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Investigation of submarine groundwater discharge

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Abstract:

Coastal hydrogeologists and oceanographers now recognize the potentially significant contribution that submarine groundwater discharge (SGD) could make to the coastal ocean. SGD may be both volumetrically and chemically important to coastal water and chemical budgets. A worldwide compilation of observed SGD shows that groundwater seepage from the land to the ocean occurs in many environments along the world's continental margins. Further, SGD has a significant influence on the environmental condition of many nearshore marine environments and provides a strong motivation for improved assessments. Our review reveals a critical lack of data from coastal zones of almost all parts of the world, especially in South America, Africa and parts of Asia, making a comprehensive compilation incomplete. SGD should be paid more attention with regard to water and dissolved material budgets at the local and global scales. SGD intercomparison experiments and coastal typologies (classification) may enable evaluation of the accuracy of the SGD estimates and up-scaling of SGD to a global scale. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS submarine groundwater discharge; recirculated sea water; groundwater–seawater interactions; coastal zone; nearshore environment; worldwide compilation

SIGNIFICANCE AND HISTORICAL PERSPECTIVE

Interactions between surface water and groundwater have been studied in the fields of hydrology and limnology for many years (e.g. Winter, 1976, 1983; Lee, 1977; Shaw and Prepas, 1990a,b). On the other hand, investigations of interactions between groundwater and coastal seawater have been restricted mainly to the case of water movement from sea to the land, i.e. saltwater intrusion (e.g. Segol and Pinder, 1976; Reilly and Goodman, 1987). The study of submarine groundwater discharge (SGD) considers the water output from a basin-scale hydrological cycle, representing an input into the ocean. Though recognized by hydrologists for many years (e.g. Kohout, 1966), SGD drew little attention from the oceanographic community until relatively recently (Burnett, 1999).

River discharge is a major pathway for discharge from land to the ocean in the global water cycle. Rivers are highly visible open channels that discharge water from great distances inland, and their contributions to the oceans are easily quantifiable. Another important source of continental freshwater to the oceans is SGD, which occurs as springs and seeps on continental margins, usually at or below the water surface. SGD per unit length of coastline could be very significant as a discharge process, because the length of coastline where SGD occurs is very great, and will occur whether or not rivers are present.

Submarine springs are found in many parts of the world and represent a more glamorous and exotic form of SGD. Today, they are considered important for their beauty and the magnificent organisms they often attract. However, some of these springs are large enough to provide fresh water for human needs. The slow seepage of groundwater that flows out along most shorelines of the world may be even more important volumetrically

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than discrete springs, but direct comparisons are lacking. Although it is difficult to detect groundwater seepage through sediments, this diffusive input may occur over broad areas and deliver potentially significant amounts of fresh water and dissolved components to the world's coastal oceans.

Knowledge concerning the undersea discharge of fresh groundwater has existed for many centuries. According to Kohout (1966), the Roman geographer, Strabo, who lived from 63 BC to AD 21, mentioned a submarine spring (fresh groundwater) 2·5 miles offshore from Latakia, Syria (Mediterranean), near the island of Aradus. Water from this spring was collected from a boat, utilizing a lead funnel and leather tube, and transported to the city as a source of fresh water. Other historical accounts tell of water vendors in Bahrain collecting potable water from offshore submarine springs for shipboard and land use (Williams, 1946), Etruscan citizens using coastal springs for 'hot baths' (Pausanius, ca 2nd century AD), and submarine 'springs bubbling fresh water as if from pipes' along the Black Sea (Pliny the Elder, ca 1st century AD). Offshore discharge of fresh water has been used in a number of cases for water resource purposes. One particularly spectacular example of such use involved the construction of dams in the sea near the southeastern coast of Greece. The resulting 'fence' allowed the formation of a fresh water lake in the sea, which was then used for irrigation on the adjacent coastal lands (Zektser, 1996). Thus, though the existence of submarine springs has been known for many years, the information has largely been anecdotal. SGD has been neglected scientifically because of the difficulty in finding and measuring these features. Therefore, direct discharge of the groundwater into the ocean has not been quantified in terms of the global water and material cycle on the Earth.

