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Submarine groundwater discharge: an outlook of recent advances and current knowledge

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Abstract Driven by the hydraulic gradient, terrestrial groundwater can be discharged directly into the coastal ocean where heads are above sea level, a phenomenon known as submarine groundwater discharge (SGD). Although long overlooked, in recent years SGD has received increasing attention due largely to its potential importance in the transport of chemical constituents to the sea. Indeed, SGD occurrence and control mechanisms are still poorly understood. Submarine discharge often represents only a minor component of regional total water budgets, but because estimated fluxes are highly variable and quantification remains challenging, the process deserves to be carefully evaluated when investigating marine ecosystems and/or the safety of geological repositories in coastal areas, notably for the underground storage of CO_2. In view of the focus the topic is gaining, reflected in the large amount of information continuously being published in this field, here we present a selected review of our current knowledge of key mechanisms determining submarine groundwater discharge, and an updated compilation of most recent advances in research both in Japan and other regions of the world. In addition, we identify some potential pitfalls that need to be borne in mind in future work on SGD. Particularly in view of globally increasing urbanization and climate change, this contribution should prove useful also to local governmental authorities and scientists involved in groundwater coastal ecosystem management.

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Introduction

In most parts of the world, and especially in overpopulated countries such as Japan, the economic development of maritime regions is leading to a series of problems that highlight the urgent need of implementing adequate measures to preserve coastal and offshore environments. One key component is groundwater. Fresh groundwater comes into contact with the ocean at the downstream end of its flow path. This direct seepage of groundwater into the sea is termed submarine groundwater discharge (SGD), theoretically occurring wherever an aquifer is hydraulically connected with the sea through permeable sediments (Johannes 1980). The interaction between saltwater and freshwater modifies water characteristics, and therefore large amounts of groundwater discharged into the ocean may exert a substantial effect on the physical characteristics, chemistry, and ecology of near-shore waters. Indeed, even a small net flux of groundwater can, for example, deliver a comparatively large quantity of nutrients to the sea (Stieglitz 2005). Therefore, SGD constitutes a key topic of research for both hydrologists and marine scientists. Nevertheless, SGD has long been overlooked in other fields including coastal management, until recent years when the number of reports has augmented significantly in the literature. The increased attention the topic is receiving is leading to important and continuous advances regarding the magnitude and mechanisms of SGD, and its role as a pathway for the cycling of chemical constituents.

Because groundwater discharge is being studied by an ever broader range of research groups and governmental authorities, and although much valuable information has to date been gained, conceptual approaches, quantification methods and evaluation of data may differ widely, leading to some ambiguity and confusion regarding factors controlling SGD. For instance, while hydrogeologists are used to working on land, marine scientists focus on coastal environments, meaning that often both groups approach the problem of SGD literally from opposite directions, and so have not always been working with the same concepts and definitions of the phenomenon (Oberdorfer 2003). Moreover, discrepancies and incompatibility in terminology and units of measurements presented in the literature often prevent one of making comparisons among datasets and calculations of SGD. On another but essentially related aspect, Flemming and Delafontaine (2000) demonstrated that among scientists working in marine sedimentary environments, the misuse of common terms has often resulted in serious misinterpretation of otherwise good data by geochemists, biologists and sometimes even geologists.

The present work reviews a series of representative studies carried out on SGD in recent years, illustrating state-of-the-art advances and current knowledge based on the use of new analytical techniques and numerical models, thereby contributing to clarifying the occurrence and magnitude of submarine groundwater discharge in the coastal zone. Although some reviews are already available in the literature (Taniguchi et al. 2002; Burnett et al. 2003), this study attempts to cover aspects not evaluated in these earlier reports, such as the relation between SGD and CO_2 disposal. The paper centers its attention on recent and ongoing research in Japan, complemented with some leading, newly published studies dealing with other regions of the world, with emphasis on areas where no earlier data were available.

Mechanisms of submarine groundwater discharge

As stated by Church (1996), SGD is defined as the direct outflow of groundwater across the land–sea interface, meaning it comprises either one or several components of subsurface flow, which includes pure freshwater, groundwater recirculated due to wave setup, tidally driven waters, and flow recirculated by thermal or density convection. This definition encompasses all flows of water moving across the seabed, regardless of flow direction, the greatest concern being posed by fresh groundwater originating on land, as this component is the most likely to carry pollutants (SCOR-LOICZ 2004).

Groundwater discharges to the sea through a seeping face (Fig. 1), which has a width nearly proportional to the volume of freshwater flow (Glover 1959). The input may be in the form of low-rate seepage, detected mainly by the generation of a series of anomalies in the chemical composition of the water column. Alternatively, it can occur rapidly through fractures, faults or karstic galleries, sometimes connected with land aquifer formations far away from the shoreline (Shaban et al. 2005). A good example of the latter mechanism can be seen in the Yucatan Peninsula, Mexico, where rainfall infiltrates through an extensive network of underground caves and channels to vent directly into coastal lagoons through submarine springs and fissures (Back 1985). Theoretically, under uniform conditions, groundwater flow discharges at the junction with seawater. However, structural heterogeneities in geological formations result in submarine fluxes being limited not only to the narrow littoral or tidal zone, but in places occurring also at considerable distances offshore, up to some kilometers from the coastline (Dzhamalov 1996).

