de passage, le débit de SGD dans le plateau sous-marin ont été décrits par des mesures océanographiques. Pendant les reconnaissances de terrain, des équipements embarqués ont permis de réaliser des profils de CTD (conductivité, température, profondeur), de champs de vitesses (mesures ADCP, Acoustic Doppler Current Profiler), et de fluorescence à 25 stations différentes. Les données hydrographiques collectées ont confirmé un site SGD présumé dans la partie centrale de la zone d'étude, où une baisse locale de la salinité jusqu'à 0.06 PSU a été observée dans la partie basse (0.2 à 1.5 m) de la colonne d'eau. Grâce à des preuves explicites de lieux possibles d'écoulement, les mesures d'exfiltration ont été déployées sur le fond de la mer pour mesurer le flux sortant, qui d'environ 6.0 ml h^{-1} m^{-2} en saison sèche. Basés sur les données relevées, les emplacements probables des sources de SGD ont été spécifiés, et tous ont été délimités à l'intérieur du plateau à une profondeur inférieure à 8 m. Copyright © 2013 John Wiley & Sons, Ltd.

MOTS CLÉS: décharge sous-marine d'une nappe souterraine; Ping-Tung; conductivité; température; profondeur; ADCP; Taiwan

INTRODUCTION

Submarine groundwater discharge (SGD) is perhaps the least well-understood and quantified component of the ocean's freshwater budget. While the volume of SGD into the coastal ocean may be relatively minor, especially in areas dominated by surface runoff, several studies have

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†Caractérisation et évaluation de la décharge sous-marine d'une nappe souterraine dans la région côtière de Ping-Tung, au sud-ouest Taiwan.

indicated that groundwater may sometimes account for a significant fraction of the total freshwater inflow (Valiela and D'Elia, 1990; Buddemeier, 1996, Kontar and Zektser, 1999; Kontar, 2001, Burnett *et al*., 2002, 2003). Moreover, SGD is a potentially significant deliverer of anthropogenic pollutants and nutrients into the coastal area of the ocean. The pollutant input via SGD has been shown to be the cause of eutrophication in nearshore areas. Groundwater contamination is obviously a serious problem in Taiwan, and it will lead to ecosystem variation and sustainable development issues in tidal areas.

The inner shelf of the Taiwan Strait adjacent to the Ping-Tung Plain area was selected as a research region (Figure 1). The Ping-Tung Plain, located in the southern part of Taiwan, is rich in groundwater with an average annual recharge volume of about 1 billion m^3 (Pan *et al*., 1998) to 2 billion m^3 (Chang *et al*., 2004), but suffers from land subsidence in coastal areas. The area is the principal production place of grouper and is full of breeding ponds. Based on the quality, quantity, and temperature requirements of fresh water, these ponds draft groundwater day after day. Temporal and spatial concentrated pumping of groundwater leads to severe land subsidence. The maximum accumulative subsidence measured exceeded 3.2 m in Ping-Tung Plain in 2011, and ground elevation below mean sea level had increased the flooding potential not only in the typhoon season but also in spring tide periods.

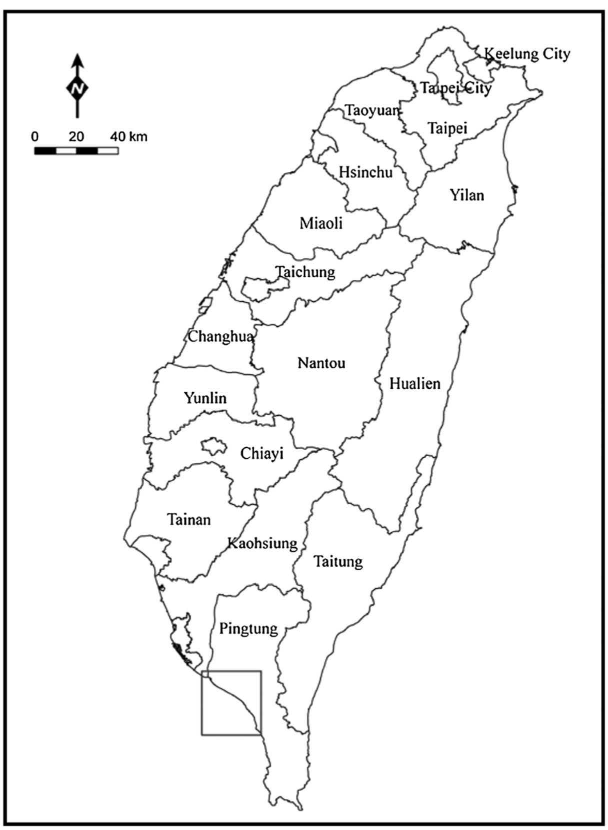


Figure 1. Study area located at southern part of Taiwan. The box indicates the area covered by the field survey.