The direct discharge of groundwater into the coastal zone has received increased attention in the last few years as it is now recognized that this process may represent a potentially important pathway for material transport. One of the outcomes of this recent interest in SGD has been the establishment of a working group of scientists '...to define more accurately and completely how submarine groundwater discharge influences chemical and biological processes in the coastal ocean' (Burnett, 1999; Kontar and Zektser, 1999). This group (SCOR Working Group 112, 'Magnitude of Submarine Groundwater Discharge and Its Influence on Coastal Oceanographic Processes') is co-sponsored by the Scientific Committee on Oceanic Research (SCOR) and the Land–Ocean Interaction in the Coastal Zone (LOICZ) project, a core activity of the International Geosphere Biosphere Program (IGBP). The group initially produced a work plan and organized itself into three main components: modelling/calculation, measurements, and typology/globalization. The modelling team has been actively reviewing current computational approaches and examining avenues for improvement. The measurement group quickly recognized the need to define further and improve the methodologies of SGD assessment. As a consequence, SGD assessment intercomparison exercises have been organized at several 'flagship' coastal sites. These experiments, which are currently in progress, are being performed in order to compare directly several independent methodologies, such as the use of tracers and of automated seepage meters (Taniguchi and Fukuo, 1993, 1996), which were developed to evaluate the groundwater discharge rate into Lake Biwa, Japan. The aim is to develop standardized approaches for evaluation of SGD in the coastal zone. In order to extrapolate groundwater flux results from well-characterized local-scale sites (such as the 'flagships') to the regional scale, coastal typologies (classifications) based upon more readily available data (e.g. rainfall, coastal geomorphologies, etc.) are being developed using clustering/visualization techniques. Combined, these efforts should advance the current state of the art concerning the distribution and magnitude of SGD in the coastal zone.

Global estimates of SGD vary widely (approximately 0·2–10% of river flow; Garrels and MacKenzie, 1971; COSOD II, 1987). However, in some cases, SGD may be both volumetrically and chemically important to coastal water and chemical budgets (*Johannes*, 1980). Geochemical cycles of some major and minor elements (such as nitrate, phosphate, etc.) may be strongly influenced either by the direct discharge of fresh groundwater into the sea or by chemical reactions that occur during the recirculation of seawater through a shallow coastal aquifer system (COSOD II, 1987; Buddemeier, 1996). Therefore, SGD via submarine springs and seeps is now recognized as a potentially significant pathway of dissolved substances and diffuse pollution into the coastal zone (e.g. Burnett *et al.*, 1996, 2001; Monastersky, 1996; Burnett, 1999).

SGD has been reviewed previously by Fairbridge (1966), Stringfield and Legrand (1969, 1971) and Zektser *et al.* (1973). However, no overview has been undertaken since the 1970s, a period in which significant advances and insights have occurred. Although no review can be completely exhaustive, we have tried to include as many studies as possible to emphasize the variety of approaches and applications that scientists have undertaken in studying this phenomenon. The objectives of this paper are to review SGD investigations, and to compile the existing observed and calculated SGD estimations. Furthermore, we shall point out which areas require further analysis and study.

DEFINITION OF SGD

The term SGD has been used in different ways over the years. Zekster *et al.* (1983) defined SGD to be the net groundwater discharge to the ocean, which comes essentially from aquifer recharge. On the other hand, Church (1996) defined SGD to be 'direct groundwater outflow across the ocean–land interface into the ocean' which would include recirculated seawater. The definition of SGD with or without recirculated seawater has thus far been ambiguous in the literature (Younger, 1996). This ambiguity could lead to serious misunderstandings, especially when comparing SGD with other freshwater discharges. Li *et al.* (1999) considered SGD to be the sum of net groundwater discharge, outflow due to wave-setup-induced groundwater circulation, and outflow due to tidally driven oscillating flow.

In the coastal environment, total water discharge into the ocean consists of surface water discharge and SGD. Submarine porewater exchange (SPE) occurs across the seabed by SGD and submarine groundwater recharge (SGR). In this paper, we use the term SGD to represent all direct discharge of subsurface fluids across the land–ocean interface (Figure 1). The SGD rate is defined as

$$\mathrm{SGD} = \mathrm{SFGD} + \mathrm{RSGD} \tag{1}$$

where SFGD is the submarine fresh groundwater discharge; RSGD is the recirculated saline groundwater discharge, which comprises a number of components that may be defined as

$$\mathrm{RSGD} = \mathrm{RSGD}_w + \mathrm{RSGD}_t + \mathrm{RSGD}_c \tag{2}$$

where RSGD_w is recirculated water due to wave set-up, RSGD_t is recirculated water due to tidally driven oscillation, and RSGD_c is recirculated water due to convection (either density or thermal). Thus the total net SGD includes both a net fresh groundwater and a recirculated seawater discharge component.

Defining SGD has presented a dilemma for hydrologists and oceanographers over the years. Oceanographers studying the coastal zone and discharge tend to view any subsurface fluid fluxes as groundwater, whereas traditional hydrologists term groundwater as only that water originating from an aquifer, which does not include recirculated seawater (Moore, 1999). This discrepancy in definitions has resulted in confusion when comparing SGD results from hydrologic models and oceanographic mass balances. It thus appears absolutely essential, when publishing SGD fluxes, that scientists define their use of the term SGD. For the purposes of this review, SGD refers to total flow across the seafloor. We take this approach because few studies of coastal groundwater inputs in the past 20 years have distinguished between 'new' and 'recycled' subsurface fluid discharges across the sediment–water interface.

