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Groundwater and pore water inputs to the coastal zone

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Abstract. Both terrestrial and marine forces drive underground fluid flows in the coastal zone. Hydraulic gradients on land result in groundwater seepage near shore and may contribute to flows further out on the shelf from confined aquifers. Marine processes such as tidal pumping and current-induced pressure gradients may induce interfacial fluid flow anywhere on the shelf where permeable sediments are present. The terrestrial and oceanic forces overlap spatially so measured fluid advection through coastal sediments may be a result of composite forcing. We thus define "submarine groundwater discharge" (SGD) as any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force. SGD is typically characterized by low specific flow rates that make detection and quantification difficult. However, because such flows occur over very large areas, the total flux is significant. Discharging fluids, whether derived from land or composed of re-circulated seawater, will react with sediment components. These reactions may increase substantially the concentrations of nutrients, carbon, and metals in the fluids. These fluids are thus a source of biogeochemically important constituents to the coastal ocean. Terrestrially-derived fluids represent a pathway for new material fluxes to the coastal zone. This may result in diffuse pollution in areas where contaminated groundwaters occur. This paper presents an historical context of SGD studies, defines the process in a form that is consistent with our current understanding of the driving forces as well as our assessment techniques, and reviews the estimated global fluxes and biogeochemical implications. We conclude that to fully characterize marine geochemical budgets, one must give due consideration to SGD. New methodologies, technologies, and modeling approaches are required to discriminate among the various forces that drive SGD and to evaluate these fluxes more precisely.

Introduction and scope

Although not as obvious as river discharge, continental groundwaters also discharge directly into the ocean wherever a coastal aquifer is connected to the sea. Artesian aquifers can extend for considerable distances from shore, underneath the continental shelf with discharge to the ocean at their points of outcrop (Kohout 1966; Zektser 2000). In some cases, these deeper aquifers may have fractures or other breaches in the overlying confining layers, allowing fluid exchange between the groundwater and the sea.

Submarine groundwater discharge (SGD) was neglected scientifically for many years because of the difficulty in assessment and the perception that the process was unimportant. This perception is changing. Within the last several years there has emerged recognition that in some cases, groundwater discharge into the sea may be both volumetrically and chemically important (Johannes 1980). A decade after Johannes' benchmark paper, Valiela and D'Elia (1990) published a compilation on the subject and stated, "we are very much in the exploratory stage of this field." The exploration has continued, and there is now growing agreement that groundwater inputs can be chemically and ecological important to coastal waters.

Within the last few years, the Scientific Committee on Oceanic Research (SCOR) formed two working groups to examine this emerging field more closely. SCOR WG-112 ("Magnitude of Submarine Groundwater Discharge and its Influence on Coastal Oceanographic Processes") was established in 1997 to "define more accurately and completely how submarine groundwater discharge influences chemical and biological processes in the coastal ocean" (Burnett 1999). Working Group 114 ("Transport and Reaction in Permeable Marine Sediments") was established in 1999 to investigate the importance of fluid flow through permeable sediments to local and global biogeochemical cycling and its influence on surrounding environments (Boudreau et al. 2001). The overlapping interests of both groups will become obvious in this paper.

We present here an updated review of SGD. While we will present an historical overview to provide context, we will emphasize work done over the past decade and especially work pertinent to the two SCOR working groups. We will define exactly what we mean by SGD since this has remained a point of confusion in the literature. We will then discuss the components and forces that drive SGD and follow with sections on seawater intrusion, SGD assessment, fluxes, and biogeochemical implications. We end with recommendations for additional research needed to better understand this often-invisible pathway between land and sea.

Historical perspective

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 B.C. to 21 A.D., mentioned a submarine spring 2.5 miles offshore from Latakia, Syria near the island of Aradus in the Mediterranean. 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 A.D.), and submarine "springs bubbling fresh water as if from pipes" along the Black Sea (Pliny the Elder, ca. 1st century A.D.).

The offshore discharge of fresh water has been investigated and 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 that was then used for irrigation on the adjacent coastal lands (Zektser 1996). Thus, while the existence of the direct discharge of groundwater into the sea has been realized for many years, the impetus was largely from water resource considerations, and much of the information was anecdotal.

Groundwater hydrologists have traditionally been primarily concerned with identifying and maintaining potable groundwater reserves. At the shoreline, their interest is naturally directed landward and attention has been focused only on the identification of the saltwater/freshwater "interface" in coastal aquifers. The classic Ghyben-Herzberg relationship sufficed in many practical applications (Badon-Ghyben (1888) and Herzberg (1901) both as cited in Bear et al. (1999)) even though it represented an unrealistic, hydrostatic situation. The gravitational balance between the fresh groundwater and the underlying salty groundwater cannot predict the geometry of the freshwater lens but only estimate the depth of the saltwater/freshwater interface if the elevation of the water table is measured. A truly stable, hydrostatic distribution, however, would find saline groundwater everywhere below sea level. Maintaining a freshwater lens requires a dynamic equilibrium supported by freshwater recharge. The Dupuit approximation ((Dupuit 1863) as cited in Freeze and Cherry (1979)) was incorporated to account for this equilibrium. The assumption is essentially that the flow of groundwater is entirely horizontal. In that treatment, the saltwater/freshwater interface is a sharp boundary across which there is no flow, which intersects the shoreline, and the salty groundwater is stationary. None of this is strictly true, and the Dupuit-Ghyben-Herzberg relationship leads to the awkward, but not debilitating, result that all the freshwater recharge had to escape exactly at the shoreline. This awkwardness was removed by Hubbert (1940) who introduced the concept of an outflow gap. The saltwater/freshwater interface was still sharp and was considered a boundary of no flow. The saline groundwater was still stationary, but the interface did not intersect the shoreline. Rather it intersected the sea floor at some distance from shore leaving a band or gap through which the fresh groundwater could escape into the sea. If the depth of the saltwater/freshwater interface at the shoreline is measured, the Dupuit-Ghyben-Herzberg methodology can be used, with this as a boundary condition, to calculate the width of the outflow gap (Vacher 1988). Potential theory (Henry 1964) and the Glover solution (Glover 1964) provided independent means to calculate the size of this gap and the position of the saltwater/freshwater interface. These representations, simplified for calculational necessity, unfortunately could lead one to the mistaken impression that SGD is entirely freshwater derived from land. Hubbert (1940) had also pointed out that the interface was not necessarily sharp and that the cyclic flow of salty groundwater needed to maintain a transition zone that must be driven by the presence of hydraulic gradients in the saline groundwater. It thus became recognized that the saline groundwater is not necessarily stationary.

With the development of numerical models, it became possible to calculate more realistic hydrodynamics. One early numerical model calculated the groundwater seepage into lakes (McBride and Pfannkuch 1975). While this had nothing to do with the saltwater/freshwater interface, it is noteworthy because it was the first use of the notion of an exponential decrease to approximate the distribution of seepage rates offshore.

The next generations of models allowed the saline groundwater to circulate in response to hydraulic gradients but still prohibited flow across the "interface" although the interface itself might move. Modern, two-phase models recognize that water can cross isohalines and can track both salt and water in the continuum and they allow density driven circulation as well as flows driven by other hydraulic gradients onshore. Bear et al. (1999) provide a review of the complex array of modern models. There is, however, a serious lack of data to calibrate and verify such models. In addition, dispersion is usually incorporated in a single parameter although it is recognized that numerous processes can cause salt dispersion on a wide range of time and space scales.

Definition of submarine groundwater discharge

In addition to fresh groundwater flow driven by hydraulic gradients on land, it is now widely recognized that there are several oceanic processes that drive advective flow of recirculated seawater through permeable sediments. The terrestrially driven and oceanically-derived flows grade into each other, especially near the coast. Thus, it is important to have a nomenclature that is compatible to both types of flow.

We begin by asking what is "groundwater" (or is it "ground water")? The modern convention is to write the term as one word. The earlier practice was to write it as two words and hyphenated (or compounded) when used as an adjective. We prefer writing it as one word to emphasize "the fact that it is a technical term with a particular meaning" (Todd 1980). The most general and frequently cited definition of groundwater is water in the saturated zone of geologic material (e.g., Tolman (1937) and Todd (1964), Nelson and Nelson (1967), Pfannkuck (1969), Hackett (1972), Freeze and Cherry (1979), Visser (1980), Price (1982), Bates and Jackson (1984), Wyatt (1986), Fetter (1988), Skinner (1991), Walker (1991), Kearey (1993, 1996), Parker (1997), Jackson (1997)). Water in the pores of submerged sediments or rock is, therefore, properly "groundwater" since the geological material below the sea floor will be saturated. As a result, we define "submarine groundwater discharge" as any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force (Figure 1). We thus define SGD without regard to its composition (e.g., salinity), origin, or phenomena driving the flow. Where the sediments are saturated, as expected in submerged materials, "groundwater" is synonymous with "pore water."

