

# Submarine groundwater discharge from tropical islands: a review

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**Abstract** Submarine groundwater discharge (SGD) is a rarely recognized pathway for nutrients and other solutes from land to sea. The sensitive coastal ecosystems around tropical islands could be particularly affected by nutrient discharge associated with SGD in relation to surficial nutrient transport by rivers, but have received comparatively little attention to date. This study reviews the findings of local assessments of submarine groundwater discharge from tropical islands. In addition, the ratio of coast length and land area of individual land bodies is suggested as an

appropriate first-order estimate of the relevance of SGD versus river discharge, demonstrating the potential relative importance of SGD from tropical islands over rivers. The review highlights the need for targeted research of submarine groundwater discharge from tropical islands and highlights its relevance for biogeochemical fluxes in these geographic settings.

**Keywords** Submarine groundwater discharge · Biogeochemistry · Coastal zone · Nutrient · Tropical island

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## Submariner Grundwasserabfluss von tropischen Inseln – Ein Review

**Zusammenfassung** Submariner Grundwasserabfluss (SGD) vom Land in die Ozeane ist ein wenig beachteter Transportweg für gelöste Stoffe. Existierende Studien betonen allerdings seine Wichtigkeit für die Nährstoffversorgung der Küstengewässer. Insbesondere in Küstenökosystemen im Bereich tropischer Inseln kann SGD im Verhältnis zum Flusseintrag die Nährstoffbudgets dominieren, dort hat SGD aber bisher nur wenig Interesse erfahren. Diese Studie beleuchtet die Erkenntnisse lokaler Untersuchungen des SGD tropischer Inseln. Darüber hinaus wird das Verhältnis von Küstenlänge und Landfläche einer Insel als grobe Abschätzung des Verhältnisses von SGD und Flusseinträgen vorgeschlagen und damit die potenzielle Wichtigkeit von SGD von tropischen Inseln gezeigt. Das Review zeigt den Bedarf an systematischen Feldstudien über SGD von tropischen Inseln und hebt dessen Bedeutung für biogeochemische Stoffkreisläufe dieser Regionen hervor.

## Introduction

While rivers are the most obvious lateral pathway of water and material from land to the oceans, a significant proportion of water transverses the terrestrial boundary unseen below the sea surface (e.g. Johannes 1980; Church 1996; Moore 1996). In recent years, this submarine groundwater discharge (SGD) has received increasing attention in the scientific literature (cf. Moore 2010). Early works (e.g. Kohout 1964) reported submarine groundwater discharge from numerous sites around the world. Since the new millennium, the annual number of SGD studies has grown rapidly. A SCOPUS search for “submarine groundwater discharge” reveals on average 1.3, 32.7, and 60.3 studies per year in the time ranges 1980–2000, 2001–2010, and 2011–2013, respectively.

Submarine karstic springs are prominent locations of SGD, which are known in the Mediterranean Sea since Roman times and have been mapped around the world (Williams 1977; Roxburgh 1985; Stüben et al. 1996; Swarzenski et al. 2001; Fleury et al. 2007; Hays & Ullman 2007; Garcia-Solsona et al. 2010b; Tsabaris et al. 2010; Polemio et al. 2011; Tsabaris et al. 2011). The flow of some of these springs is visible at the sea surface. In addition, SGD occurs in porous sediments, where water diffusely seeps across the sediment-water interface. SGD can be identified in the field based on physical changes of the sea water, e.g. salinity or temperature, close to the SGD sites (e.g. Ridgway & Stanton 1969). It has classically been quantified in situ using seepage meters, i.e. benthic chambers with an outlet to capture seeping water to which a collection bag is attached (Lee 1977). Such simple manual seepage meters have recently been accompanied by automated flow measurements which measure time series of SGD based on heat flux (Taniguchi et al. 2003b; Mwashote et al. 2010), dye dilution (Sholkovitz et al. 2003; Koopmans & Berg 2011), electric conductivity (Stieglitz et al. 2008), or electromagnetic fields (Swarzenski & Izbicki 2009). Recently, mass balances of radionuclides, e.g. of radium and radon, have been used to quantify SGD (e.g. Cable et al. 1996; Burnett & Dulaiova 2003; Beck et al. 2007). Remote sensing of temperature via satellite or airborne infrared is another addition to the arsenal of SGD quantification methods (e.g. Fischer et al. 1964; Roxburgh 1985; Johnson et al. 2008; Wilson & Rocha 2012; Mallast et al. 2013). Methods to identify and quantify SGD are detailed in a number of studies (e.g. Buddemeier 1996; Taniguchi et al. 2003a; Burnett et al. 2006).

Per definition, SGD includes “any and all flow of water on continental margins from the seabed to the coastal ocean” (Burnett et al. 2003; Moore 2010). This definition includes seawater recirculation, which is ubiquitous on the seafloor. Other terms used for SGD in the literature are benthic flux (e.g. King 2012), or submarine spring (e.g. Elhatip

2003). Of the different forms of SGD, the one most relevant to net land-ocean matter fluxes is the freshwater component of SGD from land areas to the coast. Freshwater SGD to the oceans has been estimated to amount to 6–10% of the surface water inputs (cf. Taniguchi et al. 2002). Locally, SGD can be a major contributor to land-ocean water flux. It contributes e.g. 17, 20 or 29% of the freshwater inflow into the Swan river estuary (Johannes 1980), the Great South Bay, NY (Bokuniewicz 1980), or the Adriatic Sea (Sekulic & Vertacnik 1996), respectively. Based on hydrological modelling, more than a third of the world’s freshwater SGD component has been estimated to originate from large islands, with particular high SGD from tropical islands (Zektser & Loaiciga 1993). A typological approach of global SGD zones resulted in a spatially resolved extrapolation covering the world coastlines (Bokuniewicz et al. 2003). Global estimates are becoming increasingly relevant given the potential impact of sea level rise and depletion of coastal groundwater resources (Masterson & Garabedian 2007).