Three different units of measurement are applied commonly to SGD: (1) volume per unit time (e.g. $\mathrm{m^3\ day^{-1}}$, $\mathrm{l\ s^{-1}}$); (2) volume per unit time per unit length of shoreline (e.g. $\mathrm{m^3\ day^{-1}}$ (m shoreline)$^{-1}$, $\mathrm{m^3\ year^{-1}}$ (km shoreline)$^{-1}$); and (3) volume per unit time per unit area which is Darcy's flux (e.g. $\mathrm{cm^3\ cm^{-2}\ s^{-1}}$, $\mathrm{cm\ s^{-1}}$, $\mathrm{m\ year^{-1}}$). If the discharge area of SGD is known, the values are compatible. However, in most cases, the areal extent of offshore SGD is unknown. Therefore, for case (1), which is more useful for larger-scale studies, the values of SGD in terms of groundwater flux are unavailable. For case (2), which is appropriate for smaller-scale investigations at a local or regional scale, the groundwater flux also cannot

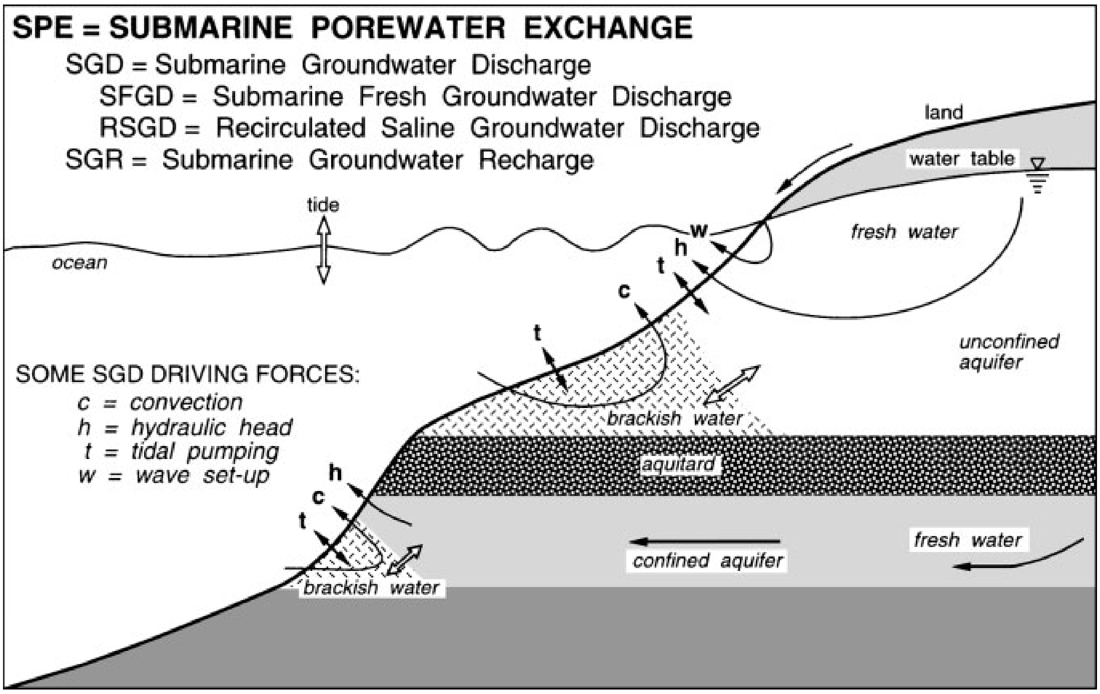

Figure 1. Schematic depiction (no scale) of processes associated with SGD. Arrows indicate fluid movement

be obtained because the distance from the shoreline for SGD may be unknown. In some cases, however, sufficient information may be available to integrate SGD with distance away from the shoreline. In that case, relatively precise estimates of groundwater flux per unit coastline are possible. For case (3), the total volume of SGD cannot be evaluated without knowing the size of the area subject to the SGD flux.

For up-scaling or generalizing SGD, we need comparisons between observed (local) SGD and modelled/calculated (regional or global) SGD. This is not only for validating the modelling that includes previous global estimates, but also for estimating recirculated water. A continental-scale hydrogeological model that includes heterogeneity of the aquifer may be needed to estimate the extent of recirculated seawater. Generic models or other globalization approaches, such as typology, are needed to extrapolate to wider areas (Buddemeier, 1996).

SGD AND COASTAL ZONE MANAGEMENT

Coastal environmental management concerns should certainly consider SGD where undesirable contaminants in groundwater can be discharged into the nearshore marine environment. Although nutrient discharge from fertilizers and sewage is by far the most common concern, virtually any form of contamination is possible. For instance, nuclear-waste disposal plants are often planned to be located near the coastal zone in some countries, such as in the UK (Chapman *et al*., 1986) and Japan, because it is difficult to find an arid environment in these countries and it was accepted previously that the water does not move below the saltwater–freshwater boundary. The coastal groundwater regime can also act as a geotechnically stabilizing (or destabilizing) element to coastal zone systems, in terms of coastal zone sediment stability and coastal zone subsidence. For example, Gambolati (1998) and Gambolati *et al*. (1999) revealed that coastal regression, erosion, and sediment transport occurred in the Romagna region, Italy. They described that geomorphological changes were caused by natural land subsidence due to deep downward tectonic movements and consolidation of geologically recent deposits, and by anthropogenic land subsidence due to groundwater withdrawal, as well as sea level rise.