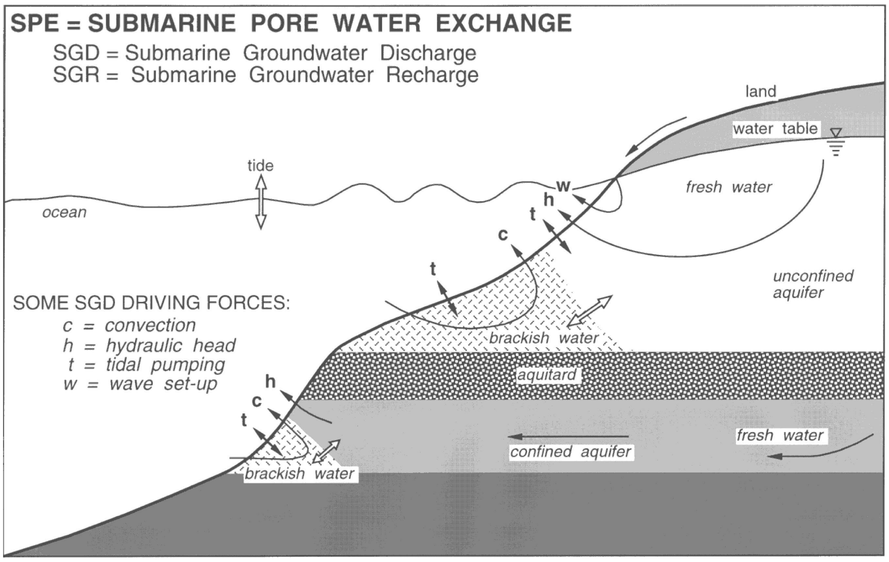

Figure 1. Nomenclature of fluid exchange and schematic depiction (no scale) of processes associated with submarine groundwater discharge and recharge. Arrows indicate fluid movement. Modified from Thibodeaux and Boyle (1987)

Since hydrology has traditionally been concerned with terrestrial fresh water, some definitions identify groundwater as meteoric water, i.e., rainwater that has infiltrated and percolated to the water table or other qualifications that are consistent with the applications to fresh-water, terrestrial systems (e.g., (Considine 1995; Stiegeler 1977)). We believe that such limitations on the definition of groundwater are too restrictive and lead to conceptual problems when dealing with submarine discharges. In our view, SGD does not have to be terrestrially derived, although it can be and is in many prominent situations. An important point here is that when one measures SGD, there is seldom a way to evaluate its source or its driving force. While it may be legitimate to require water classified as “groundwater” to move according to Darcy’s Law, even that may be too restrictive in some highly channelized (e.g., karst) situations. At least one definition of groundwater explicitly excludes underground streams (Wyatt 1986), while another specifically includes them (Bates and Jackson 1984; Jackson 1997). Since karst is such an important setting for SGD, we will include such features.

In the marine environment, submarine groundwater recharge (SGR) also occurs, as tides, waves, currents, sea level fluctuations, and density differences force seawater into the sea floor. This water eventually must leave the aquifer. Recycling of ocean water has been referred to as “irrigation” or “ventilation” or “transportation;” terms usually applied to the surficial layers within a meter or so of the sea floor (e.g., (Conley and Inman 1994; Kays 1972)). In some cases, the recharged waters are discharged locally. In other cases, waters can emerge far from the source, even subaerially as in saline springs in Hawaii (Cooper et al. 1964).

SGD can vary widely over time and space. Short-period water waves stir or agitate pore water without, necessarily, producing any net flow. This has been referred to as “wave pumping” or “wave stirring” (e.g., Harrison et al. (1983) and Riedl et al. (1972), Webb and Theodor (1968)). If the density of the ocean water increases above that of the pore water for any reason, pore water can float out of the sediment by gravitational convection in an exchange with denser seawater, again, without a net discharge. This process has been referred to as “floating” (Thorstenson and Mackenzie 1974) or “salt fingering” (Gorsink and Baker 1990). SGD has also been referred to as “flushing.” This generally involves a continuous replacement of pore water involving a discharge driven by the hydraulic gradients on shore or pressure gradients in the coastal ocean. Gradients may be due to wave set-up at the shore (Li et al. 1999), tidal pumping at the shore (Nielsen 1990), or differences in tidal elevations across narrow reefs or barrier islands (Bokuniewicz and Pavlik 1990; Reich et al. 2002).

So we have a system of terminology as follows (Figure 1). The flow of water across the sea floor can be divided into SGD, a discharging flow out across the sea floor, or SGR, a recharging flow in across the sea floor. The two terms do not have to balance because SGD can, and often will, include a component of terrestrially recharged water. Alternatively, some, or all, of the SGR can penetrate the subaerial aquifer, raising the water table or discharging as terrestrial surface waters (e.g., saline springs) rather than discharging out across the sea floor. The net discharge is the difference between SGR and SGD. The “submarine pore water exchange” (SPE) is the amount of water displaced within the sediments by these processes, i.e., it is the difference between the larger of the two (SGD or SGR) volume fluxes and the net. Quantitatively, SPE is equivalent to the smaller absolute value of either SGD or SGR.

Our definition of SGD does not include such processes as deep-sea hydrothermal circulation, deep fluid expulsion at convergent margins, and density-driven cold seeps on continental slopes. We will restrict the scope of our discussion in this paper to fluid circulation through continental shelf sediments with emphasis on the coastal zone.

Composition and forcing of SGD

Components

SGD may consist of multiple components. One is meteoric water that fell on dry land as atmospheric precipitation, infiltrated the soil or rock, and percolated to the water table. It can be driven across the sea floor by the onshore hydraulic gradients although it is possible that this exchange takes place as gravitational convection, that is, buoyant fresh pore water “floating” across the sea floor into the open salt water. Another important component of SGD is recirculated seawater that may also be driven in part by hydraulic gradients on land as well as various oceanic forces.

Table 1. Summary of some of the components of SGD, its driving forces, and contributing factors that influence its magnitude. The divisions are somewhat arbitrary – it is recognized that many crosscutting relationships are possible.

Components	Driving Forces	Contributing Factors
Meteoric waters (fresh)	Hydraulic gradient	Topography, Transmissivity, Precipitation, Evapotranspiration
Recirculated seawater (salt)	Hydraulic gradient, Tidal pumping, Wave set-up	Tidal range, Period, frequency, Wind force, direction
Connate waters (very salty)	Density, Thermal gradient	Geology, Geothermal heating

In some cases SGD could contain saline connate groundwater or groundwater whose salinity has been raised by dissolution of salt within the aquifer itself. Thus, "fresh" versus "salt" is not necessarily a good indicator of source or origin. Although it is tempting to subdivide SGD in a terminology according to its main components, i.e., fresh water and seawater, we have elected not to do this, as one would have the difficulty of making somewhat arbitrary decisions when mixtures of fresh and salt waters are encountered. We will thus not attempt to answer the question: "How fresh is fresh?"

Driving forces

We might also envision several classes of SGD based on the driving forces. Terrestrial hydraulic gradients and the consequent motion of the meteoric groundwater can drive a seepage flow of infiltrated seawater as well. Alternatively, SGD could be driven by any number of oceanic processes, such as wave pumping, wave set-up or set-down, tidal pumping, etc. In addition, we should also consider a third class of endogenic drivers such as thermal gradients, osmotic pressures, inverted density stratification, consolidation, etc. Again, although such divisions are useful in our efforts to understand the mechanisms involved, they do not serve as a useful basis for classification and terminology because we rarely have sufficient information to define the driving forces when field measurements are made. Furthermore, it should be recognized that these forces do not necessarily operate in isolation, i.e., flow through coastal sediments may, and often does, represent a composite of both terrestrial and marine forces and components. Table 1 summarizes some of the more obvious or important components and driving forces of SGD. We acknowledge that the matrix shown in this table oversimplifies the relationships between contributing factors and driving forces. There are many possible crosscutting relations. The tidal range, for example, would certainly influence tidal pumping of recirculated seawater, but the tides also affect the hydraulic gradient in a coastal setting and that could result in a change in the discharge of meteoric waters.