Several terrestrial and marine mechanisms have been proposed to explain the input of groundwater to the coastal zone: basically, water moves through the sediments in response to the hydraulic gradient, although flow migration may also be related with other mechanisms. Of these, diffuse seepage is generally confined to the near-shore, and would be a typical process for shallow, unconsolidated, coarse-grained aquifers occurring, for example, in Florida and along the NE coast of the USA (Slomp and Van Cappellen 2004). Moreover, even if the rates of advection recorded in most porous media including deep oceanic sediments are slow (Sayles and Jenkins 1982), this represents another mechanism of groundwater transport that should not be overlooked (Cornett et al. 1989). In permeable coastal sediments, advection can be driven by pressure fluctuations generated by the passage of waves and by bottom currents, which induce interstitial water flow between the grains (Shum and Sundby 1996). Such fluid exchange increases considerably with sediment

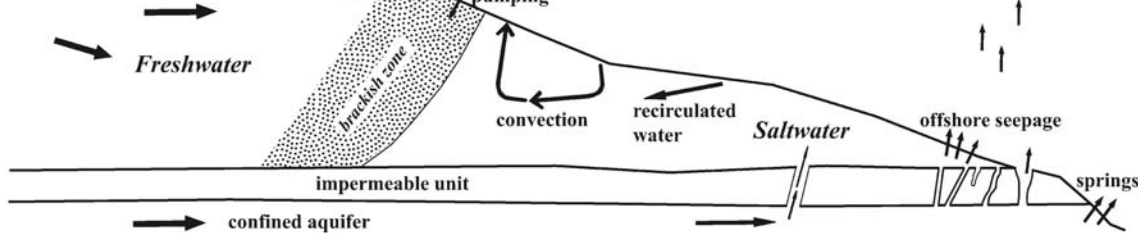

Fig. 1 Schematic representation of the SGD mechanisms (based on Burnett et al. 2001 and Taniguchi et al. 2002)

conductivity, ripple slope, and wave height, but is insensitive to the thickness of the permeable layer (Shum 1992, 1993).

Another driving force responsible for groundwater–seawater exchange along continental margins is geothermal convection, whereby cold seawater drawn into the platform replaces rising waters (Kohout 1966). In addition, water convection in sandy sediments may be triggered by sudden temperature changes in the overlying ocean (Moore and Wilson 2005), and in response to salinity variations (Webster et al. 1996). Finally, several studies have demonstrated that groundwater seepage is influenced by tidal changes that drive pressure variations in the subsurface (Knight 1981; Taniguchi 2002; Chanton et al. 2003). These data show that perturbations caused by the tides exert a direct effect on the spatial and temporal patterns of discharge, which may result in cyclic fluctuations in seepage rates. While some correspondence between tides and seepage flux is typical for near-shore environments, the timing of the seepage spikes relative to the tidal stage varies in function of the local hydrologic setting (Burnett et al. 2003), thus preventing one of making generalizations or of simplifying the situation. Therefore, the effects of tides on groundwater flow should be investigated at each particular location of study.

Investigations of SGD

Methodology

Globally, flow of groundwater into the sea has been recorded at several sites along the East Coast of North America, the Caribbean, Europe, the Middle East, Australia, New Zealand, and Japan (cf. Marui 1997; Taniguchi et al. 2003a).

SGD estimates are based either on direct measurements by means of seepage meters or multi-level piezometer nests, or on indirect assessments of physicochemical characteristics. The latter include temperature depth profiles, and both natural and introduced chemical tracers (e.g., nutrients, isotopes, dyes). Dissolved nutrient assessments include measurements of methane (CH_4) and of stable isotopes such as $^{15}NO_3$. Natural radioactive elements such as ^{222}Ra and other radium isotopes (^{223}Ra, ^{224}Ra, ^{226}Ra, ^{228}Ra), and stable isotopes such as ^{18}O and deuterium have been employed successfully particularly as signatures of large-scale water transport. Recently, Povinec et al. (2006) presented a novel and effective detection system for the monitoring of SGD, based on an in situ analysis of radon-decay products in seawater using underwater gamma-ray spectrometry.

Another new advance is the use of the extremely rare radioactive isotope krypton-81 as groundwater chronometer at the million-year time scale. Measurements are made by a revolutionary laser-based method known as atom-trap trace analysis (Du et al. 2003, 2004).

In addition, water-balance approaches, hydrograph separation techniques, and numerical simulations have been widely applied for basin-scale estimates of groundwater flow into the ocean (cf. Taniguchi et al. 2003a).

Japan

In Japan, inputs of fresh groundwater to the seafloor have been reported at various locations, especially on the southern coast of Honshu Island (Fig. 2). Early observations date back to the Kaiko project, carried out in 1985 at the eastern front of the Nankai accretionary wedge and on the adjacent Philippine Sea plate. Here, a narrow corridor at the top of a 2,000-m-deep ridge is characterized by manifestations of fluid seepage along an active faulting zone (Lallemand et al. 1992). Seepage occurs at a location that has remained essentially fixed over geological time scales, constituting constant venting related with a possible shear zone. Discharge presumably takes place along a network of cylindrical conduits approximately 2 m in