Ecological effects in estuaries and the coastal zone may depend on water quality, that is influenced by SGD. Thus, the location and volume (or flux) of SGD may affect fauna and flora that live in these zones. Biological zonation associated with groundwater discharge was identified in Biscayne Bay, Florida (Kohout and Kolipinski, 1967). Possible relationships between SGD and seagrass distributions were reported from the coastal zone near Perth, Australia (Johannes and Hearn, 1985; Department of Environmental Protection, 1996), and in the coastal northeastern Gulf of Mexico (Rutkowski *et al.*, 1999). Interactions between fresh water and salt water in coral reefs were also discussed as ecological issues, including material transports by SGD (Oberdorfer and Buddemeier, 1986; Tribble *et al.*, 1992).

Understanding SGD is also important for coastal zone management from the hydrological perspective. Saltwater intrusions, for example, occur in many areas near the coast due to excessive groundwater mining. Ghyben (1889) and Herzberg (1901) first studied the phenomenon of seawater intrusion into groundwater aquifers in coastal regions. Many numerical simulations and related studies attempted to evaluate mechanisms governing this process (e.g. Segol and Pinder, 1976; Freeze and Cherry, 1979; Huyakorn *et al.*, 1987; Reilly and Goodman, 1987; Person *et al.*, 1998). At first glance, the processes of SGD and seawater intrusion may seem to be exactly opposite. However, it is clear that saltwater intrusion into coastal aquifers and SGD are entirely complementary processes. The extent of SGD or seawater intrusion at a given location is essentially an issue of balance between hydraulic and density gradients in groundwater and seawater along a transect perpendicular to the shoreline. For example, a sea-level change alters both the SGD rate and the location of the subsurface saltwater–freshwater boundary because it changes the elevation of the boundary condition experienced by coastal aquifers. During the ice ages, the hydraulic gradient between the continent and ocean was greater than during interglacials if the groundwater level under the continent was maintained at a constant level. This increased hydraulic gradient would deepen the saltwater–freshwater boundary and increase the SGD rate per unit shoreline length. Furthermore, the changes both in elevation and spatial positions of the coastline cause a shift of SGD distribution along the transect from the continent to the ocean. A sea-level rise of 120 m during the last 12 000 years requires that the groundwater–marine interface is dynamic on the time scale of groundwater flow in some coastal aquifers, especially deep coastal aquifers. Thus, many reasons exist to evaluate SGD near the coast as a coastal management issue.

DATA COMPILATION OF OBSERVED SGD

In order to compile existing SGD data on a worldwide basis, we present a review of all available studies that have attempted to estimate the magnitude of SGD or indicated that SGD in the area studied was significant. We limited this compilation to literature citations of discharge estimates using seepage meters, piezometers, and/or geochemical/geophysical tracers.

Locations of specific SGD estimates show that many independent studies have been performed on the east coast of the USA, Europe, Japan, and Oceania (Figure 2). Fewer studies have been done on the west coast of the USA and Hawaii. We were unable to find any quantitative data from South America, Africa, India, or China, though indications of groundwater discharge were reported for India (Moore, 1997) and Kenya (Kitheka, 1998) (Table I).

The compilation of worldwide SGD estimates indicates that most SGD seepage rates are below about 0·1 m day^{-1}. In some cases the SGD at the shore is above 10 m year^{-1}, which is greater than annual precipitation in most places. Since the area of groundwater discharge is commonly less than the area of groundwater recharge (Freeze and Witherspoon, 1967), some concentration or focusing of groundwater flow in the subsurface occurs in many systems, and this should include SGD into the coastal zone as well. In many cases, SGD fluxes near the coast appear larger than the groundwater recharge rate, which is always less than precipitation. In some cases, SGD fluxes are larger than recharge by about two orders of magnitude.

