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Unheralded Submarine Groundwater Discharge

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Abbreviations: SGD: Submarine Groundwater Discharge; DOC: Dissolved Organic Carbon; DIC: Dissolved Inorganic Carbon; DO: Dissolved Oxygen; TA: Alkalinity; pCO_2: Partial Pressure of CO_2

Opinion

Land meets the ocean in the coast zone, which is of great importance for aquaculture, fisheries, tourism and transportation, among other things. As fifty percent of the world population lives within 100 km of the coast, human activities have put tremendous pressure on the coastal environment. For instance, excess nutrients that are generated by agriculture and present in domestic waste have been discharged into the oceans by rivers, making many coastal regions hypoxic or even anoxic. Most people do not realize that a substantial fraction of the freshwater on land enters the oceans directly from the seabed, unseen by human eyes. This process is called submarine groundwater discharge (SGD) [1-5]. Burnett and coworkers [6] were among the first to provide a ballpark estimate that the amount of SGD is 0.2-10% of global river discharge. Since groundwater has been frequently in contact with soil and bedrock for hundreds of years, if not longer, some of the dissolved organic carbon (DOC) in the groundwater as well as particulate organic carbon and $CaCO_3$ in the soil and bedrock are expected to have decomposed or dissolved.

These processes release nutrients, alkalinity (TA), and dissolved inorganic carbon (DIC) into the groundwater while reducing its dissolved oxygen (DO) content and pH [7-11]. The partial pressure of CO_2 (pCO_2) in the groundwater normally exceeds the saturation level. The variation of DOC concentration depends on the balance between its decomposition in groundwater and its generation from soil and bedrock. Groundwater is isolated from the atmosphere but when it enters the oceans, supersaturated CO_2 may be released to the atmosphere [12]. Excess nutrients that are carried by the SGD promote primary production, which reduces pCO_2. Whether the SGD eventually functions as a carbon source or a sink into the receiving coastal waters cannot be determined a priori. Only recently did two investigations provide a preliminary answer. First, Chen and coworkers [13] estimated that the freshwater component of the SGD in Taiwan equals around 5.2% of the annual river discharge in Taiwan, where the over pumping of groundwater has been a serious problem.

Table 1: The N, P, Si, TA and DIC fluxes from the SGD and rivers in Taiwan.

	SGD Flux[a] (10^9 mol)	River Flux[b] (10^9 mol)	SGD/Rivers (%)
N	1.18 ± 0.83	9.31 ± 6.29	12.7
P	0.0093 ± 0.0065	1.06 ± 0.47	0.9
Si	0.68 ± 0.48	7.34 ± 2.05	9.3
TA	34 ± 24	161 ± 19	21.1
DIC	32 ± 22	163 ± 20	19.6

[a] Taken from [14]; [b] N and P are taken from the EPA (https://www.epa.gov.tw/); Si, TA, and DIC are unpublished data of C.T.A. Chen

Even in such an environment, the SGD is substantial. Additionally, Wang and coworkers [14] indicated that in Taiwan, the SGD exports N, P, Si, TA, and DIC in amounts equivalent to 12.7, 0.9, 9.3, 21.1 and 19.6%, respectively, of those in riverine fluxes (Table 1). Finally, Wang and coworkers found that primary production, supported by nutrient outflows from the SGD in Taiwan and from the Jiulong River across the Taiwan Strait, do not suffice to compensate for the DIC that is supplied by the SGD. Consequently, the SGD helps to make the coastal waters in Taiwan and Jiulong River heterotrophic, releasing CO_2 to the atmosphere. Unfortunately, such a conclusion cannot be generalized to a region

- let along to all coastal seas around the world - because the total area of Taiwan (35,873km^2) and the Jiulong River watershed (14,740km^2) is only 0.034% of the area of all land on earth. Whereas rivers have been extensively studied, only a handful of reports concerning nutrients, TA and DIC fluxes have focused on SGD [15-21].

Worse, the relevant literature is mainly concerned with the flux per unit area of discharge into oceans. Such data cannot be extrapolated to the global oceans as the discharge area is unknown. On the other hand, the yield, which is the flux per unit area of the river basin, can be extrapolated from readily available river basin data. According to the latest tabulation of Wang et al. [14] yield data for N, P, Si, TA and DIC are available only for Taiwan, the Jiulong River and the Pearl River. An accurate estimate of the SGD flux is essential to predicting coastal environments in an era of rapid global change but most - if not all - coastal biogeochemical models have no SGD component. Substantial errors may arise if SGD is ignored, especially in estuaries, bays, inland seas, deltas and salt marshes. Since the areas of thousands of river basins worldwide are known, with a knowledge of the yield the global amount of material flux by SGD can be reasonably estimated and its effect on the coastal biogeochemistry better evaluated.

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