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Evidence for submarine groundwater discharge on the Southwestern shelf of Taiwan

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ABSTRACT

This study was aimed at identifying the locations of the submarine groundwater discharge (SGD) on the shelf of Southwestern Taiwan by means of oceanographic measurements, quantifying its influence on the hydrographic conditions in the area, and estimating the volume rates of the discharge. Two high resolution hydrographic surveys of the region, including water and bottom sediment sampling campaigns, were completed in February and October of 2009. Water samples were also collected from the neighboring on-land groundwater wells.

At some locations in the study regions, the vertical profiles exhibited a slight but detectable (0.009 to 0.105 psu) decrease of salinity manifested in the near-bottom portion of the water column. Although convectively unstable, this feature appeared robust and persisted for the eight months between the surveys. The salinity anomalies in the near-bottom layer were often accompanied by the maxima of fluorescence, chlorophyll, silica, nitrate, and iron concentrations, as well as the minima of turbidity. In February, 2009, the n-alkane composition of organic matter in the water collected from an on-land groundwater well exhibited high content of C_{24} alkane. A similar anomalously high concentration of C_{24} alkane was encountered in the bottom sediment samples from the suspected SGD sites. In October, 2009, the dominant marker of SGD signature was the C_{16} alkane.

Based on these data, we specified the likely locations of the SGD sources in the study area, all of which were restricted to the inner shelf at the depths less than 8 m. We argue that the influence of the SGD on oceanographic regime in the region is small but observable. Its signature is confined to the lowermost 0.1–2.1 m layer of the water column. The groundwater seepage rates roughly estimated under the assumption of the advection–diffusion balance based on the eddy diffusivity values typical for the bottom layer, are of the order of 0.1 to 1 $g\,m^{-2}\,s^{-1}$.

1. Introduction

Submarine groundwater discharge (hereinafter SGD) is the least well quantified component of the ocean's water budget. The annual volume of SGD into the ocean at the global scale is unknown, but is believed to be less than 6% of the fluvial discharges, i.e., below 2500 km^3 (Intergovernmental Oceanographic Commission, 2004), and this is why the SGD is considered unimportant in many cases. Studies of the impacts that SGD may have on the regime of the water column are relatively rare in the oceanographic literature, perhaps, because the measurements of SGD are technically rather difficult, although set of methods to determine the magnitude of the discharge have been developed. SGD can be measured directly using the equipment called seepage meters, either mechanically or electromagnetically (e.g., Lee, 1977, Zhang and Satake, 2003, Rosenberry and Morin, 2004). However, SGD is often highly inhomogeneous and distributed in a patchy pattern, and, therefore, measurements at one or a few points are not always representative. There is also a variety of geochemical techniques estimating SGD indirectly based on different tracers, such as radium, strontium, or oxygen isotopes, barium, and radon (e.g., Moore, 1996, Burnett et al., 2001, Swarzenski et al., 2001, Lin et al., 2010, Huang et al., 2011).

There is strong evidence that the role of SGD can be significant at the regional scales, especially in coastal waters, and at specific locations, where its input to the ocean can be comparable with or even exceed that of the surface runoff (e.g., Moore, 1996, Bokuniewicz and Pavlik, 1990). Moreover, SGD is a potentially significant pathway for the pollutants and nutrients into the coastal areas of the ocean. This is especially so for the regions

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where the ground water is subjected to anthropogenic pressures associated with extensive urban, industrial, or agricultural use of lands (Valiela and D'Elia, 1990, Moore, 1999). The input of pollutants via SGD has been shown to be the cause of euthrophication in the coastal waters in New England, Florida, and other locations. The island of Taiwan is likely to be one of such regions.

Groundwater is an essential natural resource for Taiwan's economy and population. The annual consumption of the groundwater for agricultural, industrial, and household uses is about 7 km^3 (Ting, 1997), while the recharge totals only 4 km^3 (Cheng et al., 1995). The overexploitation of groundwater and, possibly, climate change resulted in a serious deterioration of groundwater resources in the last decades, and the future projections raise a concern regarding the decrease of available groundwater (Hsu et al., 2007). Overpumping has resulted in land subsidence in some areas, especially on the southwestern side of the island (TPCWB, 1995). Seawater intrusions into the land aquifers have also been reported (Ting, 1997). There is a large number of monitoring wells all over the territory of Taiwan, so the topography of the groundwater tables in the confined and unconfined aquifers, as well as the recharge rates and the water quality indicators, have been assessed in detail. One of the regions where the slope of the table points to likely outflow of groundwater towards the South China Sea is the Pingtung Plain in the southwestern part of the country. According to (Ting, 1997), the groundwater in this region generally moves westward to the Kaoping River, Donggang River, and southwestwards to the sea. The total annual outflow to the sea in this region is estimated from the available land hydrology data to be mere 0.03 km^3 (Ting and Overmars, 1995). However, (Lin et al., 2010) and (Huang et al., 2011) concluded, from the analysis of isotopic tracers, that SGD may play an important role in the near-bottom portion of the column in the Kaoping canyon (depths 400–1200 m). They argued that up to 0.6% of water in the canyon may have originated from SGD.