According to geological investigation reports, there are four aquifers and three aquitards in the Ping-Tung Plain; the aquifers are not sealed on the coastal side, which provides groundwater with a pathway to flow into the sea. The estimated SGD volume of the Ping-Tung Plain is 0.6 million $m^3\ yr^{-1}$ (Pan *et al*., 1998) to 3 million $m^3\ yr^{-1}$ (Ting and Overmars, 1995). Some indirect evidence from numerical modelling point to the existence of SGD (Ting, 1997; Lin *et al*., 2003), but direct measurements of SGD in the area were only carried out in 2004 (Cheng *et al*., 2005). They deployed SGD collecting devices (seepage meters) buried in the bottom sands at five sampling sites around Taiwan, and one of them that was located in the Ping-Tung Plain, at Fang-San, observed a distinct SGD signal, manifested in significantly reduced salinity and pH, and elevated concentrations of nutrients, as compared with the surrounding ocean waters. A seepage meter was deployed 300 m from the Fang-San coast at a depth of 7.8 m, where the bottom water sample reportedly had a salinity of only 0.2 psu, which was essentially fresh.

The Ping-Tung Plain possesses abundant groundwater resources, but the overdraft phenomenon existed routinely in the coastal area characterized by shortages of fresh water. From the standpoints of water and land resources sustainable development and flooding reduction, it is necessary and urgent to establish an adequate groundwater management system for conjunctive utilization and allocation between surface and groundwater resources in an appropriate manner. In addition, SGD information along the shore is essential to define the shore (downstream) boundary conditions for a management model that can precisely reflect the hydrogeological conditions of the groundwater environment in a catchment.

INVESTIGATION FIELD

The field surveys of the study area were conducted in February and October 2009, using a fishery ship equipped with instruments. The track consisted of 25 stations distributed along 7 transects, transversal with respect to the shelf. The stations closest to the shore were located at approximately 5 m isobath, with those furthest from the shore at about 50 m isobath (except stations 3 and 4 located in a relatively deep canyon, with depth exceeding 200 m). The locations of all stations are depicted in Figure 2.

The hydrographic measurements included CTD (conductivity, temperature, depth) profiling at 25 selected stations, ADCP (Acoustic Doppler Current Profiler) profiling, the UV-lidar measurements of chlorophyll, suspended matter