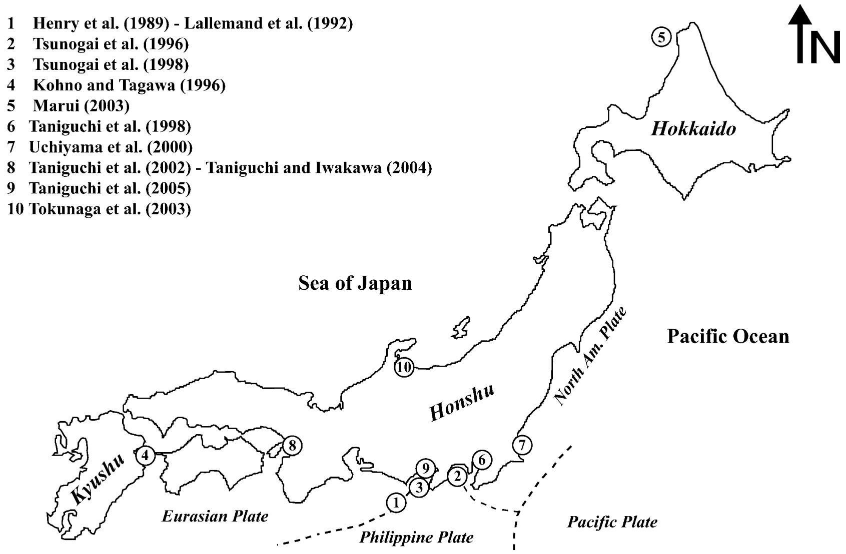

Fig. 2 Investigations on SGD within Japan

diameter, associated with tension fractures active for no more than a few tens of years, through which overpressured pore water is venting at velocities of about 0.27 m day^{-1} (Henry et al. 1989; Table 1). In this region, Tsunogai et al. (1996) evaluated the sources of water seepage at Sagami Bay, on a convergence front of the Philippine Sea plate beneath the Japanese islands (Fig. 2). Shallow waters in the continental margin were markedly depleted in SO_4^{2-} and Cl^- relative to ambient seawater, suggesting the existence of a freshwater component at this coastal site. The flow reaching the seafloor could be a mixture of seawater, pore water, and land-derived groundwater, discharging at rates of 310–500 m^3 day^{-1} over an area of 2 km^2 (Table 1). More to the west, anomalously high CH_4 concentrations were

Table 1 Representative rates of SGD throughout the world[a]

Location	Method	SGD rate	Reference
Nankai wedge, Japan	Temperature	0.27 m day^{-1}	Henry et al. (1989), Lallemand et al. (1992)
Sagami Bay, Japan	Geochemistry, heat flow	310–500 m^3 day^{-1}	Tsunogai et al. (1996)
Suruga Bay, Japan	Carbon isotopes	No data	Tsunogai et al. (1998)
Oita Prefecture, Japan	Temperature, electrical conductivity, video	No data	Kohno and Tagawa (1996)
Rishiri Island, Japan	Electrical conductivity	No data	Marui (2003)
Tokyo Bay, Japan	Temperature	8.2×10^{-5}–1.1×10^{-3} m day^{-1}	Taniguchi et al. (1998)
Kashima coast, Japan	Modeling	283–640 m^3 day^{-1} km^{-1}	Uchiyama et al. (2000)
Osaka Bay, Japan	Seepage meters	2000: 1×10^{-2}–3.3×10^{-2} m day^{-1}, 2001: 4.9×10^{-3}–8.2×10^{-2} m day^{-1}	Taniguchi and Iwakawa (2004)
Suruga Bay, Japan	Remote sensing, seepage meters	0.04–1.56 m day^{-1}	Taniguchi et al. (2005)
Kurobe fan, Japan	Temperature, conductivity, geochemistry	No data	Tokunaga et al. (2003)
Florida coast, USA	Boreholes, sampling	No data	Kohout (1966)
Crescent Beach, FL, USA	Boreholes, sampling	2.6×10^{4}–7.3×10^{5} m^3 day^{-1}	FGS (1998)
World basis	Water balance	31% of land water flux	Lvovich (1974)
World basis	Water balance	2% of global precipitation	Zektser and Loaiciga (1993)
World basis	Water balance	0.01–10% of surface runoff	Church (1996)
World basis	Literature review	6–10% of surface water inputs	Burnett et al. (2003)
World basis	Literature review?	5% of total global water flux	Slomp and Van Cappellen (2004)
Donnalucata, Sicily	^{222}Rn	1.2×10^{3}–7.4×10^{3} m^3 day^{-1}	Burnett and Dulaiova (2006)
Chesapeake Bay, USA	^{222}Rn	2.7×10^{7} $m^3 day^{-1}$	Hussain et al. (1999)
Yellow Sea	^{226}Ra, ^{228}Ra	1.8×10^{9} m^3 day^{-1}	Kim et al. (2005)
Ovacif-Silifke, Turkey	Hydrochemical tests, dye tracers	6.4×10^{4} m^3 day^{-1}	Elhatip (2003)
Baltic Sea	Modeling	4.6×10^{3}–6×10^{3} m^3 day^{-1} km^{-1}	Kaleris et al (2002)
Biscayne Bay, Fl, USA	Modeling	3.4×10^{4}–3.7×10^{5} m^3 day^{-1}	Langevin (2003)
Western Australia	Temperature	9×10^{-3}–3.6×10^{-3} m day^{-1}	Taniguchi et al. (2003b)
Kenya, southern coast	Modeling	6.1–17.9 m^2 day^{-1}	Kamermans et al. (2002)
Zanzibar island	Modeling	0.4–10.2 m^2 day^{-1}	Kamermans et al. (2002)
Patos Lagoon, Brazil	Hydrochemistry	6.25×10^{7} $m^3 day^{-1}$	Windom and Niencheski (2003)
Sao Paulo, Brazil	^{226}Ra, ^{222}Rn	0.021–0.048 m day^{-1}	Oliveira et al. (2003)
Delaware estuary, USA	^{222}Rn	1.21×10^{6}–2.51×10^{6} m^3 day^{-1}	Schwartz (2003)
NE coast Gulf of Mexico, USA	^{222}Rn, CH_4	2.5×10^{4}–9.9×10^{4} $m^3 day^{-1}$ km^{-2}	Cable et al. (1996)
Great South Bay, NY, USA	Sediment chemistry	3.6–18.3 m^3 m^{-2} $year^{-1}$	Capone and Bautista (1985)
Yeoja Bay, Korea	Nutrients, Ra isotopes	2.6×10^{7} m^3 day^{-1}	Hwang et al. (2005)
Lebanon coast	Temperature, remote sensing	9.3×10^{5} m^3 day^{-1}	Shaban et al. (2005)