Coastal ecosystems are sensitive to nutrient availability. On the one hand, land-derived nutrients are an important factor of coastal primary productivity, on the other hand, eutrophication can severely inhibit ecosystem functionality (Officer & Ryther 1980; Smayda 1990; Smith 2003; Wild et al. 2011) with potentially harmful effects particularly in coral reefs (Fabricius 2005), but also to other ecosystems and commercial fisheries. Although rivers are commonly the main source of nutrients (e.g. Meybeck 1982; Jickells 1998), SGD can be a significant supplier of “new” nutrients to coastal waters in particular where nutrient concentrations in coastal aquifers are high due to human activity (Capone & Bautista 1985; Simmons & Netherton 1987; Paerl 1997; Slomp & Van Cappellen 2004; Paytan et al. 2006; Zhang & Mandal 2012). For example, early studies reported that SGD has delivered substantial amounts of nitrate to coral reefs around Guam (Marsh 1977), the Swan river estuary in Western Australia (Johannes 1980), and Discovery Bay, Jamaica (D’Elia et al. 1981). Nutrient concentrations in groundwater correlate with land use and population density (e.g. Cole et al. 2006; Bowen et al. 2007). Contrary to most terrestrial aquatic systems, near-shore coastal water bodies are generally expected to be nitrogen (N)-limited (Howarth & Marino 2006). River water inputs generally do not have the potential to alleviate this, as they are mainly at or slightly below Redfield ratio (N/P~14) (Seitzinger et al. 2005). SGD, however, can show N/P ratios  $\gg 16$ , in particular in agricultural areas with additional nutrient input from fertilizer and manure. All forms of nitrogen can readily enter the coastal zone through SGD (Bowen et al. 2007; Kroeger & Charette 2008) and do so increasingly in the past decades (Beusen et al. 2013), whereas phosphorus is usually retained in groundwater systems (e.g. Spiteri et al. 2008).

Groundwater travel times are many magnitudes longer than transport by river water, and delayed discharge of contaminated groundwater is possible. Global scale box modelling has shown that nutrient inputs via SGD have the potential to affect coastal zone nutrient cycling significantly (Slomp & Van Cappellen 2004). In addition, natural chemical weathering can supply nutrients to the groundwater (Newman 1995; Derry et al. 2005; Statham et al. 2008). In individual locations, SGD can dominate over riverine nutrient inputs (e.g. Hwang et al. 2005; Waska & Kim 2011), and could be particularly relevant regarding iron fluxes (Windom et al. 2006).

Nutrient flux via SGD can have significant ecological consequences (e.g. Cuet et al. 1988; Lapointe & Oconnell 1989; Hu et al. 2006; Lee & Kim 2007b; Basterretxea et al. 2010). SGD has been associated with eutrophication and algal blooms, e.g. brown tides (Gobler & Sanudo-Wilhelmy 2001) or red tides (Hu et al. 2006; Lee & Kim 2007b). On Yap Island (Micronesia), SGD has been reported to be negatively correlated with *Thalassia* seagrass density (Houk et al. 2013), whereas in Jamaica and on Ishigati, nitrogen introduced by SGD was hypothesized to positively affect *Thalassia* growth (Umezawa et al. 2002a; Peterson et al. 2012). In addition, SGD-affected *Thalassia* showed higher N:P ratios, which may, however, be reduced along the food chain, as herbivores seem to prefer P-rich shoots (Peterson et al. 2012). SGD was also reported to increase biomass of mat-forming algae (Lapointe & Oconnell 1989; Mioche & Cuet 1999; Blanco et al. 2008). Coral communities shift towards more tolerant blue corals on Santiago Island correlated with SGD inputs (Cardenas et al. 2010). Seawater recirculation through animal burrows in mangrove ecosystems has been suggested to be a major transport pathway for dissolved carbon from mangroves to tropical coasts (Stieglitz et al. 2013).

Previously, Gilmartin & Revelante (1974) postulated an “island mass effect”, where remote islands in the oligotrophic open ocean could spike large-scale phytoplankton blooms. Planquette et al. (2007) hypothesized that SGD could be a major player in causing such island mass effects, for example by providing iron to high-nutrient low chlorophyll (HNLC) regions of the Pacific. High iron fluxes by SGD were observed in the Patos Lagoon (Windom et al. 2006), but iron fluxes should in general be inhibited by iron oxide precipitation in the subterranean estuary (Charette & Sholkovitz 2002). Tropical islands were hypothesized as hot spots of chemical rock weathering based on stream discharge (Louvat & Allegre 1997; Hartmann & Moosdorf 2011; Schopka et al. 2011) and groundwater fluxes (Rad et al. 2007; Schopka & Derry 2012). In particular, basic igneous rocks, forming many tropical islands, are enriched in phosphorous, iron and comparably soluble silicate minerals (Hartmann et al. 2012). The combination of high SGD

(Zektser & Loaiciga 1993), fast weathering (Hartmann & Moosdorf 2011), nutrient-rich rocks (Hartmann et al. 2012), active natural ecosystems (Brooks et al. 2002) under strong anthropogenic pressure (Duncan 2011), and often intensive fertilizer use (cf. Widowati et al. 2011), as well as the absence of other nutrient sources in remote regions suggests that SGD could be an important nutrient source for marine ecosystems around tropical islands, with significant implications at the global scale.