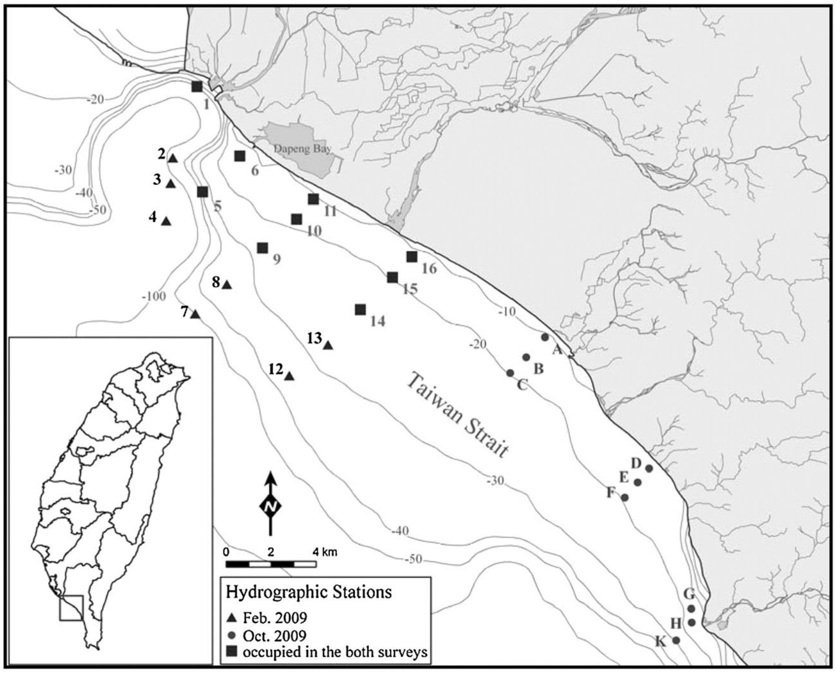


Figure 2. Map of study area and locations of hydrographic stations. The stations indicated by triangles were occupied in February, 2009, the stations shown by circles were occupied in October 2009, and those shown by rectangular boxes were occupied in both surveys.

and dissolved organic matter at the sea surface along the ship's track, and the water and sediment sampling campaign at all stations, and also from the river and groundwater wells on shore (water and sediment sampling analysis is not presented in this paper).

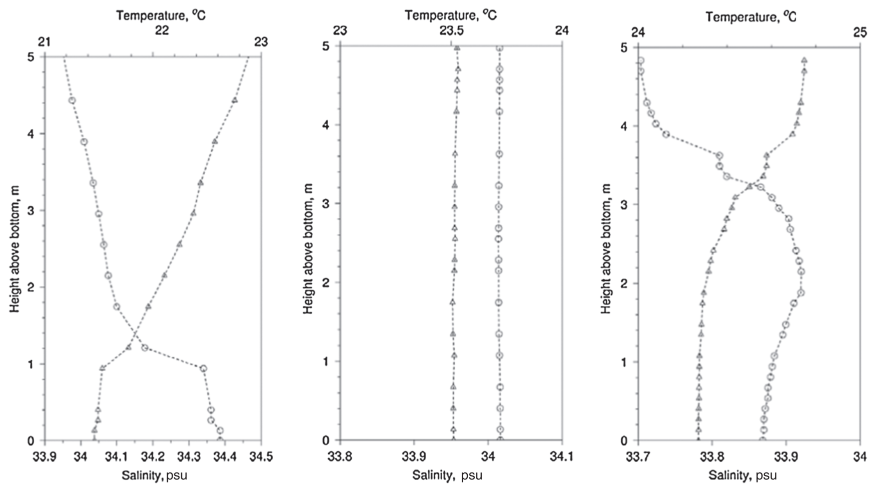
HYDROGRAPHIC DATA

The CTD profiling revealed that in the near-bottom layer, there existed three types of saline and thermal stratification in the study region (Figure 3). Note that throughout this paper, the focus is on the near-bottom layer, so the ordinate axis in Figure 3, as well as some other figures herein, represent the height above the bottom and not the depth as in conventional oceanographic plots. Stratification type 1, characteristic for stations 2 ~ 8 in February and stations 2 ~ 5, 7 ~ 10, 12 ~ 15, and C ~ F and K in October, exhibited a salinity maximum at the bottom. This type can be considered characteristic of normal oceanic conditions with no SGD influence, where the salinity and density increase downwards from the surface which may be freshened by fluvial discharges. The part of the study region adjacent to the river estuary is dominated by this type of near-bottom stratification. Stratification type 2, observed at locations 9, 10, 12, and 13 in February, and H in October, is characterized by a fully mixed bottom layer. It points to the presence of a strong current near the bottom, leading to enhanced shear-generated turbulent mixing. This type does not show any indication of SGD.

However, the most interesting stratification type is type 3, observed at stations 1, 11, 14 ~ 16 in February, and 1, 6, 11, 16, and G in October, in the eastern coastal part of the study region. It is characterized by weak but distinct salinity decay near the bottom, as shown in Figure 3(c). The maximum manifestation of near-bottom salinity drop was confined to the lowermost 2 m of the water column, with the magnitude of the drop up to 0.06 psu.