Tidally driven flows

Seepage meter records that display temporal trends in seepage flux in near-shore regions typically show variations that correspond in timing to the tidal period in that area. For example, Lee (1977) showed that seepage rates were distinctly higher at low tide in a coastal setting in Beaufort, North Carolina. Taniguchi et al. (this issue) showed a semidiurnal pattern in seepage flux at a coastal site in the northeastern Gulf of Mexico used by SCOR WG-112 for an SGD assessment intercomparison experiment (Fig. 2a). 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 depending upon the hydrologic setting at each location. Some areas show a direct inverse correlation between seepage rate and tidal stage, probably reflecting increased hydrologic flow resulting from decreased hydrostatic pressure. In other situations, a process of tidal pumping or flushing, where the coastal aquifer is recharged with seawater on the flood tide and drains further seaward on the ebb tide, will complicate this simple picture (Nielsen 1990).

Recent investigations have reported longer-term (weeks to months) tidally modulated cycles in seepage fluxes based on continuous measurements of natural groundwater tracers (Fig. 2b; Kim and Hwang (2002)) and automated seepage meter observations (Taniguchi 2002). The seepage meter data was recorded every ten minutes in Osaka Bay, Japan, from May 29 to August 23, 2001, and analyzed via the Fast Fourier Transfer (FFT) method to discern the dominant periods of variation (Fig. 2c). Both of these studies showed that there is not only a semi-diurnal to diurnal tidal relationship between fluid flow through near-shore sediments but also a semi-monthly variation in flow reflecting the neap-spring lunar tide cycle. Superimposed on this somewhat predictable behavior in tidally driven response, are variations in terrestrial hydrologic properties (water table height, etc.). This showed up in the tracer data from Korea, where Kim and Hwang (2002) noted that tidal pumping appeared to be much less effective in the dry season when the aquifer was not recharging.

While automated seepage meter records often show seepage spikes with periods corresponding to the dominant tides, other factors could be playing a role. It is well known that benthic chambers deployed on the seabed cause local pressure perturbations that can drive advective pore water flow (Huettel and Gust 1992). Shinn et al. (2002) recently described “too high” seepage meter results from Florida Bay that they ascribed to this process and referred to it as “Bernoulli’s Revenge.” Tidal currents could also be at a maximum during tidal transition periods suggesting that pressure gradient induced flows may be responsible for these spikes. However, groundwater tracers (^{222}Rn, Ra isotopes and methane) measured in the overlying water column also show the same patterns (Burnett et al. 2002; Kim and Hwang 2002). It is difficult to imagine that a Bernoulli effect could have produced similar flux data in the chamber as those inferred from the tracer concentrations in the overlying water column. Such pressure-induced artifacts may be important in some situations, however, and should be investigated further.

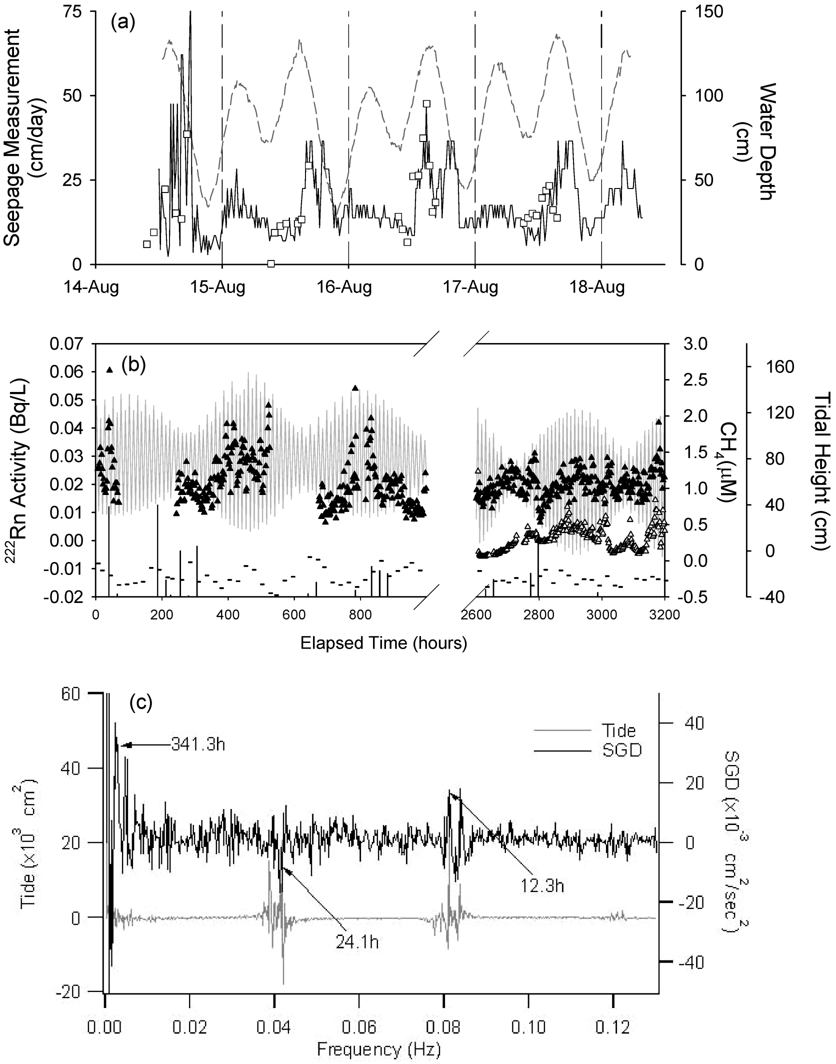

Figure 2. (a) Record of an automatic seepage meter (solid line) in a coastal setting in Florida over 4 d in August 2000 together with measurements from manual seepage meters (open symbols) and the tidal record (dashed line). Redrawn from Burnett et al. (2002). (b) Long-term (July 3 to Nov. 14, 2001) variation of the groundwater tracers radon (closed triangles) and methane (open triangles) in a coastal station near Busan, South Korea, together with the tidal record, precipitation (solid lines), and wind speed (dashes) during the same interval. The highest wind speed is about 5 m/s and the highest precipitation was 80 mm – the other measurements are shown in proportion to those values. Redrawn from Kim and Hwang (2002). (c) Time series analysis (FFT method) of SGD measurements and tides in Osaka Bay, Japan, from May 29 to August 23, 2001. The main frequencies recognized by the FFT analysis correspond to semi-diurnal (12.3 hr), diurnal (24.1 hr), and bi-weekly (341.3 hr) lunar cycles (Taniguchi 2002).

Moore et al. (2002) recently reported the discovery of a subsurface semi-confined high permeability zone (HPZ) two meters below the seabed about 20 km off Holden Beach, North Carolina. A temperature probe placed in the HPZ recorded a 1 °C semidiumal cycle indicating water exchange between the coastal aquifer and the ocean. The cycle was exactly in phase with the tide – again suggesting tidal pumping as either a forcing mechanism or a modulating factor.

Advective pore water exchange in the shallow shelf

As discussed above, the flow of water through coastal sediments is not exclusively tied to terrestrially driven (fresh) groundwater seepage. Interaction of boundary layer currents and sea bed topography causes advective pore water flow in permeable coastal sediments that can be an important mechanism controlling water column geochemical characteristics in the coastal zone (Shum and Sundby 1996).

Prerequisite for such advective water exchange is a relatively high permeability of the sediment; the lower permeability limit for pore water transport that significantly exceeds diffusive transport is approximately 10^{-12} m^2 (Huettel et al. 1996). In general, the mean grain size and the permeabilities of the sediment surface layers increase from the continental rise towards the coast (Emery and Uchupi 1972). The decrease in water depth amplifies the effect of bottom currents. At water depth less than 100 m, the wave orbital motion reaches the seabed and tidal current speeds increase, producing strong bottom shear and sediment erosion (Nittrouer and Wright 1994; Jing et al. 1996). In this zone, frequent resuspension of the terrigenous shelf deposits and the removal of the fine material by cross-shelf currents, result in well-sorted sand beds that are characterized by high permeabilities that permit measurable pore water flows. In the upper part of the continental slope, most of the 10^{-12} m^2 permeability isolines turn parallel to the 200 to 500 m isobaths (Riedl et al. 1972). The contribution of the porous component to the surface sediments of the eastern USA shelf is approximately 92% (gravel 11%, shell 14%, sand 67%; Hayes (1967) and Stoddart (1969), Riedl et al. (1972)). The area of higher permeability sand sediments on an average shelf may be approximately 65%, in agreement with the estimates of Emery (1968); Figure 3.