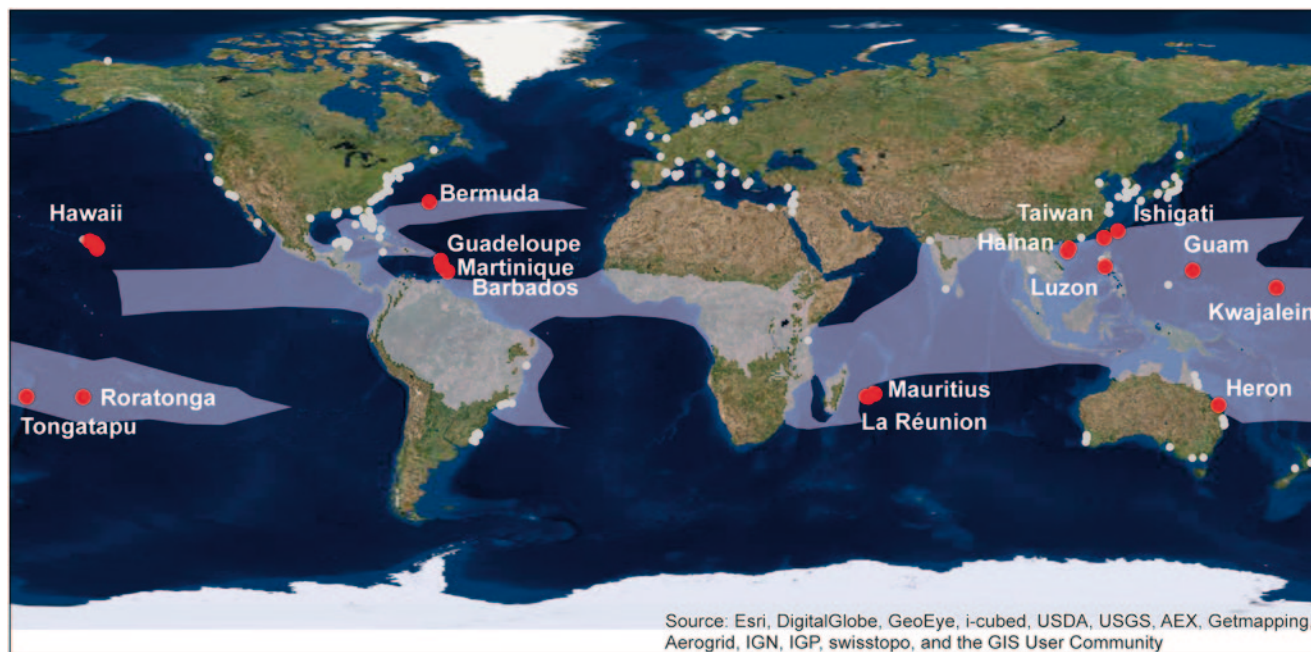
About 33 years ago, D’Elia et al. (1981) called for the “pantropic evaluation of phreatic nutrient inputs to the coastal ocean”. However, to date our knowledge of SGD from tropical islands is still restricted to a few sites only (Fig. 1). This study reviews the information from the available studies of SGD from tropical islands and highlights their importance based on geomorphological clues. This will lay the foundation to follow the suggestion by D’Elia et al. (1981) and comprehensively assess the biogeochemical and ecological consequences of SGD from tropical islands.

### Field studies of SGD from tropical islands

An extensive literature study was performed searching the ISI Web of Knowledge for “submarine groundwater discharge” in original research articles, related articles, and references therein. In total about 400 references were assessed. Most of them were added to a GIS database (Fig. 1), with their positions defined based on provided location maps, coordinates or location names. From these, the studies situated on tropical islands were selected. The tropical region was defined as based on all four types of equatorial climates in an updated map of the Koeppen-Geiger climate typology (Kottek et al. 2006), which was extrapolated over the oceans based on an earlier map following the same classification (Köppen & Geiger 1954). Equatorial climates were defined by the mean temperature of the coldest month  $> 18^{\circ}\text{C}$  and precipitation of the driest month ( $P_{\text{Min}}$ )  $> 60$  mm or annual precipitation  $= 25 \times (100 - P_{\text{Min}})$  (Kottek et al. 2006). Studies situated within 50 km of equatorial climates were considered tropical. The studies were visually verified if they are located on an island. Of course, also extra-tropical islands can show significant SGD, like e.g. Jeju Island, Korea (Kim et al. 2003; Lee & Kim 2007a; Kim et al. 2011; Lee et al. 2011; Jeong et al. 2012) or the Balearic Islands (Basterretxea et al. 2010; Garcia-Solsona et al. 2010a). Reported extra-tropical sites of SGD are included in Fig. 1 as background information.

Table 1 lists the 26 identified studies reporting quantitative data of SGD from tropical islands. The islands were grouped according to bedrock type, based on a classification introduced by Falkland (1991). Here, the classes of volcanic, carbonate, and mixed type islands are used, while





**Fig. 1** Study locations with quantitative SGD data on tropical islands (red, values in Table 1) and other SGD study locations (grey, not referenced, for overview only). The shaded area indicates the tropical climate zone according to the Koeppen Geiger classification.

the carbonate islands are separated into low (atoll-like) and high (uplifted carbonate platforms). The classes “bedrock islands” and “islands formed from unconsolidated sediments” (Falkland 1991) are not considered here, because of missing available SGD studies on tropical islands of those classes. Table 1 summarizes available quantitative information on SGD from tropical islands and associated nutrient fluxes, as well as precipitation. However, no correlation is visible between average precipitation of the islands and the measured SGD values (Table 1).

### Volcanic islands

Volcanic islands are dominated by often very permeable igneous rocks, sometimes featuring lava tubes, which may act as large conduits for SGD. Their generally steep relief implies often elevated hydrological gradients and strong orographic precipitation that can create large local discharge variability.

SGD on the Hawaiian Archipelago has been intensively researched. On Hawaii, SGD was traditionally used in brackish water fishponds, and identified very early by resistivity studies (Swartz 1937) and infrared images (Fischer et al. 1964). Duarte et al. (2006) used handheld infrared cameras to show SGD in one of the fishponds, and Kay et al. (1977) quantified fluxes in a local water budget. Groundwater in Hawaii seems only weakly influenced by hydrothermal activity and SGD exceeds river fluxes on Big Island (Schopka & Derry 2012). In particular, Kona Coast on Big

Island has received strong attention (e.g. Duarte et al. 2006; Johnson et al. 2008; Knee et al. 2008; Street et al. 2008). It has negligible surface runoff (Knee et al. 2010), and was long known for SGD (Fischer et al. 1964), which Kay et al. (1977) quantified in a water budget. The identified groundwater seepage face reaches 65 m offshore, and anecdotal evidence tells of cold seeps that can be felt 500 m offshore in the reef (Dimova et al. 2012). The mixing zone between sea- and freshwater could extent up to 1 km towards both sides of the shoreline (Knee et al. 2010). In Honokohau, Kona district, a yacht harbor built in the late 70ies was studied extensively by Bienfang (1980), and later by others (Oki et al. 1999; Johnson et al. 2008; Knee et al. 2010). It shows a mixture of point sources and diffuse SGD (Bienfang 1980; Peterson et al. 2009) which result in a cold surface layer maintained by continuous groundwater inflow through the harbor walls and floor, on top of a warm oceanic layer (Bienfang 1980). The salinity and oxidation state follow this pattern, which suggests fresh groundwater previously out of contact with the atmosphere (Bienfang 1980). The outflow from the harbor is continuous, regardless of the tide (Bienfang 1980). Fresh groundwater accounts for approximately 20–90% of the total SGD at Honokohau. After expansion of the harbor, SGD increased (Peterson et al. 2009). While the groundwater discharge at Honokohau varies considerably between the years (Bienfang 1980) and tides (Knee et al. 2010; Dimova et al. 2012), the dissolved matter concentrations stay rather constant (Bienfang 1980). Differences in reported SGD between studies assessing the same sites in Kona (Johnson et al. 2008; Peterson et al. 2009; Knee et al.