[a] Where possible, SGD rates were converted to common units for comparison purposes; the data are listed in the order in which they appear in the text

detected in near-shore waters of the Suruga Trough, another subducting front of the Philippine Sea plate. These plumes were centered a few kilometers off the southern Honshu coast, presumably associated with cold venting fluids other than hydrothermal fluids flowing through the seafloor (Tsunogai et al. 1998). Rates of venting are expected to vary strongly in conjunction with hydrological changes occurring in response to sudden events on the seafloor, such as large earthquakes. Despite magmatic activity being unlikely in the Suruga Trough, increases in groundwater discharge and fluctuations in chemical characteristics (cf. new vents at the seafloor and emissions from deeper regions) would in this case have been associated with a triggering earthquake of magnitude 4.7 occurring a few days before the sampling campaign.

Kohno and Tagawa (1996) demonstrated the existence of submarine discharge in Oita Prefecture, on the eastern coast of Kyushu Island (Fig. 2). By means of video filming, as well as temperature and conductivity measurements, they inferred that groundwater is recharged under confined conditions in the nearby mountains, subsequently discharging along the coast as freshwater springs, a good example of the classical theoretical discharge scenario (cf. above; Fig. 1).

The scarcity of good-quality water for drinking and industrial uses on the volcanic Rishiri Island, northwest of Hokkaido Island (cf. Marui 1997) prompted Marui et al. (1999) to evaluate submarine discharge as an alternative source for freshwater supply for the region. These authors suggested that by maximizing abstraction rates, SGD could also become a possible solution to subsidence and saline intrusion of coastal aquifers affected by excessive pumping. Within this context, Marui (2003) investigated several submarine springs on Rishiri Island (Fig. 2). Although this research is still in progress, it is already clear that along its advance from land, groundwater pushes seawater offshore the island, giving rise to a flow of freshwater even below the sea bottom. This flow would be large enough to produce measurable deviations in the shape of the freshwater/seawater interface.

It is well known that movement of groundwater can strongly affect near-shore temperature distribution patterns. At a given depth, water temperature in a groundwater discharge area is higher than that in the recharge area (Domenico and Palciauskas 1973). Taniguchi et al. (1998) applied this key signature to estimate SGD in Tokyo Bay, Honshu Island (Fig. 2). Temperature profiles indicated the rate of groundwater discharge fluctuated between 8.2×10^{-5} and 1.1×10^{-3} m day^{-1} (Table 1), these being somewhat low values compared with seepage calculations at other sites in Japan.

The theoretical seawater/freshwater interface is commonly represented on the basis of Ghyben–Herzberg's law, but in most real situations this does not yield accurate results where freshwater flows to the sea (Freeze and Cherry 1979). Bearing this in mind, Uchiyama et al. (2000) developed a numerical model accounting for the effects of the water table and tides on the saltwater wedge along 16 km of the shore of Kashima, about 70 km northeast of Tokyo (Fig. 2). The estimated flux of groundwater from the landward aquifer ranged from 283 to 640 m^3 day^{-1} km^{-1} (Table 1), representing no more than 0.035% of the flow from neighboring rivers to the ocean. Since pipe flow through macropores and wave effects were neglected, it is possible that the simulation underestimated total groundwater input at this site.

As pointed out above, tides may exert a significant influence on the temporal and spatial patterns of groundwater discharge and salt concentrations in the near-shore zone (Robinson and Gallagher 1999). Investigations based on continuous seepage meter measurements in Osaka Bay, southwestern coast of Honshu Island, demonstrated that the volume of submarine groundwater discharge was negatively correlated with tidal levels at this site (Fig. 2). The finding that SGD decreased at high tide is likely a consequence of the concurrent reduction in hydraulic gradient (Taniguchi and Iwakawa 2004). Diurnal and semidiurnal periods of SGD variation were reported to correspond exactly with the periods of sea-level fluctuations, and therefore SGD changes were attributed to tidal effects. The amplitude of SGD ranged from about 1.7×10^{-3} to 8.6×10^{-3} m day^{-1} (2 to 10×10^{-8} m s^{-1}), and the amplitude of sea-level change from about 0.3 to 0.7 m. The monthly averages in observed SGD varied between 1×10^{-2} and 3.3×10^{-2} m day^{-1} for the year 2000, and between 4.9×10^{-3} and 8.2×10^{-2} m day^{-1} for 2001 (Table 1). However, only 4–29% of the flow would correspond to the freshwater component. Therefore, SGD rates depend mainly on the volume of recirculated seawater, not on the terrestrial component.

Another study based on seepage meters has recently been carried out in Suruga Bay, southern Honshu Island, where the effect of bay curvature was evaluated (Taniguchi et al. 2005; Fig. 2). Indeed, because of the convergence of discharge fluxes, SGD should increase with bay curvature (Cherkauer and McKereghan 1991). Similarly to the findings in Osaka Bay (cf. above), semidiurnal fluctuations in discharge flow were attributed to tidal effects. Furthermore, SGD near the shore was positively correlated to changes in groundwater level close to the coast, but depended on sea-level changes further offshore. At the site, discharge rates ranged from 0.04 to 1.56 m day^{-1} (Table 1), representing approximately 14.7% of the total freshwater input into the basin. Finally, it was demonstrated that recirculated water plays a dominant role in the generation of fluids at this site, the ratio of fresh SGD to total SGD being nearly 9%.