Where the bottom currents are sufficiently strong to resuspend and winnow the sediment, the seabed surface is structured by current or wave ripples (Wiberg and Harris 1994) that cause the advective pore water exchange. The deflection of the unidirectional or oscillating boundary layer currents at sediment surface structures (e.g., ripples, biogenic topography) produces local pressure gradients that drive pore water flows and interfacial fluid exchange (Webb and Theodor 1968; Thibodeaux and Boyle 1987). In surface depressions, like ripple troughs, water penetrates into the sediment and flows on a curved path towards protruding surface structures, the ripple crests, where the pore water is released ((Huettel and Gust 1992); Figure 4). For reasons of mass balance, the same volume of water that is forced into the sediment also flows from the bed. The resulting sediment pore water exchange (SPE) carries organic matter and oxygen into the sediment, creates horizontal concentration gradients that can be as strong as the vertical gradients, and increases the flux

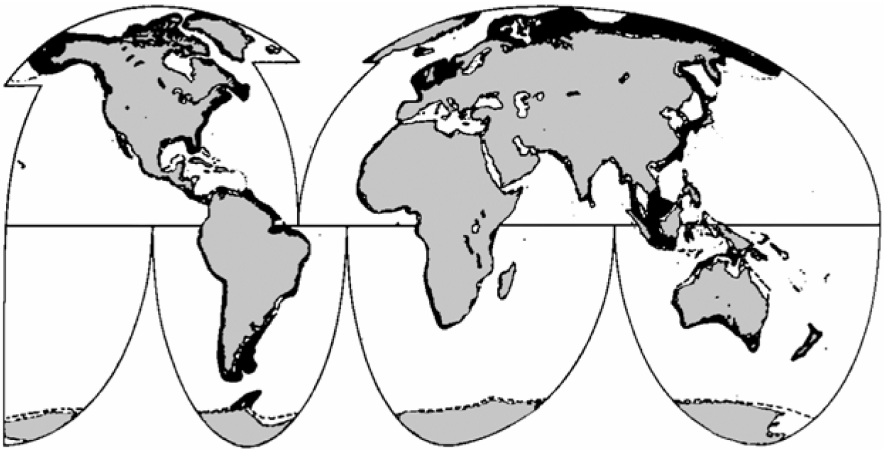

Figure 3. Generalized distribution patterns of relic permeable sediments (black areas) on continental shelves. Reproduced from Emery (1968).

of pore water constituents across the sediment-water interface. Due to the continuously changing sediment topography and boundary layer flow characteristics, advective pore water circulation and ensuing biogeochemical zonation are highly variable in space and time (Huettel et al. 1996).

The depth of the sediment layer that is affected by this advective exchange is related to the size and spacing of the ripples and, in homogenous sediment, reaches down to approximately two times the ripple wavelength (Hutchinson and Webster 1998). Under calm hydrodynamical conditions (friction velocity $u_* < 5$ cm/s) the pore water velocities in typical shelf sands (200 μm, permeability $k = 10^{-11}$ m^2) may reach vertical velocities of 2 to 3 cm/h in the uppermost centimeter of a rippled bed (5 cm amplitude, 30 cm wavelength; (Huettel et al. 1996)). With these upwelling velocities, the sediment exposed to unidirectional flow (e.g., during recessing tide) releases approximately 75 to 100 L/m^2·d. In flume experiments surface gravity waves caused pore water release rates up to 222 L/m^2·d in similar sediments, demonstrating that oscillating boundary flows can effectively enhance the fluid exchange between the seabed and the water column.

Riedl et al. (1972) used thermistor flow sensors embedded in permeable shelf sands and measured interfacial pore water exchange caused by surface gravity waves. Based on their findings they calculated that worldwide waves filter a volume of 97×10^3 km^3/y through the permeable shelf sediments. The intertidal pump, driven by swash and tidal water level changes, moves another 1.2×10^3 km^3/y through the sandy beaches of the world. These estimates suggest that wave action alone can filter the total ocean volume through permeable sediments within about 14,000 yr.

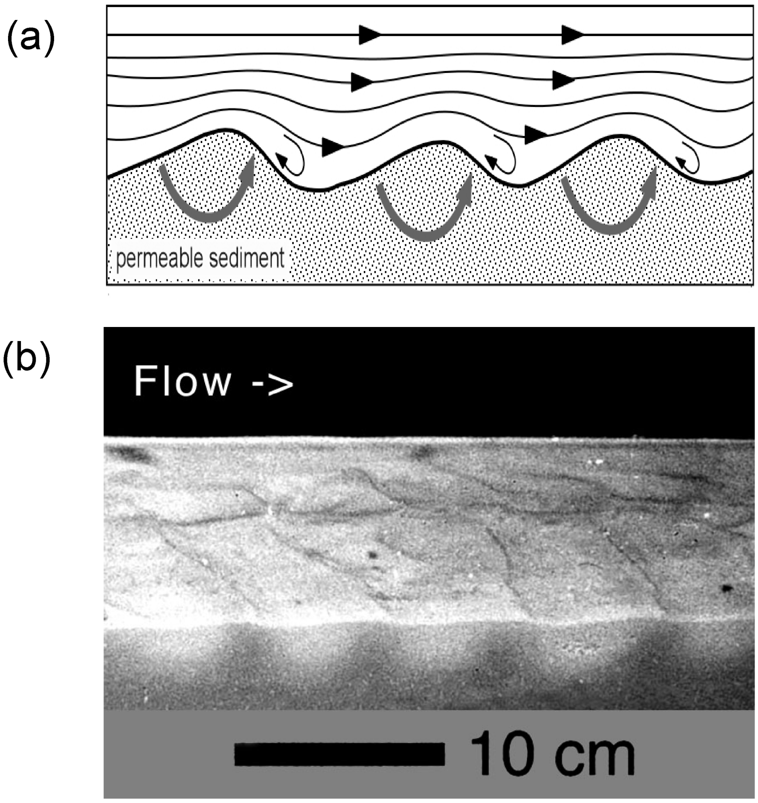

Figure 4. (a) Schematic view of pore water flow directions under ripples exposed to unidirectional flow. Water intrudes the sediment at the upstream face of the ripple and moves on a curved path to the downstream slope where it is released from the sediment. (b) Washout pattern in a sediment with ripples exposed to unidirectional boundary flow. The pore water of the sandy sediment was stained with Rhodamine dye. The cross section of the core shows dye washout under the ripple troughs caused by advective pore water flows generated by ripple-flow interaction (Huettel and Rusch 2000).

Seawater intrusion into coastal aquifers

There are numerous examples of human-induced SGR where demand for fresh water by coastal communities has intensified infiltration of seawater into coastal aquifers by decreasing the hydraulic pressure in these aquifers (Smith 1988). As an example, in the Savannah, Georgia, area, groundwater pumpage increased from 42 million gallons per day in 1943 (Warren 1944) to 96 million gallons per day in 1983 (Smith 1988). In many cases this usage is seasonal in nature and causes considerable fluctuation in hydraulic pressure and seawater infiltration into these systems. The reason for the increased demand is clearly from population growth, which is much higher in coastal areas of the U.S. and elsewhere than in non-coastal areas. For example, in 1960 an average of 187 people was living on each square mile of

U.S. coastal land (excluding Alaska). This increased to 273 persons per square mile by 1994, and is expected to reach 327 by 2015. From 1960 to 2015, the coastal population of the U.S. is estimated to increase by 71 million people. This is more than twice the size of California's current population. The noncoastal population, by comparison, will have increased during this same time period by about 59 million people across a much larger area (http://state-of-coast.noaa.nov/bulletins/html/pop_01/national.html).