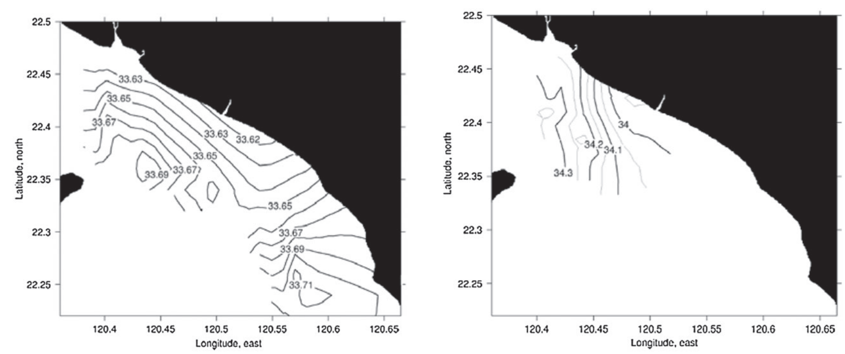
The area of suspected SGD in the eastern part of the study region was also characterized by a distinct minimum in the horizontal distribution of salinity at the bottom (Figure 4). The vertical profiles of water transparency and fluorescence are also separately illustrated in Figures 5 and 6. The former demonstrates the growth of the light extinction coefficient towards the bottom, which could be associated with the resuspension of the sediment from the bottom by shear and wave mixing. However, in the very near-bottom layer (from the bottom and up to 2 ~ 3 m height above the bottom), water transparency increased, suggesting that the water therein may be of a foreign source, and some process is pushing the suspended sediment from the bottom. This inference is also supported by the salinity–fluorescence diagram in Figure 6, showing an inflection point and a different behavior of fluorescent agents near the bottom. Generally, the higher fluorescence means the higher concentration of phytoplankton that implies the decrease of salinity might originate from SGD.

The structure of near-bottom salinity distribution during the second survey has confirmed the hypotheses that the



(a) (b) (c)

Figure 3. Three basic types of vertical stratification of salinity (circles) and temperature (triangles) observed in the lowermost 5 m of the water column. (a) – Stable (example profile from Station 2, February 2009); (b) – Neutral (example profile from Station 9, February 2009); (c) – Unstable (example profile from Station 11, February 2009). The salinity decrease in the bottom part of the salinity profile in (c) is hypothetically associated with SGD.



(a) (b)

Figure 4. Horizontal distributions of salinity at bottom in October, 2009 (a) and February, 2009 (b).

nearshore salinity minimum is typical of the study region. The comparison of vertical salinity distributions in February and October at station 11 (Figure 7), especially for the near-bottom layer, has revealed in both cases the main significant feature of SGD, decrease of salinity down to the bottom. A similar SGD signal was observed during October 2009 at station G (Figure 8).

As a summary of the investigation, Figure 9 shows the schematic identification of possible locations and pathways for SGD in the study region. Firstly, the entire set of hydrological and chemical data shows that there exist some SGD in the coastal area in the central part of the study region (stations 10, 11, 15 and 16, indicated by slashed rectangle in Figure 9). Secondly, it is also likely that there may be groundwater seepage into the river bed, and subsequent flushing of it into the area adjacent to the river mouth in the bottom layer (stations 1, 6 and G).

SGD VOLUME RATE

Estimation

In order to estimate the influence of the SGD identified above, we consider the advection–diffusion balance for water salinity to calculate the discharge rate as below. Considering the advection–diffusion balance:

$$wS = k\mathrm{d}S/\mathrm{d}z, \tag{1}$$

where w is the vertical velocity of the groundwater seepage, S is the salinity, z is the vertical coordinate, and k is the eddy diffusivity, and also assuming $\Delta S \ll S_0$, where S_0 is the salinity at bottom, we obtain

$$w = k/S_0 \Delta \mathrm{S}/\Delta \mathrm{H} \tag{2}$$

where ΔH is the thickness of the near-bottom layer of salinity drop, and ΔS is the magnitude of the maximum drop. The

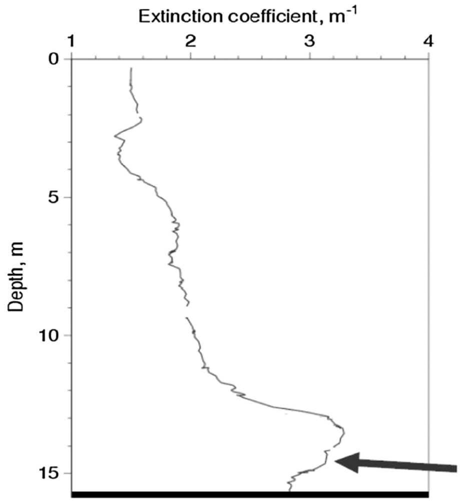


Figure 5. Vertical distribution of the light extinction coefficient (station 10). The black line indicates the bottom. Note the relative clear layer immediately above the bottom.