Groundwater discharge has also been investigated along the Sea of Japan coast in the Kurobe alluvial fan, Toyama Prefecture, north coast of Honshu Island, by Tokunaga et al. (2003; Fig. 2). Here, chemical data indicate the presence of several discharge points that would be directly connected to the shallow groundwater reservoir of the onshore fan. Compared to values recorded in adjacent rivers, higher concentrations of NO_3^- in this groundwater suggest that it constitutes an important pathway for the transport of chemicals to the ocean.

Global synopsis

Early work on SGD dates back to the 1960s (Kohout 1966; Isbister 1966; Manheim 1967; also see FGS 1998) when active search surveys on the discharge of fresh groundwater to the seafloor were conducted in the USA. Many more studies were carried out in subsequent years throughout the northern hemisphere and in Oceania, the present synopsis focusing on the most recent reports.

In terms of reference framework, it is important to note that estimates of SGD are available at both global and local scales. According to Zektser and Loaiciga (1993), only approximately 2% of global precipitation is channeled into direct groundwater discharge to the ocean (Table 1). This small fraction can nevertheless be significant for regional water balances. Based on hydrological considerations and water balances approaches, estimates of terrestrially derived SGD at the global scale generally range from 0.01 to 10% of surface water runoff (Church 1996; Taniguchi et al. 2002). According to Burnett et al. (2003), most estimates lie in the range of 6–10%, while Slomp and Van Cappellen (2004) estimated SGD to be 5% of the total global water flux (Table 1). An exceptionally high value of 31% (Lvovich 1974) seems to be improbable (Zektser and Loaiciga 1993).

At a local scale, estimated groundwater discharges present even stronger variations, in part artificial because of the ambiguous definition of SGD. Thus, some authors have concentrated on that fraction of water terrestrially derived, whereas others have included also the recirculated components in their calculations. According to Taniguchi et al. (2002), local estimates of SGD range from 3 to 87% of total water fluxes. We consider that the latter value is excessive, because a substantial decrease in the magnitude of discharge rates can be expected if density or tidally driven components were to be excluded from the calculations. On a worldwide basis, we find that SGD fluxes fluctuate strongly from almost zero up to 1.24 m day^{-1}, although most values fall within a mean range of 0.052–0.1 m day^{-1}.

Chemical tracers naturally enriched in groundwater have proven useful in quantifying rates of SGD, as they occur in the form of “anomalies” that can be conveniently recognized over larger areas (Moore 1999). Radon is a good tracer because it behaves conservatively and its concentration is very high in groundwater but low in seawater. Once radon fluxes are estimated, it is possible to calculate SGD by dividing these fluxes by the radon concentration of the groundwater (Burnett and Dulaiova 2006). By this approach, Burnett and Dulaiova (2006) estimated that 1.2×10^3–7.4×10^3 m^3 day^{-1} of submarine groundwater is being discharged in a basin in the southeast of Sicily, Italy (Table 1). Driving forces could not be distinguished by this approach, so the calculations assessed the total flow, rather than only the terrestrially derived component.

Also using ^{222}Rn signatures, Hussain et al. (1999) evaluated the contribution of groundwater to Chesapeake Bay and the Potomac River, northeastern coast of the USA. The authors suggested that if the excess tracer were entirely due to submarine discharge, then the upper limit of groundwater flow to the bay would be about 2.7×10^7 m^3 day^{-1} (Table 1), which represents approximately 10% of riverine influx. These results are consistent with data collected in 1975 by Moore at similar locations within the bay (Moore, unpublished data, cited in Hussain et al. 1999). Finally, ^{226}Ra and ^{228}Ra isotopes were recently used by Kim et al. (2005) to determine the flux of submarine groundwater and some associated material into the Yellow Sea, between China and Korea. The SGD discharge was estimated to be 1.8×10^9 m^3 day^{-1} (Table 1), an amount that potentially rivals or is even more important than river discharge in the area.

Other useful hydrochemical techniques include the employment of dye tracers and electrical conductivity measurements. In this manner, volumes of groundwater discharged into the Mediterranean Sea were estimated at the coastal village Ovacik–Silifke, Turkey, by Elhatip (2003), in one of the few studies carried out to date in the Middle East. Here, the regional geology is essentially karstic, and therefore groundwater flow is controlled largely by structural features that provide preferential transport pathways. Hydrological data indicate that flows to the sea occurred essentially through three outlets of maximum diameter 0.3 m, averaging a total discharge of 6.4×10^4 m^3 day^{-1} (0.74 m^3 s^{-1}; Table 1). The proportion of freshwater discharge from the springs varied in the range 40–66%, indicating that as discharge is taking place in the fresh-saline water zone, a certain degree of mixing is to be expected.

The high number of physicochemical parameters involved, and the complex effects introduced by waters of variable density complicate SGD analysis, making it worthwhile to use more sophisticated tools such as numerical simulations. Despite potentially dangerous oversimplifications and the risk of unfounded assumptions, models can provide valuable information beyond the monitoring network, and constitute a powerful method to deal with large-scale trends, particularly in combination with tracers of large groundwater reservoirs such as ^{226}Ra (e.g., Moore 1996). Predictive models have also been tested where field data are scarce, one good example being the study by Kaleris et al. (2002) who reconstructed groundwater outflow at the bottom of the western Baltic Sea. They concluded that locally measured rates can hardly be used to estimate mean outflow over larger areas of the seafloor, given the highly non-uniform distribution of discharge in this region. This variability could be explained by the large heterogeneity in hydraulic conductivity distributions, and uncertainties concerning conditions at the sea bottom. Calculated submarine groundwater discharge fluctuated in the range 4.6×10^3–6×10^3 m^3 day^{-1} per km land–sea interface (Table 1). Taking density effects into account, it was found that heavier saltwater occupies the central part of pockmarks at the study site, groundwater outflow being displaced toward the edges in a sort of convective movement. Thus, the simulation demonstrated that in large-scale studies dealing with the saltwater interface, effects due to density differences between groundwater and seawater strongly influence flow patterns, and should therefore not be overlooked.