**Table 1** Identified studies quantifying SGD from tropical islands. Positions of the named islands are shown in Fig. 1

Location	Reference	SGD [m <sup>3</sup> m <sup>-1</sup> a <sup>-1</sup> ]	SGD [m <sup>3</sup> m <sup>-2</sup> a <sup>-1</sup> ]	SGD [m <sup>3</sup> s <sup>-1</sup> ]	Nutrients measured?	Precipitation [L m <sup>2</sup> a <sup>-1</sup> ] <sup>b</sup>
<i>Volcanic islands</i>						
Hawaiian archipelago						
Hawaii, Honokohau	Bienfang 1980			1.18	No	1745
Hawaii, Maunaloa Bay	Dimova et al. 2012			0.07	No	1745
Hawaii, O’ahu	Garrison et al. 2003			0.16	Yes	1698
Hawaii, Honokohau	Johnson et al. 2008			0.10	No	1745
Hawaii, Kona Coast	Knee et al. 2010	35,000			Yes	1745
Hawaii, Honokohau	Peterson et al. 2009			0.10	No	1745
Hawaii, Spencer Beach	Street et al. 2008		53		Yes	1745
Hawaii, Puako Bay	Street et al. 2008		20		Yes	1745
Hawaii, Puako Bay	Paytan et al. 2006	2407			Yes	1745
Hawaii, Puako Bay	Kay et al. 1977	5494			Yes	1745
Hawaii, Kaloko Fishpond	Street et al. 2008		141		Yes	1745
Hawaii, Kaloko Fishpond	Paytan et al. 2006	4341			Yes	1745
Hawaii, Honokohau	Street et al. 2008		102		Yes	1745
Hawaii, Keauhou Bay	Street et al. 2008		73		Yes	1745
Hawaii, Kealekekua Bay	Street et al. 2008		26		Yes	1745
Hawaii, Honaunau Bay	Street et al. 2008		80		Yes	1745
Maui, Honolua Bay	Street et al. 2008		35		Yes	1694
Maui, Kahana	Street et al. 2008		46		Yes	1694
Maui, Kahana	Paytan et al. 2006	3086			Yes	1694
Maui, Mahinahina	Street et al. 2008		49		Yes	1694
Maui, Honokowai	Street et al. 2008		40		Yes	1694
Moloka’i, Kapuaiwa	Street et al. 2008		139		Yes	1083
Moloka’i, Kamiloloa	Street et al. 2008		93		Yes	1083
Moloka’i, Ualapu’e	Street et al. 2008		53		Yes	1083
La Réunion						
	Cuet et al. 2011	1022			Yes	1564
	Rad et al. 2007	9882 <sup>a</sup>			No	1564
Martinique						
	Rad et al. 2007	4849 <sup>a</sup>			No	2360
Mauritius						
	Paytan et al. 2006	3556			Yes	1844
	Povinec et al. 2012	9490			Yes	1844
Rorotonga, Cook Islands						
Muri Lagoon	Tait et al. 2013		7		No	2366
<i>High carbonate islands</i>						
Barbados						
	Lewis 1987	2579	361		Yes	1350
Bermuda						
	Simmons & Lyons 1994	82 <sup>a</sup>			No	1471
Guam						
Guam, North	Matson 1993	2480			No	2349
Tumon Bay	Marsh 1977	28,794			No	2349
<i>Low-lying carbonate islands</i>						
Heron Island						
	Santos et al. 2010		55		Yes	No data
Kwajalein Island, Marshall Islands						
	Peterson & Hunt 1981	71 <sup>a</sup>			No	2588
Tongatapu Island						
	Hunt 1979	586 <sup>a</sup>				1608
<i>Complex islands</i>						
Guadeloupe						
	Rad et al. 2007	1707 <sup>a</sup>			No	2051

**Table 1** (continued)

Location	Reference	SGD [m <sup>3</sup> m <sup>-1</sup> a <sup>-1</sup> ]	SGD [m <sup>3</sup> m <sup>-2</sup> a <sup>-1</sup> ]	SGD [m <sup>3</sup> s <sup>-1</sup> ]	Nutrients measured?	Precipitation [L m <sup>2</sup> a <sup>-1</sup> ] <sup>b</sup>
Hainan						
Hainan, China	Ji et al. 2013		37		Yes	1488
Hainan, Bamen Bay	Su et al. 2011		5		Yes	1488
Hainan, Wanquan River	Su et al. 2011		2		Yes	1488
Ishigaki Island						
Shiraho Reef	Blanco et al. 2011	2200			No	2140
Luzon, Philippines						
Manila Bay	Taniguchi et al. 2008	4526			Yes	2555
Taiwan						
	Martin et al. 2013	5486			No	2529
	Zavialov et al. 2012		2		Yes	2529
<i>Averages</i>						
Global	Zektser & Everett 2000	4000 <sup>c</sup>				
Tropical islands	This study	7050	106	0.32		

<sup>a</sup>Groundwater recharge rate (mm a<sup>-1</sup>) from the referenced literature assumed to equal discharge, multiplied with island area and divided by island coastline from ISCI data (ISCIENCES L.L.C. 2009)

<sup>b</sup>Average annual average for the area of the respective Island (ISCIENCES L.L.C. 2009) based on climate data from (Hijmans et al. 2005), where available. Note that uncertainty is introduced by sometimes differing spatial representations of the island in both datasets

<sup>c</sup>Based on a global groundwater discharge of 2400 km<sup>3</sup> a<sup>-1</sup> calculated with a combined hydrogeological-hydrological method divided by an assumed global coast length of 600,000 km (Zektser & Everett 2000). Although the narrow distribution of different SGD estimations suggest a high reliability, most individual assumptions of the parameters leading to the groundwater discharge value include large uncertainties (cf. Zektser & Everett 2000)

2010) also suggest inter-annual SGD variations. Groundwater fluxes predicted from topography gradient and rainfall alone grossly underestimate the actually measured SGD at this location (Bienfang 1980).