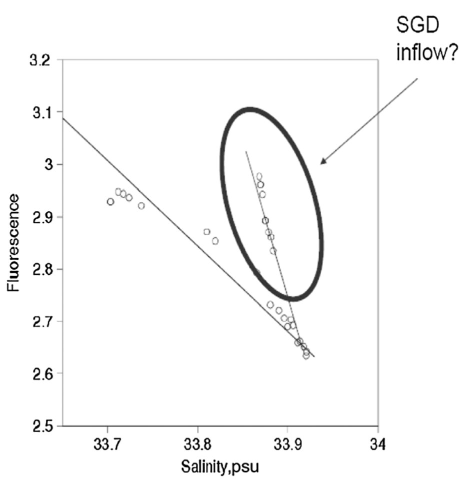


Figure 6. Plot of fluorescence against salinity (station 11) The branch in the high salinity part of the plot (the bottom part of the water column) hypothetically indicates the SGD influence.

data about this feature at different locations are summarized in Table I.

This procedure is somewhat similar to that described by Martin *et al*. (2007), although they used chlorinity instead of salinity. The SGD mass rate Q per unit area can then be obtained by multiplying w by the water density. If, for example, $S_0 = 30$ psu and $k = 10^{-4}$ m^2 s^{-1} (which, up to the order of magnitude, is typical for the bottom layer), we arrive at the following order of magnitude estimate for the groundwater inflow for the range of observed ΔH and ΔS depicted in Table I:

$$0.1 \text{ gm}^{-2}\text{s}^{-1} < Q < 1\text{gm}^{-2}s^{-1} \quad (3)$$

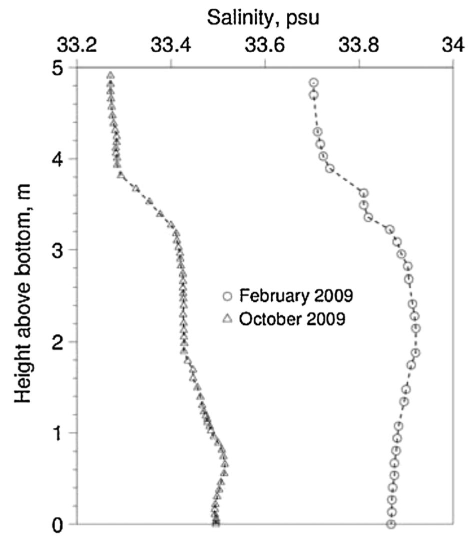


Figure 7. Vertical profiles of salinity at station 11 in February, 2009 (circles) and October, 2009 (triangles). The salinity decrease in the bottom parts of the both profiles is hypothetically associated with SGD.

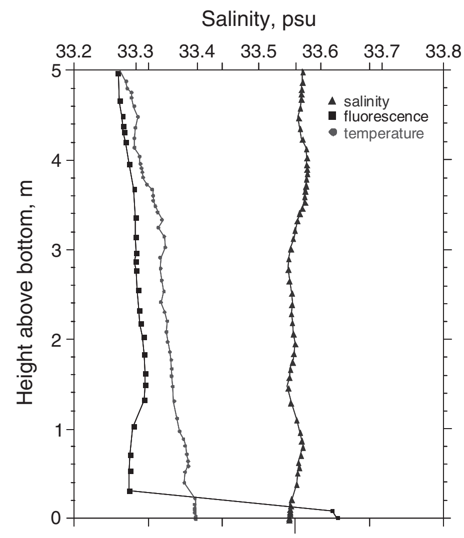


Figure 8. Vertical distributions of salinity (triangles), temperature (circles), and fluorescence (rectangles) at station G.

These values are approximately equivalent to a volume flux between 10 and 100 l m^{-2} day^{-1}. Of course, this is only an order of magnitude estimate, which is strongly dependent on the choice of k and other assumptions of our oversimplified calculation. However, it agrees well with the characteristic values reported earlier for well-developed SGD at other locations in the ocean (e.g. Intergovernmental Oceanographic Commission, 2004; Martin *et al*., 2007).