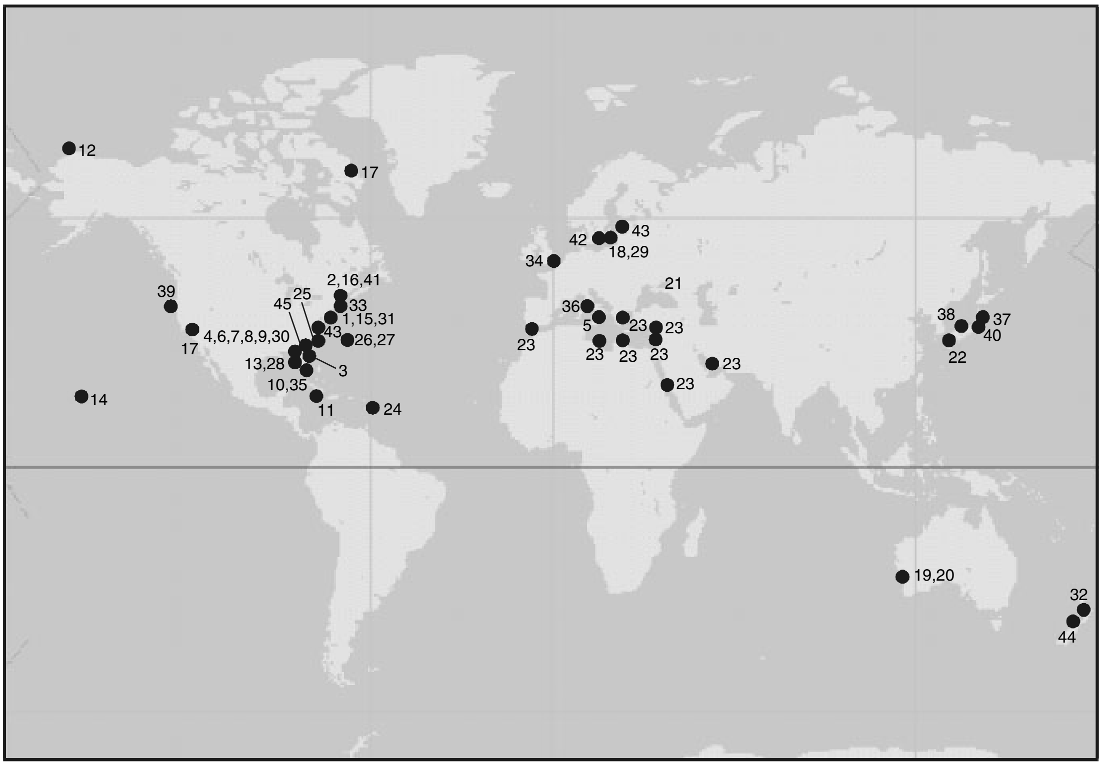

Figure 2. Location of published investigations of SGD. All studies used provided SGD estimations using seepage meters, piezometers, or geochemical/geophysical (temperature) tracers. Numbers refer to Table I

Since the areal ratio of recharge to discharge is typically about 100, this may explain the two orders of magnitude difference between SGD and groundwater recharge rates. However, the SGD rates observed by direct measurements may also be greater because these estimates may include recirculated seawater in addition to the fresh groundwater component (Gallagher *et al*., 1996; Li *et al*., 1999). Comparison of reliably measured SGD values with calculated values from water budgets or modelling (fresh water only) may be able to evaluate the extent of the recirculated seawater component.

The relationship between SGD estimates (from Table I) and water depth is shown in Figure 3. Although SGD data vary widely, discharge estimates tend to decrease fairly systematically with increasing water depth over about three orders of magnitude. In general, water depth increases with the distance from the coast, which is the main parameter for controlling SGD, as well as groundwater hydraulics and the geometry of the flow domain. Although many principles governing SGD remain to be clarified, this worldwide compilation of observed SGD shows that groundwater seepage from the land to the ocean occurs in many environments (Figure 2).

One must be cautious about drawing too many conclusions from these results. Most SGD measurements have been performed where it is easily found and large volumes of SGD are expected. Furthermore, much of the observed SGD data may include recirculated seawater. Therefore, the relationship shown in Figure 3 may be more representative of maximum values of SGD, and thus may overestimate the SFGD component into the ocean.

As the number of SGD observations is very limited on a global scale, it is difficult to find any systematic geographical features concerning the magnitude of SGD. It is significant that many SGD measurements have been made in karst areas (Table I), where the hydraulic conductivity of the aquifers is large and thus significant