In the early twentieth century, artesian (free-flowing) wells were common along the U.S. southeast coast (Warren 1944); now they are rare. Warren studied artesian flow along the entire coast of Georgia, about 125 km. He found areas in all coastal counties where artesian wells discharged at least 1 million gallons per day. In 1880, potentiometric surfaces in the Floridan Aquifer at Savannah, Georgia, were +10 m (Bush and Johnston 1988); now they are −30 m (Smith 1988), a drop of 40 m. In 1880, fresh water discharged into Port Royal Sound east of Savannah (Smith 1988, 1993); now the Floridan Aquifer in this area is being recharged with seawater from the Sound (Burt 1993). Analyses of ^{14}C in these salty groundwaters reveal that they contain up to 74% modern carbon, in contrast to eastern and northern regions of the aquifer where the fraction is <2% (Burt 1993; Landmeyer and Stone 1995). Dredging has facilitated the salinization of the aquifer. Duncan (1972) documented breaches in the confining unit above the Floridian Aquifer that correlate well with channels and turning basins dredged through Port Royal Sound. Where the aquifer is in direct contact with the ocean, water exchange will occur. In addition to rendering the groundwater non-potable, salt water intrusion into these aquifers causes ion exchange and other reactions to occur, which chemically alter the intruding seawater and enrich the fluids in metals and nutrients (see "Global Fluxes and Biogeochemical Implications" section).

Most models of fluid flow in coastal aquifers are designed to evaluate residual flow. The boundary between salt and fresh water in such models is considered a plane that may move inland as potentiometric surfaces are reduced, or toward the sea if these surfaces are increased. Superimposed on the residual flow are fluctuations due to differences in recharge and demand. These fluctuations amplify dispersion in the aquifer and may cause considerable exchange between water in the aquifer and the coastal ocean. Models to evaluate SGR induced exchange are lacking.

Measurement of SGD

There are many factors that affect rates of groundwater flow into the coastal zone, either directly or indirectly (Table 1). The pressure head and transmissivity are the main factors that determine the flux of terrestrially-derived SGD. Furthermore, the head is a function of the hydraulic gradient (influenced by topography) and the terrestrial groundwater recharge rate (affected by precipitation and evapotranspiration). The types and extent of vegetation as well as climate will determine evapotranspiration rates. Transmissivity may be controlled by permeability (geology) and development of river systems (geomorphology). Thus, parameters concerning geology, precipitation, vegetation (land use), and topography are all contributing factors in determining rates of terrestrially derived groundwater flow to the sea. Without the benefit of measurements, one could predict that land-derived SGD fluxes would be amplified in areas of high permeability (karst), high relief near the coast, areas without well-developed river systems (some large oceanic islands), and regions with high groundwater recharge rates (humid tropics). While useful, these generalizations hardly provide the information required to evaluate the importance of groundwater pathways to the coastal zone. One requires actual measurements for that purpose (Burnett et al. 2001).

There are three general approaches to assessment of SGD: (1) modeling; (2) direct physical measurement; and (3) tracer techniques. There are several modeling approaches ranging in complexity from simple on-shore groundwater mass balance calculations through to comparatively complex numerical models of sub-surface flow (Smith and Nield, this issue; Oberdorfer, this issue). Direct physical measurements are typically limited to seepage flux meters and measurement of the direction and magnitude of hydraulic gradients across the sediment-water interface. Several variations in design of seepage meters have been developed (Taniguchi et al., this issue). Chemical tracing techniques may make use of either natural geochemical species such as radium isotopes and radon (Cable et al. 1996; Corbett et al. 1999; Moore, this issue; Lambert and Burnett, this issue) or artificial tracers such as sulfur hexafluoride and ^{131}I (Dillon et al. 1999, 2000; Corbett et al. 2000).

When SGD assessments are performed, the rate of groundwater discharge can be described in several different ways. One that is widely used is the specific volume flux across the sea floor, for example cubic centimeters of water per square centimeter of the sea floor per second ($cm^3/cm^2{\cdot}s$) that is equivalent to a velocity (cm/s). Note that a correction for the porosity of the sediment must be applied to derive the rate of travel of the water in the sediment itself. Such volume fluxes could also be expressed as liters per square meter per day ($L/m^2{\cdot}d$) or equivalent terms. SGD has also been expressed as the total volume discharge per unit length of shoreline per unit time (e.g., L/m·d). While more difficult to gauge because more measurements are required, such integrated assessments are very useful for extrapolating to larger areas.

Unfortunately, there are two fundamental problems in the manner that assessments of SGD have traditionally been undertaken: (1) rarely are two or more approachs employed in any one study; and (2) uncertainty estimates are almost never provided. Errors are rarely reported for groundwater flux estimates because there are typically so many assumptions made in the calculation that putting reasonable uncertainty limits on the final result is extremely difficult. Obviously, this is an area where improvements can be made.

One of the tasks of SCOR WG-112 was to conduct a series of assessment intercomparison experiments in order to compare various measurement and modeling approaches on a level playing field. Each intercomparison involved as many methodologies as possible. These experiments were held at coastal sites on the northeastern Gulf of Mexico, Florida (August 13–18, 2000); Cockburn Sound, Western Australia (Nov. 25 - Dec. 6, 2000); and on eastern Long Island (May 17–24, 2002). In general, the results have shown good agreement between the geochemical tracers and seepage meter measurements, both of which measure total flow (Burnett et al. 2002; Taniguchi et al. 2003; Moore, this issue; Lambert and Burnett, this issue). On the other hand, hydrologic modeling in at least one case (Smith and Zawazski, this issue) tended to produce results 8–10 times lower than the measurement-based estimates. Smith and Zawazski suggest that flow driven by transient processes such as tidal pumping, which appear to influence the total flow but are not included in the model, may be responsible for the observed discrepancy.

A review of all locations where SGD estimates have been made by measurement techniques shows that many independent studies have been performed on the east coast of the United States, Europe, Japan, and Oceania (Taniguchi et al. 2002). Fewer studies have been done on the west coast of the U.S. and Hawaii. It is significant that many SGD measurements have been made in karst areas where the hydraulic conductivity of the aquifers is large and thus significant amounts of fresh groundwater discharge are expected under reasonable hydraulic gradients. Additional data collection is required in many areas, especially in South America, Africa, and southern Asia, where, to our knowledge, no assessments are currently available in the literature.

Global fluxes and biogeochemical implications

Water fluxes

The magnitude of terrestrially derived (fresh) SGD on a global (or even regional) scale has proven to be very difficult to estimate. The effects on global geochemical cycles are thus impossible to evaluate with any precision. This situation is significantly different than that for other major inputs to the ocean. The major rivers of the world are gauged and well analyzed, thus allowing relatively precise estimates of riverine input to the ocean (Berner and Berner 1987). Elemental fluxes at hydrothermal systems along mid-oceanic ridges and elsewhere have been studied in considerable detail and although there is still considerable debate concerning the absolute magnitude of hydrothermal discharge, it is well established that hot springs are significant for the marine budgets of many elements (Edmond et al. 1979; von Damm et al. 1985; von Damm 1990).

Global-scale estimates have been based on hydrological assumptions and water balance considerations. 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/d, and the unit flow rate to be 35 L/s. COSOD II (1987) assumed that 33 % of rainfall that occurs on land infiltrates into aquifers, and half of this is subsequently discharged into the ocean as submarine springs, resulting in an estimated global SGD of 100 km^3/yr or ~ 0.3 % of total runoff to

Table 2. Some estimates of terrestrially-derived fresh SGD on a global scale. Assuming a mean river flow of 37,500 km^3/y, SGD ranges from 0.3% to 16% of the global river flow.

Amount of SGD* km^3/y	Estimation Method	Reference
1700	Hydrological assumptions	Chandury and Clauer (1986)
100	Hydrological assumptions	COSOD II (1987)
2200	Literature	Berner and Berner (1987)
2400	Hydrograph separation, Combined hydrological-hydrogeological method	Zektser and Loaiciga (1993) and Zektser (2000)
2200	Water balance	Shiklomanov (1999)
1000-3000	Water balance	Milliman (pers. comm.)
4500-6500	Water balance	Seiler (2003)

*All estimates are for fresh water SGD; river discharge = 35,000-40,000 km^3/y

the ocean (total runoff estimated at ~37,400 km^3/y, Berner and Berner (1987); Milliman [pers.comm.] estimates river flow at 35,000-40,000 km^3/y). The ratio of fresh SGD to surface water inputs based on hydrological assumptions tend to be lower than those estimated by water balance approaches (Table 2). This may be a result of underestimating the thickness of coastal aquifers (therefore the distance from the shoreline for SGD).