Using all necessary SGD parameters obtained from two field surveys (examples are given in Figure 10) the estimated volume rate of SGD varies from 0.1 to 1.0 g s^{-1} m^{-2}, i.e. about 360–3600 ml h^{-1} m^{-2}.

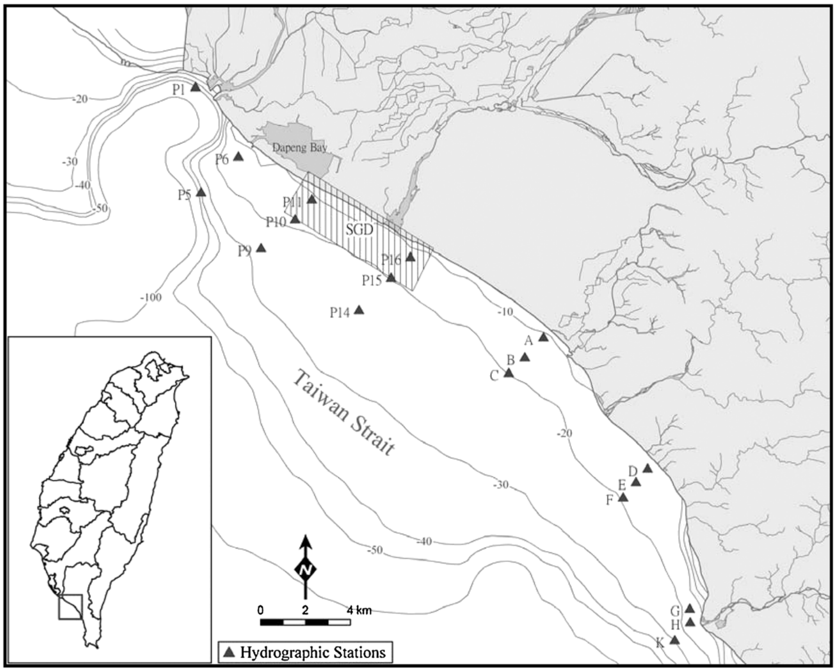


Figure 9. Schematic sketch of plausible SGD area.

Table I. Summary of data on SGD-affected near-bottom layer at different locations in February and October 2009

	February		October	
Station	ΔH, m	ΔS, psu	ΔH, m	ΔS, psu
1	0.13	0.035	0.15	0.009
6	0.27	0.061	0.42	0.046
11	2.15	0.052	0.46	0.023
16	0.14	0.010	0.33	0.105
G	Unknown	Unknown	0.19	0.048

Measurement

Following up the plausible location of SGD, a field survey was conducted by deploying a steel drum type seepage meter in January of 2011. The survey consisted of four deployed SGD collecting sites near the suspected area around station 11, extending approximately from 8 to 11 m isobaths (Figure 11). The successful measurements of the volume of water as collected in the collection bag of the seepage meter over a 12-day time interval are listed in Table II. According to measured data at locations 3 and 4, the average seepage rate of SGD was about 6.0 ml h^{-1} m^{-2} during the dry season around station 11 (rainy season generally begins from April to October in Taiwan).

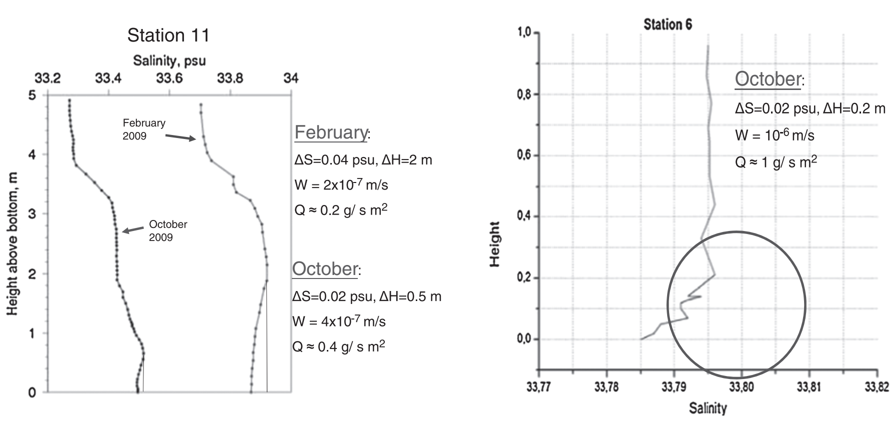


Figure 10. Measured parameters to estimate SGD volume discharge.