Although variable-density flow models are usually avoided due to the difficulties involved (e.g., parameter identification, sediment heterogeneity, non-unique solutions, calibration problems), the three-dimensional variable-density SEAWAT code (Guo and Langevin 2002) was introduced to estimate rates of SGD in the coastal estuary of Biscayne Bay, Florida (Langevin 2003). In agreement with some global-scale studies, results indicate that fresh groundwater discharging through the limestone aquifer averaged 3.4×10^4 to 3.7×10^5 m^3 day^{-1} (Table 1), representing approximately 10% of the land-surface water discharge, or 2% of annual rainfall at the study site. This freshwater component is highly sensitive to salt concentrations in the bay, there being an inverse relationship between discharge rates and salinity levels in these estuarine waters. This highlights the importance of an appropriate selection of boundary conditions in developing a model: even slight variations in boundary type and/or specified salt concentrations can have marked impacts on simulated SGD. More recently, another numerical simulation using the code FAST-C (2D; Holzbecher 1998) was performed by Kaleris (2005) to investigate the contribution of recirculated seawater in SGD, as well as the exchange fluxes between surface water and groundwater, for cases in which surface water bodies such as lagoons, lakes or wetlands are embedded in aquifers near the shore. The study led to the result that SGD in homogeneous aquifers can contain up to 75% seawater, but in the case of heterogeneous units, it was difficult to derive general rules because the large number of processes and interactions involved can both increase or decrease the proportion of recirculated seawater. In addition, the author showed that under certain conditions terrestrial groundwater may discharge directly to the surface water bodies, and not to the sea. As expected, the proportion of recirculated water in SGD increases with a decreasing value of the width and the salinity of the surface water body.

Monitoring of groundwater temperature with depth along a coastal aquifer was carried out by Taniguchi et al. (2003b) at an experimental site in Western Australia. Calculations depicted discharge velocities of 9×10^{-3}–3.6×10^{-3} m day^{-1} (Table 1), the values being as high as 0.16 m day^{-1} for measurements based on seepage meters. This discrepancy in the results may be because temperature measurements may reflect only terrestrial fresh groundwater discharge, whereas SGD measured by seepage meters may include both fresh groundwater and recirculated saline water. Thus, data from seepage meters would need to be interpreted with caution because they can strongly overestimate the flow of freshwater into the ocean. The choice of meter type would be less critical and would not have a major impact on the results. Indeed, data obtained by automated meters agree relatively well with those of manual meters, although underestimates or overestimates of discharge may result when measurements are limited to shorter time periods (Taniguchi et al. 2003b).

There exists a paucity of SGD data for South America and Africa, although inland groundwater budgets have long been published, notably for South Africa (Davies and Day 1998). Recently, ecological consequences of anthropogenic impacts on groundwater reserves have been emphasized for a mangrove ecosystem in Kenya (Gillikin et al. 2004). In addition, Kamermans et al. (2002) have reported predicted mean groundwater flow rates of 0.4–17.9 m^2 day^{-1} for the coastal zone of southern Kenya and the island of Zanzibar (Table 1), based on MODFLOW-96 simulations (cf. Harbaugh and McDonald 1996). In another novel study, based on the newly developed atom-trap trace analysis method (cf. above), Sturchio et al. (2004) have recently demonstrated the presence of an extensive, one-million year old groundwater reservoir in the Nubian Aquifer (Egypt), which is moving northward at 1–2 m per year.

In South America, groundwater paths and mixing processes at the freshwater–seawater interface have been investigated by Windom and Niencheski (2003) in the Patos lagoon, southern Brazil. Lagoon barriers impede surface exchange with the sea, but when permeable they facilitate water flow and mixing. These systems are highly influenced by seasonal variations in water flow: large quantities of freshwater move through the barrier toward the coast during periods of high river runoff, alternating with the influx of oceanic waters into the lagoon and associated mixing processes during stages of low river flow. In the Patos lagoon, freshwater flow through a 10-m section below 9 m depth was calculated to be about 6.25×10^7 m^3 day^{-1} (Table 1), representing nearly 2% of mean freshwater discharge to the lagoon. Also in Brazil, Oliveira et al. (2003) carried out measurements of ^{226}Ra and ^{222}Rn in the coastal waters of Sao Paulo state, estimating advective SGD velocities of 0.021–0.048 m day^{-1} (Table 1). Generally higher values were measured by seepage meters (0.014–0.21 m day^{-1}). These values are similar to those reported by Taniguchi et al. (2003b) for Western Australia (cf. above). Compared with those documented on the Nankai Ridge (cf. above), however, the estimated rates are rather low, probably because of atmospheric losses and mixing.

In a similar approach, Schwartz (2003) identified a zone of SGD in the Delaware estuary, East Coast of the USA. Based on a ^{222}Rn budget, this author demonstrated that enrichment of the element within the estuary can be explained solely by the contribution made by groundwater influxes of 1.21×10^6–2.51×10^6 m^3 day^{-1} (14–29 m^3 s^{-1}; Table 1). On an areal basis, the calculated groundwater flux (5.18×10^4 to 1.05×10^5 m^3 day^{-1} km^{-2}) is of the same order of magnitude as the values of 2.51×10^4 to 9.94×10^4 m^3 day^{-1} km^{-2} (0.29 to 1.15 m^3 s^{-1} km^{-2}) determined in the northeastern Gulf of Mexico by Cable et al. (1996; Table 1). Unlike many of the studies discussed above where it was estimated to be a minor component of the water budget, SGD in the Delaware estuary is significant with respect to the total discharge fluxes into these coastal waters, as the calculated flux is equivalent to the discharge of the second and third largest tributary rivers of the estuary.