Most estimates of terrestrially-derived fresh SGD range from 6 to 10 % of surface water inputs, with one exceptionally high value (31%; Lvovich (1974)) that seems unlikely (Zektser and Loaiciga 1993). Because of the methodologies used, all of the estimates shown in Table 2 are only for fresh water groundwater inputs. Since we have defined SGD as any and all fluid flows across the seabed, regardless of composition and driving force, estimates from such hydrological assumptions and water balance considerations will underestimate the total flow. From a marine geochemical balance perspective, the total flow should be considered, as chemical reactions occurring in the subsurface will affect the composition of recirculated seawater.

A summary of estimated and measured fluid discharges to the ocean and across the seabed shows that while unit fluxes are small, total discharge values can be huge (Table 3). We have attempted to identify in this table the composition (fresh or salt) and general energy source (terrestrial or marine) of fluids discharging or exchanging with the ocean. We define terrestrial forcing as originating from an on-land hydraulic gradient, while marine forcing may be due to tidal pumping or the effects of waves (Riedl et al. 1972). In some cases the composition and source is obvious (e.g., river discharge) but in others (e.g., the “intertidal pump”) there may certainly be mixtures, both in composition and forcing (see Table 1). In order to make comparisons among some of the global-scale estimates of SGD with fluxes evaluated over a local to regional scale, we have converted several of the discharge estimates to units of flux per unit width of shoreline. This will allow us to examine how fluxes measured in a particular area relate to these large-scale estimates and other important inputs to the ocean. In order to make this unit conversion for glo-

Table 3. Fluxes of terrestrially-derived water and recirculated seawater to the coastal zone and shelf expressed as volumetric discharge per unit time, flux per unit length of shoreline, and unit area fluxes.

Flux	Fluid Composition/Origin[1]	Reference
Global Discharge (km^3/y)		
Total runoff (rivers ~94%) = 37,400	fresh/terrestrial	Berner and Berner (1987)
Fresh groundwater seepage = 2,400[2]	fresh/terrestrial	Zektser (2000)
"intertidal pump" = 1,170	composite/mixed	Riedl et al. (1972)
"subtidal pump" = 95,700	seawater/marine	Riedl et al. (1972)
Shoreline Fluxes ($m^3/m{\cdot}day$)[3]		
Total runoff = 171	fresh/terrestrial	Calculated using shoreline length = 600,000 km
Subtidal pump = 437	seawater/marine	Riedl et al. (1972)
Intertidal pump = 5.34	composite/mixed	Riedl et al. (1972)
Groundwater seepage = 11	fresh/terrestrial	Calculated from Zektser (2000)
Measured (Florida) = 3–35	composite/mixed	Cable et al. (1997) and Burnett et al. (2002)
Measured (Australia) = 2–8	composite/mixed	Burnett and Turner (2001) and Smith and Nield (2003)
Measured (New York) = 30–120	composite/mixed	Bokuniewicz (unpublished results)
Unit Fluxes ($m^3/m^2{\cdot}y$)		
Seepage meters = 5–100	composite/mixed	Calculated from Taniguchi et al. (2002)[4]
Subtidal pump = 3.5	seawater/marine	Calculated from Riedl et al. (1972)
Intertidal pump = 195	composite/mixed	Calculated from Riedl et al. (1972)[5]

[1] Composition refers to fresh (meteoric) water, seawater, or a mixture; "origin" refers to driving force, either terrestrial hydraulic gradients or marine forcing (tidal pumping, wave set-up, etc.), or a mixture of terrestrial and marine. [2] Estimates for the fresh water component of groundwater discharge to the ocean vary tremendously, see Table 2. [3] We used 600,000 km as an estimate of the global shoreline length. [4] Approximately 85% of the measured seepage values from the coastal zone in this compilation fall in this range (1–30 cm/day). [5] Calculation assumes an intertidal width of 10 m and a shoreline length of 600,000 km

bal estimates, we need to assume a global shoreline length. Since the length of a shoreline depends upon the resolution of the measurement interval (Bokuniewicz et al. 2003), there are no definitive values. Estimates from about 500,000 to 600,000 km appear reasonable (R. Buddemeier, pers. comm.). Zektser (2000) states that "…a shoreline length of 600,000 km excludes Antarctica, Greenland, the Arctic, and some permafrost regions."

Using a value of 600,000 km for global shoreline length, we show the shoreline fluxes ($m^3/m{\cdot}d$) graphically (Figure 5) in three sections: (1) new coastal inputs (rivers and direct fresh groundwater discharge); (2) seawater exchange driven by

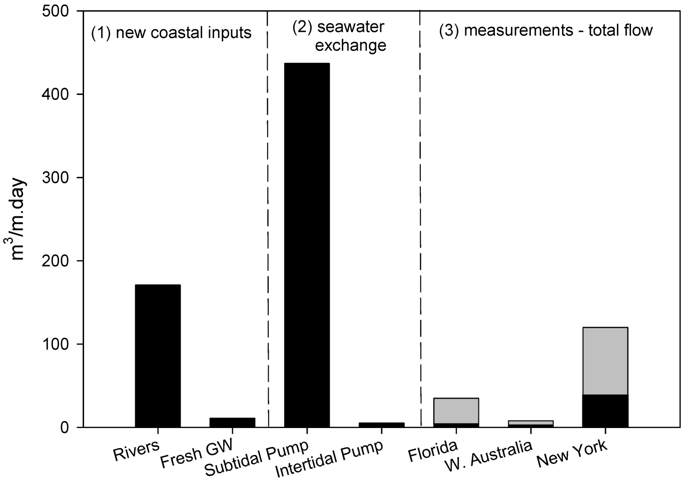

Figure 5. Fluid discharge and exchange in the ocean normalized to units of flow per unit width of shoreline (m^3/m.d) for new inputs (rivers and fresh groundwater), exchange due to the subtidal and intertidal pumps, and from measurements of total flow in three coastal environments investigated by SCOR WG-112. The black and grey bars show the lower and upper measurements at the three sites, respectively. Data and references are from Table 3.

the subtidal and intertidal pumps (Riedl et al. 1972); and (3) a few actual measurements of total flow at three sites investigated recently by SCOR WG-112 (Burnett and Turner 2001; Burnett et al. 2002). We used an estimate of the global fresh groundwater discharge of 2400 km^3/y or about 6% of the total discharge to the sea for this comparison. The largest flux of water by far is the exchange of seawater driven into and out of permeable sediments via wave pumping, the SPE due to surface wave-induced hydrostatic pressure oscillations at the sea floor, called the “subtidal pump” by Riedl et al. (1972). This wave pumping is estimated to drive 95,700 km^3/y of seawater exchange into sandy sediments from the shoreline to the edge of the continental shelves of the world. Note that the unit fluxes for this process are very small (3.5 m^3/m^2.y or ~ 1 cm/d) but the area over which it operates is huge – essentially most of the continental shelves of the world out to the 200-m isobath. Exchange driven by the intertidal pump, propelled by the swash-tide interaction, is only about 1% of that driven by the subtidal pump. The shoreline flux for the intertidal pump, however, is within the range of seepage measurements in many areas and could be locally important. The actual measurements shown are for total (fresh plus seawater) SGD and may have a very large component of recirculated seawater (e.g., up to 80–90% seawater was measured in seepage meters during the Florida experiment).

It has been observed in many studies that SGD generally decreases in a somewhat systematic fashion away from the shoreline. Taniguchi et al. (2002) recently compiled data from all published sources, that reported both measured rates and water depth, and examined the relationship between direct measurements of SGD and depth (Figure 6). SGD data vary widely but discharge estimates decrease fairly

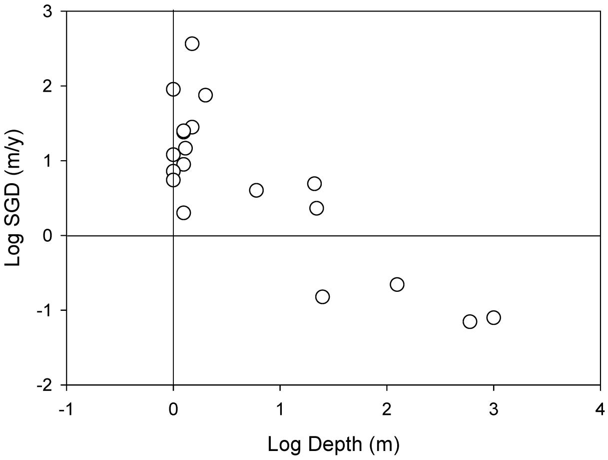

Figure 6. Relationship between measured SGD and water depth. Data from Table 1 in Taniguchi et al. (2002).

systematically with increasing water depth over about three orders of magnitude. This shows that SGD can be expected to decrease with increasing depth (and increasing distance from shore); however, one should obviously be cautious about drawing too many conclusions based on such limited results. Most SGD measurements have been performed where it is easily found and large volumes of SGD are expected. Many additional measurements in a variety of coastal environments are necessary to improve and clarify these relationships.