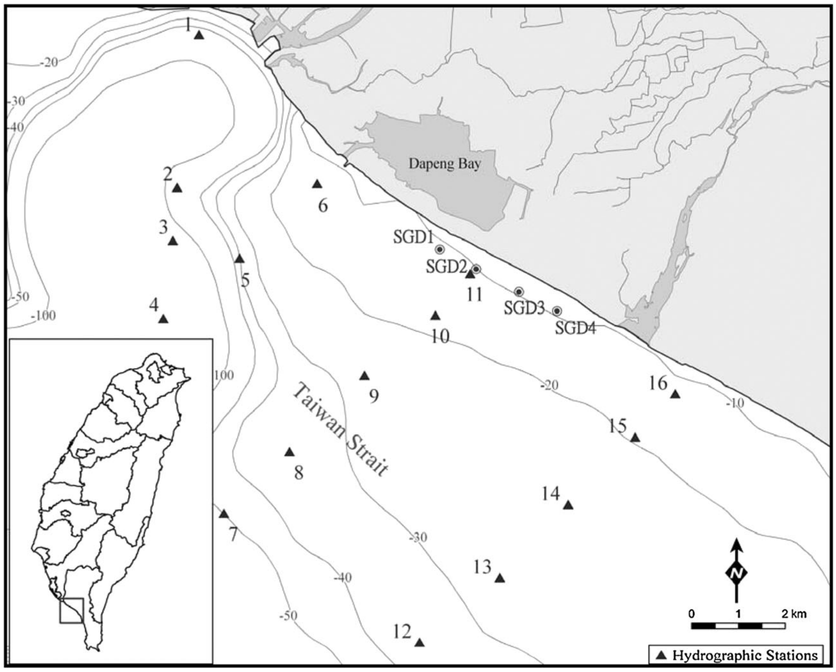


Figure 11. Locations that deployed seepage meters.

Table II. Calculated seepage rate from meters on site (2011/01/27 ~ 02/08, 12 days, Drum diameter: 60 cm)

St. ID	*V* (ml)	*t* (h)	*A* (m^2)		SGD rate ($ml/h/m^2$)
SGD1	missed*	288	0.282743		-
SGD2	missed*	288	0.282743		-
SGD3	440	288	0.282743		5.40
SGD4	530	288	0.282743		6.51
				Average	5.96

Missed
*: collection bag broken by tidal wave
V: volume of water collected by drum type seepage meter (milliliter)
t: measured time interval (hour)
A: cross-section of drum type seepage meter (square meter)

Thus, the measured rate of SGD is lower than the value estimated from the salinity profiling by at least two orders of magnitude. However, it should be remembered that the hydrographic and seepage meter measurements were not simultaneous. Therefore, the quantitative disagreement possibly originates from the seasonal and interannual variability of precipitation and SGD. The other possible explanation may lie in the small-scale patchiness of the SGD, considering that the locations of the seepage meters and CTD profiles did not exactly coincide. Nevertheless, both sets of results did confirm the permanent existence of SGD in the study region.

CONCLUSION

The SGD is often highly inhomogeneous and distributed in a patchy pattern. Therefore, measurements at one or a few points are not always representative. The surveys attempted to detect the SGD signals in the area by means of oceanographic measurements, and also quantify SGD influence on the sea water column. Based on the field investigation of SGD in the Ping-Tung Shelf, some conclusions could be drawn:

- there do exist distinctive features in the survey area restricted to the very near-bottom layer that are very likely associated with SGD. These features are typically small-scale patches, but their locations seem to be robust;
- the plausible locations of SGD have been identified, and the corresponding anomalies quantified. SGD influence is shown to be confined to the bottom up 0.2–1.5 m of the water column, and produces observable anomalies in salinity (0.01 ~ 0.05 psu maximum), turbidity and fluorescence. The average measured rate of SGD discharge in the study area is 6.0 ml h^{-1} m^{-2} in the dry season. More data are needed to fully describe the spatial and temporal pattern of SGD of the Ping-Tung Shelf.

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