Table I. Direct SGD measurements

No.	SGD: Volume or flux in reference	SGD: Flux (m $year^{-1}$)	Location	Method	Depth (m)	Distance (m)	Hydrogeology/ soil	Reference
1	Unknown		Chesapeak Bay, MD	Thermal image analysis	—	40–80	Pleistocene deposits	Banks *et al.* (1996)
2	40 l day^{-1} m^{-2}	14·6	Great South Bay, NY	Seepage meter	1·3	30	Sand, silty sand	Bokuniewicz (1980)
3	42 m^3 s^{-1} (1500 ft^3 s^{-1})		Crescent, FL	Salinity	38	4 km	Limestone	Brooks (1961)
4	10–80 ml m^{-2} min^{-1}	5·2–42	Northeast Gulf of Mexico, FL	Seepage meter	0·5–2	<500	Silty sand	Bugna *et al.* (1996)
5	Unknown		Italy	Salinity Water quality	72	—	—	Burdon (1964)
6	10–80 ml m^{-2} min^{-1}	5·2–42	Northeast Gulf of Mexico, FL	Seepage meter	0·5–2	<500	Silty sand	Cable *et al.* (1996a)
7	180–710 m^3 s^{-1} 500 m^3 s^{-1}	9·2–36·1 25·4	Northeast Gulf of Mexico, FL	Rn Ra	0·5–2	Area: 620 km^2	Silty sand	Cable *et al.* (1996b)
8	0·23–4·4 m^3 s^{-1}	1·04–18·6	Northeast Gulf of Mexico, FL	Seepage meter	0·5–2	Area: 7 km^2	Silty sand	Cable *et al.* (1997a)
9	17·7 ml m^{-2} min^{-1}	8·9	Northeast Gulf of Mexico, FL	Seepage meter	0·5–2	<500	Silty sand	Cable *et al.* (1997b)
10	7·2–21·2 ml m^{-2} min^{-1}	3·6–10·7	Keys and Florida Bay, FL	Seepage meter	<2	<30 km	Limestone	Corbett *et al.* (1999)
11	Unknown		Discovery Bay, Jamaica	Nitrate	2	<500	Limestone	D'Elia *et al.* (1981)
12	0·07 m $year^{-1}$	0·07	North slope of AK	Heat Flow	600	—	Sandstone (Tertiary)	Deming *et al.* (1992)
13	25 l s^{-1}		West FL	Flowmeter on the drum placed over the vent	12–13	20 km	Continental shelf (limestone)	Fanning *et al.* (1981)
14	10–100 million gallons per day		HI Island	Thermal image analysis	—	<300	—	Fischer *et al.* (1964)

(*continued overleaf*)

Table I. (*Continued*)

No.	SGD: Volume or flux in reference	SGD: Flux (m year^{-1})	Location	Method	Depth (m)	Distance (m)	Hydrogeology/ soil	Reference
15	0·63 l m^{-2} h^{-1} (including 65% recirculated water)	5·5	Chesapeake Bay, VA	Seepage meter	1	5–9	Sandy loam	Gallagher *et al*. (1996)
16	(4·3–5·0) × 10^{4} m^{3} day^{-1}	11·2–13·0	Cape Cod, MA	Seepage meter	<2	Area: 1·4 km^{2}	Mud and sand	Giblin and Gaines (1990)
	(0·94–1·20) × 10^{4} m^{3} day^{-1}	2·4–3·1		Water balance				
	(4·4–8·9) × 10^{4} m^{3} day^{-1}	11·5–23·2		Salinity budget				
	0·79 × 10^{4} m^{3} day^{-1}	2·1		Hydraulic dynamics				
17	0·34 m^{3} s^{-1}		Baffin Island, Canada	Remote acoustic imaging of the plume	47	—	—	Hay (1984)
18	Unknown		Puck Bay, Baltic Sea	Temperature Conductivity	25–55	<10 km	Sand–gravel	Jankowska *et al*. (1994)
19	Unknown		Perth, Australia	Nitrate	—	—	Sand	Johannes (1980)
20	4·8 × 10^{4} m^{3} day^{-1}		Perth, Australia	Salinity	5	50	Sand	Johannes and Hearn (1985)
21	Unknown		Black Sea, Crimea	Salinity, Rn	3	250	Limestone	Kir'yakov *et al*. (1983)
22	Unknown		Beppu, Japan	Temperature Water quality	5	20	Alluvial deposits	Kohno and Tagawa (1996)
23	Unknown Unknown		Mediterranean FL	Salinity Coring	— 250	— 43 km	— —	Kohout (1966)
24	(8·5–14·4) × 10^{-4} cm s^{-1}	268–454	Barbados, West Indies	Seepage meter Piezometer	1·5	A few metres	Sand	Lewis (1987)
25	Unknown		East coast, FL Peninsula	Seafloor coring Salinity	500	—	—	Manheim (1967)
26	Unknown		Off the coast, GA	Seafloor coring Salinity	900	—	Neo-Holo Eo-Oligo	Manheim and Paull (1981)
27	350 m^{3} s^{-1}		Off the coast, SC	Ra	—	<20 km	Continental Shelf	Moore (1996)
28	Unknown		Off the west coast, FL Peninsula	Temperature Water quality Biological community	3000	120 km	Florida Platform (limestone)	Paull *et al*. (1984)
29	4·7 l s^{-1} km^{-2}	0·15	Puck Bay, Baltic Sea	Nutrient, isotope	<50	—	Sand	Piekarek-Jankowska (1996)