Generally, the N/P ratio of the SGD is similar to that of the deep sea (Bienfang 1980), but nutrient ratios vary substantially between sites at the Kona coast (Knee et al. 2010). Interestingly, there is apparently little to no nutrient consumption in the immediately coastal waters (Johnson et al. 2008). The correlation between SGD nutrient fluxes and land use between different outlets at the Kona coast is generally weak, but in proximity of golf courses, nutrient concentrations in groundwater are significantly elevated (Knee et al. 2010). A lack of significant positive correlations between urban development and nutrient concentrations in SGD of the Kona coast exists, but does not necessarily mean that further development will not increase nutrient fluxes, because of the unclear capacity of nutrient buffering in the coastal zone (Knee et al. 2010). In addition, dead coral cover was shown to be correlated with high N concentrations in reef waters offshore the Kona coast (Parsons et al. 2008).

On O'ahu, Garrison et al. (2003) analyzed SGD in Kahana Bay, which is highly variable with depth and occurs to 90% within 1 km from the shore. Terrestrial SGD in Kahana Bay, which is 16% of the total SGD, amounts to one sixth of the water discharge from a the nearby river, but carries five- and two- fold higher P and N, respectively, rendering it a significant nutrient source (Garrison et al. 2003). Finally, Street et al. (2008) identified SGD on two other Hawaiian

islands, Maui and Moloka'i, where SGD was responsible for significant nutrient fluxes, supporting about 1–18% of the daily primary productivity in the assessed areas.

Away from the Hawaiian archipelago, SGD was quantified on La Réunion Island (Join et al. 1988; Rad et al. 2007). The associated nutrient fluxes revealed SGD as a major source of nitrogen on La Saline fringing reef, the largest coral reef of the island (Cuet et al. 2011).

On Mauritius, where surface runoff is negligible, an IAEA-UNESCO SGD intercomparison experiment was carried out to assess different methods of SGD measurement (Povinec et al. 2012). The field study was located in a lagoon close to Flic-en-Flac, where groundwater mainly discharges around one major lava tube conduit. Seepage meter measurements showed slightly higher fluxes of SGD (35 m<sup>3</sup>/m/d) compared to groundwater budget models (26 m<sup>3</sup>/m/d) (Povinec et al. 2012). This difference was attributed to the fact that a portion of the observed SGD was recirculated seawater. Generally, the two SGD estimates were in good agreement with calculations based on radon mass balances (Povinec et al. 2012). The lagoons around Mauritius experience eutrophication (Turner et al. 2000), and nutrient levels in SGD can be high (Ramessur et al. 2012). Nutrients in the water have been at least partly ascribed to inland sewage pollution (Gendre et al. 1994) and agricultural land use (Povinec et al. 2012).

In Muri Lagoon on Rarotonga, the largest of the Cook Islands, SGD contributed significantly to the water budget (Tait et al. 2013) and elevated alkalinity substantially above

that of similar locations (Cyronak et al. 2013). Cyronak et al. (2013) hypothesized that this could counteract effects of ocean acidification. Alkalinity flux via SGD amounted to 10–107% of the alkalinity taken up by coral communities in the lagoon (Cyronak et al. 2013). These results contrast reports from O’ahu (Hawaii), where SGD dilutes alkalinity in coastal waters (Garrison et al. 2003). Both islands are of volcanic origin and thus lithology does not explain this difference (cf. Thompson et al. 1998; Hartmann & Moosdorf 2012).

### Low-lying carbonate islands

Low-lying carbonate islands, e.g. atolls, are often characterized by complex geology where vertical changes in permeability dominate groundwater flow (Wheatcraft & Buddemeier 1981; Schneider & Kruse 2003). Their shallow morphology induces a shallow hydrological gradient and inhibits orographic precipitation.

In Australia, SGD was studied on Heron Island in the Great Barrier Reef, surrounded by a 26 km<sup>2</sup> reef lagoon, which receives SGD with strong tidal variability (Santos et al. 2010). The SGD from Heron Island is mostly recirculated seawater, but connected to the island by a freshwater lens (Santos et al. 2010). SGD-transported nitrate replaces the nitrogen inventory of the lagoon within < 19 days (Santos et al. 2010). Santos et al. (2010) assume that the nitrate stems to a large proportion from bird guano, which forms deposits of up to 1000 kg N ha<sup>-2</sup> a<sup>-1</sup> on Heron Island (Allaway & Ashford 1984).

Finally, on the atolls of North Andros Island, Bahamas, Whitaker & Smart (1990) reported discharge of saline groundwater potentially driven by differences in the marine hydraulic heads between the west and east side of the island. A study focusing on groundwater withdrawal qualitatively mentioned SGD from the tiny (area: 4 km<sup>2</sup>) Kavaratti Island, India (Singh & Gupta 1999).

### High carbonate islands

High carbonate islands are mostly uplifted reef platforms. Their karstification can induce large conduits for groundwater discharge.

In Bermuda, SGD was shown to contain anthropogenic nitrogen (Lapointe & Oconnell 1989; Simmons & Lyons 1994). Similar conditions were found in Barbados, where nitrogen-rich SGD was reported to vary strongly between wet and dry seasons and also spatially between different seepage meter locations (Lewis 1987). However, SGD salinities were close to ocean water, indicating only a minor freshwater component. Nevertheless, the observed nitrogen

concentrations correlated with salinity indicating that the fresh groundwater was contaminated with fertilizer (Lewis 1987).