Chemical inputs

The advective flux of terrestrially-driven groundwater through coastal sediments is becoming recognized as an important mechanism for transferring material from the land to the ocean (Cathles 1990; Valiela and D'Elia 1990; Moore 1996; Jickells 1998). This flow may occur through the surficial aquifer or through breaches in deeper semi-confined coastal aquifers (Moore 1999). As stated above, the overall flow of fresh groundwater into the ocean is likely no more than about 6% of the total runoff; however, it has been estimated that the total dissolved salt contributed by terrestrially-derived SGD may be as much as 50% of that contributed by rivers (Zektser and Loaiciga 1993). This process will thus affect the biogeochemistry of estuaries and the coastal ocean through the addition of nutrients, metals, and carbon (Moore 1996).

While data on chemical inputs to the ocean via groundwater are largely lacking, some rough estimates have been made and serve to illustrate the potential importance of SGD to marine geochemistry. Table 4 summarizes some estimates for various inputs of Ca^{2+} to the ocean from all known sources. Milliman (1993) showed that in order to balance a steady-state ocean with respect to its present calcium content and other known inputs, a groundwater flux of 1.6×10^{13} moles per

Table 4. Various estimates of global Ca^{2+} inputs to the ocean. The groundwater estimates are for fresh discharges and are known to have very large uncertainties.

Source	Inputs 10^{13} moles/y	Reference
Rivers	1.2–1.5	Meybeck (1979) Berner and Berner (1987) Morse and Mackenzie (1990) Milliman (1993)
Hydrothermal activity	0.2–0.3	Wolery and Sleep (1988)
Aeolian inputs	0.005	Milliman (1993)
Groundwater	0.5	COSOD II (1987)
Groundwater	0.5–1.6	Milliman (1993)

year would be required. This is about 20% higher than estimated riverine inputs! In an alternative model where the ocean does not maintain a short-term steady-state but requires a complete glacial cycle to achieve constant composition, Milliman calculates an input value (0.5×10^{13} moles/y) that is about 40% of the present river contribution. Again, these estimates were based solely on the fresh (meteoric) water cycle. If one considered Ca^{2+} fluxes from seawater exchange via the subtidal pump, then fresh water inputs would be correspondingly lower. There is very likely an exchange of Mg^{2+} for Ca^{2+} when seawater circulates through carbonate sediments (e.g., Fanning et al. (1981)). A rough estimation in COSOD II (1987) showed that about 0.5×10^{13} moles/y of Mg^{2+} (same order of magnitude as river input) is removed from seawater and an equal amount of Ca^{2+} is released during fluid flow through carbonates.

One of the reasons why so little data exist on advective transport of chemical species through sediments is that most geochemical studies of sediments have concentrated on muddy sites where diffusion and biological mixing drive exchange with the overlying ocean. The techniques and models used in those studies are not applicable to sites where advection through permeable sediments is the primary exchange agent. Results based only on muddy areas may seriously underestimate the fluxes of biogeochemically important materials in the coastal ocean. Since advection tends to overwhelm diffusion on most scales, such calculated fluxes could be underestimated by orders of magnitude.

During the passage of terrestrially derived fluids through sediments in a coastal aquifer, mixing of seawater with fresh groundwater and chemical reactions of the fluids with solid phases will occur. The emerging fluid is chemically distinct from both the groundwater and seawater end members. Concentrations of nutrients, trace metals, organic carbon, methane, and CO_2 may be considerably higher than surface ocean waters (Simmons 1992; Bugna et al. 1996; Paerl 1997; Cai and Wang 1998). Major ions may be affected by diagenesis of solid phases (Burt 1993). Since terrestrially-derived SGD may bypass the estuary filter, this source term may affect the coastal ocean quite differently than river discharge. Noting the similarities to surface estuaries, Moore (1999) has advanced the concept that many coastal aquifers are "subterranean estuaries."

In subterranean estuaries, chemical reactions between the mixed waters and aquifer solids modify the fluid composition much as riverine particles and suspended sediments modify the composition of surface estuarine waters. Geochemists studying coastal aquifers have long recognized the importance of chemical reactions between aquifer solids and a mixture of seawater and fresh groundwater (Runnels 1969; Back et al. 1979). For example, the mixing of seawater supersaturated with respect to calcite with fresh groundwater saturated with respect to calcite can result in solutions that are either supersaturated or undersaturated (Plummer 1975). This mechanism was proposed by Back et al. (1979) to explain the massive dissolution of limestone along the northern Yucatan Peninsula. Dissolution of submarine limestone by groundwater flow creates distinctive canyons and escarpments on continental margins (Paull et al. 1990).

Calcite dissolution may also be driven by the addition of CO_2 to fluids in the subterranean estuary. Burt (1993) has shown that salt water penetrating the Floridan aquifer near Savannah, Georgia, is enriched in inorganic carbon and calcium, as well as ammonia and phosphate, relative to sea water and fresh groundwater end members. He attributed these enrichments to oxidation of organic carbon within the aquifer or CO_2 infiltration from shallower aquifers. Cai and Wang (1998) have shown that shallow coastal groundwaters are highly supersaturated with respect to CO_2.

Many workers have recognized the biogeochemical importance of groundwater discharge through coastal sediments. Such fluids may be an important source of nutrients for coral reefs (Marsh 1977; Johannes 1980; D'Elia et al. 1981) or other communities on the continental shelf (Simmons 1992; Jahnke et al. 2000). In addition to freshwater, both natural and anthropogenic materials can be carried by groundwater to surface waters. Sewage, mining waste, and other soluble refuse percolating into an aquifer may eventually enter coastal waters via groundwater discharge. Depending on the concentrations and flow paths of these contaminated plumes, the ecology of the coastal waters could be impacted. It was shown, for example, that groundwater nutrient loading of several bays in New England increased eutrophication, thus increasing fin-and shellfish kills (Valiela and D'Elia 1990). Bokuniewicz (1980) showed that subsurface discharge accounts for greater than 20% of the freshwater input into the Great South Bay, New York. In follow-up studies by Capone and Bautista (1985) and Capone and Slater (1990), it was shown that SGD is a significant source ($\geqslant 50\%$) of nitrate to the bay. These investigators also argued that the amount of nitrate reaching Great South Bay would be even higher if some denitrification didn't occur during groundwater transit through the bay sediments. Simmons (1992) and Krest et al. (2000) estimated that the fluxes of nitrogen and phosphorus to the Georgia and South Carolina shelf from SGD exceeded fluxes from local rivers.

Groundwater-borne nutrients may have significant effects on water quality in surface estuaries (Reay et al. 1992). Groundwater may have nutrient concentrations several orders of magnitude greater than surface waters, either from contamination

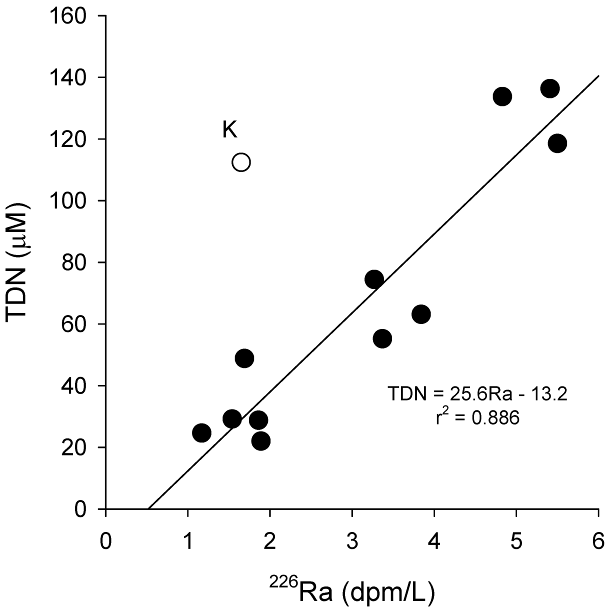

Figure 7. Concentrations of total dissolved nitrogen (TDN) versus ^{226}Ra in water samples from various depths in six offshore wells on the shelf of North Carolina. Well "K" was excluded from the correlations. A regression of total dissolved phosphate (TDP) versus ^{226}Ra (not shown) results in an equation TDP = 0.61 + 1.3; $r^2 = 0.82$. Diagram plotted from data in Moore et al. (2002).

sources (septic systems, etc.) or natural processes. Thus, nutrient concentrations in coastal groundwaters may be a significant factor in the eutrophication of near-shore waters (Valiela et al. 1990) and may provide nutrition to sea floor vascular plants (Rutkowski et al. 1999).