The broad range of scientists involved, and the great number of techniques available to quantify discharge rates appear to foment one of the most persistent problems in evaluating the influence of SGD: the lack of a standard terminology for the presentation of data, as well as the usage of different units of measurement. This can complicate (if not make impossible) the integration or comparison of SGD estimations across a variety of field sites. For one, this seems to be the case for the East Coast of the USA, which serves to illustrate the problem. For example, Capone and Bautista (1985) reported SGD values of 3.6–18.3 in units of cubic meter per square meter per year for Great South Bay, NY (Table 1), whereas other studies document SGD only in units of volume per unit time. Without additional information, the datasets can evidently not be compared. This important prerequisite for meaningful intercomparison of site- or region-specific datasets has been overlooked in some recent overview reports for the East Coast (e.g., Schwartz 2004). Thus, rather than reporting only the one or other parameter (and this despite additional data being available; e.g., Kamermans et al. 2002), it is essential to reach a consensus about which units should be applied in publishing results of SGD. One possibility would be that, in a generally adopted standard procedure (and if the data exist), one would report two main components of SGD budgets, i.e., seepage *flux* in cubic meter per square meter per day (or equivalent units) and aquifer thickness (e.g., m), the product of these being seepage *flow* in square meter per day (or equivalent units; for example, see Kamermans et al. 2002).

Most groundwater discharge may take place at shallow depths (Dzhamalov 1996; Taniguchi et al. 2002), and in some cases coastal eutrophication and the increase of algal blooms have been directly connected to SGD (Corbett et al. 1999; Hussain et al. 1999; Charette et al. 2001). In Yeoja Bay, South Korea, shallow groundwater is associated with short residence times (about 7 days), and with substantially high rates of submarine discharge, in the order of 2.6×10^7 m^3 day^{-1} (Hwang et al. 2005; Table 1). High rates of SGD determine that nutrients are flushed with submarine groundwater at rates an order of magnitude higher than those associated with stream flow and diffusion from bottom sediments in the bay. This excess nutrient input from coastal groundwater is especially rich in dissolved inorganic N and Si, and is thought to be the most likely cause of harmful algae blooms occurring in the open sea outside of the bay.

Conversely, a wide variety of organisms have been demonstrated to significantly modulate SGD dynamics. Animal burrows in riparian and mangrove settings can facilitate the recirculation of seawater, and of course groundwater, and promote convective fluxes below the root zone. For example, crustacean burrows below the root system of a tropical mangrove swamp in Hichinbrook Channel, Australia have been shown to be flushed quickly and efficiently by tidal currents. Per tidal cycle, 100–1,501 m^{-2} was calculated to be exchanged across the forest floor, equivalent to 10–40% of the tidal water flowing through the burrows (Stieglitz et al. 2000; Stieglitz 2005). A novel, even more complex crab–fish–groundwater interaction has recently been demonstrated to promote stream formation in coastal wetlands in Argentina (Perillo et al. 2005).

Paleochannels connected to the shore can provide pathways for groundwater movement. Freshwater wetlands situated above dune systems on inland beaches (cf. above sea level) may constitute additional sources of discharge along the coastline all year round (Stieglitz 2005). Routes that facilitate groundwater flow to the sea may serve as pathways for seawater intrusion, too. Therefore, structural features of the terrain, such as fractures, faults, bedding, and karstic galleries, need to be carefully evaluated before making definitive decisions in SGD management. In Lebanon, for example, the overexploitation of coastal wells has led to saltwater intrusion along fractures that earlier discharged freshwater into the ocean (Shaban et al. 2005). At least 27–39 sites of groundwater discharge have been identified in this case. These spots form part of a highly fractured karstic formation and tilted strata along the coastline, where some of the pathways extend offshore as far as 700 m. As expected, large volumes of water are released through these springs during discharge periods, roughly totalizing 9.3×10^5 m^3 day^{-1} (Table 1).

Discussion and conclusions

The data presented above indicate that SGD can generally be considered a subtle process taking place at low rates in coastal aquifers. An exception would be karstic and fractured formations, where substantial fluxes are commonly expected. Thus, although groundwater outflow theoretically occurs at any site where heads are above sea level, SGD usually constitutes only a minor component of the total water budget. This means that it runs the risk of being overlooked, unless it is recognized that integrating over larger areas can substantially increase regional and global SGD significance (e.g., Johannes 1980; Kamermans et al. 2002). Indeed, on a global scale, and although the proportion of fresh water is exceedingly small—3.5% of the Earth's total—of this, only a minimum fraction is surface water, the rest (1.05×10^7 km^3) being fresh groundwater (Gleick 1996). Considering that the water volume in rivers reported by Gleick (1996) is 2,120 km^3, and in view of estimates of the global flux of groundwater entering the oceans through SGD usually varying between 0.01 and 10% of surface water runoff (Zektser and Loaiciga 1993; Church 1996; Taniguchi et al. 2002; Slomp and Van Cappellen 2004), the magnitude of SGD at a global scale would range from 2.12×10^{-1} to 212 km^3, which represents approximately 2×10^{-3} to 2×10^{-6}% of the total amount of fresh groundwater. This calculation should be considered as only a crude approximation, however, and derived values must therefore be taken with caution. Unlike other estimates of terrestrially derived fresh SGD on a global scale (see Taniguchi et al. 2002; Burnett et al. 2003), the present estimation yields low values, essentially because the assumed water distribution in rivers, and the role of

SGD considered, were lower than those used in other approaches.