Guam is one of the sites where SGD was identified and linked to ecological consequences very early. Emery (1962) first noted that considerable fresh water escapes the island through its beaches. Within the northern limestone plateau of Guam, a freshwater lens is situated above salt water in a limestone aquifer (Denton & Sian-Denton 2010). No rivers are flowing in this area. Taborosi et al. (2013) provide a detailed overview on the SGD features of Guam from more than 20 locations. Marsh (1977) linked the SGD to nutrient fluxes in two Bays of Guam. They found very high nitrate levels in the anthropogenically impacted Tumon Bay and lower levels in the lesser affected Pago Bay. Marsh (1977) concluded that regularly occurring algae blooms were connected to SGD nutrient fluxes. Since then, numerous studies assessed nutrients transported via SGD from Guam. However, measurements are complicated by a Pleistocene reef platform underlying the beach sediment (Matson 1993). As elsewhere, leakage from high carbonate islands like Guam is not uniformly distributed at its shores, and multiple discharge mechanisms occur (Matson 1993; Gamble et al. 2003). Matson (1993) estimated SGD with a water balance for the whole of North Guam, while earlier reported values (Table 1) were only representative for a coastal stretch of 50 m. Using the Guam example, Matson (1993) developed a simple conceptual model to approximate the impact of nutrient flux from unconfined carbonate aquifers on tropical islands. It represents leakage per linear meter of shoreline as a function of the circumference. Fertilizer inputs from Guam are small, since harvested cropland covers only a small proportion of the island (Redding et al. 2013). Redding et al. (2013) interpreted the presence of anthropogenic  $\delta^{15}\text{N}$  values even in reefs without surface sewage inputs (Haputo Bay) as strong indicator that SGD is a major transport pathway for nutrients to coastal waters around Guam. In addition, Redding et al. (2013) linked SGD to declining coral health, showing that anthropogenic N is a strong predictor of the coral disease “white syndrome” around Guam. This problem is likely going to grow in importance, because the aquifer, which can transport nutrients to the coast within hours to days (Matson 1993) is situated below more than 10,000 septic tanks (Denton & Sian-Denton 2010).

### Complex islands

The group of complex islands combines larger islands with a complex geology. It was called “mixed islands” by Falkland (1991). The genesis of these islands is diverse. Their elevation is often high, which induces high hydrological gradients and strong effects of orographic precipitation.



In the South China Sea, SGD on Hainan was identified with high regional variability by a comparison of two neighboring bays, where SGD amounted to 0.06% (Wanquan River estuary) or 16% (Bamen Bay) of the local river discharge (Su et al. 2011). While in the Wanquan River estuary, SGD contribution to nutrient budgets was negligible, SGD accounted for up to 50, 31, and 34% of the total dissolved inorganic nitrogen, phosphorus, and silica (DIN, DIP, and DSi) inputs to Bamen Bay. In addition, substantial SGD was reported to transport sufficient N and Si (but not P) to support local biogeochemical inventories in Laoye Lagoon at the southeastern coast of Hainan (Ji et al. 2013).

At Shiraho Reef, Ishigaki Island, spatially and temporally highly variable SGD controls the nutrient levels of the reef (Umezawa et al. 2002a, b; Blanco et al. 2011). Along Shiraho Reef, elevated abundances of benthic blue-green microalgae in the vicinity of agricultural fields were linked to groundwater seeps (Blanco et al. 2008). Although SGD comprises only 30% of the water flux of the nearby Todoroki River, the nitrogen fluxes via SGD are higher and increase the DIN/DIP ratio well above the Redfield-ratio (Blanco et al. 2011). However, microbiological N<sub>2</sub> fixation in the reef is also an important input of “new” DIN to the lagoon (Miyajima et al. 2007). The introduced P-limitation may trigger primary production bursts in case of higher P supply (Blanco et al. 2011).

Discovery Bay in Jamaica was another of the early places where SGD was demonstrated as a pathway for nutrients (D’Elia et al. 1981). Although the authors of that study did not quantitatively analyze SGD-driven nutrient fluxes, they showed a clear negative correlation between DIN and salinity. In addition, the very high N/P ratio of ~300 indicated that SGD can change the nutrient composition in coastal waters (D’Elia et al. 1981). The authors concluded that anthropogenic P inputs could trigger eutrophication events in combination with the N-rich groundwater supply (D’Elia et al. 1981). Later, Peterson et al. (2012) confirmed SGD as nitrogen source to Discovery Bay, demonstrating its local variability.

On the Philippines, two islands were the foci of SGD studies: In Manila Bay, Luzon Island, SGD salinities between 20 and 30 indicate a mixture between fresh and salt water, overall providing DIN in the same order of magnitude as river discharge to the coastal waters, while DIP inputs are between 7% and 17% of the river inputs (Tani-guchi et al. 2008). A fringing reef North of Santiago Island has been reported to receive substantial freshwater inputs by fresh SGD (Cardenas et al. 2010). SGD appeared diffusely throughout the reef, although it was more pronounced around projected geological faults (Cardenas et al. 2010). Although only little anthropogenic impact on the SGD nutrient levels was reported (Senal et al. 2011), the freshwater seepage into the reef has been shown to influence coral

species composition towards blue coral (*Heliopora coerulea*), which is thought to be tolerant to low salinities and nutrient rich conditions (Cardenas et al. 2010). In addition, freshwater seeps are considered to have affected restoration efforts of coral reefs in that area (Shaish et al. 2010).