Moore et al. (2002) reported that nutrients were highly correlated to radium in subsurface fluids investigated in wells 2 meters below the seabed 20 km off North Carolina (Figure 7). Temperature excursions in these wells indicated exchange with the overlying seawater. Since the ^{226}Ra balance in this area was derived previously (Moore 1996), the nutrient-radium correlations could be used to estimate nutrient fluxes. They estimated that the total dissolved nitrogen (TDN) flux to offshore waters between Cape Fear, North Carolina, and the Savannah River is 4.0×10^6 moles/d and the total dissolved phosphate (TDP) to the same area is 1.4×10^5 moles/d. Krest et al. (2000) had earlier estimated large groundwater fluxes of dissolved inorganic nitrogen (DIN; $\sim 1.8 \times 10^6$ moles/d) and dissolved reactive phosphate (DRP; $\sim 8.8 \times 10^4$ moles/d) to salt marshes in the same area. When the offshore groundwater fluxes are combined with those to salt marshes, the overall groundwater fluxes exceed estimated riverine (DIN: 1.6×10^6 moles/d; DRP: 7×10^4 moles/d; Krest et al. (2000)) and atmospheric (N: 3.5×10^6 moles/d; Prospero et al. (1996)) fluxes to the same area. These numbers are very impressive and suggest that underlying aquifers are important sources of nutrients to coastal waters and likely a source of "new" nutrients to the ocean.

The chemical and ecological significance of the advective pore water flow that occurs beyond the zone of influence of SGD derived from land is fundamentally different from that of the terrestrially-derived groundwater inputs, as advective pore water flow does not include import of allochtonous substances into the coastal zone. Nevertheless, the current-induced pore water transport may be important for the coastal cycles of matter through the acceleration of the deposition and mineralization process (Marinelli et al. 1998). Due to advective pore water exchange, coastal permeable sands function like expansive biocatalytic filter systems and may, in part, be responsible for the tight cycling of matter in the shelf, reducing the export to the deep ocean (Huettel et al. 1998).

For example, Bacon et al. (1994) reported that in permeable Middle Atlantic Bight shelf sediments (>90% sand), where no net accumulation of sediment and organic matter presently occurs, the excess ^{210}Pb inventories are nearly in balance with the atmospheric supply. Because ^{210}Pb only enters the sediment adsorbed to fine particles, these results imply that the sands efficiently retain fine particulate matter due to a trapping mechanism. Distributions of ^{210}Pb in suspended particulate matter and in the fine fraction of shelf sediments suggest that the average fine particle must undergo several cycles of deposition-resuspension-redeposition and requires a number of decades for its transit and ultimate export from the shelf. Thus, only the most refractory organic matter is likely to be exported. Bacon et al. (1994) concluded that the export of particulate organic carbon from the shelf to the deep sea is probably less than 25% of the primary production.

Flume and in-situ studies have showed that suspended particles and phytoplankton are filtered from the water column during seawater flow through sediments, thereby increasing the deposition rate (Rusch and Huettel 2000; Huettel and Rusch 2000). Within the sediment, the organic particles are exposed to higher mechanical stress, higher bacterial abundances, and higher exoenzyme concentrations, accelerating their decomposition. Directed advective transport of oxygen and other electron acceptors into the sediment has been shown to occur based on both flume (Ziebis et al. 1996) and field studies (Lohse et al. 1996). The simultaneous transport of metabolite products (HCO_3^-, inorganic nutrients) out of the sands has been shown by flume studies (Huettel et al. 1998). Marinelli et al. (1998) found evidence for advective nutrient release from permeable sediments on the south Atlantic Bight continental shelf. The uptake of organic particles and subsequent regeneration of metabolites convert these seemingly unreactive permeable sands into efficient bioreactors (Huettel and Rusch 2000).

The effect of advective pore water flow from the biocatalytic sand filter is documented by high benthic primary production on coarse organic-poor sands reaching 800 mg C/m^2·d. Roughly 30% of the continental shelf sea floor, an area of approximately 3.4×10^8 km^2, receives sufficient light to support significant rates of benthic primary production that would result in an estimated production of 2.9×10^{14} g C/y (0.3 Gt C/y; Nelson et al. (1999) and Jahnke et al. (2000)). However, this indirect evidence for advective nutrient release may be strongly affected by the impact of nutrient-rich terrestrially-derived groundwaters through the sandy seabed.

Investigations using isotopes and other novel techniques are needed to assess the contribution of the two processes to benthic primary production.

How these advective processes affect the biogeochemistry of estuaries and the continental shelf is only beginning to be appreciated. A great deal of work remains before SGD can be evaluated relative to more conventional processes. For example, nutrients may enter the coastal ocean through rivers, the atmosphere, or upwelling at the shelf break, as well as SGD. The biological effects of these inputs depend not only on the magnitude of the input but how and where the nutrients are delivered. A relatively small input to an isolated embayment may have an effect much different than a more substantial input spread over a large fraction of the shelf. Differing amounts of nitrogen, phosphorus, and silica may also create distinct responses. To achieve a more complete understanding of the role of advective processes in sediments, studies over a range of scales and environments are required.

Summary and recommendations

Over the past decade, there has been a substantial increase in the recognition of the importance of both hydrologically driven and oceanically forced fluid flow through shelf sediments. In the coastal zone, both processes may be important and will have important biogeochemical effects in many cases. It is clear that the magnitude and influence of fluid discharge and exchange in coastal sediments on the cycles of matter on the shelf is not well understood. This lack of understanding is due to missing quantitative data on SGD and confusion regarding the definition and functioning of the processes. We have attempted to resolve this confusion by presenting a straightforward definition of SGD and summarizing our understanding of the processes that drive this flow. We have also summarized the estimated magnitudes of fluid flow through shelf sediments, and the potential implications for chemical and biochemical budgets. The fact that the scientific community has advanced from a position where these advective processes were essentially ignored to the current appreciation is a major step; however, several additional challenges remain.

Huge coastal areas of the world have no measurements to assess terrestrially-driven SGD. Data are particularly lacking from south Asia, Africa, and South America. We recommend an approach that targets representative types of coastal aquifers based on geology (e.g., karst, coastal plains, deltaic, etc.) and environmental parameters (e.g., precipitation, temperature, etc.). The production of an SGD database and globalization efforts using typological approaches is necessary to more completely describe SGD on a global scale.

Improvements must be made to techniques used for measurements of SGD. The sensitivity of pore water exchange to local pressure perturbations necessitates the development of new non-invasive methods, and we need to revise our monitoring, measuring, and sampling strategies in permeable seabeds. The calculation of realistic estimates of advective pore water exchange in the coastal zone and on the shelf requires concurrent data on bottom current characteristics, sediment topography, and sediment permeability. In particular, we must attempt to distinguish fluid flow caused by terrestrial groundwater discharge, hydrodynamical forcing, density gradients, sediment compaction, geothermal convection, etc. Application of less disruptive in-situ measurement techniques is very desirable.

Long-term studies and isotopic signatures, as well as certain chemical and physical properties of the pore fluids may provide indications of the origin and physical forcings of the pore fluid flows. However, in many cases, several of these processes will be active simultaneously and their separation based on measured data may be very difficult if not impossible. An indispensable tool for overcoming this problem is modeling of the different transport processes and their effects on the biogeochemical cycles. Most existing hydrogeological models, for example, do not include transient processes such as tidal pumping that may induce and modulate SGD. A new generation of dynamical models is needed to explain the pore water flow observed in natural environments. These models should add the lateral to the vertical spatial dimension, include surface topography, boundary layer flows, transient processes acting on the shelf, and temporal changes of boundary conditions (e.g., movement of ripples).

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