30	$1–10\ l\ m^{-2}\ day^{-1}$ $4·5–7·3\ l\ m^{-2}\ day^{-1}$	0·37–3·7 1·6–2·7	NE coastal Gulf of Mexico, FL	Seepage meters Numerical modeling	0·5–2	<500	Silty sand	Rasmussen (1998)
31	$0·02–3·69\ l\ m^{-2}\ h$	0·18–32·3	Chesapeake Bay, VA	Seepage meter	—	0–50	Sandy loam	Reay *et al.* (1992)
32	Unknown		Hawke Bay, New Zealand	Sea temperature, salinity	200	60 km	—	Ridgway and Stanton (1969)
33	Unknown		Off the coast, NJ	Side-scan sonar image	1000	—	—	Robb (1984)
34	Unknown		Plymouth, UK	Thermal image analysis	—	500	Limestone	Roxburgh (1985)
35	$6–20\ l\ m^{-2}\ day^{-1}$	2·2–7·3	Off the coast, Wilmington (NC)	Seepage meter	10–33	37 km	Continental shelf limestone	Simmons (1992)
	$5·4–8·9\ l\ m^{-2}\ day^{-1}$	2·0–2·7	Off the coast, FL Keys		10–35	15 km	Limestone	
36	Unknown		Capo Palinuro, Italy	Geochemistry	10–30	—	Limestone (hot spring)	Stuben *et al.* (1996)
37	$0·03–0·42\ m\ year^{-1}$	0·03–0·42	Tokyo Bay, Japan	Groundwater temp.–depth profiles	150	—	Silty sand	Taniguchi *et al.* (1998)
38	$(1·4–4·3) \times 10^{-4}\ cm\ s^{-1}$	44–136	South of Osaka Bay, Japan	Seepage meter	1	5	Sand	Taniguchi (2000)
39	Unknown		Off the coast, OR	Side-scan sonar image Biological community	1500–2000	150 km	Oregon Accretionary Prism	Tobin *et al.* (1993)
40	$310–500\ m^3\ day^{-1}$ (area: $2\ km^2$)	0·057–0·092	Sagami Bay, Japan	Heat flow Chemical composition	1000	12 km	Philippine Sea Plate	Tsunogai *et al.* (1996)
41	$2–4\ l\ m^{-2}\ h^{-1}$	17·5–35	Coastal bays of New England	Salinity Seepage meter	—	35–200	Coarse sand	Valiela *et al.* (1990)
42	$75\ m\ year^{-1}$	75	Laholm Bay, Sweden	Seepage meter	2	<200	Sand	Vanek and Lee (1991)
43	$0·15–0·75\ l\ m^{-2}\ h^{-1}$	1·3–6·6	Saltmarsh estuaries, SC	Seepage meter	2–10	1–2	Hydraulic conductivity: $1·4 \times 10^{-5}–4·5 \times 10^{-4}\ cm\ s^{-1}$	Whiting and Childers (1989)
44	Unknown		Golden Bay, New Zealand	Water quality	—	6 km	—	Williams (1977)
45	$(0·77–1·03) \times 10^{-6}\ m\ s^{-1}$	24–32	East coast of FL (Indian River Lagoon)	Seepage meter	1·5	25	Hydraulic conductivity $K = 10^{-3}\ cm\ s^{-1}$	Zimmermann *et al.* (1985)

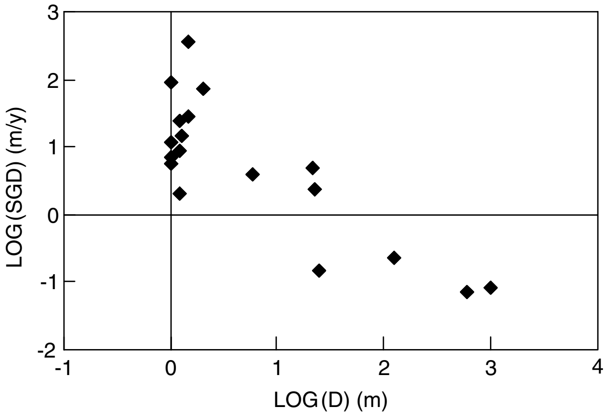

Figure 3. Relationship between observed SGD rate and water depth D (data from Table I)

amounts of groundwater discharge are expected under reasonable hydraulic gradients. It is also clear that wide areas of the world (South America, Africa, southern Asia) have little to no SGD assessments at all.

To integrate SGD on a global scale, some type of SGD database may be necessary. There are two main factors determining SGD rate: (a) driving force and (b) development of river systems. The driving force is a function of hydraulic conductivity (geology) and groundwater recharge rate (precipitation, evapotranspiration (vegetation)), and river development may be controlled by geology and topography. Therefore, parameters concerning geology, precipitation, vegetation (land use), and topography are the main factors necessary for SGD estimates. Future work on SGD estimates should concentrate on evaluating these parameters and taking a more holistic view of the environment that produces SGD. Research in this arena has been initiated by a group of experts to construct a typological integration of global databases (Buddemeir, 1996). SGD intercomparison experiments and coastal typologies (classification) may enable an evaluation of the accuracy of the SGD estimates and up-scaling of SGD to a global scale.