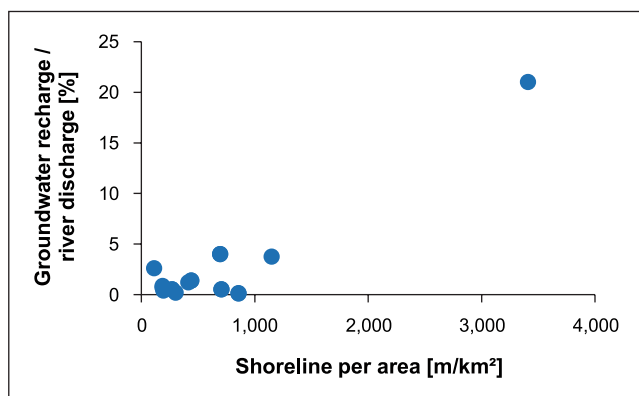
Taiwan is a particularly interesting location, because it received some research as weathering hotspot with a strong contribution of groundwater to overall weathering fluxes (Calmels et al. 2011). Most of the groundwater in Taiwan is of meteoric origin, but a significant part of the dissolved elements is sourced from thermal waters (Martin et al. 2013). Martin et al. (2013) analyzed the contribution of SGD to chemical weathering derived element fluxes to the coast. In general the short distance between topographic highs and the coast should promote SGD matter transport (Martin et al. 2013), but for most elements this transport remains on the order of a few percent compared to river transport (Zavialov et al. 2012; Martin et al. 2013). However, the suspected SGD zones show signs of elevated bioactivity which could be attributed to elevated nutrient concentrations, compared to average ocean water in this region (Zavialov et al. 2012). In addition to near-shore SGD, deep SGD was reported in 400–700m water depth offshore Taiwan (Lin et al. 2010), which may add to the SGD matter flux from Taiwan (Martin et al. 2013). Most of this SGD appeared to be recirculated seawater, but a reduced salinity in the water column at these depths indicated a freshwater component of 1–3% (Lin et al. 2010), with large uncertainties (Huang et al. 2011). Yet, evidence for deep fresh SGD could be shown as far as 25 km off the coast of Taiwan which may indicate widespread point sources of SGD in the region, with potentially important implications for the nutrient and trace element budgets (Lin et al. 2010).

Finally, at the west coast of Yap Island, Micronesia, SGD was reported to significantly contribute freshwater to a coral reef in dependence on tidal water level (Houk et al. 2013). *Thalassia* sea grass occurred less near discharge locations (Houk et al. 2013). Houk et al. (2013) conclude that SGD was an influential source of new nutrients in the lagoon, which in general shows very low nutrient concentrations without traces of human impact.

### Relevance of small tropical islands based on coastline shape

Contrary to river discharge, which at the coast is focused at a single point (the outlet) with a potentially large catchment in the hinterland, SGD usually is ‘scattered’ along the coastline, either as diffuse discharge or through conduits, e.g. karst structures or lava tubes. Thus, as a first order approximation, it seems appropriate to consider long convoluted coastlines to favor SGD, while large land area favors river discharge.





**Fig. 2** Relationship of the ratio shoreline per land area with the relative importance of SGD (here represented as groundwater recharge as reported in source publications) over river discharge. Each point represents a water budget of one island (data are from: Falkland 1991; Rad et al. 2007; Robins 2013). Geographical attributes are from (ISCIENCES L.L.C. 2009)

The ratio of coast length to land area should thus give a first order approximation of the potential relative importance of SGD versus river discharge. This approximation is supported by comparing the respective ratios based on water budgets (Falkland 1991; Rad et al. 2007; Robins 2013) and geographical parameters (ISCIENCES L.L.C. 2009) of 12 islands (7 of which provide water budgets) (Fig. 2). While the trend between both ratios seems to be positive (also without the outlier), the data are scarce and need improvement to robustly evaluate the proposed relation.

Note that the shoreline/land area ratio is a scale-sensitive parameter. First, due to its fractal structure, coastline length increases with increased resolution of the used representation (Mandelbrot 1967). Second, the number of land bodies represented in global spatial data itself varies largely between geographic scales of the respective database. For this study, a global coastline dataset with a resolution of 1 arc second was used, which represents >140,000 land bodies globally, with a shoreline of 2.3 million kilometers in total (ISCIENCES L.L.C. 2009). Analyzing their ratio of coastline versus land area supports the intuitive hypothesis of its reduction with the size of the land body (Fig. 3). The graph shows that small islands, showing very high coastline versus land area ratios, are locations where potentially SGD is particularly important compared to river flux. The coastline of tropical islands amounts to 468,000 km in this dataset (20% of the total global coastline of the here used high resolution dataset: ISCIENCES L.L.C. 2009). These small islands should not be ignored in large-scale SGD studies, which usually use coarser representations of the shoreline. While this simplified approach neglects different influence factors on total SGD fluxes (e.g. Santos et al. 2012) or the necessity to classify different coastal types regarding SGD

(Bokuniewicz et al. 2003; Dürr et al. 2011), it can be used to identify priority regions and locations.

Firstly, South East Asia shows particular potential for high susceptibility to effects from submarine groundwater discharge. However, comparing the map in Fig. 4 with the distribution of existing studies in Fig. 1 shows that the study density is lowest in the potentially most important regions. Secondly, particularly the small islands of Oceania with their very high shoreline versus land area ratios are situated in a low-productivity marine surrounding (cf. Behrenfeld & Falkowski 1997). There, nutrient additions by SGD could be important and add to the postulated island mass effect.