The coastal waters of the Pingtung Plain are not only sources of fisheries but also serve for recreational purposes, therefore, it is important to estimate the rates of SGD in the area and evaluate the impact on the sea water column. Until 2004, no attempts were made to quantify SGD in Pingtung shelf based on an observational data, although some indirect evidence pointing on its existence has been reported (e.g., Ting, 1997, Lin et al., 2003). Virtually the only direct measurements of SGD in the inner shelf were carried out in 2004 by Cheng et al. (2005). They deployed SGD collecting devices buried in the bottom sands at 5 sampling sites (Kaohsiung city, Kaoping River mouth, Fangsan, Jinshawan, and Yaniliao townships). The collected samples were analyzed for salinity, pH, and nutrients (nitrate, nitrite, phosphate, and silicate). At 2 of the locations, namely, Xiziwan within Kaohsiung city limits, and Fangsan township, distinct SGD signatures were observed, manifested with significantly reduced salinity and pH, and elevated concentrations of nutrients, as compared with the surrounding ocean waters. The freshening was particularly dramatic at a station named "Eureca" by these researchers, situated 300 m from the Fangshan coast at the depth 7.8 m, where the bottom water sample reportedly had salinity of only 0.2 psu (!), i.e., was essentially fresh.

These published observations yielded enlightening results. However, they were restricted to the very inner part of the shelf immediately adjacent to the coast (0–300 m from the shoreline, 0–8 m depth), and focused on the groundwater within the bottom sands and sediments. In the present study, we attempted to detect the SGD signatures in the area by means of oceanographic measurements, and also quantify the SGD influence on the sea water column.

2. Data

The study area was located on the Pingtung shelf, between the Kaoping River mouth in the north and Fangshan township in the south (Fig. 1). Two field surveys of the area were organized in 2009. In the both cases, small fishing ships were used for the measurements. The first survey (February 14–19, 2009) consisted of 16 stations organized in 4 cross-shore sections in the northern part of the study area, extending approximately from the 5 m to the 50 m isobaths. Since there were no indications of SGD at the deep stations in February, they were not occupied during the second survey (October 23–27, 2009). Instead, the area of the second survey was extended to the south. The station G of the southernmost section coincided with the "Eureca" site as specified by (Cheng et al., 2005).

At each station, surface-to-bottom CTD profiling was done. In the February survey, a *SBE19plus* profiler equipped with complementary fluorescence and turbidity sensors was used. In the October survey, we used the same instrument and, additionally, *Idronaut* CTD profiler equipped with turbidity sensor. At all stations, the profilers were lowered until the contact with the bottom.

At all stations, velocity profiling was also performed using an ADCP instrument. The collected data are not reported in this paper. However, it may be worthy of mentioning as a background information that during the both cruises, the mean current in the lowermost 2 m of the water column was directed northeastward along the shore at 20–30 cm/s, modulated by a semidiurnal tide with the amplitude of about 10 cm s^{-1}. The vertical shear in the near-bottom part of the column was up to 0.1 s^{-1}.

The bottom sediment samples were obtained by a bottom grab. The hydrocarbons were extracted using *Branson-1210* ultrasonic water bath. The sediments were then analyzed for n-alkane composition at Shirshov Institute of Oceanology, Russian Academy of Sciences (SIO RAS), through chromatography by *Shimadzu GC-2010* instrument equipped with *Supelco* capillary GC column. Silica-gel was used as a filler and hexane was applied as an eluent. The samples were analyzed under isothermal conditions at 300 °C. The nominal accuracy of the instrument is 10^{-3} μg/g, while the reproducibility of the analysis result is ± 5%.

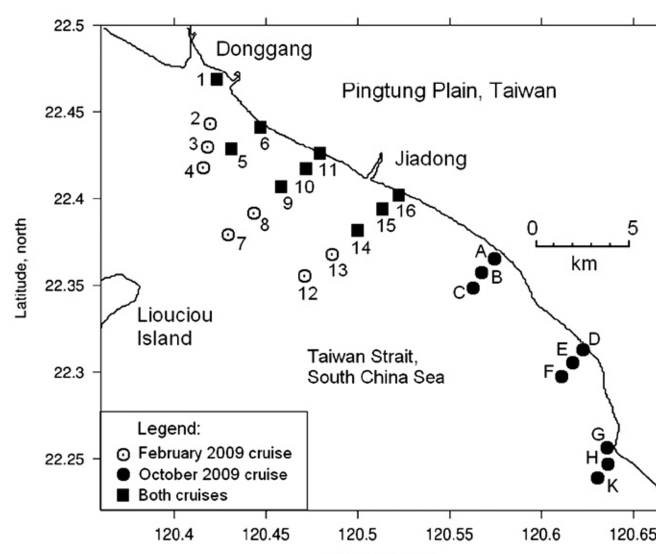

Fig. 1. Map of study area and locations of hydrographic stations. The stations indicated by circles were occupied in February, 2009, the stations shown by filled circles were occupied in October, 2009, and those shown by boxes were occupied in the both surveys.