DATA COMPILATION OF CALCULATED SGD

Various estimates of the role of SGD in the global water balance range over about three orders of magnitude (approximately 0·01 to 10% of total river flow). The importance of the role of SGD (i.e. the ratio of SGD to surface runoff or total water flux) can be found in global (Table II) and local studies (Table III).

Table II. Importance of SGD in global studies

Amount of SGD	Method	Reference
6% of the total water flux	Literature	Berner and Berner (1987)
0·01–10% of surface runoff	Literature	Church (1996)
0·3% of surface runoff	Hydrological assumptions	COSOD II (1987)
10% of surface runoff	Water balance	Garrels and MacKenzie (1971)
31% of the total water flux	Water balance	Lvovich (1974)
1% of surface runoff	Hydrogeologic assumptions	Nace (1970)
10% of surface runoff	Water balance, etc.	Zektser *et al.* (1973)
6% of the total water flux	Hydrograph separation	Zektser and Loaiciga (1993)

Table III. Importance of SGD in local studies

Amount of SGD	Study area	Method	Reference
20% of total water flux	Great South Bay, NY, USA	Seepage meter	Bokuniewicz (1980)
10% of total water flux	Chesapeake Bay, Virginia, USA	Rn, Ra	Hussain *et al*. (1999)
33% of surface runoff	NY, USA	Water balance	Isbister (1966)
17% of total water flux	Swan River Estuary, Western Australia	Nutrient balance	Johannes (1980)
40% of surface runoff	Off the coast, Carolina, USA	Ra	Moore (1996)
29% of total water flux	Adriatic Sea	Water balance	Sekulic and Vertacnik (1996)
3% of total water flux	Great Sippewissett Marsh, MA, USA	Chemical budget	Valiela *et al*. (1978)
87% of total water flux	Buttermilk Bay, MA, USA	Nutrient balance	Valiela and Costa (1988)

Some global-scale estimates are based on hydrological or hydrogeological assumptions (Nace, 1970; COSOD II, 1987). For instance, Nace (1970) assumed the thickness of the world's coastal saturated zone for SGD to be 4 m, the aquifer porosity to be 25%, the groundwater flow rate to be 3 m day^{-1}, and the unit flow rate to be 35 l s^{-1}. COSOD II (1987) assumed that 33% of rainfall on land area (equal to 5% of the continental shelves) infiltrates into aquifers, and half of this is discharged into the ocean as submarine springs, resulting in an estimated global SGD of 100 km^3 year^{-1} or 0·3% of surface runoff. The ratio of SGD to surface water inputs based on hydrological or hydrogeological assumptions is likely to be smaller than that estimated by other methods, such as those based on water balances (Table II). This may result from the underestimate of the depth of coastal aquifers (and, therefore, the distance from the shoreline for SGD).

Water balance methods are the most widely used for global-scale estimation of the role of SGD (Table II). Most estimates range from 6 to 10% of surface water inputs, with one exceptionally high value (31%; Lvovich, 1974), which seems unlikely (Zektser and Loaiciga, 1993). For local studies of SGD, groundwater discharge rates are known to vary widely, depending on the location and many other factors (Table III). It is important to recognize that the ratio of SGD to the total water flux into the ocean has a different meaning depending on whether SGD includes recirculated seawater or not. Many studies (Tables II and III) do not make this distinction. It is most likely that recirculated seawater is included as a component when direct measurement methods, such as seepage meters or tracer techniques, are used. On the other hand, SGD would not include recirculated seawater when the estimate is based on water balance methods.

CONCLUSIONS

SGD estimates have generally been made in the more wealthy regions of the world, where the infrastructure is in place to focus on this poorly constrained oceanic input term. A compilation of all available observed data shows that SGD generally decreases with water depth over about three orders of magnitude. Additional data collection needs to occur, especially in South America, Africa, and southern Asia, where no SGD assessments are currently available in the literature. SGD database and globalization efforts are necessary to integrate SGD on a global scale. SGD intercomparison experiments and coastal typologies (classification) may enable one to evaluate the accuracy of the SGD estimates and up-scaling of SGD to the global scale.

SGD rate is determined by a driving force and the development of river systems. Therefore, parameters concerning geology, precipitation, vegetation (land use), and topography are the main factors necessary for SGD estimates. Inclusion/exclusion of recirculated seawater in SGD estimates depends on the scale and the purpose of the study. It is highly recommended that future studies specify the inclusion/exclusion of recirculated seawater in SGD inputs. We have tried to set some ground rules for a consistent definition and framework for consideration of SGD. Comparisons between observed SGD and modelled/calculated SGD are needed. This is not only for validating the modelling that includes previous global estimates, but also for estimating recirculated water. A continental-scale hydrogeological model that includes heterogeneity of the aquifer may be needed to estimate the extent of recirculated seawater. In conclusion, SGD should be paid more attention with regard to water and dissolved material budgets at the local and global scales.

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