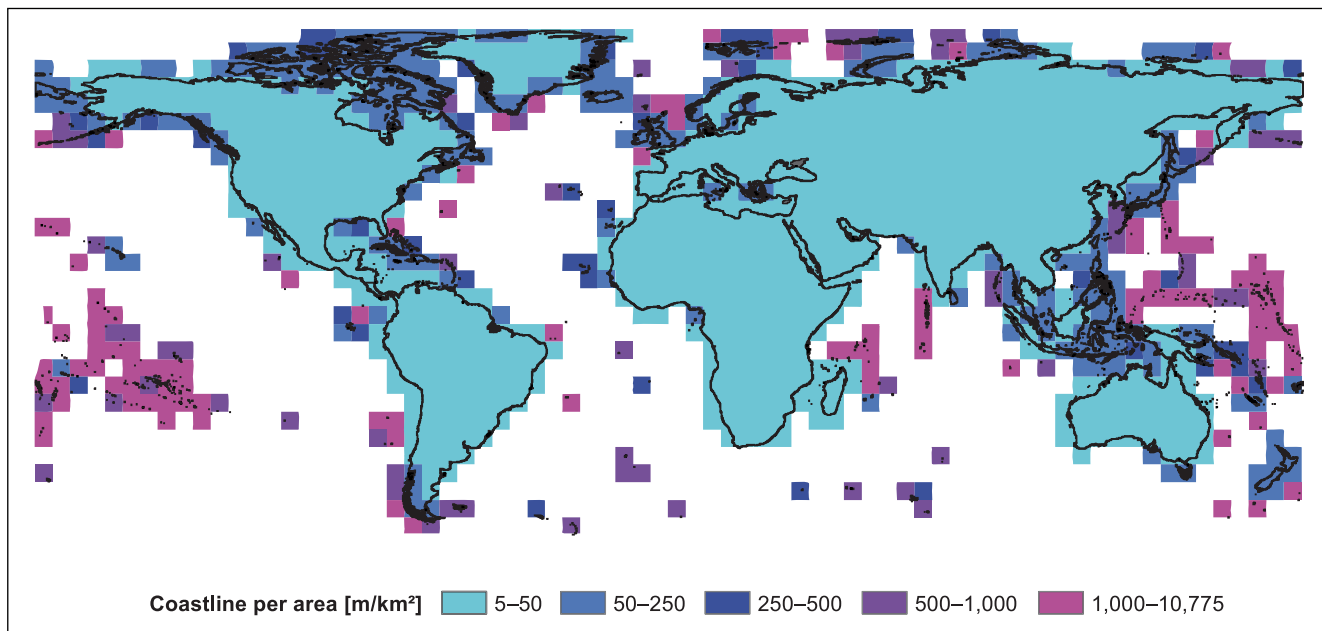
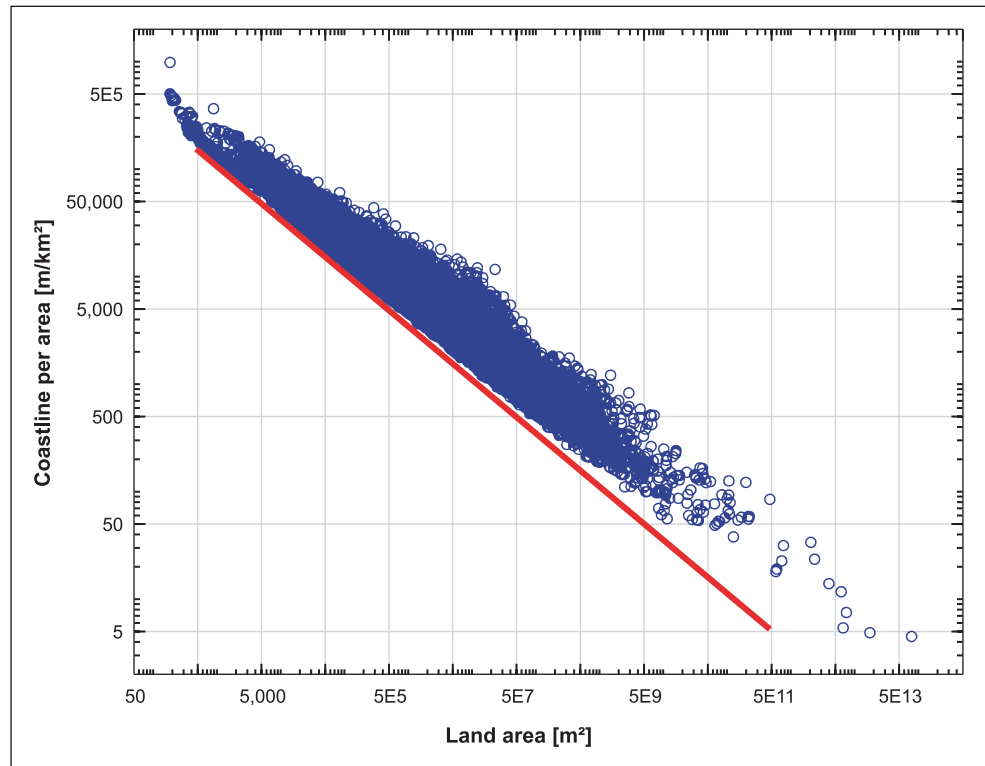
In summary, the geographic analysis presented here clearly suggests the need for further SGD research on tropical islands, which—despite being potential hotspots of SGD—have received very little scientific attention to date.

## Conclusions and outlook

Although it has been 33 years since D’Elia et al. (1981) called for a “pantropical assessment of SGD” from tropical islands, to date only 26 local studies could be identified that quantify SGD fluxes from these geographical settings. All of these studies report significant SGD at their locations. Nevertheless, the abundance of qualitative studies of nutrient fluxes by SGD from tropical islands and the often shown dominance over other sources of nutrients highlight the importance of this hidden and often neglected pathway from land to sea. However, the use of different normalizations impedes its quantification and the comparison between studies. One group of studies normalizes SGD per meter of shoreline, while the other normalizes per m<sup>2</sup> seepage area (Table 1). Others report only point discharge without normalization. Future local studies of SGD should endeavor comparability with other datasets when reporting SGD values.

A second bias observed during the literature study is the choice of study locations based less on thematic criteria but on location close to a marine research facility. Only two locations on tropical islands were identified that were explicitly chosen because of their local attributes: Kona coast (e.g. Bienfang 1980) and Manila Bay, Philippines (Taniguchi et al. 2008). As research progresses, we suggest that a structured approach to identify the most important locations based on geographical attributes should be adopted, in combination with mapping tools where possible. Regional scale mapping of SGD, either by remote sensing (e.g. Wilson & Rocha 2012; Mallast et al. 2013), aerial infrared imaging (e.g. Johnson et al. 2008), or by tracers as radon (e.g. Stieglitz et al. 2010), can identify hot spots and help extrapolate findings from local studies.

**Fig. 3** Scatterplot of coast line versus area of a land body against its area. One single point with very high coastline per area was removed manually. The *red line* represents a perfect circular shape, the smallest possible coast length



**Fig. 4** Map of the ratio of coast length versus land area (in m shoreline per km<sup>2</sup> land area). Larger values indicate an increased contribution potential of SGD to the total land-ocean water fluxes

The spatial analysis presented here indicates that on many tropical islands SGD likely exceeds the importance of river discharge for coastal nutrient budgets.

In conclusion, improving our understanding of the role of SGD in the overall water and solute inputs to the world oceans needs more systematically planned field studies—in

particular from tropical islands. Findings in this study may help to select future study sites at a global scale.

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