As submarine discharge is dependant on the hydraulic gradient, it commonly decreases with increasing water depth and distance from the coast (Bokuniewicz 1980; Cable et al. 1997). However, it has been shown that this is not always the case, as structural conduits can facilitate the transport of groundwater from land aquifers to points several km away from the shoreline. As an example, this can be observed at several sites beneath the tectonically active plates of the Japanese islands, and along karstic coasts in the Mediterranean Sea, where large volumes of groundwater are discharged into the ocean through preferential pathways such as conduit vents and galleries.

One question remains: is SGD beneficial or detrimental? The answer is individual to each specific site, but it is also somewhat subjective, as this is influenced by the point of view from which SGD is investigated. Discharge of freshwater beyond the coastline was initially conceived as a possible source for water supply. Submarine springs in many parts of the world are large enough to provide fresh water for human needs (Kohout 1966). However, difficulties in detecting groundwater seepage, the usually low rates measured at the discharge points, and considerations regarding cost, technology and performance of water extraction appear to have discouraged investigations on SGD as a supply source. Nevertheless, increasing population size, coastal development, and the threats of land subsidence and saltwater intrusion make it critical to find alternative sources of potable water, at least as an emergency reserve, so there is still a necessity to initiate systematic studies on SGD with the goal of opening up new water resources. On the other hand, the tendency these last years seems to be to consider SGD as an undesirable component of the water cycle. Recent studies suggest that chemical loading from submarine discharge may rival other major sources such as rivers in many coastal areas (Mulligan and Charette 2006), and thus this would eventually have a considerable impact on coastal biogeochemistry and ecosystem functioning (Burnett et al. 2001). In this paper, we documented only a few of several reports that have analyzed the impacts of SGD in the contamination of coastal waters. Many more are continuously being released. Such a high number of case studies undoubtedly prove that submarine groundwater exerts a direct influence on the chemistry and nutrient balance of the coastal zone, and therefore seepage potential, seepage magnitude, and the mechanisms responsible for solute transport should be carefully considered in coastal and freshwater ecosystem management and prioritization, particularly in view of globally increasing urbanization (e.g., Conway 2005; Abellán et al. 2005).

Despite advances in this field and the increased attention the topic is receiving, little has been done to evaluate practical problems associated with SGD management. For example, it is worth noting that the Government of Japan is currently actively investigating the feasibility of underground storage of CO_2 to reduce emissions to the atmosphere, in accordance with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (1997; http://unfcc.int/resource/docs/convkp/kpeng.html), which entered into force in February 2005. Given the geographical characteristics of Japan, stable coastal environments are being prioritized for the installation of the repository. Disposal of CO_2 has been proven to be highly feasible (Holloway 1997), but all risks associated with its storage have to date not been satisfactorily investigated (Damen et al. 2003), implying that deeper insight of rates (or the absence) of SGD constitutes a key issue to completely assess the environmental effects of geological repositories in coastal zones. Undoubtedly, regional geology is a crucial factor determining the magnitude of freshwater discharge, so disposal in “safe” formations must be prioritized. Since groundwater may constitute the fundamental pathway by which CO_2 can migrate from the subsurface to the biosphere, a host medium where flow is non-existent, or at least very slow, seems to be the most suitable for trapping this gas. As a rule of thumb, deep sedimentary basins, reservoirs confined by units of low permeability, and inactive zones such as cratons and plutonic massifs where groundwater movement is restricted can be considered favorable units for storage. Hydrocarbon reservoirs, which have been well researched, are also considered to be safe sinks, since these media have held oil/gas for millions of years without large, spontaneous releases (Damen et al. 2003). However, some increase in formation fracturing, and the creation of zones of increased hydraulic conductivity might potentially occur at newly developed sites such as deep saline aquifers, as a consequence of construction and injection activities. Unlike depleted hydrocarbon fields, CO_2 injection in aquifers induces a temporary pressure increase in the reservoir, because the space to store CO_2 becomes available only as a result of compression of the fluids and rock in the reservoir, or displacement of formation water into adjacent units or to the surface (Holloway 1996). Thus, in addressing the safety and stability of storage, it would be also desirable to evaluate possible generation and/or SGD response under CO_2 burial pressure, and to draw conclusions about the possible migration of submarine groundwater induced by stresses on the overlying strata.

Adding to these complexities, it must also be noted that the freshwater–seawater interface occurs always beneath the bottom of submarines slopes where terrestrial groundwater is discharged (Marui 2003). Conceptually, groundwater is assumed to discharge as a seepage front of water moving toward the ocean, presenting a well-defined interface between pure freshwater and undiluted saline waters. Although theoretically sound, this representation can be a misleading oversimplification of some, if not most systems, in which complex flow patterns and a poorly defined fresh–seawater interface usually exist. Therefore, physical and geochemical processes at the transition zone must also be considered when evaluating the role of SGD in basins. Although the present study has not dealt in depth with this topic, the obvious link between SGD and the freshwater–seawater interface opens new opportunities for research, especially those based on variable-density models, rather than the commonly used Ghyben–Herzberg principle.

Finally, since large-scale government projects, such as the abovementioned underground CO_2 repository, are constrained by strict regulations and schedules, numerical simulations supported by a network of monitoring wells seem to be one of the most powerful approaches currently available to effectively characterize the flux of groundwater, and the shape and fluctuations of the saltwater edge at coastal sites. This review is expected to serve local authorities and scientists as reference in the assessment of appropriate sites for waste disposal.

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